the ENERGY lab

Office of Fossil Energy

Hydrogen Turbine Program Project Portfolio 2013

U.S. DEPARTMENT OF ENERGY | NETL

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SECTION 1: INTRODUCTION

On behalf of the U.S. Department of Energy (DOE) Office of Fossil Energy (FE), the Hydrogen Turbine program is pleased to present the fiscal year (FY) 2013 *Hydrogen Turbine Program Project Portfolio*. This report summarizes current progress of research and development (R&D) that is focused on developing fuel-flexible turbines that produce power in a way that is clean, efficient, less costly, and minimizes carbon dioxide (CO_2) emissions.

BACKGROUND AND TECHNOLOGY STATUS

Turbines in power plants convert heat energy to mechanical energy by expanding a hot, compressed working fluid through a series of airfoils. Utility-scale combustion turbines draw in air, compress it, send it to a combustor where it is combusted with a fuel (to include natural gas, coal-derived synthesis gas [syngas], or hydrogen), and then expand the combustion gases through the airfoils (see diagram below, left to right). The exhaust gas of a combustion turbine is very hot (>1,000 °F) and can be used to preheat combustion air in a simple cycle application, or generate steam in a heat recovery steam generator for a steam turbine in a combined cycle application. The efficiency of combustion turbines has steadily increased as advanced technologies have provided manufacturers with the ability to produce highly advanced turbines that operate at very high temperatures (>2,600 °F).

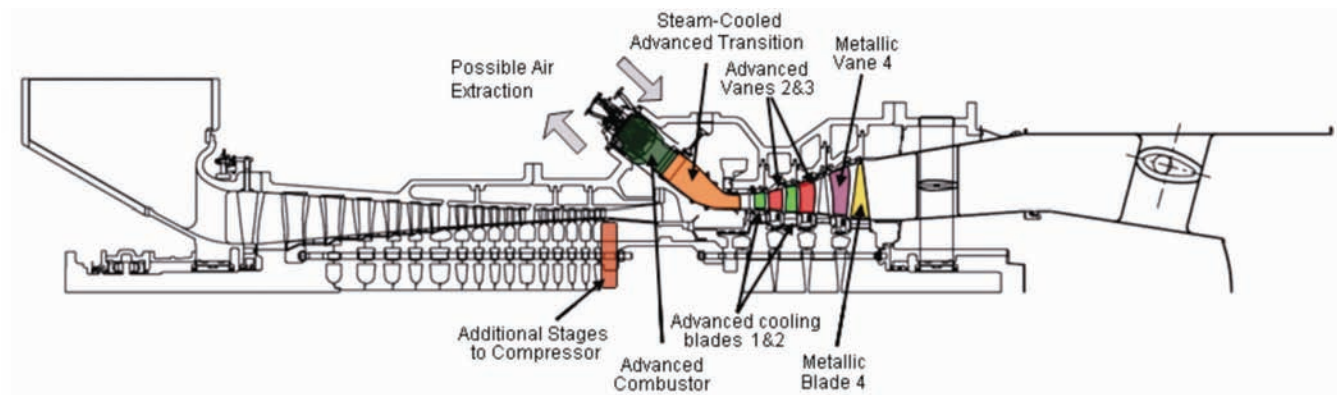


Figure 1-1. Advanced Hydrogen Turbine Schematic

Turbines are a proven technology for power generation, which is typified by the sheer number of turbines in use today. Turbines find use in a variety of applications, ranging from turbines for propulsion in the aviation industry to steam turbines in pulverized coal combustion boilers. Turbine technology is responsible for the vast majority of power production in the United States and the world. Integration of a steam turbine and advanced gas turbine forms the combined cycle electric-power-generation module in the integrated gasification combined cycle (IGCC) for coal-based power plants and natural gas combined cycle (NGCC) for gas-based power plants. For the past 25 years, increases in the U.S. power-generation capacity have been dominated by natural gas turbines in the combined cycle configuration due to excellent performance in terms of cost, efficiency, emissions, and power density. This trend has become more apparent as the cost of natural gas has declined and is projected to continue through 2040, according to the Energy Information Administration.

DOE is committed to using coal in ways that are cleaner, more efficient, and that reduce CO_2 emissions. Advancing hydrogen turbine performance in the IGCC power plant offers the most significant near-term performance benefit for reducing emissions and cost while increasing efficiency. The ultimate goal of the Hydrogen Turbine program is to facilitate the development of advanced components and technology for turbines that provide tangible benefits to the public: lower cost of electricity (COE), reduced emissions of criteria pollutants, and carbon capture options.

The DOE investment in advanced turbine technology promotes positive outcomes in U.S. technology leadership, global competitiveness, a cleaner environment, and domestic job growth. Scientific and engineering challenges are being met through cost-shared R&D partnerships between industry, academia, and the Government. The Hydrogen Turbine program strives to meet these challenges through R&D on hydrogen combustion, aerodynamics, heat transfer and cooling, leakage control, and material systems development. Examples of technical approaches being undertaken within the Hydrogen Turbine program to address these challenges include the following:

- **Combustor Design—**Design and develop the combustion portion of the turbine to leverage the best current and advanced technologies to meet strategic system-level goals of an advanced syngas- or hydrogen-fueled gas turbine. Efforts are focused on the measurement and assessment of the fundamental properties of hydrogen combustion and the use of these properties to design and develop low-NO_x combustion systems. Several combustion technologies are under evaluation including, but not limited to, high- and low-swirl premixed, diffusion, hybrid forms of premixed and diffusion, axial staging, and rich-lean catalytic.
- **Thermal Barrier Coatings (TBCs)—**Assess and develop TBCs that can provide the performance and durability required for use in syngas- and hydrogen-fueled advanced gas turbines. Efforts are focused on identifying candidate TBC architectures and material compositions with the proper thermal, mechanical, and chemical properties for use in reducing heat flux to combustor transition pieces, stationary nozzles, and rotating airfoils. Advanced TBC and bond coat architectures are being developed to improve durability and thermal performance in the harsh environment found in the syngas-fueled gas turbine used in an IGCC power system.
- **Aero-Thermo-Mechanical Design—**Assess the unique aero-thermo-mechanical operational conditions associated with hydrogen turbines and investigate design improvements for addressing these unique design spaces. Efforts are focused on reducing cooling flows, reducing sealing and leakage flow rates, reducing rotating blade count, increasing expansion stage areas, and increasing airfoil length. The goal of these efforts is to develop machines that are more efficient with a higher power output.

Resolving the scientific and engineering design challenges using the approaches outlined above will allow hydrogen-fueled turbines to be used in IGCC power systems with carbon capture and storage (CCS).

SECTION 2: PROGRAM OVERVIEW

OFFICE OF FOSSIL ENERGY AND HYDROGEN TURBINE PROGRAM GOALS

The Department of Energy's Office of Fossil Energy manages a portfolio of research programs directed to demonstrate advanced coal-based electric power generation with near-zero emissions. These programs catalyze the timely, material, and efficient transformation of the Nation's energy system, secure U.S. leadership in clean energy technologies, and help maintain a vibrant U.S. effort in science and engineering as a cornerstone of our economic prosperity with clear leadership in strategic areas. The programs managed by FE's Office of Clean Coal under the Clean Coal Research Program and where the Hydrogen Turbine program's R&D is situated within the portfolio is depicted below.

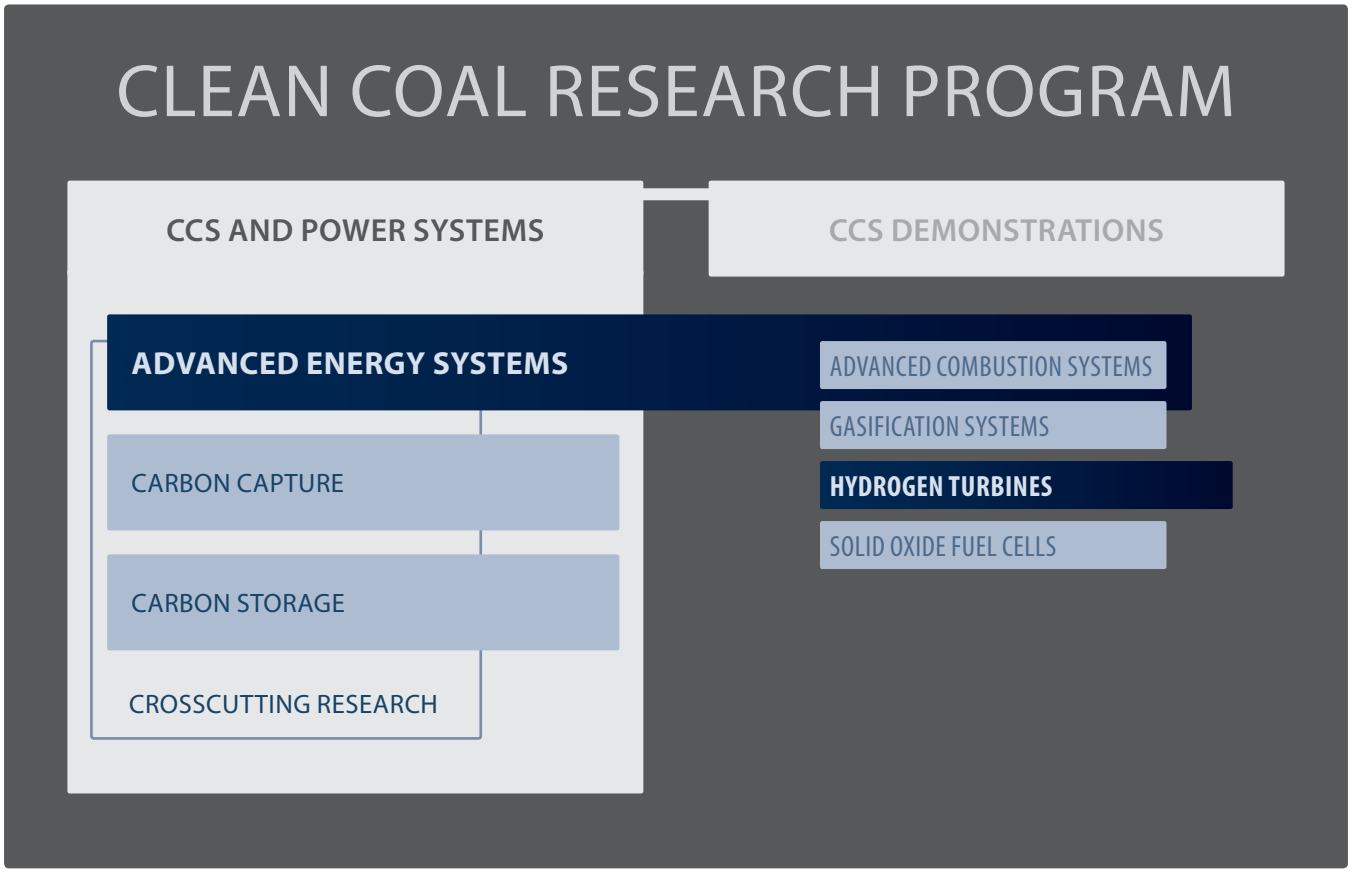


Figure 2-1. Clean Coal Research Program Structure

President Obama has articulated a priority energy goal for his Administration: "catalyze the timely, material, and efficient transformation of the Nation's energy system and secure U.S. leadership in clean energy technologies." Related to this goal, the Administration has established the following targets:

- Reduce energy-related greenhouse gas emissions by 17 percent by 2020 and 83 percent by 2050, from a 2005 baseline.
- Generate 80 percent of America's electricity from clean energy sources by 2035.

In response to these targets and other drivers, the DOE/FE program is focused on:

- Research, development, and demonstration (RD&D) to enable CCS deployment in the post-2020 timeframe.

- Sufficient demonstrations of first-generation CCS and power plant technologies to provide confidence that these technologies can be safely and reliably integrated into power plant and industrial plant operations.
- Development and demonstration of new, advanced second-generation CCS and power plant technologies for deployment in the post-2020 timeframe.

To realize this initiative and provide program area priorities, the following best practice performance targets have been established:

- <10 percent increase in COE with CCS at 90 percent capture (pre-combustion for IGCC)
- <35 percent increase in COE with CCS at 90 percent capture (post- and oxy-combustion for pulverized coal power plants)
- <$700/kW fuel cell power blocks (2007$)
- 50 percent plant efficiency, up to 60 percent with fuel cells
- 90 percent CO_2 capture
- 99 percent CO_2 storage permanence
- +/-30 percent storage capacity accuracy

In response to these targets, the Hydrogen Turbine program has laid out goals to deliver hydrogen-fueled combined cycle power modules for the 2020 time horizon that demonstrate the following achievements:

- Efficiency
  - 2–3 percentage points improvement in combined cycle efficiency (2010) and 3–5 percentage points by 2015 above the baseline
  - 4 percentage point improvement in overall IGCC plant efficiency with CCS by 2015
- Cost Reduction
  - 20–30 percent reduction in combined cycle capital costs
  - 25 percent reduction in total overnight capital cost for IGCC with CCS
  - 25 percent reduction in COE for IGCC with CCS
- Emissions
  - Turbine NO_x emissions in single digits (at 15 percent O_2)
  - IGCC plant optimized for firing temperature with 2 ppm NO_x at the stack (includes selective catalytic reduction)

HYDROGEN TURBINE PROGRAM OBJECTIVES

The Hydrogen Turbine program is organized into five key areas: Hydrogen Turbines, Oxy-Fuel Turbines, the University Turbine Systems Research (UTSR) program, Advanced Research, and Small Business Innovation Research (SBIR) projects. The program is augmented by a portfolio of American Recovery and Reinvestment Act (ARRA) funding for advancing industrial application of CCS, and the National Energy Technology Laboratory (NETL) Regional University Alliance (RUA) collaboration that utilizes the extensive expertise and facilities available at NETL and five nationally recognized regional universities. The following diagram illustrates the program organization and the research focus for each key area.

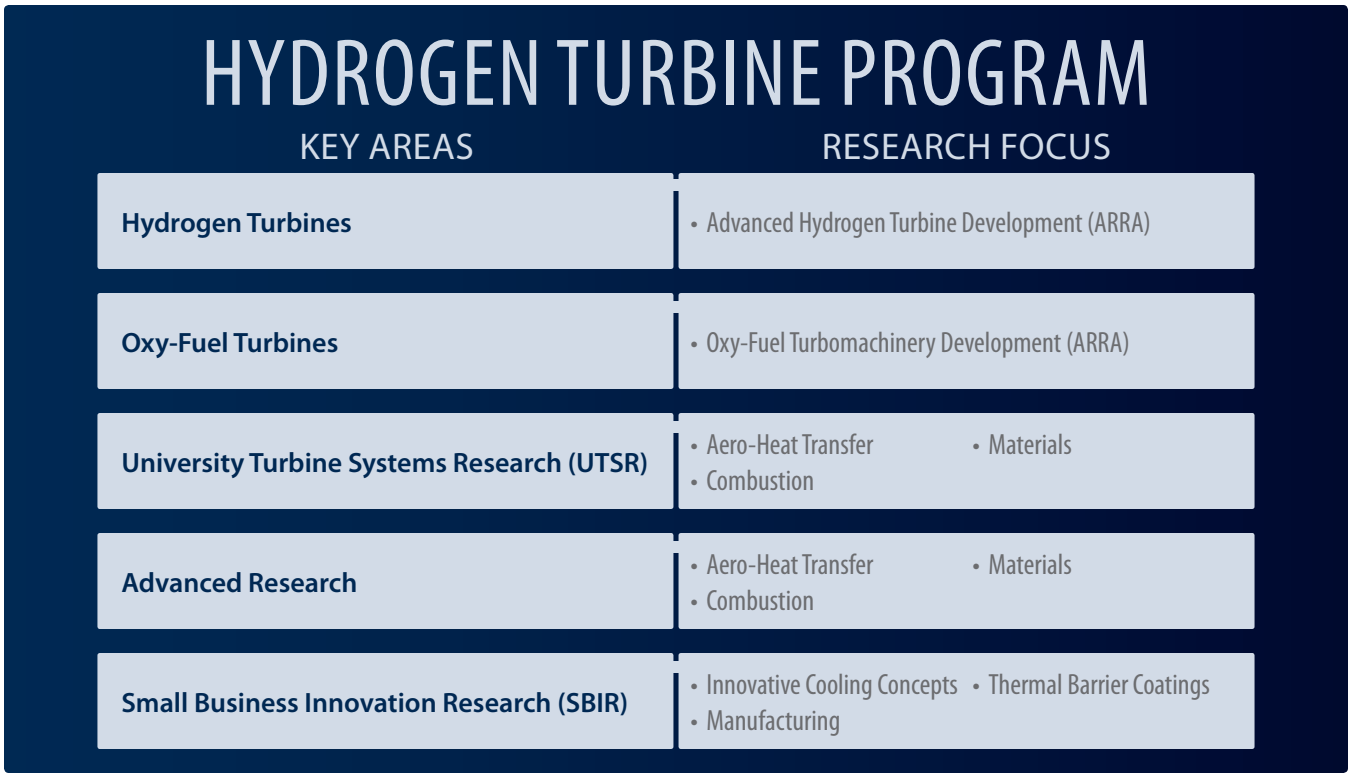


Figure 2-2. Hydrogen Turbine Program Organization

The Hydrogen Turbine program has contributed to the performance targets and best practices outlined above by pursuing the following objectives:

- Demonstration of a hydrogen-fueled combined cycle gas turbine (previously fueled with syngas) that maintains the same combined cycle efficiency performance improvement realized in 2010 (2–3 percentage points above the baseline[1]), realizes 3–5 percentage points improvement by 2015, and realizes 4 percentage points improvement in overall IGCC plant efficiency with CCS.
- Cost reduction of 20–30 percent (below the baseline) in combined cycle capital cost, plus enhanced value for lower COE through reduction of total capital costs and total cost of electricity generation.
- Emissions reduction to 2 ppm NO_x from the power plant exhaust and single-digit NO_x emissions in the simple cycle exhaust (at 15 percent O_2).

System studies indicate that the 2012 objectives described above have been met through the R&D sponsored by the program to date. The continued achievement of the objectives will be demonstrated by incorporating the latest technological advances in a gas turbine power plant. It is envisioned that this turbine could be installed with a pre-planned technology improvement philosophy. This approach would allow the machine to be optimized in the field for hydrogen combustion, aerodynamics, heat transfer and cooling, leakage control, and other performance-enhancing components or subsystems. This approach would also allow for a machine fueled with 100 percent hydrogen to operate with the highest efficiency and lowest NO_x emissions.

The Hydrogen Turbine program is now focused on further advancements to turbine technology to attain the ultimate performance targets for IGCC power plants with CCS. Thus, by 2015, the program plans to demonstrate:

- Hydrogen-fueled turbines with 3–5 percentage points improvement in combined cycle efficiency (total above baseline)
- At least 4 percentage points improvement to the overall IGCC plant performance with CCS

1 Baseline efficiency is defined in "Development of Baseline Performance Values for Turbines in Existing IGCC Applications." Richard A. Dennis, Walter W. Shelton, and Patrick Le. Proceedings of GT 2007. May 2007.

- Competitive COE for near-zero-emissions systems
- Hydrogen-fueled IGCC with 2 ppm NO_x at the power plant exhaust

PROGRAM PARTICIPANTS

Throughout its history, the Hydrogen Turbine program has maintained a diversified portfolio of R&D projects to address the technical challenges and ensure a high-probability of achieving the desired cost and performance targets. The strategy includes a mix of near-, mid-, and long-term R&D projects as well as laboratory, proof-of-concept, and component and system development projects to foster the advancement of advanced turbine technologies, including those fueled by coal-derived syngas or natural gas, which meet or exceed the targets for efficiency, cost, and emissions.

In FY 2013 the Hydrogen Turbine program portfolio contains 38 projects that range from understanding the fundamental reaction kinetics of syngas and high-hydrogen fuels, to the development of the next class of advanced turbines for deployment in next-generation IGCC plants. Figure 2-3 presents the project portfolio for FY 2013; Figure 2-4 shows the geographical distribution of the respective projects. Additionally, a list of the projects by State is provided in Table 2-1.

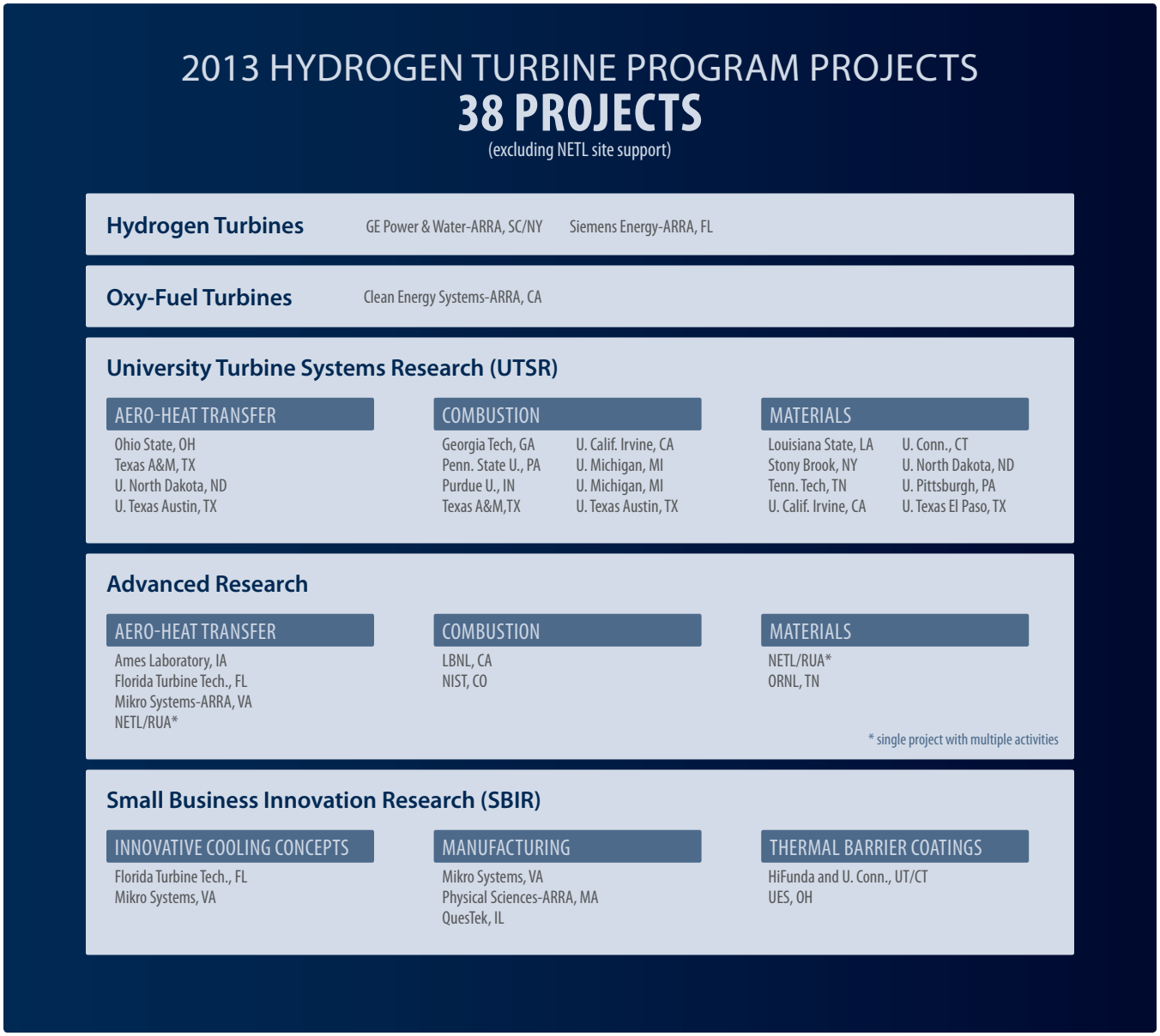


Figure 2-3. Hydrogen Turbine Program Portfolio Chart

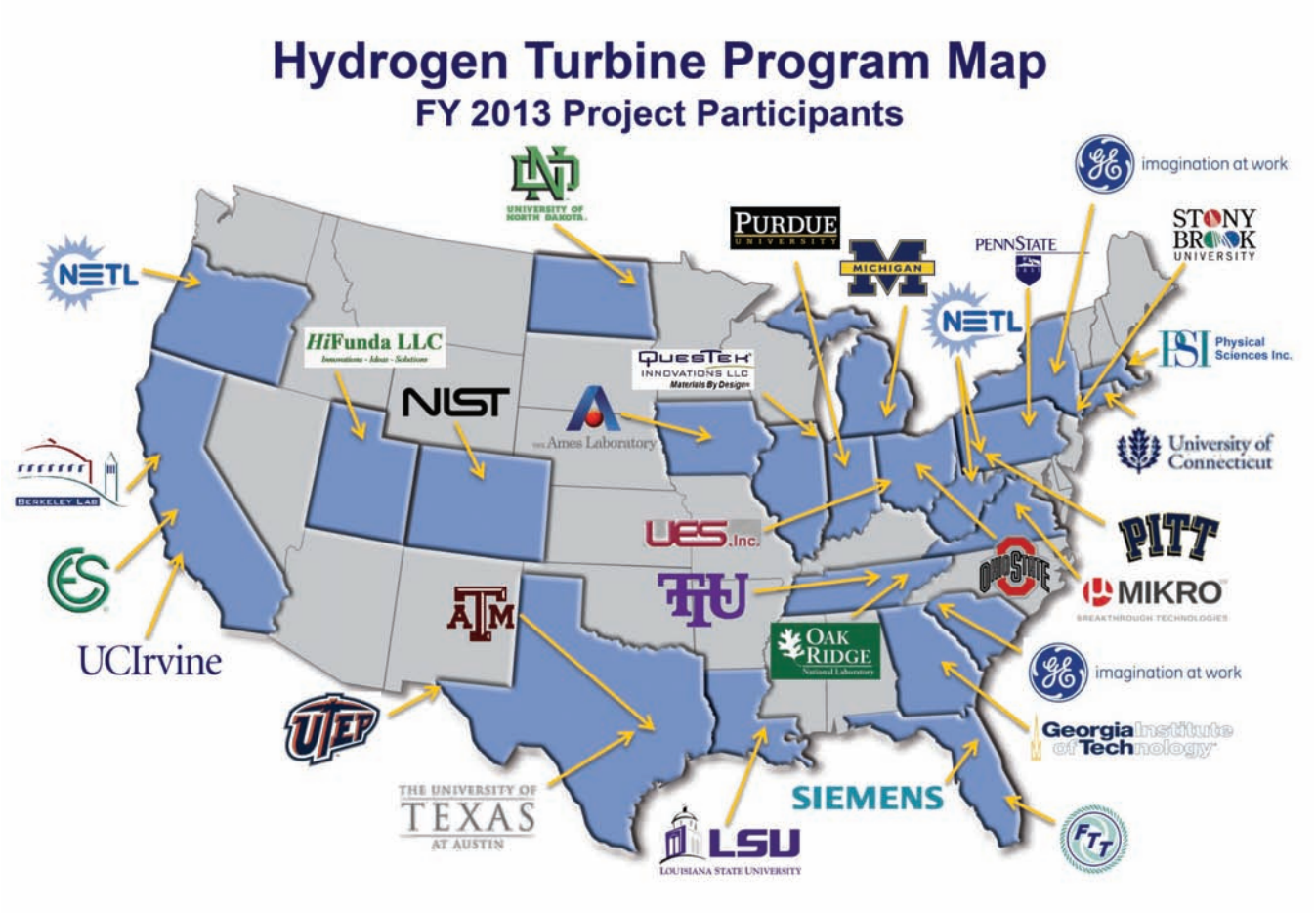


Figure 2-4. Hydrogen Turbine Program Map

Table 2-1. 2013 Hydrogen Turbine Projects by State
(new projects in italics)

State	Project Title	Performer Name
California	*Abradable Sealing Materials for Emerging IGCC-Based Turbine System*	*University of California, Irvine*
	Development of Criteria for Flameholding Tendencies within Premixer Passages for High Hydrogen Content Fuels	University of California, Irvine
	Development of Criteria for Flashback Propensity in Jet Flames for High Hydrogen Content and Natural Gas Type Fuels	*University of California, Irvine*
	Low-Swirl Injectors for Hydrogen Gas Turbines in Near-Zero-Emissions Coal Power Plants	Lawrence Berkeley National Laboratory
	Mechanisms Underpinning Degradation of Protective Oxides and Thermal Barrier Coating Systems in HHC-Fueled Turbines	University of California, Irvine
	Recovery Act: Oxy-Fuel Turbomachinery Development for Energy Intensive Industrial Applications	Clean Energy Systems, Inc.
Colorado	Thermophysical Properties of CO_2 and CO_2-Rich Mixtures	National Institute of Standards and Technology
Connecticut	Low Thermal Conductivity, High Durability Thermal Barrier Coatings for IGCC Environments	University of Connecticut
Florida	Demonstration of Enabling Spar-Shell Cooling Technology in Gas Turbines	Florida Turbine Technologies, Inc.
	Recovery Act: Advanced Hydrogen Turbine Development	Siemens Energy
	Air-Riding Seal Technology for Advanced Gas Turbine Engines	Florida Turbine Technologies, Inc.
Georgia	*Microstructure-Sensitive Crystal Viscoplasticity for Ni-Base Superalloys*	*Georgia Tech Research Corporation*
	Turbulent Flame Propagation Characteristics of High Hydrogen Content Fuels	Georgia Tech Research Corporation
Illinois	Computational Materials Design of Castable Single Crystal Ni-Based Superalloys for IGT Blade Components	QuesTek Innovations LLC
Indiana	*Exhaust Gas Recirculation-Based CO_2 Recycling in Advanced Gas Turbine Combustors with High Hydrogen Content Fuels*	*Purdue University*
	New Mechanistic Models of Creep-Fatigue Interactions for Gas Turbine Components	*Purdue University*
	Structure and Dynamics of Fuel Jets Injected into a High-Temperature Subsonic Crossflow: High-Data-Rate Laser Diagnostic Investigation	Purdue University
Iowa	Analysis of Gas Turbine Thermal Performance	Ames Laboratory
Louisiana	Computational Design and Experimental Validation of New Thermal Barrier Systems	Louisiana State University
Massachusetts	Recovery Act: Advanced Laser Machining Techniques for Cooling Holes in Gas Turbines	Physical Sciences Inc.
Michigan	Development and Experimental Validation of Large Eddy Simulation Techniques—Syngas Combustion	Regents of the University of Michigan
	Fundamental Studies to Enable Robust, Reliable, Low Emission Gas Turbine Combustion of High Hydrogen Content Fuels	Regents of the University of Michigan
Multiple	Turbine Thermal Management	National Energy Technology Laboratory—Regional University Alliance
New York	Recovery Act: Advanced Hydrogen Turbine Development	GE Power & Water
	Advanced Thermal Barrier Coatings for Operation in High-Hydrogen-Content-Fueled Gas Turbines	The Research Foundation of SUNY at Stony Brook University
North Dakota	Environmental Considerations and Cooling Strategies for Vane-Leading Edges in a Syngas Environment	University of North Dakota
	Preparation and Testing of Corrosion- and Spallation-Resistant Coatings	University of North Dakota Energy & Environmental Research Center
	Thermally Effective and Thermally Efficient Cooling Technologies for Advanced Gas Turbines	*University of North Dakota*
Ohio	Effects of Hot Streak and Phantom Cooling on Heat Transfer in a Cooled Turbine Stage Including Particulate Deposition	The Ohio State University
	High-Temperature Unique Low-Thermal Conductivity Thermal Barrier Coating Architectures	UES, Inc.
Pennsylvania	An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High Hydrogen Content Fuels	Pennsylvania State University
	Combustion Dynamics in Multi-Nozzle Combustors Operating on High-Hydrogen Fuels	Pennsylvania State University
	Degradation of TBC Systems in Environments Relevant to Advanced Gas Turbines for IGCC Systems	University of Pittsburgh

Table 2-1. 2013 Hydrogen Turbine Projects by State
(new projects in italics)

State	Project Title	Performer Name
South Carolina	*An Experimental and Modeling Study of NO_x-CO Formation in HHC Fuels Combustion in Gas Turbine Applications*	*University of South Carolina*
	Recovery Act: Advanced Hydrogen Turbine Development	GE Power & Water
Tennessee	An Alternative Low-Cost Process for Deposition of MCrAlY Bond Coats for Advanced Syngas/Hydrogen Turbine Applications	Tennessee Technological University
	Coating Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines	Oak Ridge National Laboratory
Texas	Aerodynamics and Heat Transfer Studies of Parameters Specific to the IGCC Requirements: High Mass Flow Endwall Contouring, Leading Edge Filleting, and Blade Tip Ejection Under Rotating Turbine Conditions	Texas Engineering Experiment Station—Texas A&M University
	High-Pressure Turbulent Flame Speeds and Chemical Kinetics of Syngas Blends with and without Impurities	*Texas Engineering Experiment Station—Texas A&M University*
	Improving Durability of Turbine Components Through Trenched Film Cooling and Contoured Endwalls	University of Texas at Austin
	Large Eddy Simulation Modeling of Flashback and Flame Stabilization in Hydrogen-Rich Gas Turbines Using a Hierarchical Validation Approach	University of Texas at Austin
	Novel Hafnia-Based Nanostructured Thermal Barrier Coatings for Advanced Hydrogen Turbine Technology	University of Texas at El Paso
	Predictive LES Modeling and Validation of High-Pressure Turbulent Flames and Flashback in Hydrogen-Enriched Gas-Turbine Combustion	*University of Texas at Austin*
	Turbulent Flame Speeds and NO_x Kinetics of High Hydrogen Content Fuels with Contaminants and High Dilution Levels	Texas Engineering Experiment Station—Texas A&M University
Utah	Ultra-High-Temperature Thermal Barrier Coatings	HiFunda LLC
Virginia	Advanced Cooling for IGCC Turbine Blades	Mikro Systems, Inc.
	Advanced Filtration to Improve Single Crystal Casting Yield	Mikro Systems, Inc.
	Evaluation of Flow and Heat Transfer Inside Lean Premixed Combustor Systems Under Reacting Flow Conditions	*Virginia Polytechnic Institute and State University*
	Phase III Xlerator Program: Rapid Commercialization of Advanced Turbine Blades for IGCC Power Plants	Mikro Systems, Inc.
	Rapid Manufacturing Method for High-Temperature Turbine Components	*Mikro Systems, Inc.*

SUMMARY

In response to the Nation's increasing power supply challenges, NETL is researching next-generation turbine technology with the goal of producing reliable, affordable, diverse, and environmentally friendly energy supplies. With the Hydrogen Turbine program, NETL is leading the RD&D of these technologies to achieve power production from coal that is clean, efficient, and cost-effective; minimizes CO_2 emissions; and will help maintain the Nation's leadership in the export of electric power equipment. Efforts are coordinated nationwide through NETL and the Hydrogen Turbine program. Critical technologies must be modeled and developed for future gas turbine engines in advanced IGCC systems running on high hydrogen content (HHC) fuels. Either new materials must be developed or coatings with novel chemistries must be engineered to protect engine components and allow further increases in engine temperatures to achieve higher efficiency. The development is limited, in part, by the available materials and manufacturing abilities.

DOE's Hydrogen Turbine program is striving to show that the United States can operate on coal-based hydrogen fuel power, increase combined cycle efficiency by 3–5 percentage points over the baseline, and reduce CO_2 and other emissions by 2015. Program and project emphasis is on understanding the underlying factors affecting combustion, aero-heat transfer, and materials for current IGCC syngas turbines; and using that knowledge to design advanced turbines and conduct the research needed to transition to nearly pure hydrogen fuels.

The subsequent sections summarize the scope, objectives, and status of each of the Hydrogen Turbine program's key areas along with the factsheets for each project. The Hydrogen Turbine program is encouraged by the technical progress made this year, and the prospects for continued advancements in the coming year are good, paving the way to achievement of the goals.

SECTION 3: ACCOMPLISHMENTS

The following section highlights the key program accomplishments for the Hydrogen Turbine program.

HYDROGEN TURBINES

PROJECT TITLE: Recovery Act: Advanced Hydrogen Turbine Development
PARTICIPANT: GE Power & Water
PROJECT NO.: NT42643

GE Power & Water is demonstrating low NO_x emissions with robustness on combustion of hydrogen, and other fuels, as it continues development of its advanced combustor for the base program and in its advanced combustor for the ARRA program. In FY 2013, the program met the lowest NO_x emissions to date, during full chamber combustion tests at GE Power & Water's state-of-the-art Gas Turbine Technology Lab in Greenville, SC. The combustion technologies have made improvements in widening the operability range as demonstrated by operating on a wide range of fuels from hydrogen to natural gas. Further improvements were made not only to increase the performance, but to achieve milestones in durability and manufacturability. Two different manufacturing processes were developed and demonstrated in durability tests. These accomplishments cumulated in the passage of key internal design reviews allowing both combustors to proceed with confidence as the development approaches technology readiness. During FY 2014 the main focus will be on further increasing operability and fuel flexibility on the base side of the program and further increasing performance on the ARRA side of the program.

Milestones for both base and ARRA accomplishments:

- Continued development and optimization of premixed combustion technology for hydrogen by utilizing extensive megawatt-scale, full head end testing on leading concepts from both the base and ARRA portions of the program—achieved lowest (single digit) NO_x emissions to date and demonstrated fuel flexibility with durability at target 2012 cycle conditions.
- Down-selected the best option for an element of the first stage architecture. Developed manufacturing feasibility and durability. Established heat transfer rig trial plans, identified key geometries, and began initial testing.
- Completed cooling effectiveness characterization for the next-generation advanced cooling design concept.
- Completed testing of an optimal purge flow configuration.
- Improved and updated cycle models to determine the performance and output characteristics resulting from the technology advancements made under the program, including systems required for CCS.
- Down-selected a new cost-effective, mechanically and environmentally capable hot-gas-path alloy. Completed initial environmental testing and a first full-size component casting. Results show good castability and improvement over baseline material.
- Continued characterization of down-selected TBC and bond coat.

PROJECT TITLE: Recovery Act: Advanced Hydrogen Turbine Development
PARTICIPANT: Siemens Energy
PROJECT NO.: NT42644

Siemens Energy engine compatible advanced combustion system successfully fired on high-hydrogen fuel in a full-scale rig test at higher than H-class temperatures with no flashback while meeting NO_x emission targets at greater than planned operating temperatures. An investigation into turndown and carbon monoxide levels was also performed and showed promise. The design will be further optimized using the data gathered during these firing tests.

Additional accomplishments include:

- Siemens Energy opened a manufacturing facility in Charlottesville, VA for the innovative commercial production of airfoil ceramic cores for gas turbine blades and vanes using the Tomo-Lithographic Molding (TOMO℠) technology, initially developed by Mikro Systems and further developed under the Hydrogen Turbine program.
- Optimized combustion system components were hot fired and results will be fed forward for additional full combustion system testing.
- Modular vanes, advanced airfoil core technology, advanced sensors, and high-temperature TBCs were all successfully tested in a full-scale engine test.
- Updated compressor and turbine flow paths were down-selected.
- Achieved a reduction of approximately 40 percent in flaking or chipping of material (known as spallation) from coated surfaces with new modified bond coats and substrates.
- Selective catalytic reduction system demonstrated over 95 percent NO_x reduction efficiency. Conducted over 3,000 hours testing in simulated IGCC exhaust and greater than 15,000 hours of continuous operation in an NGCC plant exhaust.
- Achieved Technology Readiness Level 6 on the rotor disk optimization tool.
- Significant progress was made in the manufacturing capabilities of turbine blade four and turbine blade one with advanced cooling technologies.
- Multiple rig test campaigns were run across several components and focus areas including: compressor aerodynamics and airfoil design, turbine aerodynamics and airfoil design, and sealing and heat transfer.

OXY-FUEL TURBINES

PROJECT TITLE: Recovery Act: Oxy-Fuel Turbomachinery Development for Energy Intensive Industrial Applications
PARTICIPANT: Clean Energy Systems, Inc.
PROJECT NO.: NT42645

Clean Energy Systems set out to design and develop a pre-commercial oxy-fuel combustor, able to utilize syngas, for use in a power-generation cycle able to achieve high-thermal efficiency with near-zero atmospheric emissions, including CO_2. The technology is a high-pressure oxy-fuel combustor that produces a steam/CO_2 working fluid for expansion in a turbine. The high-pressure oxy-fuel combustor utilizes syngas and pure oxygen to produce a working fluid comprised of steam and CO_2 that is used to power turbo generators.

Clean Energy Systems also set out to design and develop a commercial-scale oxy-fuel turbine (OFT) for deployment in industrial oxy-fuel plants that capture >99 percent of the produced CO_2, at competitive cycle efficiency and COE, using diverse fuels, including gasified petcoke/coal, gasified or liquefied renewable fuels, and natural gas. Accomplishments are as follows:

- Completed the detailed design of a 100-MWth oxy-syngas combustor and its enclosure.
- Completed integrated testing of a 33-MWe OFT (modified J79 engine) and oxy-natural-gas combustor.
- Designed, fabricated, and demonstrated a first-generation RH combustor, suitable for integration into an OFT-J79, in a dedicated test rig.
- Completed the detailed engineering design to convert an SGT-900 gas turbine into a 150-MWe OFT.
- Located, purchased, disassembled, and inspected a used SGT-900 B12 power plant.
- Refurbished, repaired, and replaced existing engine components to be reinstalled into a new OFT-900 engine. Manufactured new components required to convert an existing SGT-900 to an industrial-scale OFT. Assembled new OFT-900 engine and delivered to Clean Energy Systems test facility.
- Completed the install, commissioning, and test of a commercial-scale OFT-900.
- Upgraded test facility to support commercial-scale OFT demonstration testing.
- Designed, fabricated, and demonstrated a second-generation RH combustor, suitable for integration into an OFT-900, in a dedicated test rig.

UNIVERSITY TURBINE SYSTEMS RESEARCH

AERO-HEAT TRANSFER

PROJECT TITLE: Effects of Hot Streak and Phantom Cooling on Heat Transfer in a Cooled Turbine Stage Including Particulate Deposition
PARTICIPANT: The Ohio State University
PROJECT NO.: FE0007156

Multiple hot streak tests were conducted in the Ohio State University turbine reacting flow rig to study the effect of non-uniform inlet temperature profiles. Deposits accumulate more readily on the vane aligned with the high-temperature gas. This effect was corroborated by computational fluid dynamics (CFD) deposition simulations using a Fluent flow model coupled with the critical viscosity deposition model. A new particle impingement test facility was designed and constructed to study the mechanics of micron-sized particle impact, rebound, and deposition at high temperatures. High-speed particle shadow velocimetry techniques were employed to track particle impacts and rebounds. Data indicate a reduction in coefficient of restitution with increasing temperature, due to increased plastic deformation. Particle deposition does not appear to be strongly dependent on particle size. Results highlight flaws in the application of existing deposition models and hopefully will lead to a more accurate elastoviscoplasticity deposition model. Finally, a film cooling slot was designed and fabricated into a nozzle guide vane set to allow the study of hot streaks on a film cooled vane. Testing is already underway with the new vane set under uniform inlet temperature conditions.

PROJECT TITLE: Environmental Consideration and Cooling Strategies for Vane-Leading Edges in a Syngas Environment
PARTICIPANT: University of North Dakota
PROJECT NO.: FE0004588

The University of North Dakota (UND) has investigated the influence of turbulence, acceleration, and Reynolds numbers on full coverage (30 degree slot) film cooling and downstream heat transfer. High-intensity large-scale turbulence has been found to have a dramatic influence on mixing away slot film cooling protection. The influence of the turbulence is incremental in distance, dependent on the blowing ratio, and strongly dependent on turbulence level and to a lesser degree, scale. This film cooling research will be extended to the investigation of the additional

influence of realistic roughness in the near future. UND has also documented the development of leading edge region boundary layers subjected to the influence of high acceleration and a range of turbulence conditions. This research has been aimed at furthering the understanding of turbulent mixing across laminar boundary layers. These boundary layers were acquired just upstream from the film cooling discharge location. The present investigation is focused on developing the technical understanding and cooling technologies that will help gas turbine engineers develop reliable cooling designs for syngas-fired gas turbines.

A collaborator on the same project, Ohio State University, has investigated the impact of freestream turbulence levels and film cooling on deposition rates in a simulated syngas environment. Initial testing using dilution jets to elevate turbulence levels produced unacceptable variations in temperature. This was replaced with a grid generated turbulence system. The square-bar grid is placed roughly two chord-lengths upstream of the cascade inlet plane and actually reduces the turbulence levels from 6.5 percent to 4.5 percent (measured for non-combusting flow). Results to date indicate that the higher turbulence level results in higher capture efficiency. Small particles that would otherwise miss the vane surface are propelled into the surface by the elevated turbulence and thus have a higher propensity to deposit. Tests are continuing to determine the effect on different particle size ranges. To explore the effect of film cooling, a new vane set was fabricated with a two-dimensional (2-D) film slot on the pressure surface. Cooling has a demonstrable effect on deposition, even in the region upstream of the cooling slot. This is due to conduction heat transfer and lowering of the surface temperature there. Finally, deposit surfaces have been scanned and sent to UND for consideration as scaled models in their large leading edge wind tunnels. Collaboration continues to determine the appropriate surface and scaling parameters.

PROJECT TITLE: Improving Durability of Turbine Components Through Trenched Film Cooling and Contoured Endwalls
PARTICIPANT: University of Texas at Austin
PROJECT NO.: FE0005540

A significant accomplishment from this University of Texas at Austin study is the direct measurements of the combined effects of TBC and film cooling. Further studies of the combined effects of TBC and film cooling showed that TBC has a dominating effect on cooling performance for even moderate thickness TBC. Measurements were also made in the wake of the vane model to determine aerodynamic losses with and without depositions on the vane surface. As expected, the large surface roughness that occurs with deposition of contaminants causes significant increases in aerodynamic losses. Furthermore, experimental endwall studies included measurements of non-dimensional wall temperature or overall effectiveness of flat endwall configurations with internal and external cooling. Results from these measurements showed that internal impingement cooling provided much higher and more uniform effectiveness than external film cooling. In addition deposition was dynamically simulated in the endwall passage. In some locations the deposition resulted in higher wall temperatures indicating an increase in heat transfer due to roughness effects.

COMBUSTION

PROJECT TITLE: Turbulent Flame Propagation Characteristics of High Hydrogen Content Fuels
PARTICIPANT: Georgia Tech Research Corporation
PROJECT NO.: FE0004555

The objective of this Georgia Tech project is to improve the state-of-the-art understanding of turbulent flame propagation characteristics of HHC fuels. Such HHC fuels offer advantages for reducing the carbon footprint of power-generation systems. Turbulent flame propagation influences the flashback and blowoff limits of the combustor, the life of hot section components, combustor emissions, and the operating limits required to prevent harmful combustion dynamics. As such, the data, models, and knowledge achieved in the program will have important practical influences on advanced gas turbine technologies. The researchers acquired local measurements of premixed

turbulent flames over a wide range of fuel compositions, mean flow velocities, and turbulence intensities using a low swirl burner. Measurements included 2-D velocity flow fields from particle image velocimetry (PIV) and flame curvature statistics. The primary goal of this task was to develop a better physical understanding of the behavior of the leading points of the turbulent flame front in order to test the validity of the previously developed leading points correlation model for collapsing turbulent flame speed data. Specifically, the researchers previously argued that increasing turbulent flame speeds, observed with high H_2 fuels, were due to higher $S_{L,max,}$ and therefore higher flame stretch values at the leading points. The data acquired do not support this argument, showing virtually no effect of fuel composition upon either instantaneous or flame brush leading points. Rather, they show the turbulence intensity to have a far stronger influence on these curvature statistics. However, the theoretical predictions apply to the total flame stretch rate, and these measurements only quantify the 2-D component of the curvature. In addition, the contribution of curvature to the flame stretch requires multiplication by the local laminar flame speed, which will be different for different fuel compositions. In other words, probability density functions of the curvature-stretch term of the flame stretch equation may show a stronger dependence on fuel composition than probability density functions of curvature alone. Furthermore, curvature only represents one contribution to the overall flame stretch rate. Future work will be performed to calculate the contribution of the tangential strain rate to the flame stretch rate. Nonetheless, these results clearly show that work is needed to understand the physical processes through which the turbulent flame speed is altered by differential diffusion effects.

PROJECT TITLE: An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High Hydrogen Content Fuels
PARTICIPANT: Pennsylvania State University
PROJECT NO.: FE0000752

Pennsylvania State University completed measurements of laminar mass burning rates of H_2O-diluted hydrogen and syngas fuels as well as HHC mixtures including CH_4, C_2H_6, and C_2H_4. These measurements are relevant to stationary power fueling and emissions control strategies and also constrain the HHC fuel kinetic model. In addition, an analytical and computational evaluation of the thermal radiation effects on spherically propagating laminar flame speed measurements show that thermal radiation uncertainty of present flame measurements is negligible. Development and extensive evaluation of a H_2/carbon monoxide/HHC fuel kinetic model for numerical modeling of gas turbine combustion/emissions has continued to be a focus of the project. For example, consideration of unaccounted reaction pathways shows that the HOCO radical species and its reactions with other HHC species are unimportant to the quantitative prediction of HHC combustion. Additionally, significant progress has been made on the development and application of a suitable diagnostic technique for measuring the concentration of HO_2 using direct Faraday rotational spectroscopy. Recent work has shown that high sensitivity measurements (1 ppm) of HO_2 in a flow reactor can be made and compared to current kinetic models. Higher sensitivity (0.2 ppm) is envisioned using dual modulation Faraday rotational spectroscopy methods for HO_2 measurement. Finally, autoignition studies of hydrogen and hydrogen carbon monoxide mixtures have been completed using a high-pressure high-temperature flow reactor. Studies were done for two pressures (10 and 15 atm) and two equivalence ratios (0.375 and 0.750). Comparisons to results using a homogenous chemical model showed very good agreement with the experimental data. These results are in disagreement with earlier studies, which showed autoignition times shorter by one order of magnitude or more.

PROJECT TITLE: Combustion Dynamics in Multi-Nozzle Combustors Operating on High-Hydrogen Fuels
PARTICIPANT: Pennsylvania State University
PROJECT NO.: NT0005054

Gas turbine combustors for power-generation applications employ multi-nozzle combustor configurations. Researchers at Penn State and Georgia Tech have extended previous work on the flame response in single-nozzle combustors to the more realistic case of multi-nozzle combustors. Research at Georgia Tech has shown that asymmetry

of both the flow field and the acoustic forcing can have a significant effect on flame response and that such behavior is important in multi-flame configurations. As a result, the structure of the flame and its response to forcing is three dimensional. Research at Penn State using a recently developed three-dimensional flame imaging technique has shown that spatial variations in local flame confinement must be accounted for to accurately predict global flame response to acoustic forcing in a multi-nozzle can combustor.

PROJECT TITLE: Structure and Dynamics of Fuel Jets Injected into a High-Temperature Subsonic Crossflow: High-Data-Rate Laser Diagnostic Investigation
PARTICIPANT: Purdue University
PROJECT NO.: FE0007099

A reacting jet issuing into a vitiated, swirled crossflow at a momentum flux jet ratio of 3 and 8 was investigated using high-repetition hydroxyl planar laser-induced fluorescence (PLIF) and PIV at 5 kHz operating at a pressure of 5.5 bars. The jet issuing into the vitiated stream was a premixed jet composed of both natural gas and air and was injected downstream of the main combustion zone that produced the vitiated, swirled flow.

Proper orthogonal decomposition was implemented to extract quantitative information out of the PLIF images. Proper orthogonal decomposition proved to be useful in characterizing some of the dominant flow structures and the reaction zone of the jet flame in crossflow. A detailed reduced order modeling technique was employed to analyze high-speed PLIF images of a reacting jet in a vitiated swirling crossflow. The most significant finding of this analysis was that some of the reaction occurs within the loop vortices and heat release rate increases when these vortices dissipate exposing the unreacted fuel. The convection pattern of these loop vortices along the jet trajectories could be used to estimate the velocity at which these structures convect. These coherent structures are dynamic in nature and consist of characteristic frequencies. This technique provided significant insight into the complex turbulent flames. PLIF images which were mostly used for flame front imaging and transient evolution of flame structures could now be used for a more detailed qualitative and quantitative analysis.

Commercial software Davis was used for the vector field analysis obtained from the PIV experiment. A total of 3,777 image pairs were obtained at each of the measurement planes. A major difference between the PIV and PLIF experiments was the change in the measurement planes. In order to avoid scattering of the 532 nm laser beam from the TBC, the measurement planes had to be changed to jet cross section instead of the one showing jet trajectory. A cross-correlation technique using multi-pass window technique was used. The initial window size was chosen to be 64-by-64 pixels with a 50 percent overlap and in the subsequent iterations used a smaller window size of 16-by-16 pixels. The spurious vectors were removed in the post-processing process using a non-linear median filter. The measurement plane closest to the nozzle exit showed the presence of a very interesting flow structure looking similar to the counter-rotating vortex pair. Analysis of the other measurement planes for all the test condition is ongoing.

PROJECT TITLE: Turbulent Flame Speeds and NO_x Kinetics of High Hydrogen Content Fuels with Contaminants and High Dilution Levels
PARTICIPANT: Texas A&M University
PROJECT NO.: FE0004679

Computational combustion codes rely on turbulent combustion models (or correlations) for providing flame speed estimates. This method necessitates the need to evaluate the predictive capabilities of these correlations against experimentally measured data. Global displacement speeds were measured in a recently developed fan-stirred, cylindrical flame speed vessel using high-speed Schlieren imaging. Measurements were conducted in homogeneous and isotropic turbulent conditions at an average root-mean-square turbulent intensity of 1.5 m/s and at an integral length scale of 27 mm. Hydrogen and a representative synthetic gas or syngas blend containing 50:50 by volume of hydrogen and carbon monoxide, all diluted in air, were studied. A wide range of equivalence ratios was covered, and the

flame speeds were estimated when the flame radius was equal to the integral length scale. Turbulent flame speeds were computed using four widely used numerical models: (1) Zimont turbulent burning velocity model (1988); (2) Kerstein pair-exchange model (1988); (3) the coherent flame speed model (1993); and, (4) the distributed reaction zone model (1995). The Kerstein model and the Zimont model agreed well with the experimental measurements. Also, S_T/S_L was higher for syngas than methane for the same u'/S_L, which is indicative of the preferential diffusion effect of hydrogen in increasing the flame surface area by distorting it.

PROJECT TITLE: Development of Criteria for Flameholding Tendencies within Premixer Passages for High Hydrogen Content Fuels
PARTICIPANT: University of California, Irvine
PROJECT NO.: FE0007045

University of California, Irvine has nearly completed modifications to a facility to allow detailed measurements and associated analysis to develop design guides for prediction of how different geometric features within premixer passages might serve to anchor a reaction in the event of flashback. Initial commissioning tests have taken place during which baseline features were tested for their flameholding tendencies. A configuration with a 0.25" diameter rod that spanned the height of the test section was used to validate the testing procedure of the rig. The data collected during these tests showed exceptional agreement with the current literature of bluff body flameholding, indicating that the test facility and test procedures are operating as expected.

PROJECT TITLE: Development and Experimental Validation of Large Eddy Simulation Techniques—Syngas Combustion
PARTICIPANT: University of Michigan
PROJECT NO.: FE0007060

Michigan and Stanford have performed large eddy simulations of an industrial-relevant dual-swirl gas-turbine combustor. In this burner, gaseous fuel is injected through an annulus, which is embedded between two co-rotating swirlers, resulting in a partially premixed combustion regime. By considering non-reacting and reacting operating conditions, a series of comprehensive simulation-studies was performed to systematically assess the sensitivity of the flow field and flame structure to numerical and modeling parameters, including the quality and resolution of the computational mesh, combustion models, and subgrid closure. It was found that the combustor-flow-field exhibits a pronounced sensitivity to the mesh-resolution inside the swirler. This was attributed to the presence of a localized separation point in the outer swirler. This separation point controls the flame-shape, resulting in the appearance of a bifurcation in which the flame switches between a so-called "flat" and a "V-type" flame. Comparisons with measurements were performed to demonstrate model-accuracy and mesh-consistent convergence properties of the large eddy simulation (LES) computations. Diagnostics were applied and a metric has been developed in order to generate a procedural LES-method for simulating such complex burner geometries that are of direct industrial relevance.

PROJECT TITLE: Fundamental Studies to Enable Robust, Reliable, Low Emission Gas Turbine Combustion of High Hydrogen Content Fuels
PARTICIPANT: University of Michigan
PROJECT NO.: FE0007465

Syngas ignition experiments conducted using the rapid compression facility at the University of Michigan identified transitions between weak and strong ignition. The project systematically considered different pressures, temperatures and equivalence ratios of H_2 and carbon monoxide mixtures. The results clearly identified regions of high sensitivity where ignition behavior can be predicted, at least empirically, and that the transitions in ignition behavior are

not random. For conditions resulting in strong ignition, the data were in excellent agreement with predicted values using the syngas reaction mechanism developed by Li et al. For lower pressures (<10 atm), the results highlighted the high impact of uncertainties in the reaction chemistry on syngas ignition and combustion. The results also indicated the H_2/O_2 explosion limits may be good predictive indicators of the limits of the weak and strong regimes.

PROJECT TITLE: Large Eddy Simulation Modeling of Flashback and Flame Stabilization in Hydrogen-Rich Gas Turbines Using a Hierarchical Validation Approach
PARTICIPANT: University of Texas at Austin
PROJECT NO.: FE0007107

From the simulation and modeling component, the main outcome for University of Texas at Austin researchers is an understanding of the flame propagation-turbulent boundary layer interaction in turbulent channel flows. Simulations indicate that flame propagation is driven by the presence of recirculation bubbles created ahead of the flame in the near-wall region. Both direct numerical simulation and LES results confirm these findings. However, LES models fail to capture the rate of propagation indicating the need for detailed model development. On the experimental side, the main accomplishment is the application of 2 kHz PIV during flashback of CH_4-H_2-air premixed swirl flames. The PIV is conducted simultaneously with 2 kHz chemi-luminescence imaging. The results enable quantitative measurements of the relative flame speed as well as interaction of the flame with the swirling boundary layer. The experiments confirm the association of the propagating flame front with a recirculation region in the upstream boundary layer.

Additional accomplishments include:

- Completion of a kilohertz-rate particle image velocimetry study of UT swirl burner with premixed and non-premixed fuel injection
- A large eddy simulation study of UT swirl burner with inflow conditions obtained from experiments
- Simulation of flashback in turbulent channels and comparison to high-resolution direct numerical simulation study
- Development of a flamelet-based model for premixed and partially premixed combustion.

MATERIALS

PROJECT TITLE: Computational Design and Experimental Validation of New Thermal Barrier Systems
PARTICIPANT: Louisiana State University
PROJECT NO.: FE0004734

Louisiana State University conducted hot corrosion tests on yttria-stabilized zirconia (YSZ) single layer and composite YSZ + Ta_2O_5 (TaYSZ) samples in the presence of molten mixture of Na_2SO_4 + V_2O_5 at 1,100 °C. For YSZ, the reaction between $NaVO_3$ and Y_2O_3 produces YVO_4 and leads to the transformation of tetragonal ZrO_2 to monoclinic ZrO_2. For TaYSZ, minor amounts of $NaTaO_3$, $TaVO_5$ and Ta_9VO_{25} are formed as the hot corrosion products with only traceable amounts of YVO_4. Due to the synergic effect of doping of zirconia with both Y_2O_3 and Ta_2O_5, the TaYSZ sample has a much better hot corrosion resistance than YSZ.

PROJECT TITLE: Advanced Thermal Barrier Coatings for Operation in High-Hydrogen-Content-Fueled Gas Turbines
PARTICIPANT: Stony Brook University
PROJECT NO.: FE0004771

At the Center for Thermal Spray Research of Stony Brook University, process maps have been developed to link in situ particle and coating states to material properties in thermally sprayed systems. This approach has been applied to atmospheric plasma sprayed $Gd_2Zr_2O_7$ (GDZ) to determine various correlations, including relating particle temperature and velocity in a plasma flame to microstructure. Additionally one of the major developments was the evaluation of the fracture toughness of the both the TBC materials YSZ and GDZ. The intrinsically lower toughness of the GDZ coatings presents a significant challenge in incorporating them into a multi-layer architecture. Additionally thermal aging studies carried out on both these materials provided valuable insights into the evolution of the coating microstructure. Since the measured toughness of coatings is influenced by their microstructure, the changes in coating architecture and the resulting fracture toughness were carefully monitored. The densification of the YSZ coatings upon subjecting to thermal aging resulted in a significant increase in their measured values of fracture toughness. Similar investigation into the GDZ coatings revealed that the lower sintering rate of the material plays a crucial role in governing the extent of densification of the structure. For similar duration of thermal aging, the GDZ coatings showed a much lower increase in fracture toughness compared to YSZ. These developments would have a significant effect on the way these two materials would be integrated to design the proposed multi-layer TBC architecture. Studies are underway to incorporate this key understanding into an actual TBC system and utilize performance assessment methods to ultimately develop a reliable multi-layer coating.

PROJECT TITLE: An Alternative Low-Cost Process for Deposition of MCrAlY Bond Coats for Advanced Syngas/Hydrogen Turbine Applications
PARTICIPANT: Tennessee Technological University
PROJECT NO.: FE0007332

For this Tennessee Technological University project, two electro-codeposition configurations, (vertical and horizontal) also known as sediment codeposition, arrangements were employed in synthesis of composite coatings consisting of the Ni matrix and the embedded Cr-Al-Y particles. For the vertical setup, the Cr-Al-Y particle incorporation in the electro-codeposited coatings was in the range of 12–18 vol %. For the horizontal (sediment) arrangement, the gravitational force facilitates sediment of particles on the specimen and a much higher particle incorporation of 20–49 vol % was achieved. It was found that among the three main codeposition parameters (i.e., current density, stirring rate, and particle loading in the solution), the stirring speed exhibited the most profound effect on the amount of Cr-Al-Y particles incorporated the codeposited coatings. To form a dense coating with particle incorporation of ≥40 vol %, a stirring speed of ≈525 rpm is required and the particle concentration in the solution should be controlled in the range of 10–30 g/L. Although slightly higher particle incorporation can be obtained with further increased particle loading (e.g., 50 g/L), the coating tends to be more porous. The current density affects the coating growth rate and also has an effect on particle incorporation. For the current density range investigated (20–60 mA/cm^2), higher current densities of 40–60 mA/cm^2 are more desirable. In addition, the coating surface roughness also appears to be impacted by the codeposition parameters. For the same current density level and particle loading in the solution, a higher stirring speed can produce a rougher coating surface.

PROJECT TITLE: Low Thermal Conductivity, High Durability Thermal Barrier Coatings for IGCC Environments
PARTICIPANT: University of Connecticut
PROJECT NO.: FE0007382

At the University of Connecticut, solution precursor plasma spray (SPPS) YSZ TBCs were deposited with a thermal conductivity of 0.6 W/mK, a 50 percent reduction compared to air plasma spray YSZ. This breakthrough accomplishment achieved the prime goal of the project by introducing planar arrays of porosity, called interpass boundaries. The interpass boundaries are a unique microstructural feature of the SPPS process. Other low thermal conductivity TBCs rely on expensive rare-earth elements and exhibit poorer fracture toughness and erosion resistance.

PROJECT TITLE: Preparation and Testing of Corrosion- and Spallation-Resistant Coatings
PARTICIPANT: University of North Dakota
PROJECT NO.: FE0007325

The University of North Dakota Energy & Environmental Research Center (EERC) has several pilot-scale gasifiers that are continually used in a variety of test configurations as determined by the needs of the projects that fund the tests. Under the University Turbine System Research program, the EERC is sampling both non-combusted and combusted syngas produced during some of the pilot-scale gasifier tests. The gas has been scrubbed and filtered before collection. Sampling occurs both at the inlet and outlet of a downfired thermal oxidizer. The sampling train consists of a one-piece glass nozzle-probe liner, a large particulate cyclone, and a polycarbonate filter (Whatman Nuclepore™ type with 0.1-µm holes), followed by a series of six impingers for U.S. Environmental Protection Agency Method 29. The particles captured at the inlet have diameters typically between 0.2 and 0.5 µm, whereas those collected at the outlet are slightly larger and more smoothly spherical. Unfortunately, the particles are so small that good X-ray signals could not be obtained in the EERC electron microscopes, so the compositions of the particles are still unknown. Next steps include an attempt to find an available electron microscope system with greater ability to determine the composition of the small particles.

PROJECT TITLE: Degradation of TBC Systems in Environments Relevant to Advanced Gas Turbines for IGCC Systems
PARTICIPANT: University of Pittsburgh
PROJECT NO.: FE0007271

The goal of this University of Pittsburgh project is to study the degradation of individual components of the TBC system due to combined effects of fly-ash deposits and gas environments. At temperatures above 1,300 °C, melting of the commercial ash caused extensive degradation of the YSZ topcoat material. At lower temperatures, a solid-state reaction between fly ash and YSZ occurred, which was less detrimental but can nevertheless affect TBC lifetimes. This solid-state reaction was investigated with synthetic ash mixtures and found to be strongly dependent on CaO levels in the ash. The addition of sulfates to the deposits resulted in greater degradation of the YSZ, caused by enhanced infiltration of calcium zirconate into surface cracks. Using both commercial and model NiCoCrAlY alloys with systematic composition variations, the extent of metal loss during exposure to fly ash in CO_2-H_2O at 1,100 °C was shown to be related to the alloy β-γ phase fractions rather than to each phase composition. A study of individual oxide deposits revealed that CaO was the most aggressive ash constituent, as its reaction with the aluminum-lean γ phase produces a liquid calcium chromate, which rapidly consumes the alloy. These observations provide an understanding for the better resistance of β-rich alloys in the presence of more complex commercial ash deposits, and offer guidance for alloy design.

PROJECT TITLE: Novel Hafnia-Based Nanostructured Thermal Barrier Coatings for Advanced Hydrogen Turbine Technology
PARTICIPANT: University of Texas at El Paso
PROJECT NO.: FE0000765

The hot gas exposure experiments were performed for extended duration (under variable time) at high temperatures for YSH and YSZH coatings. After every span of hot gas exposure, the microstructure, morphology, and stability of the coatings were evaluated. No significant microstructure change is observed from X-ray diffraction analysis. It is evident from residual stress analysis that YSH coating holds high residual stress developed within the coating upon thermal and hot gas exposure. The results of thermal oxidation measurements indicate that the material exhibits a good resistance against oxidation at higher temperatures. The thermal conductivity of the YSZH is found to be significantly lower compared to that of end members i.e., YSZ or YSH. The mixed YSZH compositions of the coatings are promising in terms of microstructure, thermal, and thermo-chemical stability considerations.

ADVANCED RESEARCH

AERO-HEAT TRANSFER

PROJECT TITLE: Analysis of Gas Turbine Thermal Performance
PARTICIPANT: Ames Laboratory/Purdue University
PROJECT NO.: AL05205018

The U.S. Department of Energy and Purdue University proposed and studied a new Nusselt number, referred to as the SCS number, as an alternative to the widely used Nusselt number to enable more accurate quantification of experimental measurements of surface heat transfer. Currently, convective heat transfer over solid surfaces is quantified by using the Nusselt number, which involves measuring the heat-transfer coefficient (h), defined by Newton's law of cooling. To measure h in a cooling duct, one needs to know the heat transfer rate from the duct wall, the temperature at the duct wall, and the bulk temperature that the duct wall is exposed to. The bulk temperature (T_b) is difficult to measure experimentally because it involves not only the temperature but also the density, the velocity, and the specific heat in the entire cross section of the duct, and it loses its physical meaning in complicated configurations with multiple temperature streams. The advantage of the SCS number over the Nusselt number is not requiring h or T_b. To contrast the SCS number with the traditional Nusselt number (Nu), steady RANS based on the SST model were performed to study the compressible flow and heat transfer in two straight ducts with isothermal walls—a smooth duct with circular cross section and a duct with a rectangular cross section that is lined with a staggered array of pin fins—with focus on the entrance region of the ducts. For the circular duct when the wall heats the gas, Nu decreases rapidly from the duct inlet until reaching a minimum and then rises until reaching a nearly constant value in the "fully" developed region. For the conditions of the present study, the location of the minimum, the location where the Nusselt number becomes nearly constant, and the value of that constant were found to be strong functions of the wall temperature and relatively independent of the Reynolds number. When the wall cools the gas, Nu is not a constant in the "fully" developed region. It rises with a positive slope that increases with decreasing wall temperature. For the SCS number, it also decreases rapidly from the duct inlet. However, unlike Nu, the decrease is monotonic from the duct inlet to the duct exit, whether the wall is heating or cooling the gas. Also, unlike Nu, which is a strong function of the wall temperature, different SCS curves for different wall temperatures approach each other to collapse to one curve. For the rectangular duct with pin fins, Nu tends to oscillate about a constant value in the region about the pin fins, whereas SCS tends to oscillate about a line with a negative slope. The heat-transfer enhancement given by Nu/(Nu for a smooth duct) is higher than those given by SCS/(SCS for a smooth duct) because Nu provides the local heat-transfer coefficient, which depends on the local bulk temperature, and SCS provides the local heat flux, which depends on the past history. For Nu, the history is embedded in the bulk temperature. For SCS, the history is built into the SCS number itself. Thus, the magnitude of SCS is also a measure of the "capacity" of the fluid to cool or heat the wall. The SCS number may be preferred for quantifying

heat-transfer measurements since there will be no ambiguity in the T_b used to define h. However, when designing heat exchangers, Nu is preferred because T_b used in the design of heat exchangers is clearly defined. Thus, a formula was developed to convert SCS to Nu and vice versa.

PROJECT TITLE: Demonstration of Enabling Spar-Shell Cooling Technology in Gas Turbines
PARTICIPANT: Florida Turbine Technologies, Inc.
PROJECT NO.: FE0006696

Florida Turbines Technologies' most significant accomplishment to date is represented by the placement of orders for all hardware items and material and these items are well into the fabrication phase. This accomplishment is the culmination of a coordinated effort to design, analyze, develop, test, etc., to date and is a key milestone in the delivery of parts for full-scale engine demonstration and validation testing.

PROJECT TITLE: Phase III Xlerator Program: Rapid Commercialization of Advanced Turbine Blades for IGCC Power Plants
PARTICIPANT: Mikro Systems, Inc.
PROJECT NO.: FE0006220

The low rate initial production facility is complete and fully operational. Employees are trained, process control documentation is in place, and Mikro is producing cores for investment casting daily in the facility. Mikro has achieved the target overall process yield of 50 percent and is continuing to refine the process and end product.

Mikro Systems and Siemens Energy, Orlando, FL, signed a new collaborative technology license agreement to advance state-of-the-art gas turbine performance. Siemens and Mikro Systems are working together to validate and certify Mikro Systems' TOMO℠ manufacturing technology for use in commercial production of stationary and moving turbine components. This will include production trials and application-specific component testing. Siemens has established a production facility near Mikro Systems' Virginia facilities expressly for the production ceramic cores using the TOMO℠ process, which added domestic jobs. The technology will enable more sophisticated airfoil designs with improved cooling characteristics, leading to higher operating temperatures and improved efficiency. In addition to enabling designs that were previously impossible to manufacture, the technology will reduce time-to-market for future design enhancements through reduced tooling costs, reduced production lead times and more efficient manufacturing processes. Mikro Systems has worked closely with Siemens over the past year to refine and ready TOMO℠ core fabrication technology for full commercial production.

PROJECT TITLE: Turbine Thermal Management
PARTICIPANT: National Energy Technology Laboratory—Regional University Alliance
PROJECT NO.: FWP-2012.03.02

Advanced internal and trailing edge airfoil cooling concepts developed by NETL-RUA at the University of Pittsburgh have successfully been cast by Mikro Systems into CM247 coupons for demonstration testing of enhanced heat transfer effectiveness over state-of-the-art internal airfoil cooling configurations in NETL's high-temperature, pressurized aerothermal test facility. Similarly, CM247 coupons containing NETL-RUA's tripod hole film cooling concepts are being cast based on Virginia Tech's designs that were shown through Virginia Tech's CFD modeling efforts to mitigate thermal stress risers within the advanced film cooling architecture during operation under simulated actual engine conditions. As NETL-RUA continues to move airfoil cooling configurations closer to near surface locations, NETL's collaboration with Ames Laboratory has begun development and application of Ni-based oxide dispersion strengthened architectures on CM247 channeled test articles. Although these efforts are currently focused on bench-scale materials development, demonstration of concept manufacturing, as well as design perfor-

mance, the internal and film cooling geometries are intended to be further optimized and incorporated into 1.2-inch airfoils for testing in Penn State's secondary flow rotating test facility. To date, the Penn State test facility has been designed, major equipment has been procured, and the facility is being readied for assembly with shakedown testing targeted for early FY 2014.

COMBUSTION

PROJECT TITLE: Low-Swirl Injectors for Hydrogen Gas Turbines in Near-Zero-Emissions Coal Power Plants
PARTICIPANT: Lawrence Berkeley National Laboratory
PROJECT NO.: FWP 7-678402

The low-swirl injector is a simple advanced combustion concept from the Lawrence Berkeley National Laboratory (LBNL) that is being developed for the combustion turbines in an IGCC clean coal power plant that burn fuels with high-hydrogen concentrations. After a previous successful demonstration of a reduced-scale fully functional fuel-flexible low-swirl injector (high-hydrogen, natural gas and syngas), fundamental information on hydrogen flames is being pursued to support its adaptation to gas turbine combustors. In collaboration with University of California at Irvine, the turbulent displacement flame speeds of hydrogen at gas turbine relevant conditions have been measured. Although the data show them to be consistent with those measured at atmospheric conditions at LBNL, full analysis requires corresponding laminar flame information that is lacking in the combustion literatures. The situation is being addressed by analyzing the numerical simulation results obtained by researchers at LBNL's Computation Research Division. The strategy is to develop new diagnostics to extract flame structures and flame properties from simulations of low-swirl injector hydrogen flames at atmospheric conditions, and idealized hydrogen laminar flames at gas relevant conditions. Diagnostics have produced results to characterize the broken flame structures shown on experimental measurements and a modified laminar flame speeds for interpreting the turbulent displacement flame speeds. Since the low-swirl injector is an established research tool, knowledge gained from these fundamental investigations is directly applicable to the design of other IGCC combustion turbines.

PROJECT TITLE: Thermophysical Properties of CO_2 and CO_2-Rich Mixtures
PARTICIPANT: National Institute of Standards and Technology
PROJECT NO.: FE0003931

At the National Institute of Standards and Technology, an apparatus, utilizing a one-of-a-kind gravimetric hygrometer designed for humidity standards, is measuring the water content of saturated CO_2 at pressures up to 5 MPa. These measurements define the dew point with a precision approximately an order of magnitude better than existing data, better defining the requirements for drying captured CO_2 for compression and transportation. So far these measurements have been performed from 10 °C to 40 °C, and work is underway to extend the temperature range to 85 °C.

MATERIALS

PROJECT TITLE: Coating Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines
PARTICIPANT: Oak Ridge National Laboratory
PROJECT NO.: FEAA070

Laboratory evaluations of various types of TBC specimens in different environments are being conducted at Oak Ridge National Laboratory. Coatings were furnace cycled at 1,150 °C for diffusion bond coatings and 1,100 °C for spray-deposited MCrAlY-type bond coatings. While the addition of 10 percent water vapor reduced coating lifetimes by 30–50 percent compared to testing in dry air or oxygen, experiments in 90 percent CO_2-10 percent H_2O resulted in higher TBC lifetimes. Thus, the lower CO_2 levels found in conventional or syngas-fired turbines are not likely to impact TBC performance.

SMALL BUSINESS INNOVATION RESEARCH

INNOVATIVE COOLING CONCEPTS

PROJECT TITLE: Air-Riding Seal Technology for Advanced Gas Turbine Engines
PARTICIPANT: Florida Turbine Technologies, Inc.
PROJECT NO.: SC0008218

During the Phase I effort, a rig was developed that demonstrated the feasibility of the air-riding seal (ARS) concept. Test data was obtained from a nominal steady-state environment over a range of rotor speeds and pressure ratios. It was found that the seal performance was largely independent of rotor speed, indicating the ARS is fundamentally a hydrostatic seal. CFD and one-dimensional flow analytical models were created and their predictions closely matched the test data. Both the data and analytical model show, for the tested configuration, clearances less than 0.004 inches. This compares favorably with the industry standard labyrinth seals that have clearances of 0.040–0.120 inches on large industrial gas turbine (IGT) engines. With the analytical models grounded to test data, they were then used to study engine applications and design anomalies. Implementing the ARS technology into a utility-scale IGT will result in significant performance increases. With reasonable assumptions, it is shown that leakage air is reduced by over 2.6 percent, providing an additional 9 MW of power without increasing the firing temperature. Additionally, CO_2 emissions are reduced by 0.77 pounds per kilowatt of power generated and exhaust gas temperature is increased providing further performance improvements for combined cycle units. Through concept evaluation in Phase I of the SBIR, several items were identified for further development before introduction into engine applications, such as studying variables that effect system response and development of conjugate heat transfer fluid-structural interaction models that account for fluid heat up and thermal deflections.

PROJECT TITLE: Advanced Cooling for IGCC Turbine Blades
PARTICIPANT: Mikro Systems, Inc.
PROJECT NO.: SC0001359

Mikro applied its patented TOMO℠ process to the manufacture of advanced turbine blade trailing edge coupons and airfoils used in IGCC power plants. In order to improve heat transfer and lower cooling air requirements, the advanced blade designs will require more complex internal cooling passages that can be produced using current investment casting techniques. Previously, Mikro demonstrated a method for rapid prototyping testing coupons with advanced cooling features. These test coupons are critical to the understanding of heat transfer properties of features that have eluded the design community due to limitations in manufacturing methods. The current accomplishment is demonstration that these features could be incorporated into a full size turbine blade. The combination of TOMO's rapid development capability with a path to serial production will allow engineers to design engines capable of operating at inlet firing temperatures from approximately 1,260 °C to around 1,427 °C. The advantages of higher temperature operation are well-known to the industry and include higher combustion efficiency, improved fuel efficiency, and lower emissions

MANUFACTURING

PROJECT TITLE: Advanced Filtration to Improve Single Crystal Casting Yield
PARTICIPANT: Mikro Systems, Inc.
PROJECT NO.: SC0008266

Mikro applied its breakthrough TOMO℠ manufacturing technology to advance the state-of-the-art for ceramic filtration of molten metals. Mikro, along with input from PCC Airfoils, conducted an analysis to understand both the requirements for optimal filter performance in the investment casting process and the shortcomings for current ceramic filtration options. Mikro designed ceramic filter test articles with up to a seven times increase in filtration

surface area that could determine the efficacy of TOMO℠ in the production of filters with advanced, engineered designs. These filters were successfully produced and water flow tested against current state ceramic filters. The test results indicated Mikro's engineered filters provided a significant improvement to the flow rate characteristics of the filter when compared to current state-of-the-art. Mikro demonstrated that it could apply its manufacturing technology to produce next-generation ceramic filters with significant increases in design capability. This new advanced design capability expands the design space and opens the opportunity to produce engineered ceramic filters that can drastically improve current filtration performance and therefore improve investment single crystal casting yields for IGT airfoils. This will in turn make single crystal casting a more accessible option for turbine OEMs to use to increase turbine performance and efficiency and also reduce fuel consumption and emissions.

PROJECT TITLE: Recovery Act: Advanced Laser Machining Techniques for Cooling Holes in Gas Turbines
PARTICIPANT: Physical Sciences Inc.
PROJECT NO.: SC0003400

Physical Sciences has been developing methods to improve water guided laser drilling process control to improve reliability. Improvements to the water delivery system include additions of a pulse dampener to mitigate cavitation and eliminate the possibility of bubbles being generated in the water delivery system. Additional improvements include better filtration of debris and the use of longer focal length optics to reduce the maximum laser power density delivered through the water stream. These changes will minimize the likelihood of water within the stream from boiling due to direct absorption of the laser light by the water or a superheated debris particle. Both the addition of the pulse dampener and the longer focal length optics improved reliability of the drilling process to as many as 1,000 consecutive laser pulses, but this value remains too small for production drilling applications.

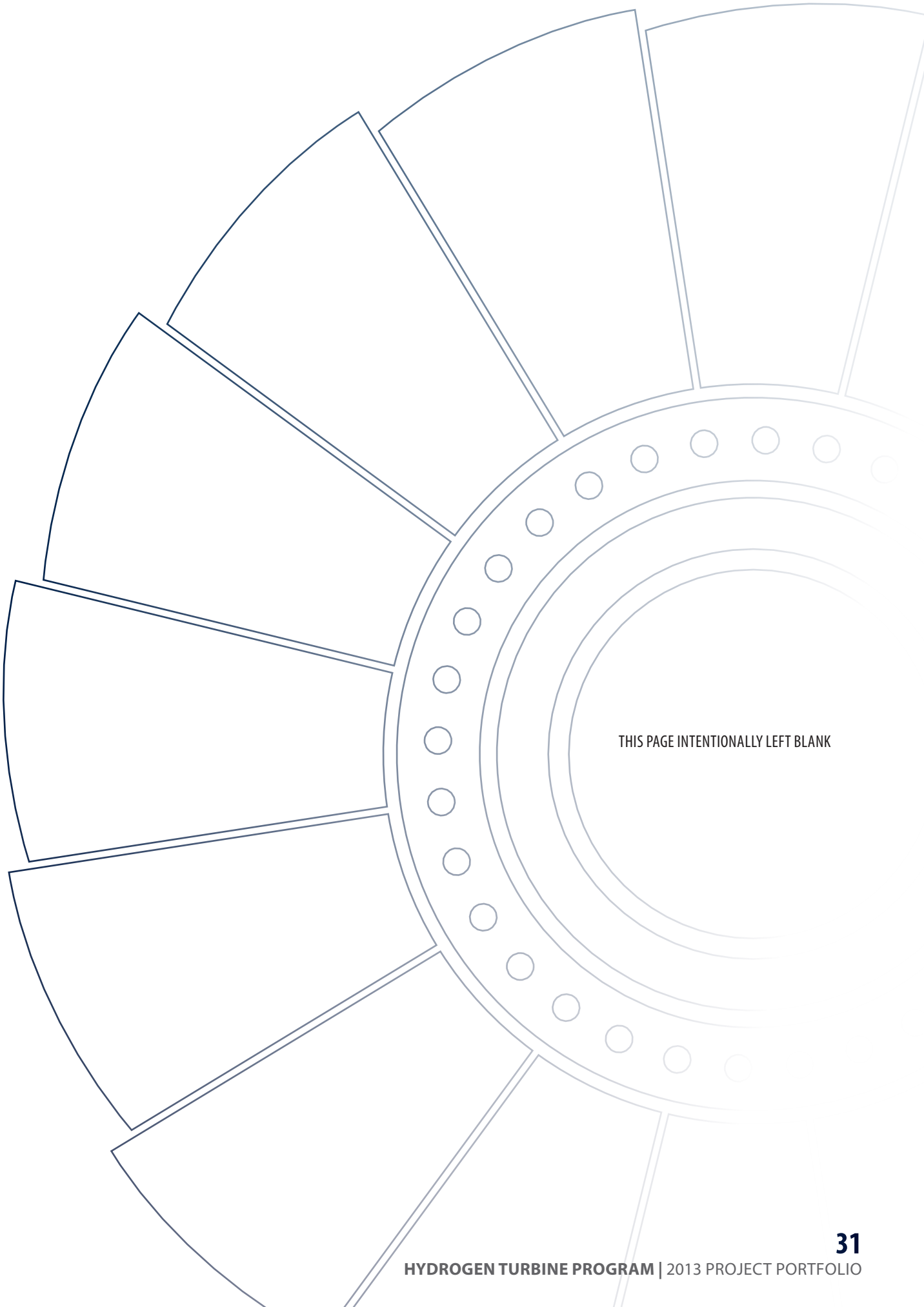
THERMAL BARRIER COATINGS

PROJECT TITLE: Ultra-High-Temperature Thermal Barrier Coatings
PARTICIPANT: HiFunda LLC and University of Connecticut
PROJECT NO.: SC0007544

Researchers at HiFunda and University of Connecticut have identified SPPS processing parameters that could achieve the desirable microstructural features of high porosity and vertical cracking. Coatings of thickness greater than 250 μm and having the desired microstructure were successfully sprayed. SPPS YAG TBCs were shown to have lifetimes that matched or exceeded baseline YSZ TBCs at both standard thermal cycling conditions and elevated temperature thermal cycling.

PROJECT TITLE: High-Temperature Unique Low-Thermal Conductivity Thermal Barrier Coating Architectures
PARTICIPANT: UES, Inc.
PROJECT NO.: SC0004356

UES has shown that appropriate manipulation of the TBC microstructure and the individual layer thicknesses within the multi-layered TBC architecture results in lower thermal conductivity, reduced erosion rates, and reduced high-temperature sintering. Thermal conductivity and erosion rates can be tailored based on the TBC composition and design architecture. It has also been shown that in appropriately tailored multi-layer TBC, sintering induced cracking can be minimized for isothermal testing at 1,316 °C.



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SECTION 4: HYDROGEN TURBINES

The Hydrogen Turbine program, in collaboration with the Nation's leading large-frame turbine manufacturers, GE Power & Water and Siemens Energy, is pursuing development of hydrogen-fueled turbine technology for IGCC applications through the Hydrogen Turbines key area. The ongoing cost-shared projects build on the developers' knowledge and expertise along with insight from national laboratories and universities. Hydrogen-fueled turbines developed through the supported projects will be highly efficient, low-cost, and have low-emissions, which will make possible an IGCC power plant that captures and stores CO_2. The inherent performance penalties associated with CO_2 capture are driving a renewed focus on gas turbine technology advancement as a means to minimize these penalties.

The Hydrogen Turbines key area focuses on developing a hydrogen-fueled turbine with the following nominal conditions: 2,650 °F turbine inlet temperature, pressure ratio of 24, and nominal inlet airflow of 4.6 million pounds per hour.

The aim is to develop this turbine by focusing on the following specific research areas:

- Developing low-NO_x hydrogen combustion systems
- Increasing turbine inlet temperature
- Reducing interstage leakage
- Minimizing cooling requirements and cooling flows
- Developing and utilizing advanced materials
- Implementing advanced airfoil designs

Key technologies, components, and subsystems being developed in this key area include:

- Low NO_x premixed hydrogen combustors for large-frame turbines
- Material systems and architectures for base materials and coatings that allow higher temperature operation
- Stationary and rotating airfoils with superior aerodynamics, strength, and cooling technology
- Revolutionary gas turbine components and designs

Developing advanced gas turbines fueled with pure hydrogen in coal-based IGCC applications that capture 90 percent of the plant CO_2 offers the single largest impact for efficiency and COE improvements as compared to other technologies being developed. System studies confirm that the Hydrogen Turbine program can meet and exceed established program goals assuming the appropriate technology can be developed and deployed.

In an IGCC plant, syngas produced from the coal is cleanly burned in a heavy-duty gas turbine. With pre-combustion CO_2 capture, the resulting gas turbine fuel is hydrogen. The hydrogen turbine projects with GE Power & Water and Siemens Energy address key technology developments required to achieve specific DOE performance goals relative to emissions, efficiency, and capital cost.

The projects comprise two phases. Phase I, (October 2005 to September 2007), was focused on conceptual design and technology identification. The output of Phase I was a down-selection of key technologies that are currently being developed in Phase II. The Phase II effort, started in October 2007, is focused on technology development and validation at a component level.

In 2010, Phase II was supplemented with ARRA funding. Using this additional funding, activities were added to the plan to expand the scope, accelerate the pace, and adapt existing development efforts to benefit gas turbines for industrial applications in addition to focusing on IGCC power plants. Phase II and the ARRA portion of these projects will conclude in 2015. Where and how the research focus areas will affect hydrogen turbine development is shown in the figure below.

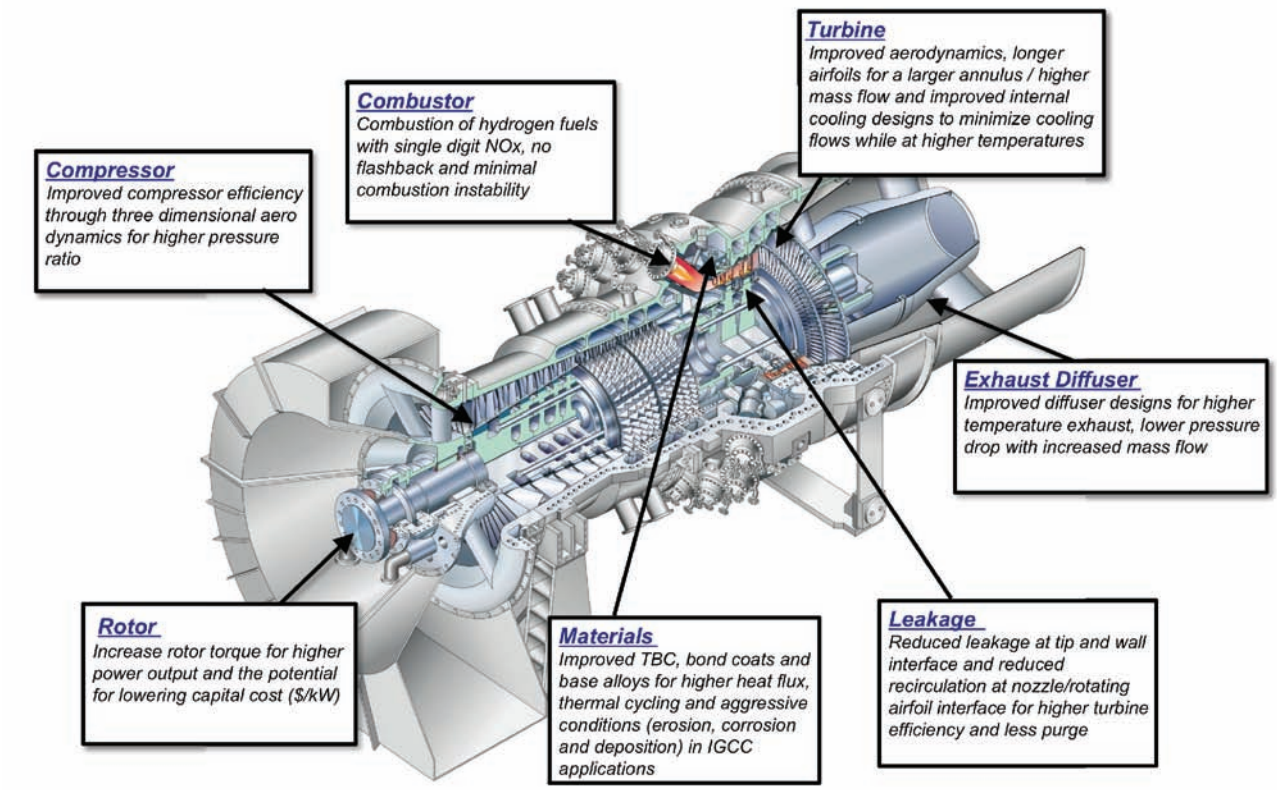

Figure 4-1. Research Focus Area Effects on Hydrogen Turbine Development

Under the ARRA-funded program, GE Power & Water is developing and validating state-of-the-art component-level technologies for hydrogen-fueled turbines. These turbines can be utilized in conjunction with pre-combustion carbon capture systems to effectively reduce carbon emissions from a variety of industrial applications. This project includes work in the following research focus areas: advanced hydrogen combustion systems, materials, sensors, and turbine airfoils. The assessment of the impact to efficiency, CO2 release, and emissions will utilize a baseline plant with CCS and a gas turbine that does not yet include the technologies to be developed as part of this project, and compare it to a similar plant with an advanced gas turbine. Validation that the program goals have been achieved will be accomplished through subscale and full-scale testing.

Siemens Energy, under the ARRA funded program, is focusing on advancing state-of-the-art large natural-gas-fired turbine technology to produce turbines specifically designed for operation on hydrogen and syngas fuels derived from industrial processes that capture a large percentage of CO_2. Advanced technologies and concepts will be evaluated, down-selected, and validated. The advanced technologies, component designs, and manufacturing processes will be developed and verified in subscale and full-scale tests and process verifications to demonstrate that the program goals can be achieved.

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Recovery Act: Advanced Hydrogen Turbine Development—General Electric

Background

GE Power & Water, along with GE Global Research Center, has an ongoing U.S. Department of Energy (DOE) program to develop gas turbine technology for coal-based integrated gasification combined cycle (IGCC) power generation that will improve efficiency, reduce emissions, lower costs, and allow for carbon capture and storage (CCS). GE is broadening this development effort, along with expanding applicability to industrial applications such as refineries and steel mills under the American Recovery and Reinvestment Act (ARRA). ARRA funding will be utilized to facilitate a set of gas turbine technology advancements that will improve the efficiency, emissions, and cost performance of turbines with industrial CCS. ARRA industrial technology acceleration, application, and adaptation will also benefit the advanced hydrogen turbine development and existing machines in typical utility applications.

This project is managed by the DOE's National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Under the ARRA funded program, GE will develop advanced industrial-frame turbine technology for hydrogen fueled turbine machinery. These turbines can be utilized in conjunction with pre-combustion carbon capture systems to effectively reduce carbon emissions from a variety of industrial applications. This project includes the following work:

- Advanced Hydrogen Combustion System: The combustion work in the project will develop a new combustion system that will enable industrial gas turbine applications with CCS to reach higher efficiencies through higher firing temperatures with low NO_x. The developed combustion system will be validated in a gas turbine operating at full conditions. The validation step from testing a full-scale combustion can in the laboratory, to testing the multi-can configuration on the gas turbine, will enable accelerated transition of the technology to future gas turbine designs.

- Materials: The materials work will develop alloys that are specifically tailored to withstand elevated temperatures in the hot gas path in the high-moisture, and potentially highly corrosive environments of hydrogen-fueled industrial applications with CCS. This will enable industrial gas turbine applications with CCS to achieve improved efficiency through higher firing temperature while preserving traditional hot gas path component durability.

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PARTNERS

GE Global Research Center
GE Aviation (base only)

PERFORMANCE PERIOD

Base

Start Date	End Date
10/01/2005	06/30/2014

ARRA

Start Date	End Date
10/01/2010	06/30/2014

NATIONAL ENERGY TECHNOLOGY LABORATORY

Albany, OR • Anchorage, AK • Morgantown, WV • Pittsburgh, PA • Sugar Land, TX

Website: www.netl.doe.gov

Customer Service: 1-800-553-7681

U.S. DEPARTMENT OF ENERGY

COST

Total Project Value
$134,309,886

Base
DOE/Non-DOE Share
$50,175,589 / $21,503,823

ARRA funded
Total ARRA Project Value
$62,630,474

DOE/Non-DOE Share
$31,315,237 / $31,315,237

Government funding for this project is provided in whole or in part through the American Recovery and Reinvestment Act.

AWARD NUMBER

NT42643

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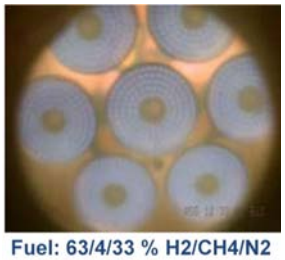

Cooled CCD camera installed in stand (on transition piece) provides view of head end.

Cut away of small multi-tube mixer for rig testing for flash back on H_2-N_2 fuel.

- Sensors: The sensors work will focus on utilizing and integrating a variety of advanced sensor technologies into gas turbine control and operation. This will enable the gas turbine to be operated with real-time knowledge of actual parameters that are affecting component conditions and operation. Therefore, industrial gas turbine applications with CCS will be able to achieve improved efficiency and operability, and reduced emissions.
- Turbine Airfoil: The turbine airfoil work will develop technology that reduces required cooling flows to enable industrial gas turbine applications with CCS to achieve improved efficiency.

Goals/Objectives

The ARRA gas turbine effort will focus on developing and validating state-of-the-art component-level technologies for a gas turbine. The assessment of the impact to efficiency, CO_2 release, and emissions will utilize a baseline plant with CCS and a gas turbine that does not yet include the technologies to be developed as part of this project, and compare that to a similar plant with an advanced gas turbine. Validation that the program goals have been achieved will be accomplished through subscale and full-scale testing.

Accomplishments

- Continued development and optimization of pre-mixed combustion technology for hydrogen by utilizing extensive megawatt-scale, full head end testing on leading concepts from both the Base and ARRA portions of the program – achieved lowest (single digit) NO_x emissions to date and demonstrated fuel flexibility with durability at target 2012 cycle conditions.
- Downselected the best option for an element of the first stage architecture. Developed manufacturing feasibility and durability. Established heat transfer rig trial plans, identified key geometries, and began initial testing.
- Completed cooling effectiveness characterization for the next generation advanced cooling design concept.
- Completed testing of an optimal purge flow configuration.
- Improved and updated cycle models to determine the performance and output characteristics resulting from the technology advancements made under the program, including systems required for CCS.
- Downselected a new cost effective, mechanically and environmentally capable hot gas path alloy. Completed initial environmental testing and a first full-size component casting. Results show good castability and improvement over base-line material.
- Continued characterization of down-selected thermal barrier coating and bond coat.

Benefits

GE has extensive experience in supplying gas turbines for use in a broad range of applications, including the industrial space. Power generation systems based on advanced gas turbines offer efficient energy conversion solutions that meet the challenge of fuel diversity, while maintaining superior environmental performance. Gas turbine technology advances from the existing program are aimed at offsetting CCS penalties in terms of efficiency and cost while improving emissions performance in preparation for CCS in coal IGCC power generation. Similarly, this proposed program is focused on gas turbine technology advances that are aimed at offsetting CCS penalties, improving emissions and performance, and accelerating technology deploymentin preparation for CCS in industrial applications.

NT42643 August 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Recovery Act: Advanced Hydrogen Turbine Development—Siemens Energy

Background

Siemens Energy, along with numerous partners, has an ongoing U.S. Department of Energy (DOE) program to develop hydrogen turbines for coal-based integrated gasification combined cycle (IGCC) power generation that will improve efficiency, reduce emissions, lower costs, and allow for carbon capture and storage (CCS). Siemens Energy is expanding this program for industrial applications such as cement, chemical, steel, and aluminum plants, refineries, manufacturing facilities, etc., under the American Recovery and Reinvestment Act (ARRA). ARRA funding will be utilized to facilitate a set of gas turbine technology advancements that will improve the efficiency, emissions, and cost performance of turbines for industrial CCS. ARRA industrial technology acceleration, application, and adaptation will also benefit advanced hydrogen turbine development and existing machines in typical utility applications.

This project is managed by the DOE's National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Under the ARRA funded program, Siemens Energy will focus on advancing state-of-the-art large natural gas fired turbine technology to produce turbines specifically designed for operation on hydrogen and syngas fuels derived from industrial processes that capture a large percentage of CO_2. Advanced technologies and concepts will be evaluated, down selected, and validated. The advanced technologies, component designs, and manufacturing processes will be developed and verified in sub-scale and full-scale tests and process verifications to demonstrate that the program goals can be achieved. Some of the key enabling technologies needed are as follows:

- Fuel-flexible, ultra low NO_x, long-life combustion system operating at the increased firing temperatures needed to achieve high efficiency. Siemens will work to develop a premixed combustion system capable of operating on hydrogen fuel at high temperatures with minimal dilution flow. As part of this development, modeling tools for thermal acoustics and computational fluid dynamics will be adapted for hydrogen fuels and validated with test data. The primary path for the hydrogen combustor is a modification of the current Siemens premixed natural gas burner to operate on hydrogen. In addition, as risk mitigation, several alternative combustion technologies will be evaluated to determine if they can provide an improvement for high-temperature hydrogen operation.

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PARTNERS (OVER $1 MILLION)

Florida Turbine Technology
NRC (Canada)
Precision Castpart
Mikro Systems
Metcut
Georgia Tech
DLR (Germany)

PERFORMANCE PERIOD

Base

Start Date	End Date
10/01/2005	06/30/2015

ARRA

Start Date	End Date
10/01/2010	06/30/2015

U.S. DEPARTMENT OF ENERGY

COST

Total Project Value
$135,213,024

Base
DOE/Non-DOE Share
$49,791,168 / $20,761,010

ARRA Funded
Total ARRA Project Value
$64,660,846

DOE/Non-DOE Share
$32,330,423 / $32,330,423

Government funding for this project is provided in whole or in part through the American Recovery and Reinvestment Act.

AWARD NUMBER

DE-FC26-05NT42644

- Development and optimization of higher temperature material system (base alloy, bond coat, and thermal barrier coatings [TBCs]) capabilities that allow operation in challenging environments, thus ensuring that the turbine components achieve high reliability and long life.
- Advanced manufacturing processes and techniques essential to producing the novel turbine cooling schemes that are being pursued in this program. Siemens will be producing full-sized engine parts using advanced core making technology, performing investment casting trials, conducting destructive and non-destructive evaluations, machining prototype parts using a proposed production process and conducting full-scale engine testing on final products.
- New sensors and diagnostics to allow more efficient, fuel-flexible, and safe gas turbine operation. Customer interviews determined key sensing needs and sensor specifications for these needs. Based on these results, Siemens will work with sensor vendors to design, develop, and validate sensor designs for engine validation or use in on-line control.

Goals/Objectives

The objective of the ARRA activity is to identify a set of gas turbine technology advancements that will improve the efficiency, emissions, and cost performance of gas turbines for industrial applications with CCS. This extension will accelerate the key technologies needed to significantly improve the efficiency of gas turbines in industrial applications, apply these technologies to the advanced hydrogen turbine, and adapt to existing turbine frames as applicable.

Accomplishments

- Siemens Energy opened a manufacturing facility in Charlottesville, Virginia for the innovative commercial production of airfoil ceramic cores for gas turbine blades and vanes using the TOMO[SM] technology, initially developed by Mikro Systems, Inc. and further developed under the Hydrogen Turbine Program.
- Optimized combustion system components were hot fired and results will be fed forward for additional full combustion system testing.
- Modular vanes, advanced airfoil core technology, advanced sensors and high temperature TBCs were all successfully tested in a full scale engine test.
- Updated compressor and turbine flow paths were down selected.
- Achieving a reduction of approximately 40 percent in flaking or chipping of material (known as spallation) from coated surfaces with new modified bond coats and substrates.
- Selective Catalytic Reduction (SCR) system demonstrated over 95 percent NO_x reduction efficiency. Over 3,000 hours testing in simulated IGCC exhaust and greater than 15,000 hours of continuous operation in an NGCC plant exhaust.
- Technology Readiness Level (TRL) 6 achieved on the rotor disk optimization tool.
- Significant progress was made in manufacturing capabilities of the turbine blade four and turbine blade one with advanced cooling technologies.
- Multiple rig test campaigns were run across several components and focus areas including: compressor aerodynamics and airfoil design, turbine aerodynamics and airfoil design, sealing and heat transfer.

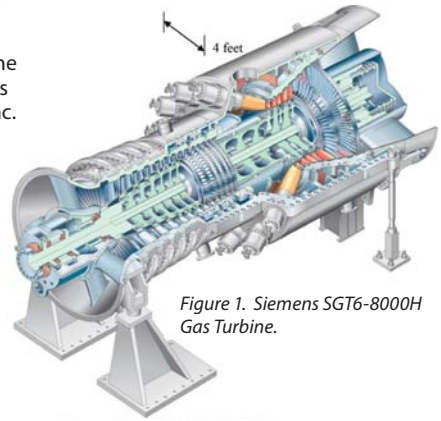

Figure 1. Siemens SGT6-8000H Gas Turbine.

Figure 2. Advanced Front Stage Compressor Test Rig.

Benefits

Siemens Energy has extensive experience in supplying gas turbines for use in industrial applications such as refineries, petrochemical plants, and iron, and steel mills. Power generation systems based on advanced gas turbines offer efficient energy conversion solutions that meet the challenge of fuel diversity, while maintaining superior environmental performance. Gas turbine technology advances from the existing program are aimed at offsetting CCS penalties in terms of efficiency and cost while improving emissions performance in preparation for CCS in coal IGCC power generation. Similarly, this proposed ARRA program is focused on gas turbine technology advances that are aimed at offsetting CCS penalties, improving emissions and performance, and accelerating technology deployment in preparation for CCS in Industrial applications.

NT42644 July 2013

SECTION 5: OXY-FUEL TURBINES

Oxy-fuel combustion provides a conceptually simple way to remove CO_2 from a fossil-fueled power plant. In these systems, hydrocarbon fuel is burned with nearly pure oxygen and evaporating feedwater for cooling to produce a working fluid comprising mostly steam and CO_2. The working fluid produces power in advanced expansion turbines, after which its water component is condensed, leaving the CO_2 to be compressed and stored or utilized. The use of high-purity oxygen (<0.5 percent N_2) and the generation of large amounts of steam from recycled water in the gas generator/combustor virtually eliminates NO_x emissions.

OFT-based technology offers a competitive power system with nearly 100 percent carbon capture and near-zero emissions of all other criteria pollutants. This system can operate with either coal-derived syngas or natural gas. Additionally, the oxy-fuel turbine concept has attributes that leverage opportunities in CO_2 enhanced oil and gas recovery market space by providing competitively priced CO_2, power, and water while using fuels of little or no market value.

Under the Oxy-Fuel Turbines key area, Clean Energy Systems is developing an oxy-fuel power system based upon their proprietary high energy density combustor (gas generator). Utilizing rocket engine design features—photo-etched platelets to create precision metering channels for the atomization of reactants—the compact gas generator combusts gaseous fossil fuels (e.g., natural gas, coal syngas, etc.) with near stoichiometric oxygen and demineralized water injection for temperature control. The gas generator produces a high pressure and temperature working fluid (150–900 psig and 600–3,000 °F on coal syngas) that is >90 percent steam and <10 percent CO_2. The fluid is then expanded through one or more turbines to generate electrical power.

Prior-year work has focused on system analyses (Phase I), the design of 100-MWth syngas-capable gas generator, and concept validation using a modified GE J79 gas turbine at Clean Energy Systems' Kimberlina power plant facility (Phase II). In 2010, Phase II A was added, with ARRA funding to develop and demonstrate an intermediate-pressure OFT capable of supporting commercial-scale oxy-fuel power generation with 99 percent CO_2 capture. Then, Clean Energy Systems partnered with Florida Turbine Technologies to complete a detailed design to convert a commercial Siemens SGT-900 gas turbine to an OFT capable of full-load turbine inlet temperatures of approximately 2,000 °F. To reduce program costs and time to demonstration, Clean Energy Systems procured a used gas turbine that was disassembled, inspected, repaired, and modified according to detailed engineering designs created by Florida Turbine Technologies. The reassembled engine designated the OFT-900 has been installed at Kimberlina power plant. The Kimberlina facility and support equipment has been modified to support low-power, short-duration turbine testing. Testing began in early 2013 with a final report due by the end of FY 2013.

Potential future work to support full-power use of the OFT-900 would include additional turbine design modifications (sealing, improved shaft torque capability, installation of turbine exit guide vanes, materials life assessment, etc.) and oxy-fuel combustion fundamentals. For FY 2013 there is no plan for adding work to the current project/contract.

Central to the DOE-FE ARRA investment in the Clean Energy Systems' oxy-fuel turbine concept is the objective to demonstrate CO_2 utilization in industrial applications. The oxy-fuel turbine concept is benefiting from the market dynamics for CO_2 enhanced oil recovery and the unique attributes the system brings to this application. The oxy-fuel turbine power system will create new opportunities for domestic oil recovery through the use of CO_2. ARRA funds facilitate the strategy that industrial CO_2 use—while in and of itself beneficial—will also accelerate R&D for power generation with carbon capture.

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Recovery Act: Oxy-Fuel Turbo Machinery Development for Energy Intensive Industrial Applications—Clean Energy Systems

Background

Clean Energy Systems (CES), with support from Siemens Energy and Florida Turbine Technologies (FTT), has an ongoing U.S. Department of Energy (DOE) program to develop an oxy-fuel combustor for highly efficient near zero emission power plants. CES is expanding this development for an industrial-scale, oxy-fuel reheat combustor-equipped intermediate-pressure oxy-fuel turbine (IP-OFT) under the American Recovery and Reinvestment Act (ARRA). Through the design, analysis, and testing of a modified Siemens SGT-900 gas turbine, the team will demonstrate a simple-cycle oxy-fuel system. ARRA funding is accelerating advancement in OFT technology for commercial industrial oxy-fueled plants as an economical means to produce power with carbon capture and storage (CCS) technologies.

This project is managed by the DOE's National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

The core of CES's technology is a high-pressure oxy-combustor that produces a steam/CO_2 working fluid for expansion in a turbine. The oxy-combustor system is adapted from rocket engine technology and burns gaseous or liquid fuels with gaseous oxygen. Compatible fuels include syngas from coal, refinery residues, biomass gases, natural gas, landfill gas, glycerol solutions, and oil/water emulsions.

These fuels are combusted with oxygen in the presence of water used for controlling temperature, producing a high pressure working fluid comprised of steam and CO_2. This project focuses on the design, fabrication, and demonstration of an IP-OFT that incorporates an oxy-fuel reheat combustor, a second combustor and a variant of the main combustor that will reheat the exhaust from the high-pressure turbine to the higher temperatures desired for the intermediate-pressure turbine. CES will work with FTT to refine and finalize detailed design modifications to the Siemens SGT-900 gas turbine. CES will work with Siemens Energy to procure a used SGT-900 that will

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PARTNERS

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Siemens Energy, Inc.

PERFORMANCE PERIOD

Base

Start Date	End Date
10/01/2005	04/30/2011

ARRA

Start Date	End Date
10/01/2010	03/31/2013

U.S. DEPARTMENT OF ENERGY

COST

Total Project Value
$51,452,748

Base
DOE/Non-DOE Share
$4,707,837 / $2,150,647

ARRA Funded
Total ARRA Project Value
$44,594,264

DOE/Non-DOE Share
$30,000,000 / $14,594,264

Government funding for this project is provided in whole or in part through the American Recovery and Reinvestment Act.

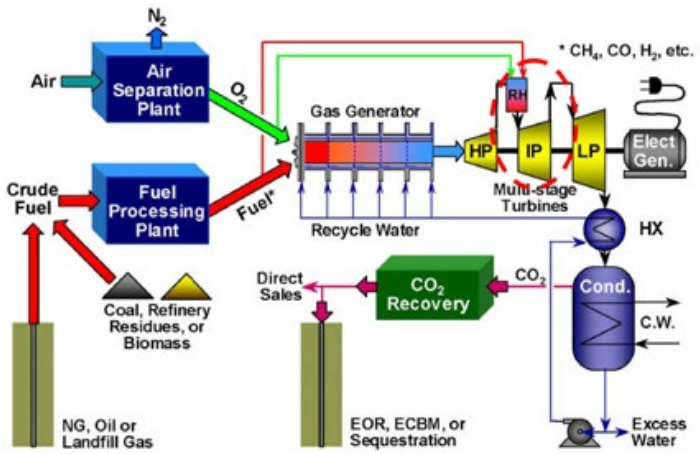
AWARD NUMBER

DE-FC26-05NT42645

be disassembled, inspected, refurbished, and modified according to the design definitions created by FTT. All necessary new components and packaging will be manufactured and installed on the IP-OFT by TurboCare with support from Siemens and FTT to take advantage of established knowledge and expertise. The final assembled unit will then be shipped to the CES test site for installation and demonstration. CES will work with experienced contractors to develop site layouts and balance-of-plant (BOP) equipment procurement plans.

Goals/Objectives

The ARRA objectives are to design, develop, and test a commercial-scale IP-OFT that can be deployed in industrial oxy-fuel plants with CCS greater than 99 percent of the produced CO_2 at competitive cycle efficiency and cost of electricity using diverse fuels.



Schematic of CES' Oxy-Fuel Power Cycle; Project Focus Circled in Red.

Accomplishments

- Completed cycle studies and analyses of 45 oxy-syngas combustor/turbine configurations, down-selecting to one near-term and one long-term baseline.
- Completed the detailed design of a 100-megawatt thermal (MWth) oxy-syngas combustor and its enclosure.
- Completed integrated testing of a 33-megawatt electric (MWe) OFT (modified J79 engine) and oxy-natural gas combustor.
- Designed, fabricated, and demonstrated a first-generation reheat combustor (capable of raising steam temperatures from approximately 600 °F to 2,000 °F), suitable for integration into an OFT-J79, in a dedicated test rig.
- Completed the detailed engineering design to convert an SGT-900 gas turbine into a 150-MWe OFT.
- Located, purchased, disassembled, and inspected a used SGT-900 B12 power plant.

- Refurbished, repaired, and replaced existing engine components to be reinstalled into a new OFT-900 engine. Major build activities included removal of the compressor blades and vanes, installation of a new thrust balance system and repair, rework and high-speed balance of the engine's rotor assembly. Manufactured new components required to convert an existing SGT-900 to an industrial-scale OFT. Assembled new OFT-900 engine and delivered to CES test facility.
- Completed the install, commissioning, and test of a commercial-scale OFT-900.
- Upgraded test facility to support commercial-scale OFT demonstration testing. Redesigned systems included natural gas and oxygen supply, electrical transformers and motor control centers, demineralized water makeup and supply and more.
- Designed, fabricated, and demonstrated a second-generation reheat combustor, suitable for integration into an OFT-900, in a dedicated test rig.
- CES experienced cost overruns in the SGT-900 overhaul and balance of plant failures at the Kimberlina test site, leaving insufficient resources to complete the full OFT test plan.

Benefits

A primary goal of DOE's Hydrogen Turbine Program for Oxy-Fuel Rankine Cycle Systems is to achieve highly efficient, near-zero-emission coal-based power systems. At the same time, DOE hopes to reduce capital costs in comparison to today's coal-burning plants. By leveraging the inherent high-temperature capabilities of gas turbines, this project will accelerate the design, development, and deployment of advanced oxy-fuel power systems. Studies show that the system-level performance is greatly enhanced by increasing inlet temperatures to the intermediate-pressure turbine.

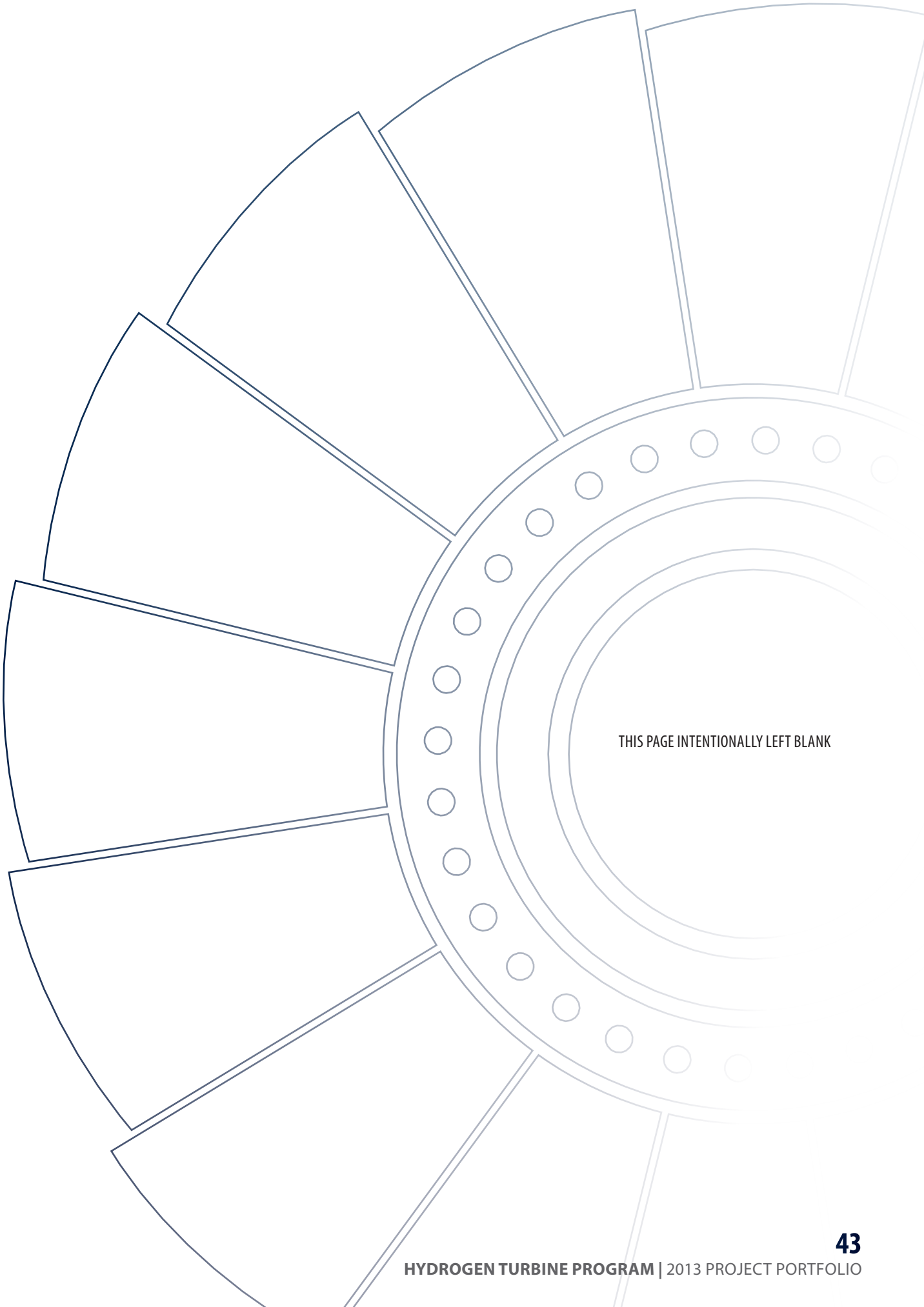
Oxy-Fuel Combustor Assembly.

OFT-J79 and Electric Generator.

OFT-900 and Generator Installation at Kimberlina Test Facility.

Completion of OFT-900 Testing; February 2013.

NT42645, July 2013



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SECTION 6: UNIVERSITY TURBINE SYSTEMS RESEARCH

The University Turbine Systems Research program addresses scientific and applied research to develop advanced turbines and turbine-based systems that will operate cleanly and efficiently when fueled with coal-derived syngas, hydrogen fuels, and natural gas. Since the inception of the DOE turbine program, the UTSR program has sought to provide the underlying scientific research to develop advanced turbines and turbine-based systems in support of DOE's turbine program goals. This research focuses on the areas of combustion, aerodynamics, heat transfer, and materials. The success of the UTSR program has been made possible by a network of universities, the collaborating gas turbine industry, and the DOE turbine program—all of which are facilitated by an annual UTSR workshop. UTSR also offers a Gas Turbine Industrial Fellowship funded by sponsoring gas turbine manufacturers. This fellowship has helped to facilitate the transition of the best students from academia to the gas turbine industry, thereby helping to maintain U.S. leadership in this important area of technology.

UTSR projects are established through a competitive solicitation open to all U.S. universities. Solicitation R&D topics are established in response to FE program goals and given specific focus through communications with the gas turbine industry. The gas turbine industry involvement and leadership is used to help guide the university research so as to keep it relevant and set the highest standards for project execution. The gas turbine industry provides leadership to define the thrust of the research program solicitation consistent with DOE goals and technical experts to evaluate the university research proposals. In many ways, the gas turbine industry is the customer for this Government-funded, university-performed research; this relationship drives R&D excellence.

The UTSR program has evolved over time in response to power-generation markets and DOE objectives. Evolution of objectives has involved a transition from turbines operating on natural gas to coal-derived syngas to very high-hydrogen fuels derived from syngas. Since conceptually advanced turbines are fuel-flexible this adaptation is possible. This fuel flexibility will also allow gas turbines to be used in IGCC applications that are configured to capture CO_2. Future IGCC plants utilizing pre-combustion CO_2 will produce an HHC fuel for the gas turbine; the fuel will then be combusted in the turbine and the CO_2 will be permanently stored underground. The transition requires the development of low-emission turbine combustion technologies for this variety of fuels, improved turbine hot section flow path aero-heat transfer methods, and durable, low-cost materials for the stressing environment.

UTSR ANNUAL WORKSHOP

The UTSR program holds an annual workshop that is open to the public and brings together experts from academia, industry, and Government to present and discuss ongoing turbine research in the areas of combustion, materials, and aerodynamics/heat transfer, with a focus on advanced syngas and hydrogen turbine systems. The agenda includes invited talks, technical presentations, panel discussions, poster presentations, and laboratory tours. Principal Investigators of DOE-funded projects present their latest results. The findings and recommendations are be used by DOE to guide future work and to make programmatic and funding decisions for the upcoming fiscal years. All of the workshop proceedings are posted on the NETL website. The 2013 workshop, co-organized by NETL and Purdue, was held at Purdue University, in West Lafayette, IN, from October 8–10.

UTSR SELECTIONS FOR FISCAL YEAR 2013

A UTSR funding opportunity announcement was announced in FY 2013 with a focus on two topic areas: (1) Combustion and (2) Hot Gas Path Parts. The Hot Gas Path Parts topic area has taken a new focus on the coupled perfor-

mance of materials and heat transfer, and sealing issues for air leakage areas within the turbine. Ten UTSR project selections were made for FY 2013–five in the area of Combustion and five for Hot Gas Path Parts R&D.

COMBUSTION TOPIC AREA

- **High-Pressure Turbulent Flame Speeds and Chemical Kinetics of Syngas Blends with and without Impurities—*Texas A&M University*:** This research project aims to further understanding of turbulent flame speeds for syngas blends at realistic engine conditions and to compile and demonstrate the validity of a comprehensive kinetics model that can predict laminar flame speed and ignition behavior of HHC fuels in the presence of likely contaminants.
- **Exhaust Gas Recirculation-Based CO_2 Recycling in Advanced Gas Turbine Combustors with High Hydrogen Content Fuels—*Purdue University*:** The objectives of the project are to develop experimental methods, kinetic models and numerical tools to quantify and predict the impact of exhaust gas recirculation on NO_x and carbon monoxide emissions, combustion kinetics, radiation heat transfer, turbulent combustion, and combustion instabilities for HHC fuels by using laminar and turbulent flow reactors and gas turbine combustors operating at high temperatures and pressures.
- **Predictive LES Modeling and Validation of High-Pressure Turbulent Flames and Flashback in Hydrogen-Enriched Gas-Turbine Combustion—*University of Texas at Austin*:** The overall objective of this project is the development of predictive computational models for LES of hydrogen-enriched combustion in gas turbines. In particular, the project will focus on two key topics, behavior of high-pressure turbulent flames with and without equivalence ratio variations, and flashback propagation through a turbulent boundary layer.
- **An Experimental and Modeling Study of NO_x-CO Formation in HHC Fuels Combustion in Gas Turbine Applications—*University of South Carolina*:** The goal of this project is to further advance the understanding needed to develop practical guidelines for realistic predictions of gas turbine combustion and emission properties during operation on HHC fuel. The project will investigate the effects of diluents and minor contaminant species on the combustion kinetics of HHC fuels and involve both detailed chemical kinetic model development for HHC-NO_x and coupled CFD-based multi-physics, multi-dimensional models.
- **Development of Criteria for Flashback Propensity in Jet Flames for High Hydrogen Content and Natural Gas Type Fuels—*University of California, Irvine*:** The goal of the project is to develop design guides that can be used to predict jet flame flashback propensity as a function of pressure, temperature, fuel composition, free stream velocity, turbulence level, and fuel-air mixing profiles. This effort will lead to a better fundamental understanding of flashback tendencies and will also provide insight into strategies for preventing flashback.

HOT GAS PATH TOPIC AREA

- **Thermally Effective and Thermally Efficient Cooling Technologies for Advanced Gas Turbines—*University of North Dakota*:** This project is designed to demonstrate the cooling effectiveness and efficiency of three innovative technologies which will offer additional tools to gas turbine cooling engineers in developing advanced cooling designs for high heat loads. This study will also document the aerodynamic losses associated with these cooling technologies which is a critical piece of information in the selection of a cooling methodology. This investigation will also assess the predictive capabilities of advanced CFD for use in cooling designs.
- **New Mechanistic Models of Creep-Fatigue Interactions for Gas Turbine Components—*Purdue University*:** This project aims to develop novel prediction tools for creep-fatigue crack growth by employing a framework of irreversible cohesive zone models together with a strain gradient viscoplastic continuum formulation. The end-goal is to create and validate a robust, multi-scale mechanism-based model that quantitatively predicts creep-fatigue crack growth and failure in nickel-based gas turbine alloys.

- **Microstructure-Sensitive Crystal Viscoplasticity for Ni-Base Superalloys—*Georgia Tech Research Corporation*:** The aim of this project conducted at Georgia Tech is to develop a microstructure-sensitive crystal viscoplasticity model that accounts for γ' precipitate morphology evolution that will be introduced through the coupling of coarsening kinetics and constitutive relations of the crystal viscoplasticity model. Long-term creep-fatigue interaction studies with specific emphasis on the role of microstructure will be conducted on two single-crystal Ni-base superalloys with potential application to IGTs.
- **Evaluation of Flow and Heat Transfer Inside Lean Premixed Combustor Systems Under Reacting Flow Conditions—*Virginia Polytechnic Institute and State University*:** The overall goal of this project is to provide a better understanding of the combustor swirling flow and its effect on liner surface heat transfer in order to improve prediction methods and design practices in combustor liner cooling for low emissions combustors. The project will focus on the interaction between the hot swirling gases and the liner wall within a gas turbine combustor. This will support the development of more effective cooling schemes to maintain and improve combustor durability.
- **Abradable Sealing Materials for Emerging IGCC-Based Turbine System—*University of California, Irvine*:** This project at will pursue an improved mechanistic understanding of factors governing performance of high-temperature abradable seals, and degradation mechanisms unique to coal-derived syngas and HHC-based combustion environments—ultimately with the goal of developing a knowledge base to support the design of coatings that retain optimal sealing characteristics and that are more resistant to the observed wear/attack mechanisms.

AERO-HEAT TRANSFER

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PROJECT FACTS

Hydrogen Turbines

Aerodynamics and Heat Transfer Studies of Parameters Specific to the IGCC-Requirements: High Mass Flow Endwall Contouring, Leading Edge Filleting and Blade Tip Ejection under Rotating Turbine Conditions—Texas A&M University

Background

The efficiency of gas turbines is affected by a number of parameters, including turbine inlet temperature (TIT) and individual component efficiencies. By utilizing the current high level of TIT, efforts are concentrated on improving the component efficiencies. This project with Texas A&M University (TAMU) introduces two different methods for turbine efficiency improvement: (1) a physics-based turbine endwall contouring and (2) blade tip cooling ejection to reduce the tip leakage and to improve the blade tip film cooling effectiveness.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment. This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers.

Project Description

This work is designed to provide the gas turbine industry with quantitative aerodynamic and film cooling effectiveness data essential to understanding the basic physics of complex secondary flows. This includes their influence on the efficiency and performance of gas turbines and the impact that different film cooling ejection

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
10/01/2009	09/30/2013

COST

Total Project Value
$499,969

DOE/Non-DOE Share
$399,891/$100,078

AWARD NUMBER

FE0000753

U.S. DEPARTMENT OF ENERGY

arrangements have on suppressing the detrimental effects of these secondary flows. TAMU is developing a new non-axisymmetric endwall contouring technology and applying it to a three stage, rotating research turbine test facility. Detailed experimental results presented below document the turbine efficiency improvement. Extensive experimental investigations relative to the blade tip ejection presented have shown the effect of different cooling injection arrangements. Both research topics treated in the current research support the gas turbine community in designing high efficiency gas turbines

Goals and Objectives

The main goal of this research is to provide the gas turbine engine designer with fundamental information pertaining to the physics of secondary flow, its influence on the efficiency and performance of gas turbines, and the impact of film cooling ejection arrangements on suppressing the detrimental effect of secondary flows. Project objectives are as follows:

- Establish a physics-based wall contouring method for turbine blades with high, medium, and low deflection.
- Investigate the aerodynamic and performance behavior of the three-stage turbine with and without endwall contouring.
- Generate detailed computer-aided design and computer-aided manufacturing (CAD-CAM) design for the final endwall contours of the second stage rotor.
- Perform an extensive optimization process for first stage contouring. The step is necessary because of the presence of a purge air slot posing a hardware constraint.
- Manufacture a new turbine hub with non-axisymmetric endwall contourings for first and second rotor row.
- Design of four pairs of blades with blade tip film cooling holes.
- Detailed experimental investigation of endwall contouring on purge flow film cooling.
- Detailed experimental investigation of four different blade tip geometries on blade tip film cooling.

Accomplishments

- Applied a new physics-based wall contouring method to the hub section of the second rotor row of an existing three-stage research turbine. A detailed numerical investigation with the new contouring revealed an efficiency improvement of 0.51 percent. The following performance measurement, however, revealed an efficiency of more than 1 percent above the one for reference non-contoured cases. The implied benefits could result in a substantial efficiency improvement for a typical four-stage gas turbine engine with four stator and four rotor rows.
- Numerical investigations highlighted a critical flow regime above which the geometry of the blade pressure side close to the hub needs to be contoured. Two alternative continuous diffusion contouring methods were applied, which reduced the pressure distributions on the blade pressure side, thus accelerating the flow in that region. While the first contouring requires a redesign of the blade geometry close to the hub, the second contouring, which introduced a sequential positive-negative contouring, is confined to the hub surface between the blade suction and pressure surface.
- Generated a detailed CAD-CAM design for the final endwall contours of the second turbine stage. The research turbine was disassembled and sent to a machine shop for modification necessary to perform endwall contour performance testing. Detailed film cooling experiments were also performed to document the impact of non-axisymmetric endwall contouring on film cooling effectiveness of the endwall exposed to purge flow.
- Performed an extensive optimization process for first stage contouring. This step was necessary due to the presence of purge air slot which posed a hardware constraint.
- Designed, manufactured and installed four pairs of blades with different tip ejection film cooling holes onto the research turbine. These configurations were used in detailed film cooling experiments to document the impact of different film cooling hole arrangements on film cooling effectiveness of the blade tips.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The new method for designing non-axisymmetric endwall contours presented in this project could eventually increase the efficiency of gas turbines.

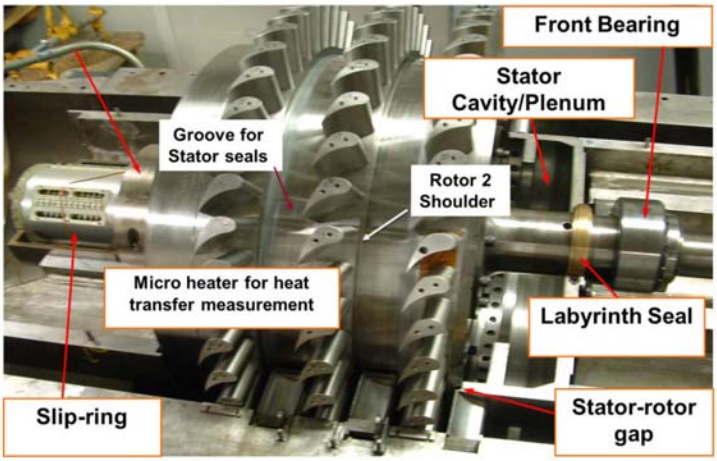

Figure 1. Turbine components with two independent cooling loops.

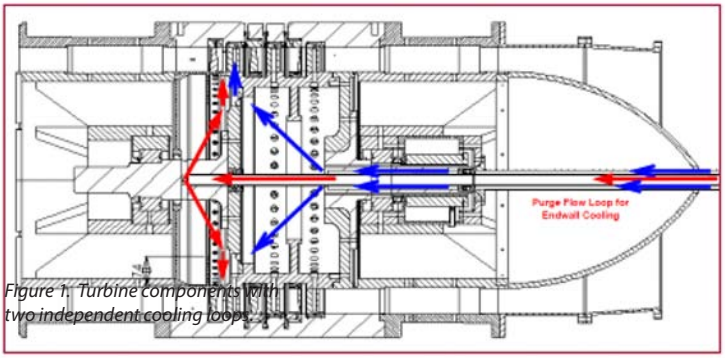

Figure 1. Turbine components with two independent cooling loops.

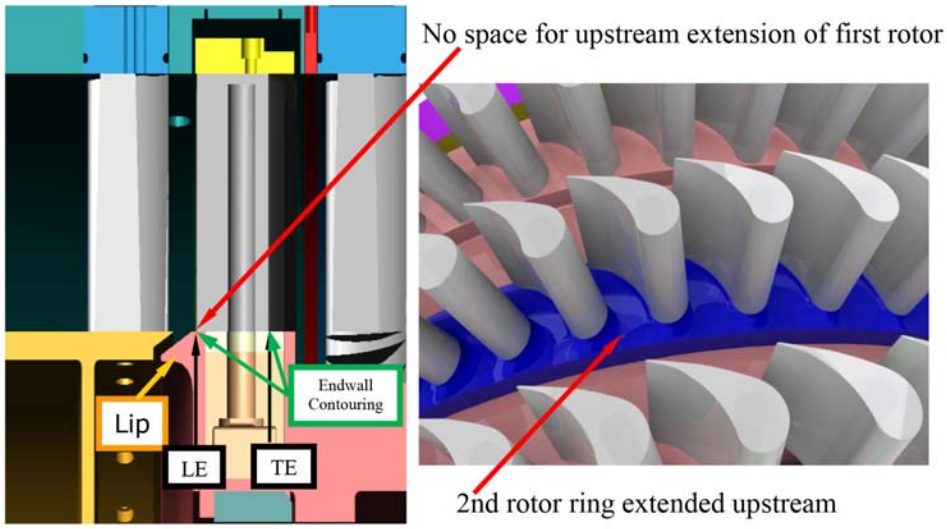

Figure 2. Details of purge flow injection (left), Contouring on second turbine row (blue) right.

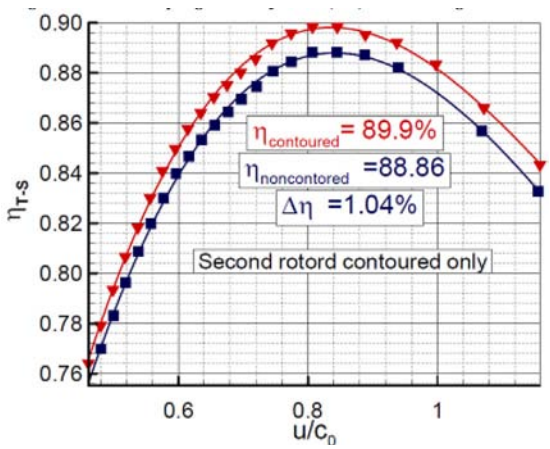

Figure 3. Measured total-to-static efficiency distribution as a function of u/co for the three-stage TPFL-research turbine. Efficiency of the non-contoured reference case is marked by solid squares, whereas the triangles designate the efficiency distribution of the contoured case.

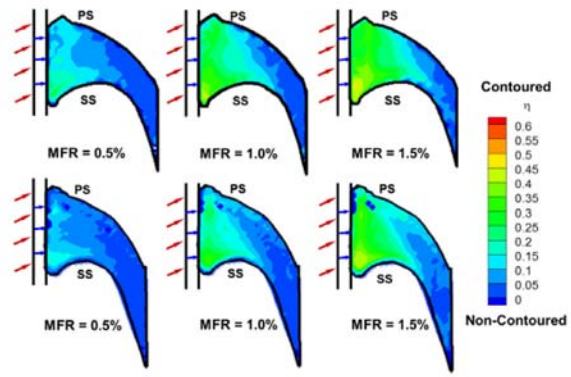

Figure 4. Comparison of film cooling effectiveness distribution on the contoured and non-contoured rotating platform for 3000 rpm.

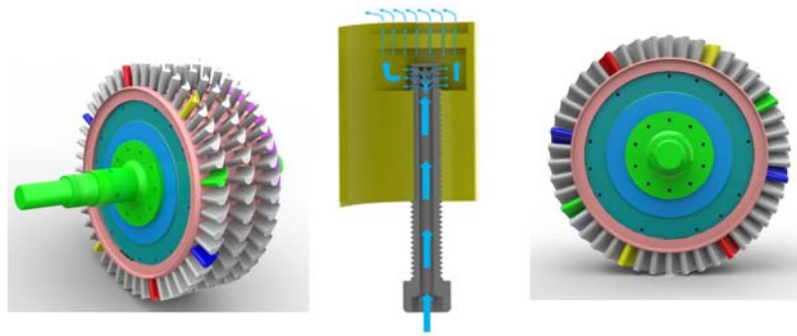

Figure 5. Comparison of film cooling effectiveness distribution on the contoured and non-contoured rotating platform for 3000 rpm.

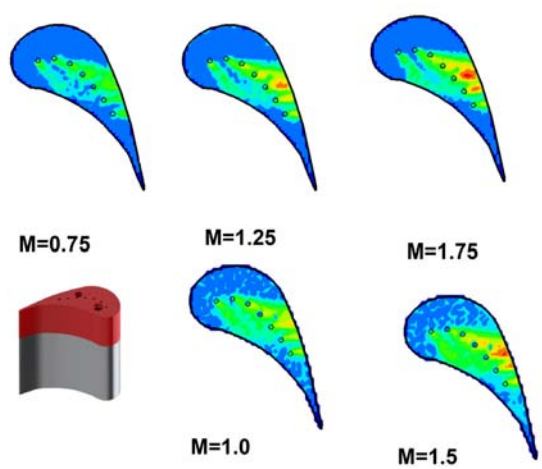

Figure 6. Blade tip film cooling effectiveness distribution on a flat tip at different blowing ratios for 3000 rpm.

FE0000753 August 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Effects of Hot Streak and Phantom Cooling on Heat Transfer in a Cooled Turbine Stage Including Particulate Deposition—The Ohio State University

Background

Sophisticated computational modeling and simulation play a crucial role in the design, analysis, and optimization of next-generation gas turbines for power generation. For example, accurate prediction of first stage heat loads and blade temperatures is critical as manufacturers increase turbine inlet temperatures and reduce cooling flows in pursuit of increased turbine efficiency. In this project, The Ohio State University (OSU) will develop a validated computational modeling capability for characterizing the effects of hot streaks (spatial variations in the working fluid temperature upon combustor exit) and particulate (e.g., fly ash) deposition on the heat load and blade temperatures in a cooled turbine stage (vane and rotor). Experimental data from OSU's Turbine Reacting Flow Facility (TuRFR) deposition cascade facility and transient turbine test rig will be used to validate the models.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

The particulate deposition model developed by OSU in prior UTSR work will be modified to better account for the fundamental physics of particle impact and sticking, including particle and surface properties. Experimental data from OSU's TuRFR deposition cascade facility will be used to validate the revised model.

The TuRFR facility will be modified to provide for the generation of inlet temperature profile non-uniformities (hot streaks), which will be tracked through the turbine nozzle passage using surface temperature infrared imagery and exit plane temperature measurements. Hot streak evolution and the effect of the hot streaks on deposition will be evaluated. Film cooling will then be added to both the experiments and the computation to evaluate its effect on hot streak migration and deposition. Finally, the model's ability to track hot streak migration will be exercised on a full turbine stage

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PROJECT DURATION

Start Date	End Date
10/01/2011	09/30/2014

COST

Total Project Value
$621,758

DOE/Non-DOE Share
$497,223/$124,535

AWARD NUMBER

FE0007156

NATIONAL ENERGY TECHNOLOGY LABORATORY

Albany, OR • Anchorage, AK • Morgantown, WV • Pittsburgh, PA • Sugar Land, TX

Website: www.netl.doe.gov

Customer Service: 1-800-553-7681

U.S. DEPARTMENT OF ENERGY

(vane and rotor) using data acquired in the OSU Gas Turbine Laboratory transient turbine test rig. The model will also be used to predict deposition in the rotating configuration, although there will be no experimental validation of deposition in the rotating frame.

Goals and Objectives

The objective of this project is to develop a validated computational modeling capability for the characterization of the effects of hot streaks and particulate deposition on the heat load of modern gas turbines. In its final form, the model will be able to accurately predict the heat load and deposition rates in a cooled turbine stage. The research effort will include model validation with data obtained from the unique deposition and rotating turbine test facilities at OSU.

Accomplishments

- Incorporated elastoviscoplasticity (EVP) model which incorporates both elastic and plastic particle deformation. Previous models accounted for either elastic (critical velocity model) or plastic (critical viscosity model) deformation only.
- Conducted preliminary hot streak clocking study to determine dependency of deposition on hot streak location, particle size, and hot streak severity.
- Generated hot streaks in TuRFR.
- Conducted hot streak deposition test with uncooled nozzle guide vanes.
- Conducted flow simulation of TuRFR test conditions to produce first-ever corroborating computational and experimental data with hot streaks and deposition.
- Designed and constructed a new high temperature particle impingement test facility for the study of rebound/deposit mechanics of micron-sized particles.
- Fundamental rebound studies show trends in coefficient of restitution and deposition rate with temperature and velocity. Results will enhance modeling capabilities.
- Designed and fabricated film slot into existing vane set.
- Conducted tests with deposition and slot cooling with uniform freestream temperature as baseline.
- Developed flow model in Fluent for cooled vane.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This project will providethe U.S. gas turbine industry with valuable insights into factors affecting the operation of state-of-the-art gas turbines and the tools for the development of new, innovative airfoil cooling designs.

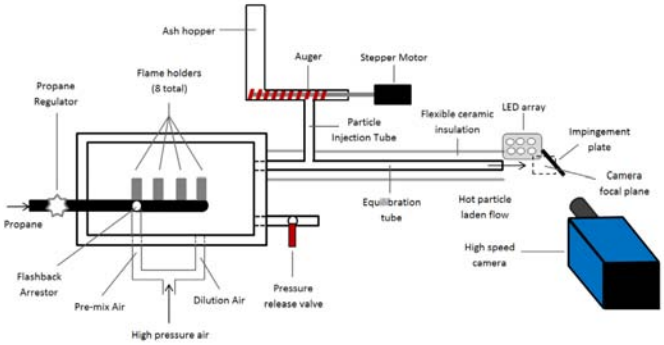

Figure 1. New high temperature fundamental particle impact testing facility showing particle shadow velocimetry arrangement.

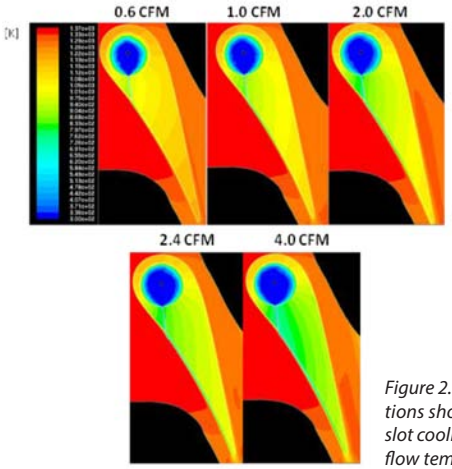

Figure 2. Fluent simulations showing effect of slot cooling on vane and flow temperatures.

Figure 3. OSU turbine reacting flow rig (TuRFR) showing upper and lower sections assembled.

FE0007156 Jul y 2013

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PROJECT FACTS

Hydrogen Turbines

Environmental Considerations and Cooling Strategies for Vane Leading Edges in a Syngas Environment—University of North Dakota

Background

Cooling airfoil leading edges of modern first stage gas turbine vanes presents a considerable challenge due to the aggressive heat transfer environment and efficiency penalties related to turbine hot gas path cooling. This environment is made more complex when natural gas is replaced by high hydrogen fuels (HHF) such as synthesis gas (syngas) derived from coal gasification with higher expected levels of impurities. In this project the University of North Dakota (UND) and The Ohio State University (OSU) will explore technology opportunities to improve the reliability of HHF gas turbines by analyzing the effects of free-stream turbulence level, geometry, deposition, and cooling on the heat load experienced by turbine vane leading edges.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

This collaborative effort studying technologies important to the reliability of HHF gas turbines has been structured utilizing three phases.

Phase I: Leading Edge Model Development and Experimental Validation

The initial task for OSU's turbine reacting flow rig (TuRFR) facility will be to determine if the deposition mechanism for faired cylinders is similar to deposition for turbine vanes. If this approach is feasible, then the relative impact of leading edge diameter on deposition can be investigated using varying diameter cylinders instead of vanes. The deposition measurements will then be made and sent to UND for surface modeling. During Phase I, UND will study the response of turbulence approaching large cylindrical stagnation regions, the associated heat transfer augmentation, and boundary layer development on the cylinder's surface. Additionally, UND will begin the development of candidate internal cooling geometries for cooling a region of a turbine vane's leading edge.

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PARTNERS

The Ohio State University

PROJECT DURATION

Start Date	End Date
10/01/2010	09/30/2013

COST

Total Project Value
$624,999

DOE/Non-DOE Share
$499,999/$125,000

AWARD NUMBER

FE0004588

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Phase II: Experimental Deposition and Roughness Study

OSU will utilize the TuRFR facility, modified to generate higher levels of turbulence, to study the influence of turbulence on deposition rates in turbines. These results will be used to improve predictive modeling and made available to UND for heat transfer measurements. UND will use surfaces generated by OSU as part of their leading edge heat transfer and boundary layer studies. UND will also develop and test candidate internal cooling schemes for large regions on a turbine vane's leading edge.

Phase III: Mitigation of Deposition Using Downstream Full Coverage Film Cooling

OSU will use faired (rounded to reduce drag) cylinders to explore various film cooling designs to assess their effectiveness at reducing deposition. Actual turbine vane geometry will be used to explore the influence of select film cooling patterns on deposition. UND will investigate the combined influence of turbulence and realistic roughness on film cooling effectiveness and surface heat transfer. As a basis of comparison, they will initially look at the influence of turbulence on film cooling effectiveness and heat transfer for selected full coverage geometries.

Goals and Objectives

The primary goal of this study is to investigate methods to mitigate the adverse effect of deposition on the life and operability of turbine nozzles. The conceptual approach will develop methods for internally cooled leading-edge regions to minimize the possibility of clogging while utilizing spent cooling air to cool and protect downstream surfaces from deposition buildup. Deposition rates will be investigated on varying-diameter leading edge regions with and without high turbulence levels while considering the mitigating influence of full coverage film cooling geometries on pressure surface deposition. This focus will lead to a greater understanding concerning the influence of varying turbulence conditions and realistic roughness on full coverage film cooling schemes. The project will also investigate stagnation region heat transfer and boundary layer development with a range of elevated turbulence levels with and without realistic roughness surfaces generated from the deposition tests.

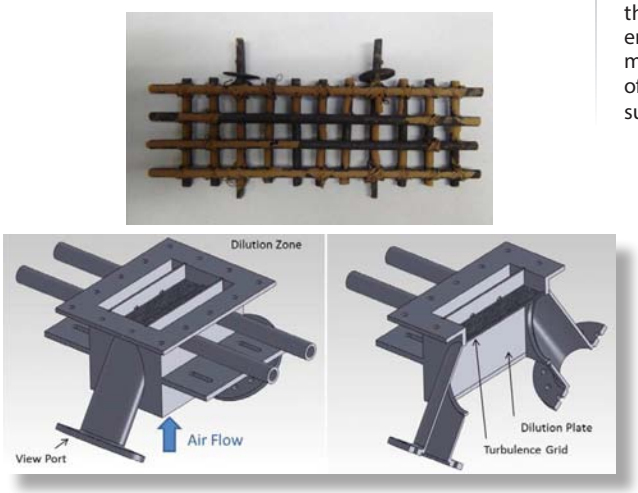

Figure 2. Grid (top) and facility installation drawings (bottom) showing grid installation in deposition facility. Elevated turbulence results in increased particulate deposition.

Accomplishments

UND accomplishments:

- Completed stagnation region heat transfer measurements for both cylinders using the six existing turbulence conditions.
- Designed and built a new smaller combustor simulator to generate turbulence intensities in excess of 20 percent. UND is currently documenting its turbulence characteristics.
- Initiated work on developing two full coverage film cooling geometries including a 30-slot. Preliminary computational fluid dynamics (CFD) studies have been conducted on the slot and discussions have been initiated with industry to help define the shaped hole geometry.
- Initiated work on developing test surfaces for cylinder approach flow turbulence measurements and cylinder surface boundary layer measurements.

OSU accomplishments:

- Conducted CFD studies of particle trajectories for faired cylinders.
- Modified TuRFR rig to accommodate a range of leading edge cylinders.
- Developed a dilution zone design in order to generate elevated turbulence levels.
- Conducted computational modeling showing the influence of transpiration on surface deposition.
- Conducted preliminary deposition tests on the impact of pressure surface film cooling on deposition.
- Documented freestream turbulence levels with and without turbulence grid.
- Documented increase in deposition rate with increasing turbulence level.
- Designed and fabricated film slot into new nozzle guide vane test section.
- Documented reduction in deposition with film cooling.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. Understanding heat transfer and surface deposition mechanisms on turbine leading edges will allow development of innovative designs leading to increased reliability in turbines subjected to a syngas environment.

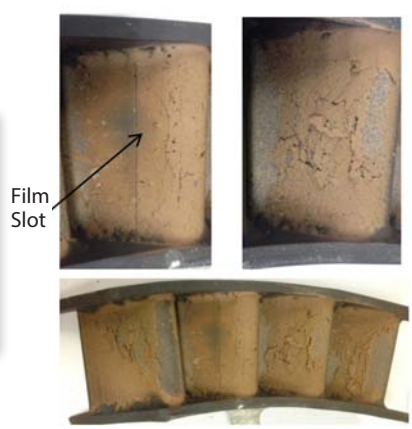

Figure 1. Deposit measurements on nozzle guide vane for slot film cooling (left); no film cooling (right).

FE0004588 July 2013

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PROJECT FACTS

Hydrogen Turbines

Improving Durability of Turbine Components through Trenched Film Cooling and Contoured Endwalls—University of Texas at Austin

Background

Gas turbine operation utilizing coal-derived high hydrogen fuels (synthesis gas, or syngas) requires new cooling configurations for turbine components. The use of syngas is likely to lead to degraded cooling performance resulting from rougher surfaces and partial blockage of film cooling holes. In this project the University of Texas at Austin (UT) in cooperation with The Pennsylvania State University (Penn State) will investigate the development of new film cooling and endwall cooling designs for maximum performance when subjected to high levels of contaminant depositions.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Wind tunnel facilities at Penn State and UT have been specifically designed to simulate film cooling of turbine vanes, blades, and endwalls. These facilities incorporate equipment that simulates the deposition of contaminants in the turbine by using molten wax particles to simulate the molten contaminant particles that occur at actual engine conditions. The wax particles used in the test facilities are sized appropriately to simulate the inertial behavior of particles that exist in engine conditions. The use of wax also allows for the simulation of the liquid-to-solid phase change that is essential to the primary deposition mechanism.

UT will be focusing on the performance of shallow trench film cooling configurations for various positions on the suction and pressure sides of a simulated vane with active deposition. Meanwhile, Penn State will be investigating the effect of active deposition on various endwall cooling configurations. Preliminary results show that deposition could be simulated dynamically using wax and that the effects of deposition could be quantified using infrared thermography. New endwall and vane surface film cooling configurations will be developed to minimize deposition and maximize cooling performance under contaminated conditions.

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PARTNERS

Pennsylvania State University

PROJECT DURATION

Start Date	End Date
10/01/2010	09/30/2013

COST

Total Project Value
$627,802
DOE/Non-DOE Share
$500,000 / $127,802

AWARD NUMBER

FE0005540

U.S. DEPARTMENT OF ENERGY

Goals and Objectives

The primary goal of this project is to develop new film cooling configurations specifically designed to mitigate the effects of depositions that cause significant degradation of turbine engine cooling performance. A specific focus is the development of trench and crater film cooling configurations that will operate successfully despite the heavy deposition of contaminants expected to occur when using syngas. These new film cooling designs will significantly improve the durability of gas turbines operating with syngas fuels. Project objectives are as follows:

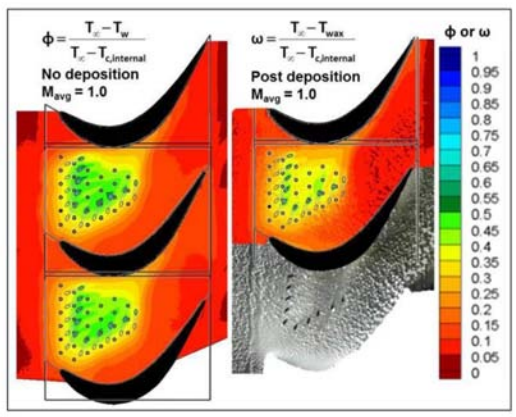
- Use a high conductivity, matched Biot number, model vane to evaluate the performance of simulated thermal barrier coating (TBC) with and without film cooling.
- Further develop the simulation of contaminant depositions to obtain more realistic deposits on simulated turbine vanes and endwalls.
- Perform deposition studies on a contoured endwall model.
- Measure aero-thermal boundary layers for flat and contoured endwalls.

Accomplishments

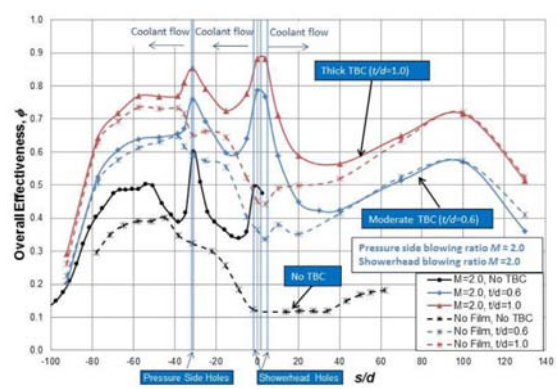
- Completed experimental simulation of a turbine vane with TBC. Measurements were made with a matched Biot number conducting model to obtain overall effectiveness with and without film cooling on the pressure side of the vane.
- Completed experiments where contaminant depositions on the leading edge and pressure side of a turbine vane with TBC were simulated using a unique molten wax spray technique. Results showed that the contaminant deposition acted as an insulating layer on the TBC surface, therefore decreasing the vane metal temperature.
- Results from the previous year showed that relatively thick TBC, with a thickness to hole diameter ratio of t/d = 1.0, caused a dramatic increase in overall cooling effectiveness. An important part of this year's work was to evaluate a moderate thickness TBC with thickness t/d = 0.6, i.e. 40% thinner than the TBC of FY2012. Although the overall cooling effectiveness was lower with the moderate thickness TBC, the cooling due to TBC still has a dominating effect.
- Measurements of temperature, velocity, and total pressure loss were taken in the wake of the turbine vane for cases with and without deposition, as well as with and without film cooling. Deposition was simulated using our unique molten wax spray technique. Results showed film cooling has a negligible effect on the velocity deficit and pressure loss in the wake, while deposition has a significant effect.
- Experiments measuring overall effectiveness of a matched Biot number flat endwall model have been conducted for film cooling only, as well as internal impingement cooling plus film cooling.
- Experiments with impingement were completed at two impingement heights representing the range of heights that will occur with the contoured endwall and in an engine.
- A one-dimensional analysis used to calculate the overall effectiveness based on results from impingement alone and film alone had good agreement at low blowing ratios, and reasonable agreement at high blowing ratios.
- Additional thermocouples were installed on the backside of the endwall, which were used to derive values for internal heat transfer coefficient.
- Deposition was dynamically simulated on the flat endwall. Internal endwall temperatures were measured to be higher with deposition, indicating an increase in heat transfer coefficient due to roughness effects.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The new turbine cooling designs developed in this project will extend component life, leading to reduced costs.



Effectiveness contours and corresponding deposition photographs at M_{avg} = 1.0 with no deposition and post deposition.



The combined cooling effects of TBC (Thermal Barrier Coating) and film cooling are shown in the distributions of overall cooling effectiveness, ϕ, presented here for no TBC, moderate thickness TBC, and thick TBC.

FE0005540 July 2013

COMBUSTION

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PROJECT FACTS

Hydrogen Turbines

Turbulent Flame Propagation Characteristics of High Hydrogen Content Fuels—Georgia Institute of Technology

Background

A fundamental problem influencing combustor design and operation of gas turbines is flame propagation characteristics of high hydrogen content (HHC) fuels. In this project, Georgia Institute of Technology (Georgia Tech) will obtain data and develop models of the turbulent burning rate of HHC fuels at realistic conditions and in inhomogeneous conditions such as in premixer nozzle boundary layers and core flows.

This project was competitively selected under the University Turbine Systems Research (UTSR) program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from HHC fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

This work will improve the state-of-the-art understanding of turbulent flame propagation characteristics of HHC fuels. The turbulent flame speed has a leading order influence on important combustor performance metrics such as flashback and blow-off propensities, emissions, life of hot section components, and combustion instabilities limits, including operating limits required to prevent harmful combustion dynamics. This research specifically addresses three of the combustion topic areas identified by DOE as of great importance for HHC systems: (1) turbulent burning velocities, (2) flashback, and (3) exhaust gas recirculation (EGR) impacts. The results of this effort will also enable advances in several other combustion topic areas; e.g., predicting combustion dynamics (which requires flame shape predictions) and improving large eddy simulation capabilities by providing turbulent burning rate sub-models for HHC fuels.

The project involves both experimental and modeling efforts. Prior work used optical flame emission in measurement of global turbulent consumption speeds of hydrogen (H_2)/carbon monoxide (CO) fuels. For this project, researchers will extend these previous efforts to a broader reactant class, including mixtures diluted with CO_2, water (H_2O),

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
10/01/2010	09/30/2013

COST

Total Project Value
$505,616

DOE/Non-DOE Share
$404,404/$101,212

AWARD NUMBER

FE0004555

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and nitrogen (N_2). Depending upon the degree of dilution, these mixtures will simulate both gasified fuel blends and systems with EGR. This data will be used to further the development of physics-based, mixture-dependent models of turbulent burning rates and to guide selection of conditions for determining more localized measurements of turbulence/chemistry interactions. Specifically, high-repetition-rate particle image velocimetry and hydroxyl radical planar laser induced fluorescence systems will be used to determine local flame speeds under realistic turbulent conditions. This is necessary for developing an improved understanding of strained flame statistics, and for testing and refining propagation models based on leading point concepts. The work plan will initially focus on uniform, premixed reactant mixtures, and then expand in focus by investigating turbulent burning rates in inhomogeneous premixed flows. An example would be obtaining measurements of turbulent propagation speeds in mixtures with stratified fuel/air profiles.

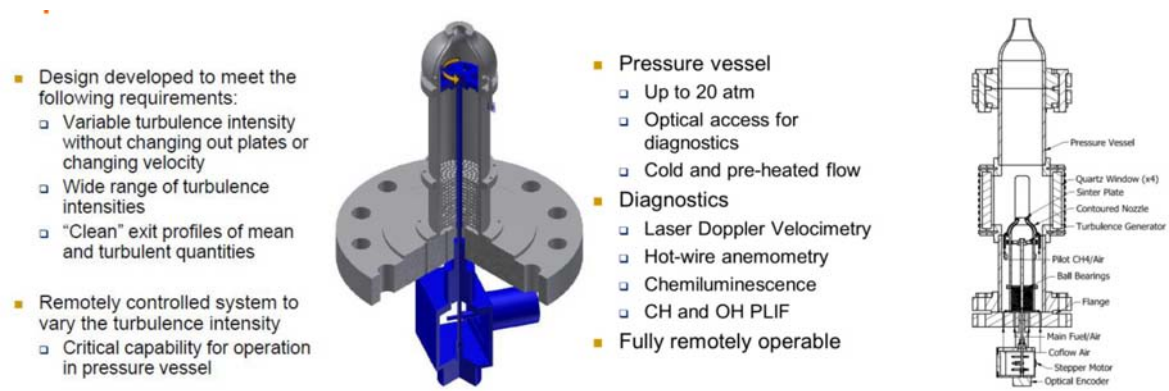

Figure 1. Features of the Variable Turbulence Generator (left) and High Pressure Test Facility (right) showing the installation of the variable turbulence generator and advanced diagnostics.

Goals and Objectives

The goal of this project is to improve the state-of-the-art understanding of turbulent flame propagation characteristics of HHC fuels. The current database of turbulent flame speed measurements will be extended to a broader reactant class that simulate both realistic HHC fuels as well as EGR situations at realistic gas turbine operating conditions. Models of turbulent burning rates in realistic flows will be developed through experimental and theoretical means. Turbulent propagation in spatially inhomogenous fuel/air mixtures will be characterized. Project objectives are as follows:

- Extend the existing data sets of turbulent flame speed measurements to a broader reactant class that is more representative of HHC fuels, such as mixtures diluted with CO_2, H_2O, and N_2, at realistic pressures, temperatures, and turbulence intensities. Depending upon the degree of dilution, these mixtures will simulate both gasified fuel blends and systems with extensive leels of EGR. The team will obtain measurements of global consumption speeds using the Bunsen burner and local displacement speeds using the low swirl burner (LSB) at realistic gas turbine conditions.
- Develop physics-based models of turbulent burning rates in realistic flows through both experimental and theoretical tasks. Experimentally, the team will obtain localized turbulence/chemistry interaction measurements using high-repetition-rate particle image velocimetry and hydroxyl radical planar laser induced fluorescence in the LSB configuration. This data will provide local characterization of instantaneous flame properties such as flame strain rate, flow fields, and burning rates, as well as time-averaged characteristics such as local turbulent displacement speed. These data can be used as both inputs to and validation of turbulent flame models. This work will be supported by parallel level set computations that will show how to relate the strained flame characteristics of the leading points of the turbulent flame brush to its turbulent burning rate.
- Characterize the turbulent burning rates in inhomogeneous flows. Specifically, the team will obtain measurements of turbulent propagation speeds in mixtures with stratified fuel/air profiles. Such data will be useful for extending turbulent flame speed data toward prediction of flashback in premixing nozzles, which have highly inhomogeneous flows and fuel/air ratio profiles.

Accomplishments

- Constructed a remotely operable high pressure test facility that will house the Bunsen burner and LSB nozzles.
- Installed a new fuel flow metering and control system, which allows for fuel compositions to be varied quickly during testing.
- Obtained global turbulent consumption speed data at 5 and 10 atmospheres (atm) for mean flow velocities ranging from 20–50 meters per second (m/s) and H_2/CO ratios of 30/70 to 90/10 by volume while investigating a wide range (5–30) of turbulence intensities.
- Performed cold flow velocity field characterization of the Bunsen burner for pressures and mean flow velocities of 1-20 atm and 10-50 m/s, respectively, using laser Doppler velocimetry (LDV).
- Performed extensive strain sensitivity calculations to investigate various parametric dependencies of key stretched flame quantities such as the maximum stretched laminar flame speed and the Markstein length.
- Acquired local displacement speed data at atmospheric conditions for mean flow velocities of 30 and 50 m/s and H_2/CO ratios from 50/50 to 100/0 by volume over a wide range of turbulence intensities using the LSB.
- Analyzed characteristics of the turbulent flame brush from flame images acquired in the Bunsen burner over a wide range of fuel compositions and pressures ranging from 1-10 atm. Investigated sensitivities of the flame brush thickness to turbulence intensity, pressure, and fuel composition.
- Calculated curvature statistics of LSB H_2/CO data from Mie scattering images obtained from high speed particle image velocimetry (PIV) experiments. Curvature measurements were also conditioned on the leading points of the turbulent flame front in order to better understand leading point characteristics with changing fuel composition and turbulence intensity.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This work will improve the reliability of gas turbines, decrease the cost of turbines, and develop predictive tools for utilizing HHC fuels. It will also advance the understanding of turbulent flame propagation characteristics of HHC fuels, including developing physics-based scaling and analyses to predict turbulent flame speed dependencies across broad fuel composition ranges that would be very useful to gas turbine designers.

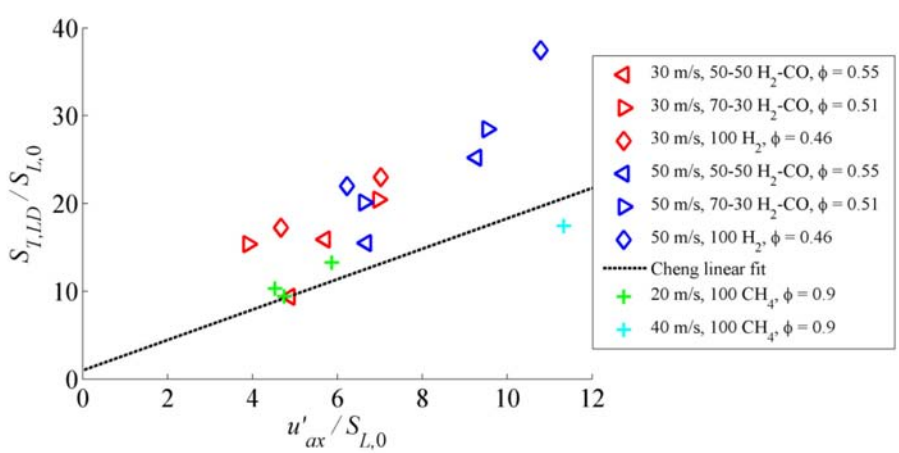

Figure 2. Variations of the turbulent local displacement speed, $S_{T,LD}$, with axial turbulence intensity, u'_{ax}, normalized by $S_{L,0}$ for CH_4 and H_2/CO cases at STP. The plotted line is a previous correlation from the literature.

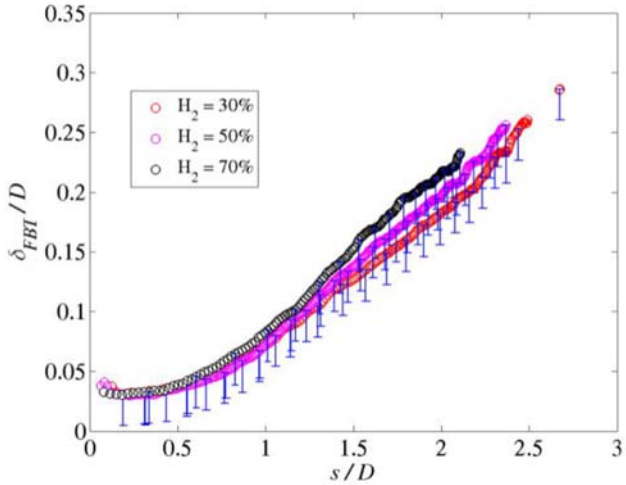

Figure 3. Variation of flame brush thickness as a function of the flame coordinate for various H_2/CO ratios whose mixture $S_{L,0}$ has been held fixed. Measurements shown are for the 12 mm diameter burner at $u'_{rms}/S_{L,0}$ = 17.4

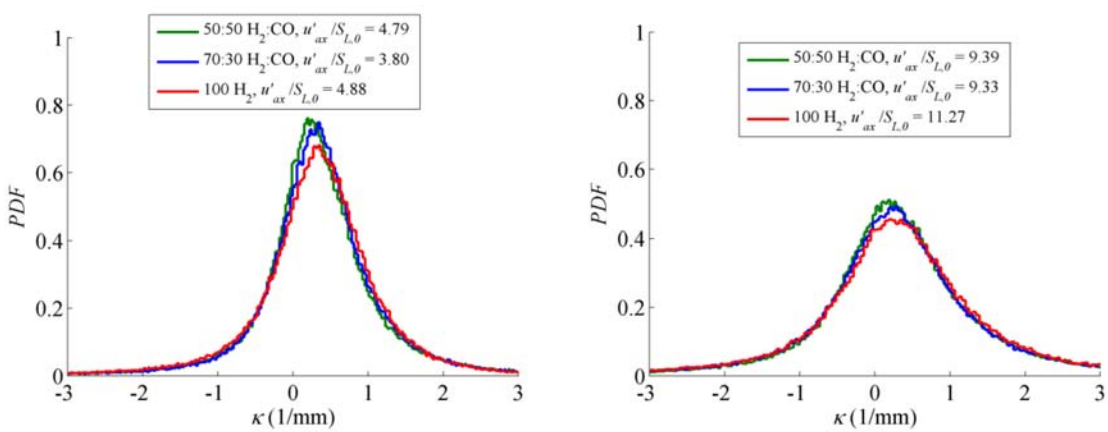

Figure 4. Flame brush leading point (0 ≤ <c> ≤ 0.1) curvature PDFs for varying fuel compositions at (left) U_0 = 30 m/s and (right) U_0 = 50 m/s.

FE0004555 July 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High Hydrogen Content Fuels—Pennsylvania State University

Background

Pennsylvania State University is teaming with Princeton University to enhance scientific understanding of the underlying factors affecting combustion for turbines in integrated gasification combined cycle (IGCC) plants operating on synthesis gas (syngas). The team is using this knowledge to develop detailed, validated combustion kinetics models that are useful to support the design and future research and development needed to transition to fuel flexible operations, including high hydrogen content (HHC) fuels derived from coal syngas, the product of gasification of coal. This project also fundamentally seeks to resolve previously reported discrepancies between published experimental data and modeling predictions of early ignition behavior of syngas and HHC fuels under controlled laboratory conditions (e.g., shock tubes, rapid compression machines, and counterflow burners).

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from HHC fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

An integrated and collaborative effort involving experiments and complementary chemical kinetic modeling is investigating the effects of significant concentrations of water and CO_2 as well as minor contaminant species (methane [CH_4], ethane [C_2H_6], NO_X, etc.) on the ignition and combustion of HHC fuels. The present research effort specifically addresses broadening the experimental data base for ignition delay, burning rate, and oxidation kinetics at high pressures, and further refinement of chemical kinetic models so as to develop compositional specifications related to the above major and minor species. The foundation for the chemical kinetic modeling is the well validated mechanism for hydrogen and carbon monoxide developed over the last 25 years

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PARTNERS

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PROJECT DURATION

Start Date	End Date
10/01/2009	09/30/2013

COST

Total Project Value
$897,252

DOE/Non-DOE Share
$716,999 / $180,253

AWARD NUMBER

FE0000752

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by Professor Frederick Dryer and his co-workers at Princeton University. This research will further advance the understanding needed to develop practical guidelines for realistic composition limits and operating characteristics for HHC fuels. A suite of experiments is ongoing that involve a high-pressure laminar flow reactor, a pressure-release type high-pressure combustion chamber, and a high-pressure turbulent flow reactor.

Goals and Objectives

The goal is to develop a computationally efficient detailed kinetic mechanism using accurate experimental guidance for designing fuel-flexible combustion systems that can achieve very low NO_X emissions, while operating at optimum efficiency. Project objectives are the following:

- Assessment of current models for HHC fuels and development of a validated HHC kinetic mechanism.
- Acquisition of new experimental data to evaluate the effects of nitrogen, water vapor, and carbon dioxide for HHC mixtures as well as trace species (e.g., NO_X, CH_4, C_2H_6, ethylene (C_2H_4) at high pressures (1-30 atmospheres [atm]).
- Incorporation of unaccounted reaction pathways, improved thermochemistry, and elementary rate constants into the kinetic models under development for HHC fuels.
- Development of a detailed HHC fuel kinetic mechanism-based multi-time scale modeling algorithm to achieve enhanced computation efficiency for numerical modeling of gas turbine combustion/emissions.

Accomplishments

- Experimental measurement of the effect of third-body collision efficiency (ε_{CO2}) of CO_2 for the reaction $H+O_2+CO_2 HO_2+CO_2$ was completed for high pressure conditions (6-8 atm) using a high-pressure laminar flow reactor. The collisional efficiency was determined to be 3.0 relative to N_2, which is approximately 25 percent lower than a commonly used value for ε_{CO2}. This effect reduces the rate of formation of HO_2, a key radical in the oxidation of H_2. Through the effect of HO_2 on subsequent formation of OH, the formation rate of H_2O is slowed at high pressures that are typical of practical land-based gas turbine operation.
- Measurements of laminar mass burning rates of H_2O diluted hydrogen and syngas fuels (Figure 1), as well as HHC mixtures including CH_4, C_2H_6, and C_2H_4. These measurements are relevant to stationary power fueling and emissions control strategies. Experimental measurements also constrain the HHC fuel kinetic model.
- Analytical and computational evaluation of thermal radiation effects on spherically propagating laminar flame speed measurements. Results show that thermal radiation uncertainty of present flame measurements is negligible.

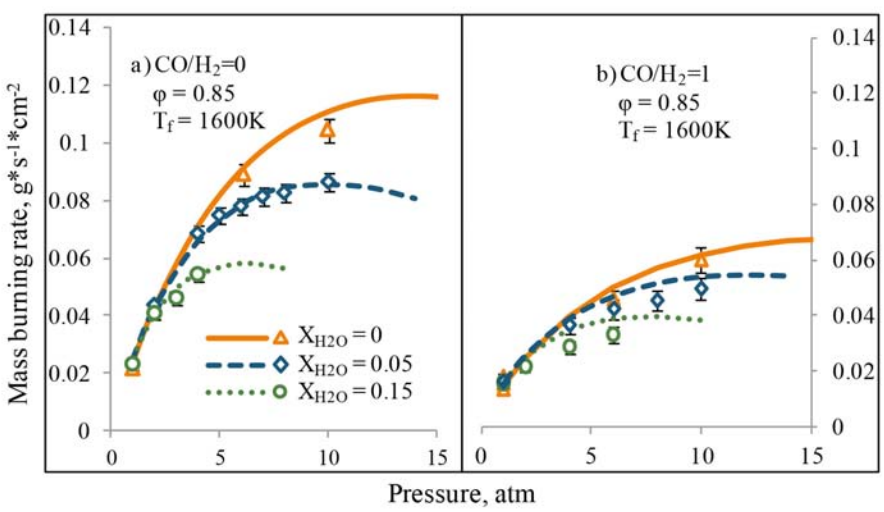


Figure 1. Effect of H_2O dilution on H_2 (left) and syngas (right) laminar mass burning rates. At constant flame temperature, increased water vapor content uniformly reduces burning rate for both H_2 and syngas. This effect is stronger at higher pressure. Relative to pure H_2, flames of 50/50 H_2/CO have uniformly slower mass burning rates, The kinetic model (lines) correctly predicts the chemical inhibition caused by the reaction $H_2O+O \leftrightarrow 2OH$, which modifies the composition of the radical pool and inhibits radical branching.

- Development and extensive evaluation of a H_2/CO/HHC fuel kinetic model for numerical modeling of gas turbine combustion/emissions. Consideration of unaccounted reaction pathways shows that the HOCO radical species and its reactions with other HHC species are unimportant to the quantitative prediction of HHC combustion (Figure 2).
- Development of direct Faraday Rotational Spectroscopy (FRS) and higher sensitivity dual modulation FRS methods for HO_2 measurement (Figure 3).
- Autoignition studies of hydrogen and hydrogen carbon monoxide mixtures have been completed using a high-pressure high-temperature flow reactor. Studies were done for two pressures (10 and 15 atm.) and two equivalence ratios (0.375 and 0.750). Comparisons to results using a homogenous chemical model showed very good agreement with the experimental data. Furthermore, no autoignition was observed below 800K for the residence times studied. These results are in disagreement with earlier studies, which showed autoignition times shorter by one order of magnitude and to extend to temperatures as low as 625K.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The importance of this project is to further advance the understanding needed to develop practical guidelines for realistic composition limits and operating characteristics for HHC fuels.

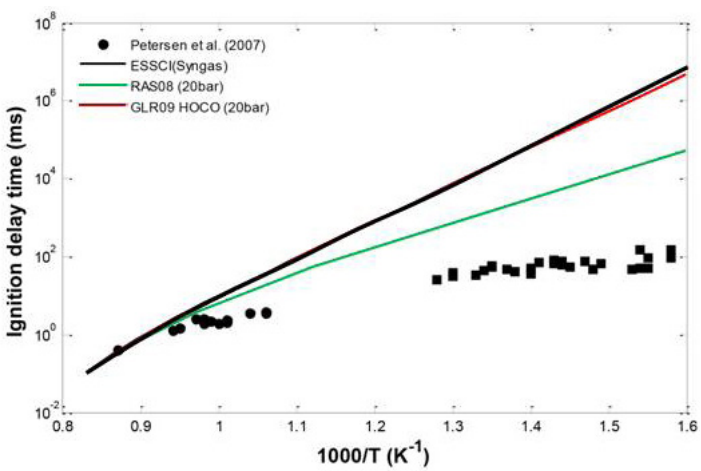


Figure 2. Initial modeling results considering unaccounted for HOCO pathways appear to result in significant changes in the HHC fuel kinetic model (compare green and black lines). A later revised rate coefficient for the reaction $CO+H_2O_2 \leftrightarrow HOCO+OH$ demonstrates that unaccounted for HOCO pathways do not quantitatively affect model prediction (compare red and black lines).

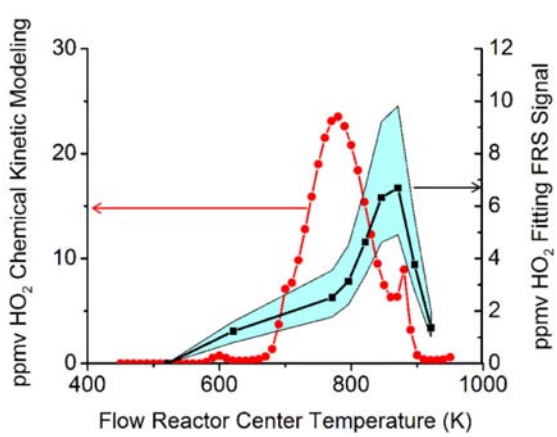
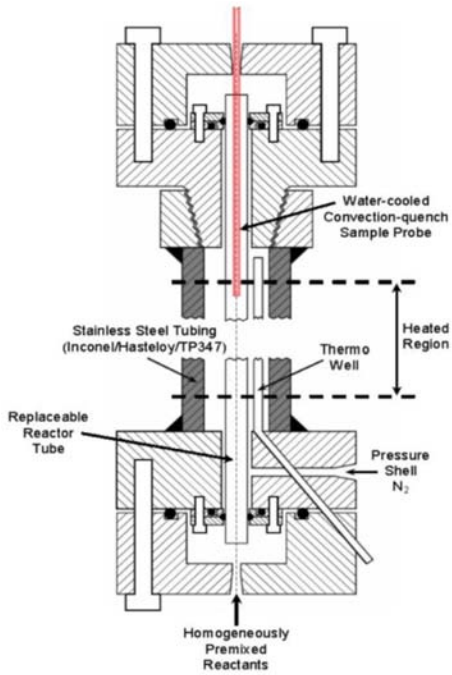


Figure 3. The HO_2 concentration versus flow reactor temperature for a mixture of ~90% He, 10% O_2, and 1% dimethyl ether was used at a total flow rate that provides a 0.35 sec residence time: data obtained from chemical kinetic modeling (red) and concentration data retrieved by fitting the experimental spectra (black). The lower and upper bounds of the retrieved HO_2 concentration were generated by using either the maximum or minimum temperature measured at the reactor exit.



Schematic of the high-pressure laminar flow reactor tube assembly.

FE0000752 July 2013

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PROJECT FACTS

Hydrogen Turbines

Combustion Dynamics in Multi-Nozzle Combustors Operating on High-Hydrogen Fuels—Pennsylvania State University

Background

Combustion dynamics is a major technical challenge to the development of efficient, low emission gas turbines. Current information is limited to single-nozzle combustors operating on natural gas and neglects combustors with configurations expected to meet operability requirements using a range of gaseous fuels such as coal derived synthesis gas (syngas). In this project, Pennsylvania State University (Penn State) in collaboration with Georgia Institute of Technology (Georgia Tech) will use multiple-nozzle research facilities to recreate flow conditions in an actual gas turbine to study complicated interactions between flames that can aggravate the combustion dynamics in syngas-fueled multi-nozzle can or annular combustion turbines.

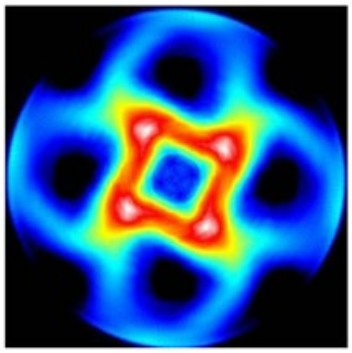

Figure 1. Two-dimensional cross-section of three-dimensional flame in multi-nozzle combustor showing complex flame structure resulting from the flame and flow field interaction.

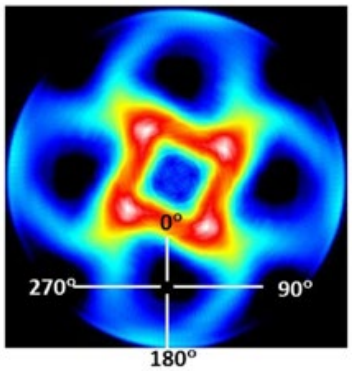

Figure 2. Positioning of two-dimensional vertical slices around outer nozzle.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the

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Georgia Institute of Technology

PROJECT DURATION

Start Date	End Date
10/01/2008	09/30/2013

COST

Total Project Value
$1,062,500

DOE/Non-DOE Share
$700,000/$362,500

AWARD NUMBER

NT0005054

U.S. DEPARTMENT OF ENERGY

nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Gas turbine combustors capable of meeting future emissions regulations must not compromise overall system operability. Furthermore, they must be capable of operating on a wide range of gaseous fuels, such as syngas and high hydrogen content fuels. One of the most significant challenges to achieving these goals is the problem of combustion dynamics, a phenomenon that arises from acoustic resonances in the combustion chamber. This research develops an understanding of the coupling between acoustics and flame behavior in multi-nozzle combustor configurations in order to better design the fuel-flexible clean combustion systems of the future. This includes both transverse acoustic excitation in multi-nozzle annular combustors and longitudinal acoustic excitation in multi-nozzle can combustors. In the first phase of the study, single nozzle flame response to both longitudinal and transverse acoustic excitation is studied in order to understand the scope of the multi-nozzle problem. In the second phase, experiments are conducted in two multi-nozzle combustor test facilities to simulate transverse acoustic forcing in an annular configuration and longitudinal acoustic forcing in a can combustor configuration. Based on the design of industrial gas turbines, these facilities allow for the investigation of the underlying physics of flame-flame interactions, including the measurement of the longitudinal and transverse flame response functions (e.g., how heat release fluctuations are influenced by fuel or velocity fluctuations) that can aid in the development of new multi-nozzle flame response models.

Goals and Objectives

The goal of this study is to understand the coupling between acoustics and flame behavior in multi-nozzle combustor configurations. The expected results fall into three categories: acoustic behavior, fluid mechanics behavior, and flame behavior in a synergistic research approach. For example, the new flame response models will be incorporated into thermo-acoustic models for predicting instability frequencies and amplitudes in multi-nozzle combustors, which are essential tools for preventing or minimizing the incidence of detrimental combustion instabilities in future gas turbines. To achieve these goals, very comprehensive sets of both experimental and modeling work will be conducted.

Accomplishments

- Characterization of velocity disturbance field of a transversely forced, single and triple-nozzle swirl-stabilized flame using high-speed particle image velocimetry (PIV).
- Developed description of the flame transfer function for transversely forced flame response.
- Measured flame transfer function using global chemiluminescence, PIV, and two-microphone techniques.
- Developed flame response model of transversely forced flame.
- Measured the velocity-forced flame transfer function in the multi-nozzle can combustor over a range of operating conditions.
- Demonstrated that multi-nozzle flame transfer function gain results scaled with Strouhal number.
- Compared the flame transfer function in single- and multi-nozzle can combustors showing qualitative similarities in the gain and phase.
- Developed a new flame imaging technique for characterizing the three-dimensional structure of multi-nozzle flames.
- Illustrated the comparison between flame transfer function for transversely forced flames and longitudinally forced flames, to show relative importance in disturbance pathway. Identified Strouhal number of importance.
- Developed a model for premixed flames excited by helical flow disturbances. Illustrated the differences in helical mode effects on local flame response and global flame response, showing only symmetric modes contributed to flame transfer function.

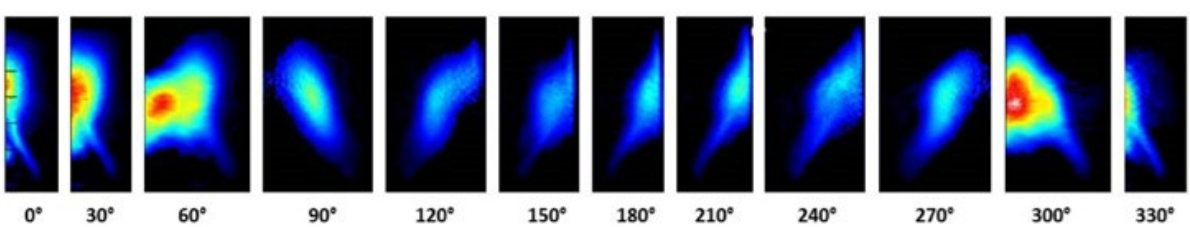

Figure 3. Two-dimensional vertical slices around outer flame showing significant variations in the degree and nature of flame confinement from flame-flame interaction at 0, no confinement at 90, flame-wall interaction at 180, and no confinement again at 270.

- Analyzed the space-time dynamics and heat release analysis for non-premixed flames excited by bulk axial velocity fluctuations. Compared results to those for premixed flames to highlight key differences in physics.
- Determined time-varying consumption speed definition for harmonically forced turbulent premixed flames.
- Obtained the first three-dimensional flame structure measurements in a multi-nozzle can combustor under steady and velocity-forced conditions, revealing the complex flame structure produced by flame and flow field interactions.
- Used three-dimensional flame structure measurements to determine the local flame response and local flame transfer function in the multi-nozzle can combustor.
- Showed that flame confinement plays an important role in relating the local flame response in the multi-nozzle combustor to the overall flame response of a single-nozzle combustor.
- Demonstrated and validated the use of a reconstruction technique for measuring heat release rate fluctuations in technically premixed flames.
- Performed the first flame transfer function measurements in the multi-nozzle can combustor under technically premixed conditions.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This project will aid in the design of fuel-flexible clean combustion turbine systems of the future.

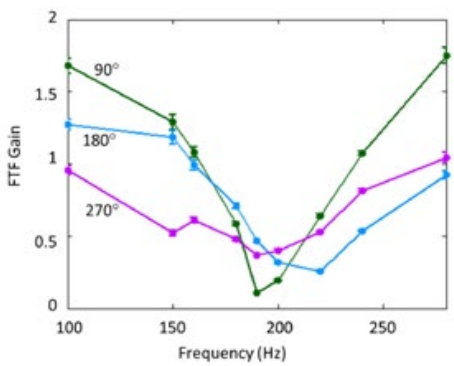

Figure 4. Flame transfer function gain versus forcing frequencies around outer nozzles at positions of 90, 180 and 270, showing a significant difference between the two unconfined cases of 90 and 270 which can be attributed to flame-swirl interactions.

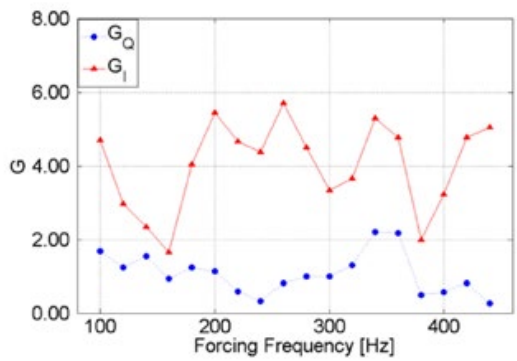

Figure 5. A comparison between the flame transfer function gain of a velocity-forced technically premixed flame using the chemiluminescence intensity as a measure of the heat release rate (GI) and using the reconstruction technique to determine the actual rate of heat release rate (GQ).

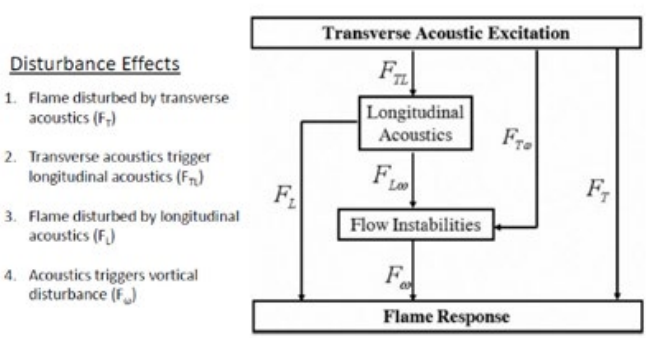

Figure 6. Velocity disturbance mechanisms present in a transversely forced flame.

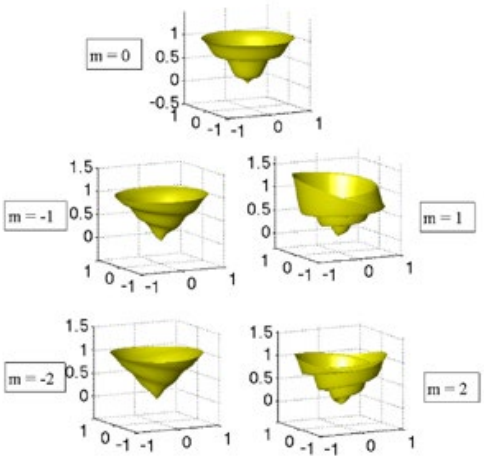

Figure 7. Flame surface plots showing response of flame to different helical modes.

Figure 8. Experimental setup for transversely excited, swirling lifted flame with a triple nozzle configuration.

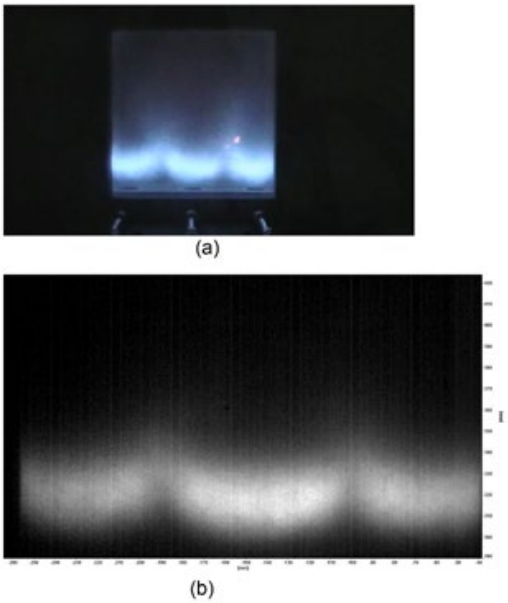

Figure 9. (a) Sample image showing triple nozzle flame, (b) Time-average chemiluminescence image.

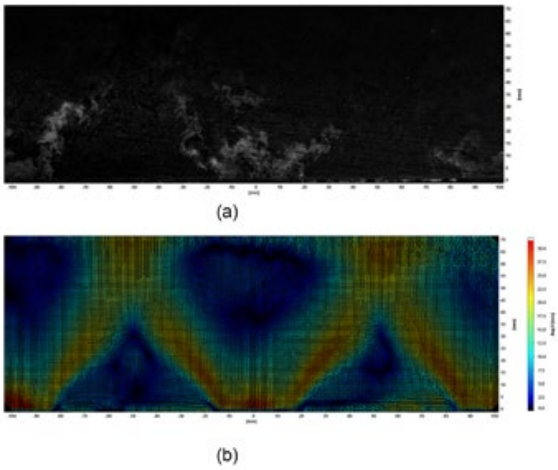

Figure 10. PIV in the axial plane showing (a) Instantaneous image of seeded flow and (b) Time-average vector field.

NT0005054 July 2013

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PROJECT FACTS

Hydrogen Turbines

Structure and Dynamics of Fuel Jets Injected into a High-Temperature Subsonic Crossflow: High-Data-Rate Laser Diagnostic Investigation—Purdue University

Background

High quality benchmark data on fuel flows in combustion turbines is useful in designing turbine engines fueled with coal-derived synthesis gas (syngas). In this project, Purdue University will use advanced laser diagnostics to provide comprehensive measurements of fuel flow conditions representative in modern gas turbine engines.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

This project is a detailed investigation of the structure and dynamics of fuel jets injected into a subsonic oxidizing crossflow in order to enhance the fundamental level of understanding of these important flows and to provide a validation database for comparison with detailed numerical models of the reacting jets in crossflow (RJIC). Advanced laser diagnostics, including high-speed particle imaging velocimetry (PIV), high-speed planar laser-induced fluorescence (PLIF), and coherent anti-Stokes Raman scattering (CARS) will be used to probe the flow fields in a high-pressure gas turbine combustion facility. PIV and planar laser induced fluorescence of OH radicals (OH PLIF) will be used to visualize fuel/air mixing and combustion at data rates of 5-10 kilohertz (kHz). One kHz CARS will be employed for temperature measurements using femtosecond lasers. The combustion facility will utilize three different fuels: a natural gas (NG) baseline and two high-hydrogen-content (HHC) fuels. Accurate high-resolution spatialand temporal measurements of the resulting turbulent flame structures will provide improved understanding of the complex processes

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
10/01/2011	09/30/2014

COST

Total Project Value
$586,271

DOE/Non-DOE Share
$468,995/$117,276

AWARD NUMBER

FE0007099

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of fuel/air mixing and turbulence-chemistry interaction with attendant impact on operability when using HHC fuels. Additionally, the representative crossflow will be forced into stationary and oscillatory conditions to simulate an unstable condition. The enhanced mixing and combustion of the fuel jet will be measured to quantify the relationship between the unsteady combustion field and the forced oscillatory field. The benchmark quality data sets resulting from these experiments will include comprehensive measurements of mean and fluctuating components of velocity, temperature, and species at high pressure and with crossflow conditions representative of modern gas turbine engines with practical applications within the turbine industry.

Goals and Objectives

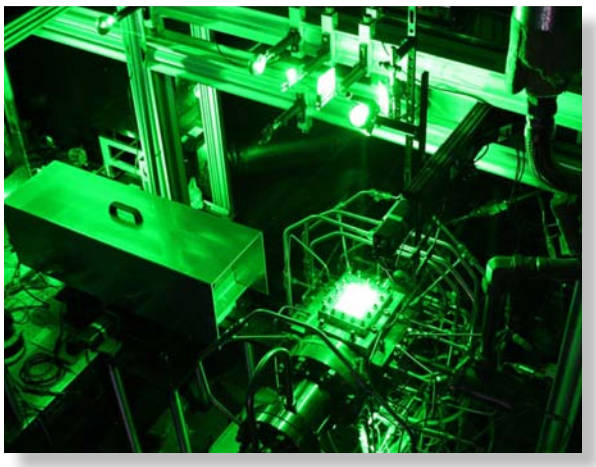
The primary goal of the project is to investigate the structure and dynamics of the reacting flow field for jets injected into a subsonic crossflow. The RJIC study has practical applications while also serving as an important test case for the development of numerical methods for turbulent reacting flow fields typical of gas turbine combustors. Secondary injection of the fuel, also referred to as distributed combustion, is being studied as a means for reducing NO_x emissions while increasing the power output of the gas turbine systems. By utilizing high-speed diagnostics techniques, the enhanced mixing and combustion of the fuel jet will be measured in order to determine the quantitative relationship between the unsteady combustion field and the forced oscillatory field.

Accomplishments

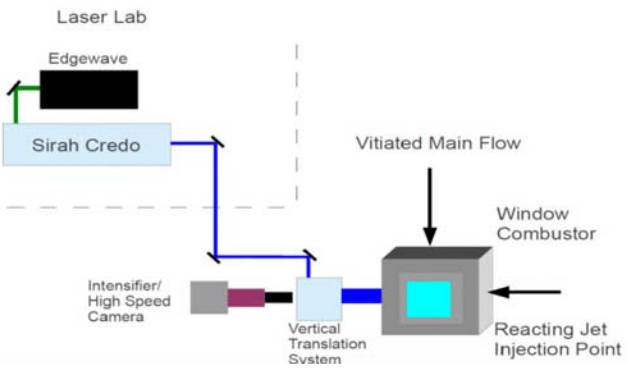
- Designed and fabricated the necessary components for the modification of the test rig for RJIC studies. The major difference between the old and new test rig configurations is that the window dimensions are considerably larger: 98 mm wide x 73 mm high in the new test rig as compared to 63.5 mm wide x 38.1 mm high in the old test rig.
- Performed a series of tests in the new test rig to compare performance and results from the new test rig with the old test rig. These measurements were performed using transverse jet injection nozzles designed in collaboration with Siemens Power Systems.
- Designed and fabricated a particle seeder for high-speed, high-pressure PIV.
- Completed dual pump (H_2/N_2) CARS experiment for 3 RJIC conditions. Data analysis is on-going and soon to be completed. For each test conditions the CARS probe volume was transverse through 140 spatial locations in a grid like pattern, and at each spatial location 300 H_2/N_2 spectra were collected, so in total for each condition 140X300 spectra were collected.
- Completed high-speed OH-PLIF measurements (@ 5kHz) of the RJIC for 4 different test conditions for NG jet injection. HHC gas jet injection will be completed in the near future. Orthogonal decomposition techniques were used to obtain qualitative and quantitative analysis of the PLIF images.
- Made rig modifications for the high speed PIV measurements.
- Completed high-speed PIV measurements at a repetition rate of 5kHz for the same test conditions as OH PLIF. Data analysis is on-going.

Benefits

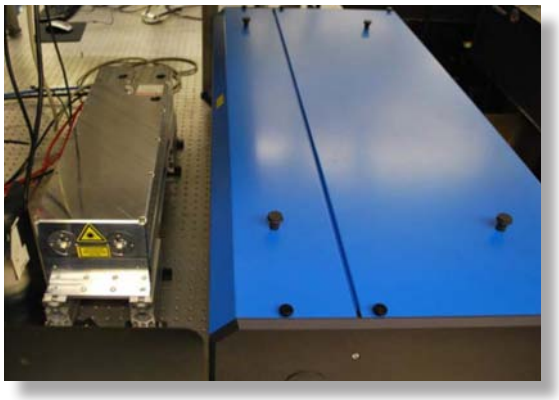
This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The importance of this project is to further advance the understanding needed to develop practical guidelines for realistic composition limits and operating characteristics for HHC fuels.



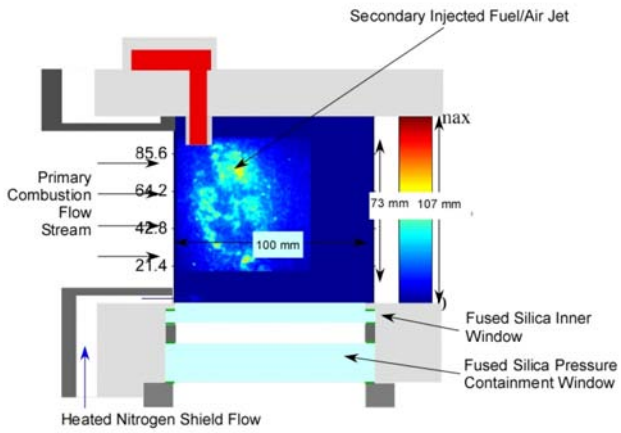
High-pressure reacting jet in vitiated crossflow test rig in operation with the new window assembly in place.



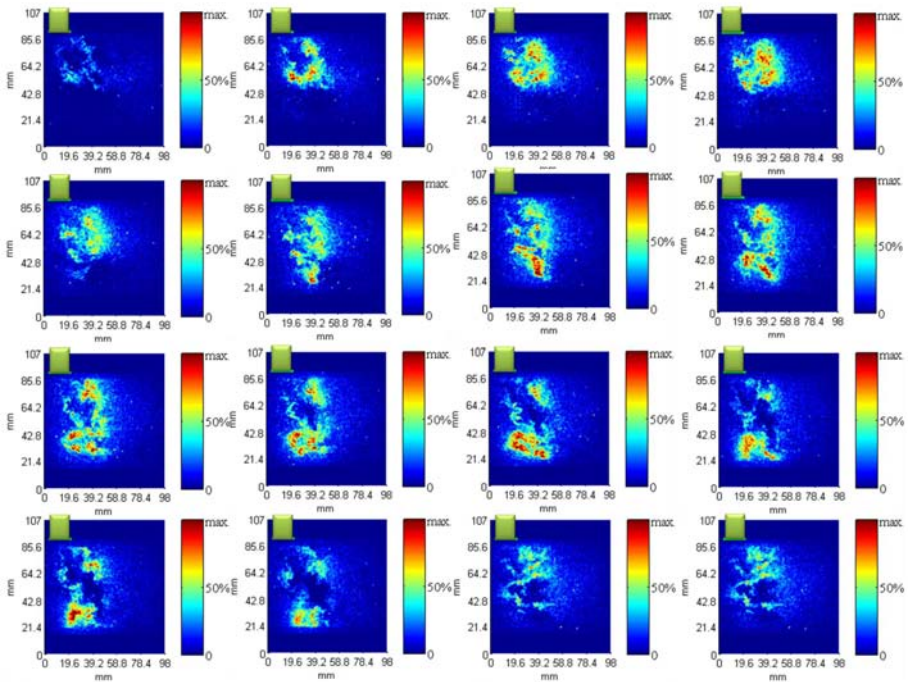
Schematic diagram of the high repetition rate OH-PLIF system with the intensified camera and combustor.



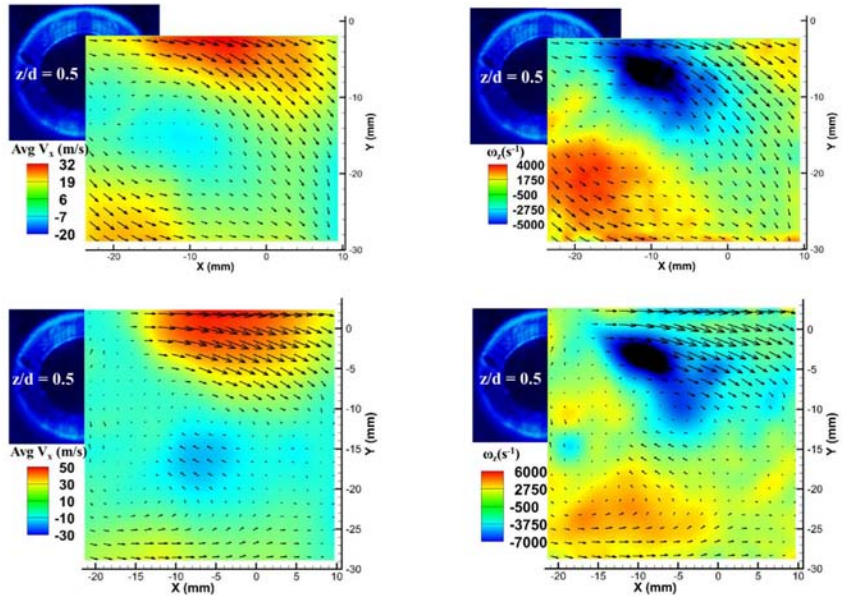
Photograph of the 5-10 kHz laser system for OH PLIF and PIV. The Edgewave diode-pumped, dual-head Nd:YAG laser is on the left. The Sirah Credo high-repetition-rate tunable dye laser in on the right.



Schematic diagram of the reacting jet in the vitiated swirling corssflow and the two window configuration.



A sequence of false colored PLIF images of J = 3 and φ = 3 case. This sequence of image is specifically chosen to show the complex flame structure and flame flapping phenomena. If the image at the top left corner represents time t = 0 sec, the last image shows time, t = 2.4 msec and all the images are taken at a Δt = 0.2 msec.



Plots showing the velocity vectors measured at the plane z/d = 0.5 from the nozzle exit plane for two test conditions, i) J = 3 and Φ_{jet}=3.0 (top) and ii) J = 8 and Φ_{jet}=3.0 (bottom). Contour on left column shows average axial velocity field and contour on right column shows average out of plane vorticity field.

FE0007099 August 2013

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PROJECT FACTS

Hydrogen Turbines

Turbulent Flame Speeds and NO_x Kinetics of High Hydrogen Content Fuels with Contaminants and High Dilution Levels—Texas A&M University

Background

Turbine design in power systems utilizing high hydrogen content (HHC) synthesis gas (syngas) fuel is impacted by flame speeds, ignition behavior, and nitrogen oxide (NO_x) emissions. The main components of this fuel are hydrogen (H_2) and carbon monoxide (CO), but the variability of the source and the synthesis process can result in a wide range of possible fuel blends that can also contain carbon dioxide (CO_2), water (H_2O), and impurities. In this project, Texas A&M University (TAMU) will add to the data already accumulated on the properties and fuel reactivity of syngas combustion in turbines and offer a validated chemical kinetics model that can be utilized for the design of new turbine power systems.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research as well as student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from HHC fuels derived from coal that is clean, efficient, and cost-effective; minimizes CO_2 emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

This project will result in a detailed database of flame speed and kinetic information and demonstrate the validity of a comprehensive kinetics model that can predict NO_x formation, flame speed, and ignition behavior in the presence of high levels of dilution and minor levels of likely contaminants. This will lead to a deeper understanding of the turbulent flame speed behavior and NO_x-formation kinetics of HHC fuels for integrated gasification combined cycle (IGCC) power plant applications. The technical approach for achieving this involves coordination with industry representatives in conjunction with a careful series of experiments using flame speed and shock-tube research facilities. The flame speed data will be obtained using two constant-volume vessels. Turbulent-burning velocities at elevated pressure will be obtained in a facility that will be modified to provide a controllable and repeatable level of turbulence. The laminar-burning velocities of mixtures with high levels of water and other diluents will be obtained with

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PROJECT DURATION

Start Date	End Date
10/01/2010	09/30/2013

COST

Total Project Value
$627,212

DOE/Non-DOE Share
$501,712/$125,500

AWARD NUMBER

FE0004679

U.S. DEPARTMENT OF ENERGY

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a heated flame speed vessel. All experiments will be compared to a comprehensive kinetics model based on prior work of the principal investigator and collaborators. This mechanism will be extended to include a NO_x model taken originally from the literature and improved in several ways, including careful examination of five distinct mechanistic pathways for NO_x formation involving various reactive intermediates, including the NNH mechanism where the planned research will measure rate coefficients that have not been previously reported in the literature. The overall validation and improvement of the comprehensive NO_x mechanism will come from shock-tube ignition tests with advanced diagnostics for recording species-time histories of reactive intermediates, and unique experiments where syngas/HHC fuels are doped with additional species to more rigorously test global mechanisms over a wide range of conditions.

Goals and Objectives

There are two primary goals for this project: to (1) produce a database of flame-speed and kinetic information, and (2) demonstrate the validity of a comprehensive kinetics model that can predict NO_x formation, flame-speed, and ignition behavior in the presence of high levels of dilution and minor levels of likely contaminants. While laminar flame speeds provide valuable data for the validation of the chemical kinetics and provide some insight into the combustion behavior of real systems, it is the turbulent flame speed that is of practical importance to the design of burners. However, less turbulent flame speed data exist for HHC fuels at gas turbine pressures. In addition, the physics of the relationship between turbulent flame speed and parameters such as turbulence intensity, stretch, and laminar flame speed are complex and not necessarily well understood. Reliable turbulent flame speed data for HHC fuels are therefore needed at practical conditions and this project seeks to carry out a methodical and unique array of experiments and analyses that will lead to a deeper and much-needed understanding of the turbulent flame speed behavior and NO_x-formation kinetics of HHC fuels for IGCC applications. In addition to a comprehensive database and improved understanding of the basic physics and chemistry of syngas in the presence of impurities and high levels of diluents, this project will provide a validated chemical kinetics model that can be utilized for the design of new systems and the improvement of existing ones.

Accomplishments

- Assembled a comprehensive chemical kinetics mechanism containing H_2, CO, hydrocarbon, and NO_x chemistry using mechanisms from the literature that were validated at elevated pressures.

- Performed laminar flame-speed measurements of H_2-O_2 mixtures at 1 atmosphere (atm) using the new high-speed camera purchased under this project; these hydrogen measurements will be used as a baseline for comparing mixtures containing CO, diluents, and contaminants.

- Performed ignition delay time measurements of a baseline series of H_2-O_2-argon experiments over a range of pressures from 1 to 30 atm, as well as baseline series of H_2-CO-O_2-argon experiments that are needed for subsequent evaluation of diluents and trace species.

- Determined the effect of nitrogen dioxide (NO_2) and nitrous oxide (N_2O) addition on the ignition of H_2 mixtures using shock-tube ignition experiments. The results were compared to the kinetics mechanism with good results. The NO_x compounds accelerated the ignition process in some cases, but in other cases, particularly at pressures near 1 atm, the NO_x had no effect on ignition delay time.

- Constructed a mock-up rig using Plexiglas® to optimize the turbulence generation system, so the best configuration can be ascertained prior to modifying the existing high-pressure flame speed vessel for the turbulent flame speed measurements.

- Completed a design-of-experiments matrix of laminar flame speeds over a range of H_2-CO mixtures with high levels of water dilution (up to 15% by volume); pressure ranged from 1 to 10 atm, with initial temperatures of 323 or 423 Kelvin (K). Comparison with the chemical kinetics model shows good agreement between data and model.

- Designed and fabricated the turbulent flame speed vessel. This new design used an existing vessel originally designed for laminar flame speeds and added a motorized fan system using the data from the mock-up rig as a guide.

- Obtained turbulent flame speed data for pure H_2 and 50/50 CO/H_2 fuels at 1 atm at a fixed value for velocity fluctuation and turbulence length scale. Correlations of the turbulent flame speed were constructed.

- Performed shock-tube measurements of ammonia-oxygen mixtures in argon over a range of pressures and temperatures and assembled a chemical kinetics model for NH_3 oxidation.

- Measured ignition delay times of hydrogen-oxygen mixtures tainted with various levels of hydrogen sulfide (H_2S) and assembled a chemical kinetics mechanism for H_2S.

- Developed and demonstrated an optical diagnostic for measuring OH concentrations in a shock tube using light absorption near 310 nm. The system using a uv lamp as the light source and a monochromator for spectral selectivity. OH time histories were obtained at 2 and 13 atm in H_2-O_2 mixtures highly diluted in argon.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This project aids in the understanding of turbulent flame speed behavior and NO_X-formation kinetics of HHC fuels for IGCC applications and will support turbine design in power systems utilizing HHC syngas fuel.

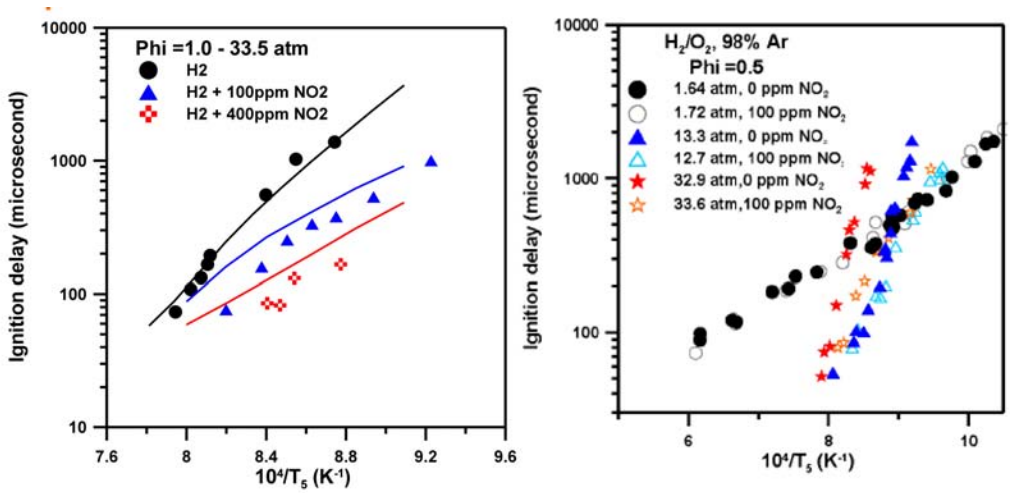

Figure 1a Figure 1b

Figure 1. Measured ignition delay times of a hydrogen-oxygen mixture with 98 percent argon, with and without NO_2 addition, compared to kinetics model (lines). Figure 1a shows results at a constant 33.5 atm. pressure and 1.0 equivalence ratio (phi), while Figure 1b shows ignition delay results as a function of pressure (from 1.6–33.6 atm.) and constant 0.5 equivalence ratio.

Figure 2. Texas A&M shock-tube test facility being used to elucidate detailed NO_X mechanism chemistry.

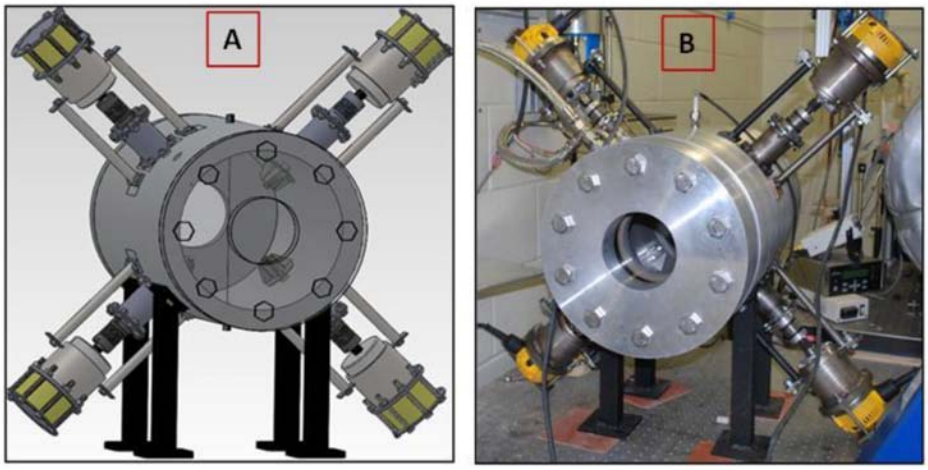

Figure 3. Fan-stirred flame speed vessel. (a) 3D solid works model (b) photograph of the facility. The four fans at the central circumference generate homogeneous and isotropic turbulence at the vessel center.

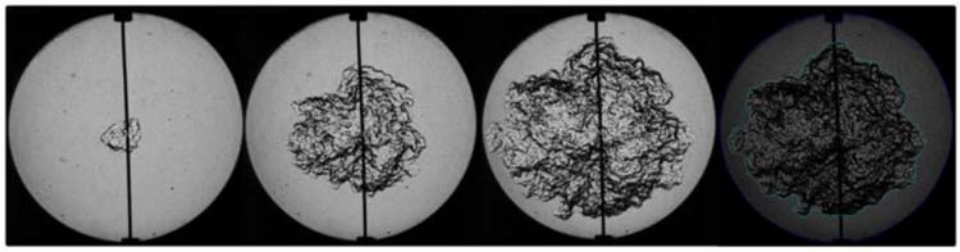

Figure 4. (a-c) Sample images from a typical turbulent flame speed experiment for a 50/50 H_2/CO mixture in air at 1 atm pressure. (d) Image processing technique used to estimate the flame radius by computing the enclosed area within the kernel boundary.

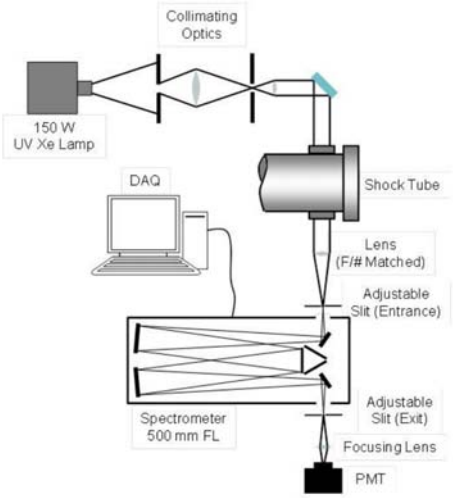

Figure 5. General schematic of OH measurement diagnostic utilizing a 0.5 m focal length spectrometer configured as a monochromator.

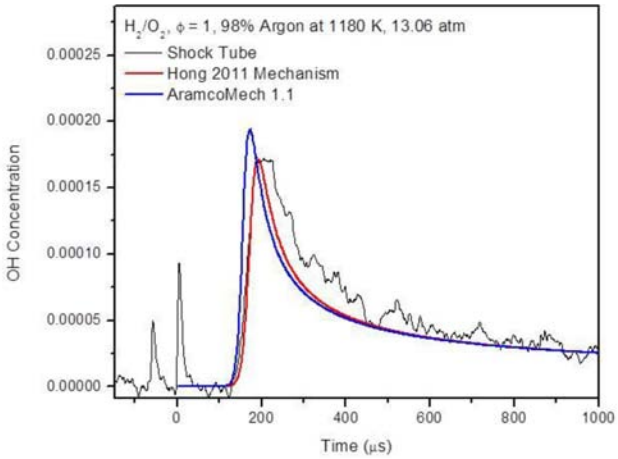

Figure 6. Shock-tube data comparison for OH with two mechanisms for a high pressure H_2/O_2 mixture diluted in argon. Measurement was taken in a shock tube using the new absorption setup (Fig. 5) at TAMU. Conditions correspond to reflected-shock temperature (1180 K) and pressure (13.06 atm) for a stoichiometric H_2-O_2 mixture in argon. Comparison with chemical kinetics mechanisms is good.

NT0004679 July 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Development of Criteria for Flame-holding Tendencies within Premixer Passages for High Hydrogen Content Fuels—University of California, Irvine

Background

The gas turbine community must develop low emissions systems while increasing overall efficiency for a widening source of fuels. In this work, the University of California, Irvine (UCI) will acquire the fundamental knowledge and understanding to facilitate the development of robust, reliable, and low emissions combustion systems with expanded high hydrogen content (HHC) fuel flexibility. Specifically, understanding flashback and the subsequent flameholding tendencies associated with geometric features found within combustor fuel/air premixers will enable the development of design guides to estimate flame holding tendencies for lean, premixed emission combustion systems for HHC fuels. Industry can use these guides to help design robust premixing passages for combustors that can accommodate a wide range of fuel types.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

This research will provide a systematic evaluation of flameholding tendencies in various combustor fuel/air premixer passage geometries. This evaluation will be completed for different fuel types (including HHC fuels) at operating conditions (temperature, pressure, etc.) typical of those encountered in industrial-scale turbines. The observations made relative to flameholding tendencies will be analyzed and used to develop design guides that can be used to infer when flameholding will occur as a function of the parameters studied.

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PROJECT DURATION

Start Date	End Date
10/01/2011	09/30/2014

COST

Total Project Value
$624,999

DOE/Non-DOE Share
$499,999/$125,000

AWARD NUMBER

FE0007045

U.S. DEPARTMENT OF ENERGY

The high pressures and temperatures required to simulate the environment of a premixing passage for a natural gas-fired gas turbine will be generated at the University of California, Irvine Combustion Lab high pressure facility. The facility is capable of generating a preheated airflow at temperatures up to 1200 degrees Fahrenheit, pressures exceeding ten atmospheres, and a maximum flow rate that exceeds three pounds per second. To provide the planned conditions, a modular test apparatus (Figure 1) will be used.

Figure 1: Completed test apparatus

Goals and Objectives

The goal of this project is to develop design guides that can be used to predict flameholding tendencies within combustor can premixer passages as a function of pressure, temperature, fuel composition, percentage of oxygen in the air, and feature geometries found within the passages such as steps, gaps, or vanes/struts. The project objectives include:

- The project objectives include:Carrying out an experimental study using a continuous flow rig that allows various premixer features (i.e., steps, gaps, vanes, gas jets) to be investigated for various operating conditions (velocity profiles, temperature, fuel composition, pressure).
- Correlating the results with respect to local flow conditions.

Accomplishments

- Completed modifications to facility to allow new test section to be constructed.
- Completed construction of new test apparatus with input from OEMs (original equipment manufacturers) Data acquisition hardware has been installed and instruments calibrated. Apparatus commissioning tests have been completed.

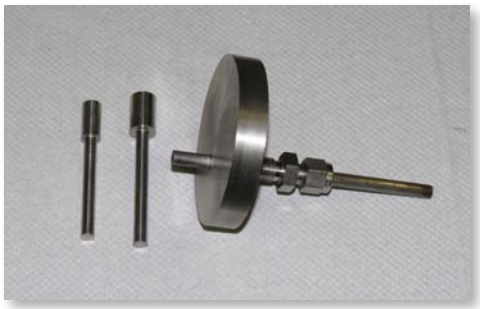

Figure 2: Cylindrical rod flameholder test feature with interchangeable rods of varying diameters

- Constructed 4 baseline flameholding test features: cylindrical rod, reverse step, airfoil, and flat strut.
- Ran tests with the cylindrical rod, located in the center of the flow, as a means to compare results from the new rig with literature findings for comparable conditions. The results for the rod were in excellent agreement with literature, effectively validating the rig operation.
- Results for the reverse step have demonstrated pressure dependency not explained with previous correlations.

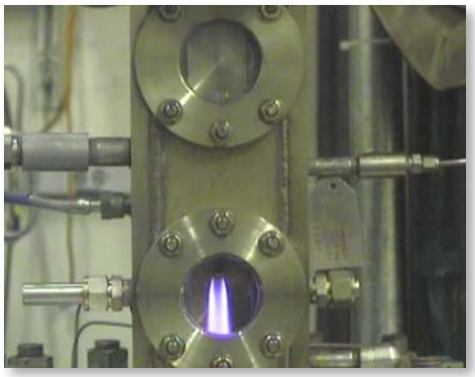

Figure 3: Natural gas flame stabilized behind ¼" diameter rod at 500 degrees F, 3 ATM, and 40 m/s

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. Data gathered in this project will aid in new designs for syngas-fueled turbines.

FE0007045, July 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Development and Experimental Validation of Large-Eddy Simulation Techniques - Syngas Combustion—University of Michigan

Background

The University of Michigan will conduct an experimental and computational research effort to develop validated simulation techniques to predict autoignition and unstable combustion processes relevant to the oxidation of coal-derived synthesis gas (syngas) and high hydrogen content (HHC) fuels at conditions pertaining to gas turbine operation. This project will develop a physics-based, fully validated, large-eddy simulation (LES) modeling capability to reliably predict unstable combustion processes of syngas and HHC fuels under high-pressure conditions representative of gas turbines, including the accurate characterization of autoignition, flashback, and flame liftoff in partially-premixed and stratified gas turbine combustion regimes. Experimental measurements in a swirl-stabilized gas turbine combustor will improve fundamental understanding of critical mechanisms that control unstable combustion processes associated with autoignition, flame liftoff, and flashback.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from HHC fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

The scope of the computational effort addresses the development of a fully validated LES-modeling capability to predict unstable combustion of HHC fuels. To incorporate effects of preferential diffusion, pressure variations, and variations in mixture composition, an unsteady flamelet-based LES combustion model will be extended. The integrated LES-validation effort includes (1) an a priori analysis of critical modeling assumptions using a Direct Numerical Simulation (DNS) database of jet-in-cross-flow configurations, and (2) a posteriori model validation in LES application of a swirl-stabilized

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PROJECT DURATION

Start Date	End Date
10/01/2011	09/30/2014

COST

Total Project Value
$570,537

DOE/Non-DOE Share
$454,540/$115,997

AWARD NUMBER

FE0007060

U.S. DEPARTMENT OF ENERGY

gas turbine combustor. The LES-combustion model will be used to develop detailed simulations to characterize facility-induced nonidealities in flow-reactor experiments. Effects arising from high-Reynolds number turbulence transition, mixture stratification, and other mechanisms associated with turbulence/chemistry interaction on the autoignition behavior will be quantified through parametric calculations. The information gained from these efforts will be used to develop a low-order model that can be utilized for chemical-kinetics investigations and for guiding and improving future flow reactor designs in order to reduce facility effects.

The experimental effort includes high-pressure measurements of HHC fuel combustion in a dual-swirl gas turbine combustor, development of a comprehensive experimental database for LES model validation by considering stable and unstable gas turbine operating conditions, and obtaining improved understanding about fundamental combustion-physical mechanisms that control flame-holding, liftoff, and flashback for HHC fuels. A range of pressures, HHC fuel compositions, and equivalence ratios will be investigated experimentally.

Goals and Objectives

- Develop a physics-based, fully validated, LES modeling capability to reliably predict unstable combustion processes of syngas and HHC fuels under high-pressure conditions representative of gas turbines, including the accurate characterization of autoignition, flashback, and flame liftoff in partially-premixed and stratified gas turbine combustion regimes.
- Perform experimental measurements in a swirl-stabilized gas turbine combustor to obtain improved fundamental understanding about critical mechanisms that control unstable combustion processes associated with auto-ignition, flame liftoff, and flashback.
- Establish a comprehensive experimental database that can be used for LES and Reynolds-averaged Navier-Stokes (RANS) model validation.
- Conduct detailed LES computations in order to isolate, understand, and quantify facility effects that are manifested by observed irregularities and stochastic ignition events at high pressure and low/intermediate temperature conditions.

Accomplishments

- Development of multi-stream flamelet/progress variable combustion model for application to partially-premixed combustion in vitiated flow environments. Validation of the combustion model in application to LES of a piloted partially-premixed jet burner configuration (see Figure 1), considering a series of increasingly complex operating conditions.
- Conduct an a priori analysis of critical modeling assumption in flamelet-combustion models, represent leading effects in flame ignition where they act as secondary heat-induced transition models. From this analysis, it could be shown that higher-order expansion terms that are commonly omitted in flamelet-combustion models, represent leading effects in flame ignition where they act as secondary heat-induced transition modes.
- Conducted LES of a gas turbine model combustor (see Figure 2); performed a detailed sensitivity study to assess and quantify effects of grid resolution, LES subgrid closure models, and inflow conditions on the unsteady flame topology, heat release, and flow field behavior.
- Development of a lower order model to investigate effects of inhomogeneities, arising from turbulent flow field and inhomogeneities in temperature and mixture composition, on the ignition characteristics. From this study, it could be shown that temperature perturbations in conjunction with flow field inhomogeneities promote localized ignition, which primarily occurs in regions of suppressed turbulent mixing in close proximity to the wall region.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This work could lead to significant fuel cost savings and a decrease in equipment downtime.

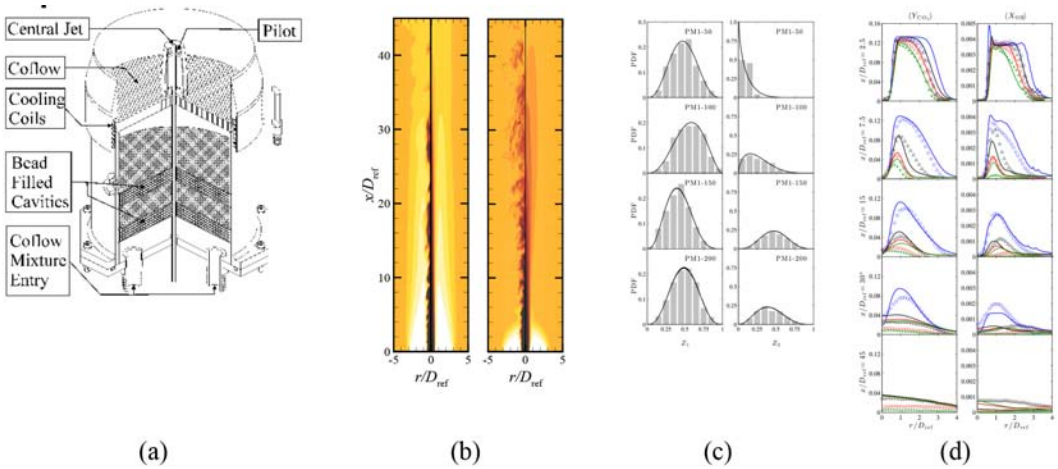

Figure 1. Large-eddy simulation of a piloted partially-premixed burner, showing (a) experimental configuration, (b) comparison of temperature fields between two operating conditions, (c) comparison of modeled and experimental probability density function of scalar field quantities (mixture fraction and oxidizer split variables), and (d) comparison of scalar profiles for carbon dioxide and hydroxyl.

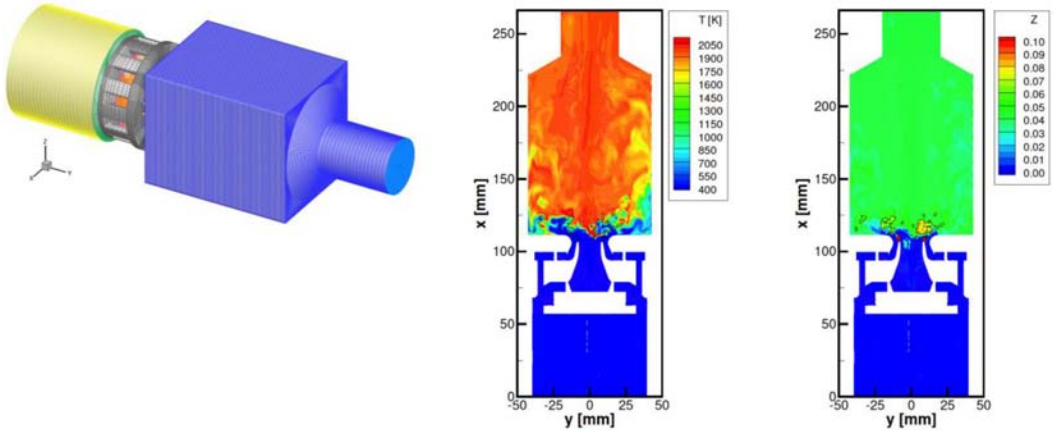

Figure 2. Large-eddy simulation of gas turbine model combustor, showing (left) computational mesh, (middle) instantaneous temperature field, and (right) mixture fraction field.

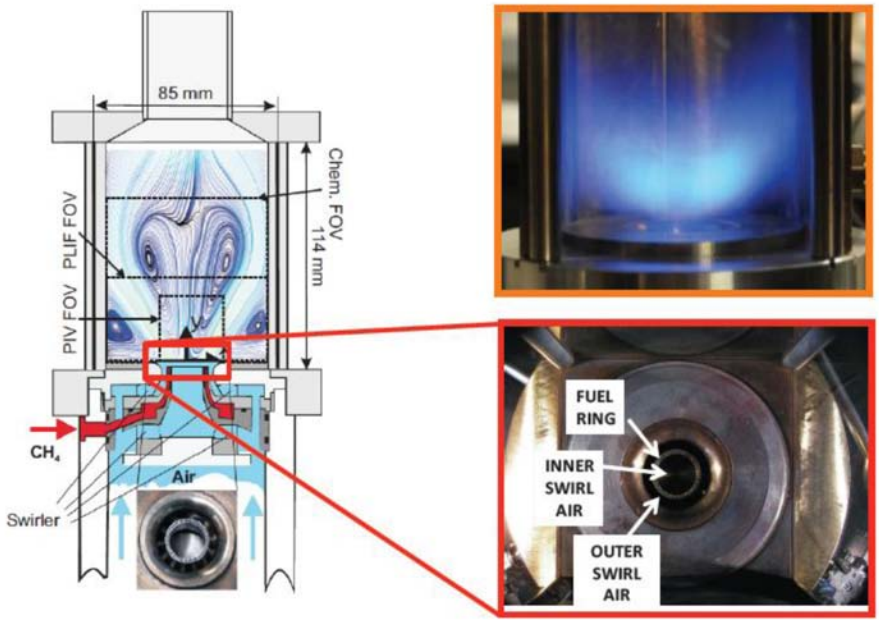

Figure 3. Illustration of Key Features of Dual-Swirl Gas Turbine Combustor with Advanced Diagnostics.

FE0007060 July 2013

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PROJECT FACTS

Hydrogen Turbines

Fundamental Studies to Enable Robust, Reliable, Low Emission Gas Turbine Combustion of High Hydrogen Content Fuels—University of Michigan

Background

The University of Michigan will perform experimental and computational studies which can provide an improved and robust understanding of the reaction kinetics and other fundamental characteristics of combustion of high hydrogen content (HHC) fuels that are vital to advancing HHC turbine design and to making coal gasification power plants environmentally sustainable and cost- competitive. The scope of work includes Rapid Compression Facility (RCF) studies of HHC ignition delay times and hydroxyl radical (OH) time-histories, flame speeds, and flammability limits. A range of temperatures, pressures, and test gas mixture compositions will be investigated experimentally and computationally. Accurate, detailed reaction mechanisms as well as simplified HHC mechanisms will be created. The reaction chemistry will be validated using the HHC RCF data and data in the archival literature. The computational work will include modeling studies of HHC flammability limits and flame auto-ignition interactions.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from HHC fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

RCF experiments will be conducted to extend the high-quality, low-uncertainty experimental database of HHC combustion kinetic benchmarks over a range of operating conditions, including pressures (10–25 atmospheres), temperatures (700–1700K), and the effects of dilution with exhaust gases (where uncertainties in third body coefficients become particularly important). Flammability limits and flame/auto-ignition interactions will be determined computationally and experimentally. The RCF data will provide rigorous targets for development of accurate, well validated, detailed, and reduced chemical kinetic reaction mechanisms for HHC combustion, including nitrogen oxide (NO_x) chemistry.

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PARTNERS

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PROJECT DURATION

Start Date	End Date
10/01/2011	09/30/2014

COST

Total Project Value
$635,561

DOE/Non-DOE Share
$499,998/$135,563

AWARD NUMBER

FE0007465

U.S. DEPARTMENT OF ENERGY

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Goals and Objectives

The primary goal of this project is to develop a thorough and quantitative understanding of important HHC fuel combustion properties at conditions relevant to gas turbine operation. Flammability limits and flame/auto-ignition interactions will be determined computationally and experimentally. The experimental data will provide rigorous targets for development of accurate, well-validated models for detailed and simplified chemical kinetic reaction mechanisms for HHC combustion, including NO_x chemistry. The efforts include distillation of the fundamental data into forms that will aid the rapid transfer of information into syngas turbine design and provide new quantitative assessment of HHC combustion at conditions directly applicable to gas turbines. Specific project objectives are as follows:

- To develop an accurate and rigorous experimental and computational database of HHC fuel combustion covering reaction kinetics, flame speeds, and flammability limits of HHC fuels, including mixtures with high levels of exhaust gases.
- To develop detailed and simplified models of HHC chemical reactions that accurately reproduce the new experimental data as well as data in the literature.
- To develop a quantitative understanding of the stability of HHC combustion in relation to fluctuations in the flow field, including the opportunities and challenges of exhaust gas recirculation (EGR) on extinction, ignition, and flame stability.
- To develop domain maps that identify the range of conditions (e.g., percent EGR) where HHC combustion can be effective in both positive and negative manners such as expanded or restricted flammability limits.

Accomplishments

- Experiments of syngas ignition targeted to identify criteria for weak and strong ignition were completed.
  - The results demonstrate that for experiments with strong ignition behavior the Li et al. (2007) chemical mechanism applied in a zero-dimensional homo geneous reactor simulation accurately predicts the measured auto-ignition delay times.
  - A close relationship between transitions in weak and strong ignition behavior and transitions across the classical and extended 2nd limits of H_2/O_2 explosion was demonstrated using a pressure/temperature map of ignition behavior.
- Uncertainties in the key reactions in the detailed reaction mechanism for syngas combustion were quantified in this study and shown to be significant at the conditions of interest to gas turbine combustors.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. Fundamental data from this project will provide a new quantitative assessment of HHC combustion at conditions directly applicable to gas turbines and aid the rapid transfer of information into syngas turbine design.

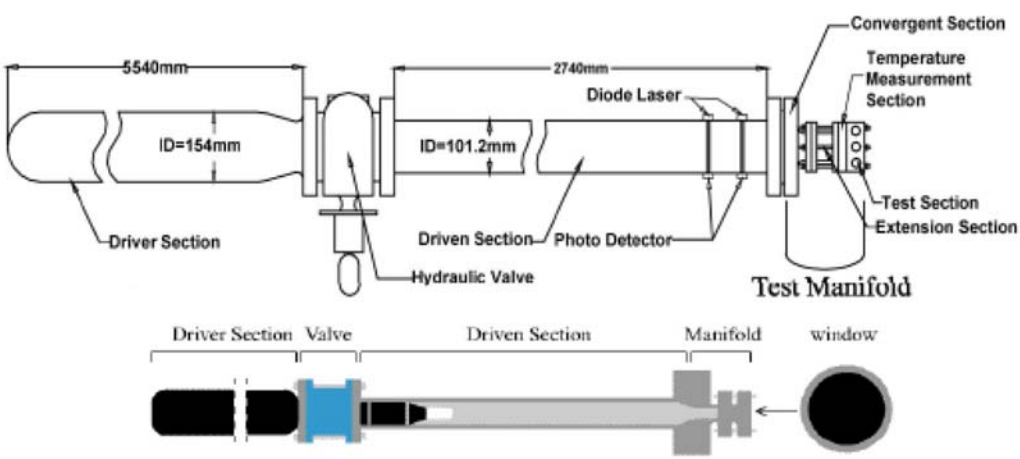

Figure 1. University of Michigan Rapid Compression Facility.

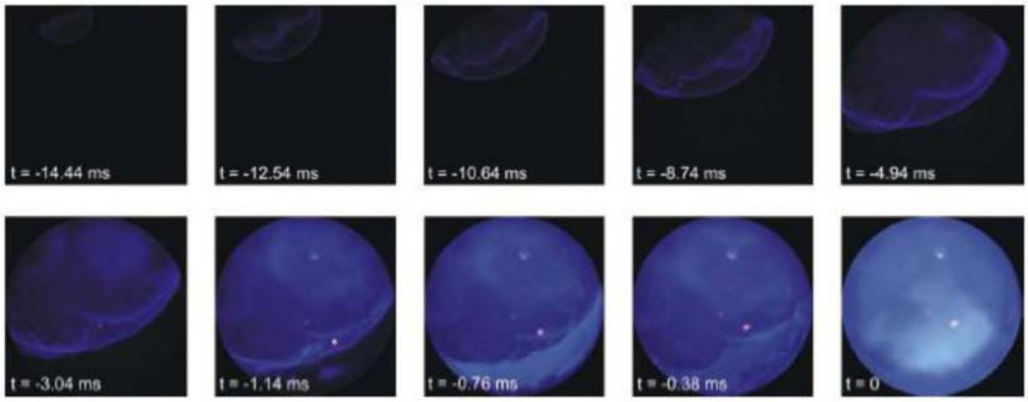

Figure 2. Example Time-Sequence of Images (Recorded with High-Speed Imaging Data Capability) that Documents a Weak/Localized Ignition Event Prior to Complete Combustion.

In Figure 2, notice how non-homogeneous the images are during the time sequence, which is indicative of some localized ignition event occurring at earlier stages before the remainder of the fuel mixture is observed to completely ignite. This localized ignition event is complex and influences the temperature, pressure, and thereby the reaction chemistry of the surrounding fuel mixture, and thus the entire experiment.

Figure 3 shows that the localized ignition event causes the pressure to increase (as the gas mixture temperature increases and more fuel gradually ignites) prior to complete combustion.

The RCF imaging capability provides a powerful diagnostic tool to evaluate fuel mixture behavior that is useful to interpret experimental data and provide insights pertinent to the underlying detailed reaction mechanisms governing ignition/combustion behavior of fuels.

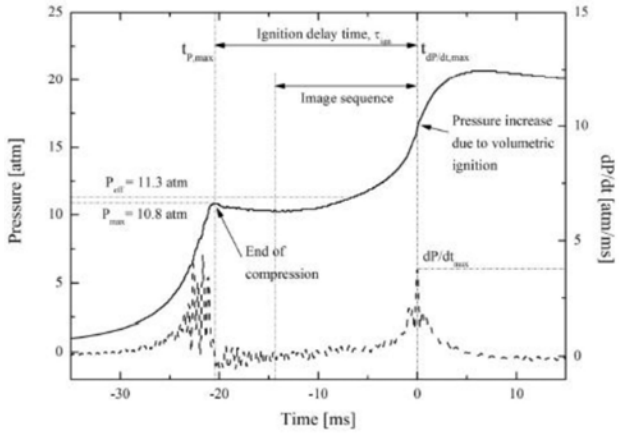

Figure 3. Pressure-Time History in RCF Experiment Where Localized "Weak" Ignition is Observed.

In the RCF experiment of Figure 3, a fuel containing 20% H_2/80% CO at an equivalence ratio of 0.4 and inert: O_2 ratio of 3.76 was initially compressed to about 11 atm. and effective temperature of 1004 K.

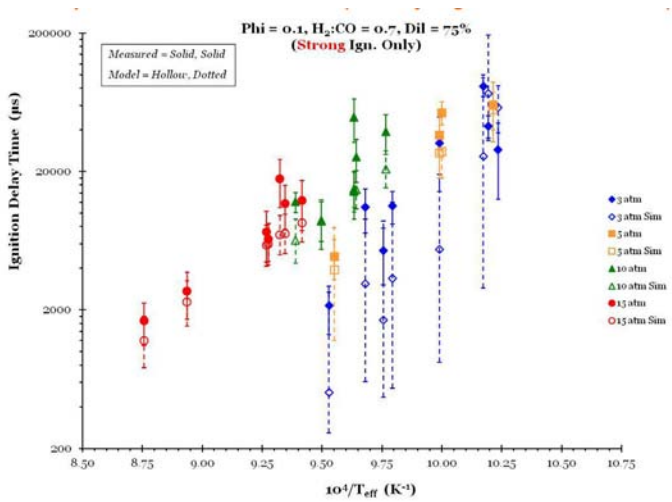

Figure 4. Comparison of experimental (solid symbols and error bars with solid lines) and modeling results (open symbol and error bars with dashed lines) for syngas ignition over a range of temperatures and pressures. There is excellent agreement between the experimental and predicted values at all conditions; however, the uncertainties in the syngas reaction chemistry are large at lower pressures as noted by the larger error bars.

Reference:
Kalitan, D.M. , Petersen, E.L. et al., 2007. Ignition and Oxidation of Lean CO / H_2 Fuel Blends in Air. Journal of Propulsion and Power, 23(6), pp.1291–1303

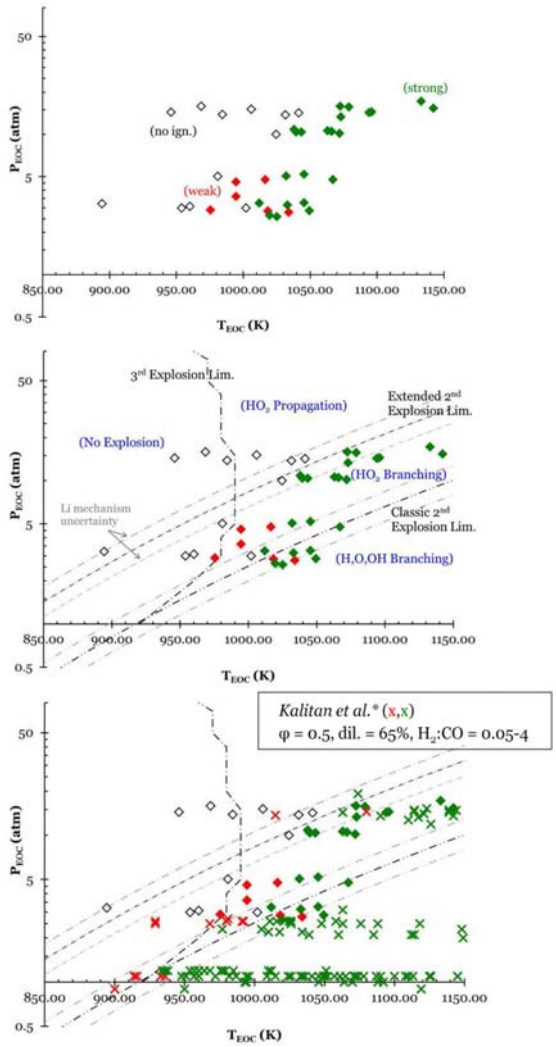

Figure 5. Pressure/temperature ignition maps. Top panel: results of ignition experiments showing the transition between weak and strong ignition as a function of fixed pressure. Middle panel: superposition of the H_2/O_2 explosion limits with the experimental data of the top panel. Note the close relationship between the transitions between ignition regimes and the explosion limits. Bottom panel: experimental results from current work and previous ignition studies by Kalitan et al. Consistent results are seen from different experimental facilities and spanning a broad range of conditions. Together the results indicate the changes in ignition behavior are not random and the relationship of the conditions to the explosion limits may be an indicator for predicting weak ignition behavior.

FE0007465 July 2013

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PROJECT FACTS

Hydrogen Turbines

Large Eddy Simulation Modeling of Flashback and Flame Stabilization in Hydrogen-Rich Gas Turbines using a Hierarchical Validation Approach—University of Texas at Austin

Background

The focus of this project is the development of advanced large eddy simulation (LES)-based combustion modeling tools that can be used to design low emissions combustors burning high hydrogen content fuels. The University of Texas at Austin (UT) will develop models for two key topics: (1) flame stabilization, lift-off, and blowout when fuel-containing jets are introduced into a crossflow at high pressure, and (2) flashback dynamics of lean premixed flames with detailed description of flame propagation in turbulent core and near-wall flows. The jet-in-crossflow (JICF) configuration is widely used for rapid mixing of reactants in both the premixing chamber and in axially staged configurations. The high reactivity of hydrogen strongly impacts the flame stabilization mechanism in JICF by altering the structure of the reaction zone. This, in turn, changes the blow-off and emission characteristics. Lean premixed combustors are also sensitive to combustion instabilities, leading to flashback where the flame stabilizes in the premixing zone. Since hydrogen is highly flammable and has a higher laminar flame speed compared to conventional fuels, the propensity for flashback is increased. The availability of high-fidelity predictive computational models will provide a significant boost to the design of next generation gas turbines.

The LES modeling work and laboratory experiments will be performed by UT. Sandia National Laboratories has agreed to provide direct numerical simulation (DNS) modeling as validation for LES combustion simulations, host and co-mentor graduate students from UT, and provide feedback on UT's planned DNS experiments. General Electric (GE) and Siemens have agreed to assist UT in developing relevant combustor configurations and flow conditions that will be most beneficial to next generation gas turbine designs. Additionally, GE and Siemens will help UT design computational experiments aimed at deriving empirical relationships between flow conditions and combustion phenomena. The computational models developed here will be directly implemented in the OpenFOAM open source computational platform and shared with the industrial partners.

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Sandia National Laboratories
Siemens

PROJECT DURATION

Start Date	End Date
10/01/2011	09/30/2014

COST

Total Project Value
$635,726

DOE/Non-DOE Share
$497,638/$138,088

AWARD NUMBER

FE0007107

U.S. DEPARTMENT OF ENERGY

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This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content (HHC) fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

The proposed work aims to develop LES models for simulating HHC gas turbine combustion, with specific focus on premixing and flashback dynamics. The project is divided into three components: (1) LES model development using DNS andcanonical experimental data, (2) targeted experimental studies to produce high quality mixing and flashback dynamics under engine relevant conditions, and (3) validation of LES models using a validation pyramid approach and transfer of models to industry using an open source platform.

Goals and Objectives

The overall goal of the project is to develop predictive computational tools for simulating gas turbines burning HHC fuels. A rigorously validated combustion model for LES-based description of flashback dynamics and flame stabilization in jet-in-crossflow (JICF) configuration will be developed. Simultaneously, validation-specific experiments of flame stabilization in JICF configuration and flashback dynamics in high-pressure systems will be conducted. The models developed will be transferred to industry using an open source infrastructure. Specific objectives are:

- Formulate LES-based hybrid probability density function (PDF)/ flamelet approach for multi-regime combustion in gas turbines.
- Develop a comprehensive set of experiments for flame stabilization in JICF and flashback dynamics.
- Use a validation pyramid approach to demonstrate model accuracy in practical operating conditions and transfer models to industrial collaborators.

Accomplishments

- Designed a new premixed swirl flame burner to study flashback in collaboration with industry experts.
- Evaluated a new technique for comparing LES results and experimental data using particle image velocimetry (PIV) data acquired in JICF. This technique reveals the inadequacy of models for turbulent, intermittent quantities.
- Developed a direct quadrature method of moments (DQMOM) approach for complex geometries and implemented it in a highly parallel open source code. Preliminary simulations of canonical flow configurations show that the methodology is capable of accurately capturing flame evolution in turbulent flows. In particular, the methodology predicts the change in flame length and location as the hydrogen content in the fuel changes.
- Based on discussions with GE and Siemens, an open source platform called OpenFOAM is being used for transferring the models. The first version of the DQMOM model has been shipped to Siemens under this framework.
- Completed Kilohertz-rate PIV study of swirl burner with premixed and non-premixed fuel injection.
- Completed LES study of swirl burner with inflow conditions obtained from experiments.
- Completed simulation of flashback in turbulent channels and comparison to high-resolution direct numerical simulation study.
- Developed a flamelet-based model for premixed and partially-premixed combustion.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The importance of this project is to further advance the understanding needed to develop practical guidelines for realistic composition limits and operating characteristics for HHC fuels.

Figure 1. Jet flames in crossflow with different levels of premixing. The fuel is 70% CH_4 +30% H_2. From left to right: non-premixed, jet fluid diluted by 25% (volume basis) with air, and jet fluid diluted by 50% with air.

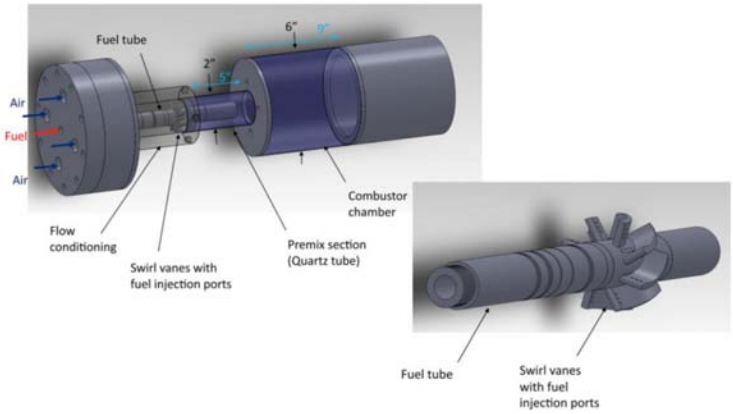

Figure 2. UT high pressure combustor.

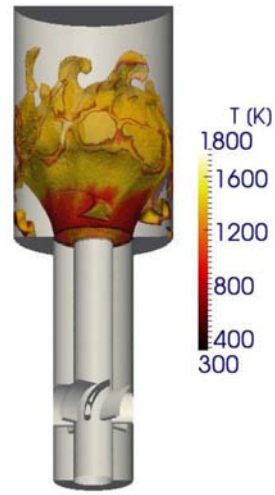

Figure 3. Instantaneous contour of mixture fraction = 0.2, colored by temperature.

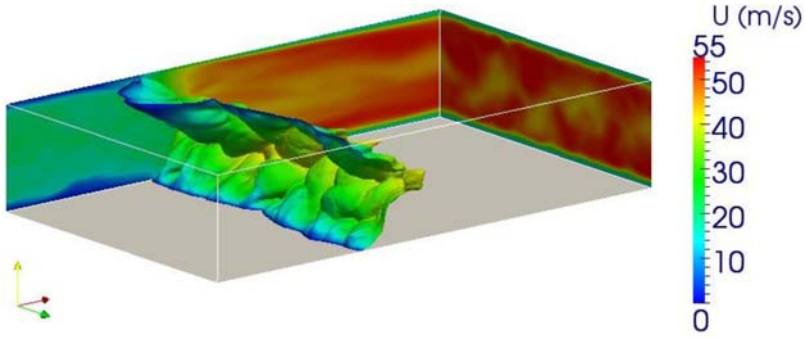

Figure 4. Instantaneous contour of T = 1400 K, colored by velocity.

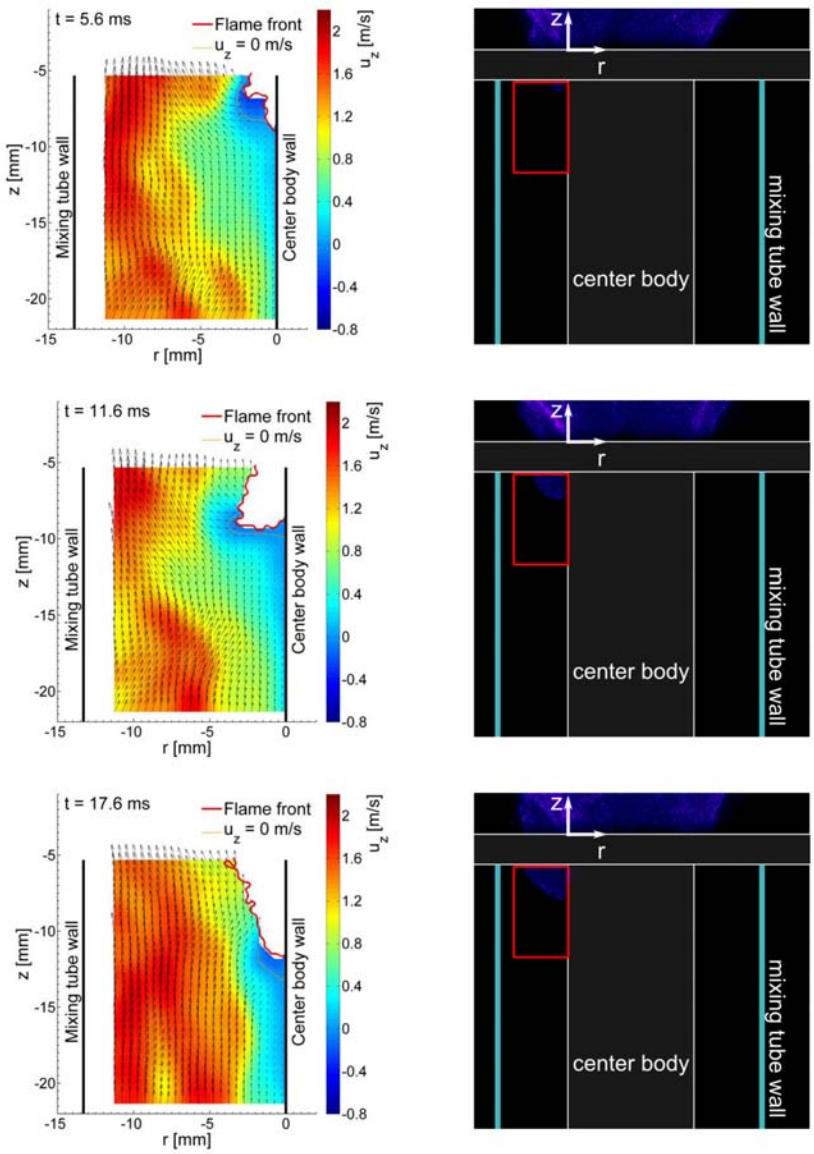

Figure 5. Time-sequenced images of simultaneous two-component PIV velocity fields and chemiluminescence of a CH_4/H_2-flame during flashback. The PIV is at left and the luminosity is at right. (a) time=5.6 ms, (b) time=11.6 ms and (c) time=17.6 ms. The edge of the flame, as marked by the evaporation of oil droplets, is shown by the red line in the PIV images. The reactants flow upward and the flame (red line in PIV image at left) propagates downward.

FE0007107 August 2013

MATERIALS

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PROJECT FACTS

Hydrogen Turbines

Computational Design and Experimental Validation of New Thermal Barrier Systems—Louisiana State University

Background

Thermal barrier coating (TBC) systems safeguard modern gas turbine engines against significant temperature extremes and degradation. In order to develop reliable gas turbine power systems operating on coal-derived synthesis gas (syngas), such as integrated gasification combined cycle (IGCC) plants, robust TBCs must be developed to overcome material degradations from corrosion, erosion, and deposition due to the usage of high-hydrogen-content syngas. With current theoretical simulation tools and computer hardware power, material static and dynamic properties can only be investigated on very small scales (nano-size or smaller), and thus are not adequate for complicated high performance TBC design. Researchers from Louisiana State University (LSU) and Southern University (SU) are working on the development and evaluation of a computational materials tool using unique calculation schemes for the identification of new TBCs for harsh IGCC environments.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

New TBC materials can be tested for mechanical, physical, and chemical properties by altering the bond coat and top coat compositions. Current studies on TBCs are usually performed by trial-and-error approach. As the trial-and-error process is usually very expensive and time consuming, the LSU/SU team proposes to design a high performance TBC with enhanced top and bond coat through a reliable and efficient theoretical/computational approach. This can be used systematically to identify promising TBC bond coat and top coat compositions. Using high performance computing (HPC) simulations, an *ab initio* (i.e., from first principles) molecular dynamics (MD)-based design tool can screen and identify TBC systems with desired

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PROJECT DURATION

Start Date	End Date
10/01/2010	09/30/2014

COST

Total Project Value
$634,671

DOE/Non-DOE Share
$504,863/$129,808

AWARD NUMBER

FE0004734

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physical properties. Such computations work from basic or fundamental laws of nature to derive effects without intervening assumptions or special models, in principle producing well-founded results. The new TBC systems will be demonstrated experimentally under IGCC environments.

Goals and Objectives

The goal of this project is to develop and evaluate a novel TBC design tool based on the integration of *ab initio* density functional theory (DFT) with classical molecular dynamics method. Project objectives are as follows:

- Implement an integrative approach of *ab initio* calculations with molecular dynamics simulation and to develop the required computer code.
- Perform *ab initio* MD simulations using HPC to identify the most promising TBC compositions.
- Perform experimental validations on the promising TBC systems identified in the computational simulations.

Accomplishments

- The UBER (universal binding energy relation) relation-fitting code with Council of European Nuclear Research (CERN) library has been tested.
- Performed *ab initio* DFT simulation on the chromium (Cr), cobalt (Co), and yttrium (Y) crystals. The simulated lattice constant, bulk modulus, and magnetic moment are in good agreement with corresponding experimental results.
- The materials design environment MedeA® was implemented in HPC lab and tested with Cr and Y crystals.
- The concentration of aluminum (Al) in ternary AlxTaIr (tantalum iridium) is between 2.7 and 5.5 atomic percent and extra dopant type may be needed to coordinate with other three component elements (Figure 1).
- Design and fabrication of the TBC durability testing rig has been completed.
- Thermal cycling tests on TBC samples for gadolinium zirconate/yttria-stabilized zirconia (GZ/YSZ, GZ50%/YSZ etc.) have been conducted (Figure 2).
- Hot corrosion tests on YSZ-Ta_2O_5 top coats have been performed (Figure 3).

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The TBC design tool and optimized high performance TBCs will play an important role in the development of next generation gas turbine engines. As no computational materials-based TBC design tool is currently available for advanced TBC design, this project makes significant contributions to the technical goals of the Hydrogen Turbine Program for developing advanced turbine materials.

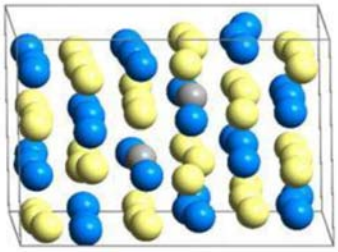

Figure 1. The 2Al-34Ta-36Ir crystal structure model used in one of our simulations. The gray balls are Al atoms, blue balls are Ta atoms, and yellow balls are Ir atoms. The two Ta atoms are substituted by two Al atoms.

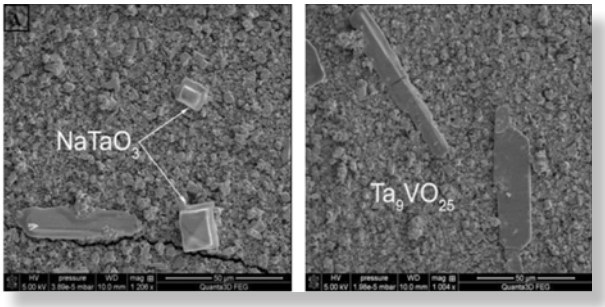

Figure 3. SEM surface images of TaYSZ after hot corrosion in $Na_2SO_4 + V_2O_5$ at 1100 ˚C.

Figure 2. (L) YSZ, (M) GZ, (R) 50%GZ/YSZ, Failed TBC samples after thermal gradient thermal cycling tests. Failure is mainly caused by the spallation at the edges.

FE0004734 August 2013

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PROJECT FACTS

Hydrogen Turbines

Advanced Thermal Barrier Coatings for Operation in High Hydrogen Content Fueled Gas Turbines—Stony Brook University

Background

Traditional thermal barrier coatings (TBCs) based on yttria-stabilized zirconia (YSZ) will likely not be suitable in gas turbines used in integrated gasification combined cycle (IGCC) power plants. This is due to higher operating temperatures that will not only affect phase stability and sintering but will accelerate corrosive degradation phenomena. Coatings provide a framework to combat degradation issues and provide performance improvements needed for higher temperature environments.

The Center for Thermal Spray Research (CTSR) at Stony Brook University, in partnership with its industrial Consortium for Thermal Spray Technology, is investigating science and technology related to advanced, thermally sprayed, metallic alloy bond coats and ceramic TBCs for applications in the hot section of IGCC turbine power systems.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content (HHC) fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Recent research data indicate that the current bill of coating materials is not directly compatible with the moisture-rich, ash-laden environment present with coal-derived HHC fuels. Thus, Stony Brook University research focuses on a multi-layer, multifunctional strategy that includes discretely engineered coating layers to combat various technical issues through a concerted effort integrating material science, processing science, and performance studies, including recent developments in advanced, in situ thermal spray coating property measurement for full-field enhancement of coating and process reliability. This project will further the science-based understanding of TBCs and elevate the roles that processing and novel materials can play in extending bond coat and top coat lifetimes, and provide a new framework for examining the processing-performance relationship in multilayer thermal barriers as a pathway for reliable IGCC coating development, and provide new insight for the thermal spray industry.

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
10/01/2010	12/31/2014

COST

Total Project Value
$517,035

DOE/Non-DOE Share
$401,238/$115,797

AWARD NUMBER

FE0004771

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In this project, TBCs will be developed through investigation into how processing affects the oxidation behavior of metallic bond coats in water vapor environments, and by developing ceramic top coat architectures using thermal spray processing of emerging zirconate materials that have shown promise as advanced thermal barriers. Novel, in situ particle and coating state sensors will be used to accelerate process development and understand processing-microstructure relationships and process reliability. A systematic evaluation of multilayer coatings on nickel superalloys will determine properties (including microstructure, compliance, residual stress, thermal conductivity, and sintering behavior) and degradation mechanisms due to high-temperature water vapor and ash exposure as well as erosion.

Goals and Objectives

The overall objective of this UTSR project is to provide enabling science and technology for increased viability of thermal sprayed multilayer coatings (metallic alloys and ceramics) in IGCC turbine systems. To address the requirements for providing effective thermal protection in the hot gas path of moisture-rich, HHC fueled turbines, a multilayer coating architecture based on state-of-the-art materials is envisaged to combat the multiple degradation mechanisms. To accomplish this overall objective, the research will concurrently address individual component-level issues as well as system-level attributes, including:

- Evaluate oxidation characteristics of different types of bond coat materials in water-vapor-containing atmospheres in order to select the most viable material and processing condition.
- Develop processing strategies and maps for plasma spraying of emerging zirconate materials.
- Investigate the role of bond coat chemistry (i.e., rare-earth doping) and bond coat processing such as different types of high velocity oxygen fuel (HVOF) thermal spray and low pressure plasma spray on the processing-microstructure-performance linkages.

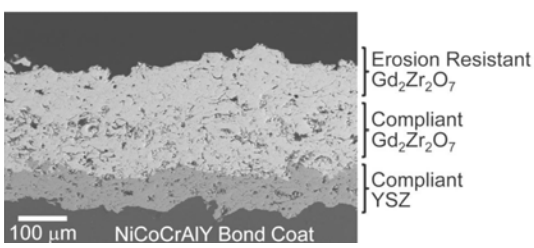

Figure 1. Cross-sectional scanning electron microscope image of the tri-layer TBC on NiCoCrAlY bond coated substrate.

- Consider single and multilayer top coats, in addition to the baseline YSZ system, incorporating an advanced zirconate composition as well as emerging co-doped compositions.
- Subject both individual components (bond coat and top coat) as well as assembled multilayers to isothermal and gradient exposures in water-vapor-laden high-temperature environments to assess the role of chemistry, micro-structure, and process induced states. Simulated erosion and chemical deposition studies will also be conducted to enable identification of both individual material performance (in its processed form) and performance of a multilayer assemblage.

Accomplishments

- Completed the process map for plasma spraying of gadolinium ium zirconate ($Gd_2Zr_2O_7$ [GZO]) with controlled mechanical properties (achieving process-enabled elastic moduli ranging from 13 to 34 gigapascals) thus facilitating the design of a compliant TBC.
- Optimized HVOF spray parameters for nickel-cobalt-chromium-aluminum-yttrium (NiCoCrAlY) and nickel-cobalt-chromium-aluminum-yttrium-hafnium-silicon (NiCoCrAlYHfSi) bond coats to minimize porosity and achieve a compressive residual stress state.
- Determined the Larson-Miller parameter for plasma-sprayed GZO as a function of spray condition in order to understand sintering kinetics and demonstrate that the material sinters more slowly than YSZ.
- Produced a multilayer TBC-YSZ/compliant GZO/dense GZO for initial industrial rig testing and ash exposure.
- Characterized the erosion resistance of GZO and compared it to that of state-of-the-art YSZ.
- Investigated the role of HVOF bond coat roughness on TBC life and developed processing strategies to address the same.
- Determined the fracture toughness of both TBC materials YSZ and GZO and also studied the thermal aging effects on the toughness of both.
- Identified durability strategy for bi layered YSZ coatings based on the parameters of fracture toughness and elastic modulus.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. TBCs developed in this project will enable increased temperatures in IGCC turbines contributing to the efficiency goals of the program. Coatings are also an economic means to extend the life of expensive structure-critical superalloys used in IGCC turbines.

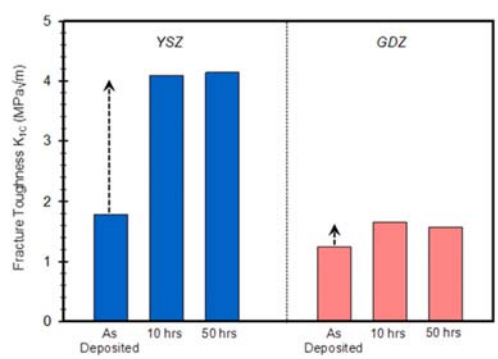

Figure 2. Measured Fracture Toughness of YSZ and GZO (Gadolinium Zirconate) coatings using Double Torsion Technique. It can be observed that with thermal aging, the measured toughness of YSZ coatings increased significantly, while that of GDZ did not increase as much. This could be attributed to the slower sintering rate of GDZ compared to YSZ. The fracture surfaces show the sintered interfaces after 50 hours of thermal exposure. This observation becomes critical while designing a TBC system comprising of the two different materials.

FE0004771 July 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

An Alternative Low-Cost Process for Deposition of MCrAlY Bond Coats for Advanced Syngas/Hydrogen Turbine Applications—Tennessee Technological University

Background

One of the material needs for the advancement of integrated gasification combined cycle (IGCC) power plants is the development of low-cost effective manufacturing processes for application of coating architectures with enhanced performance and durability in coal derived synthesis gas (syngas)/hydrogen environments. Thermal spray technologies such as air plasma spray (APS) and high-velocity oxy-fuel (HVOF) are currently used to fabricate thermal barrier coating (TBC) systems for large land-based turbine components. In this research Tennessee Technological University (TTU) will develop metal chromium-aluminum-yttrium (MCrAlY; where M = nickel [Ni], cobalt [Co] or a mixture of Ni and Co) bond coats via an alternative low-cost electrolytic codeposition process. In contrast to thermal spray processes, the electro-codeposition process offers advantages such as non-line-of-sight deposition and the capability of producing dense and oxide-free coatings.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

The proposed MCrAlY bond coats will be synthesized via an electrolytic codeposition process, followed by a post-plating heat treatment. Figures 1 and 2 are schematics of the laboratory electro-codeposition process and the targeted microstructure of the as-deposited coating, respectively. In contrast to traditional electro-codeposition processes where sulfate or sulfamate bath is used for Ni/Co deposition, a sulfur-free electrolyte will be employed to control the impurity levels in the MCrAlY coatings. The reduced sulfur

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
09/12/2011	09/11/2014

COST

Total Project Value
$466,515

DOE/Non-DOE Share
$371,288/$95,227

AWARD NUMBER

FE0007332

U.S. DEPARTMENT OF ENERGY

(S) levels will be expected to improve oxide scale adhesion. The amounts of Cr, Al, and particularly the Y reservoir, in the MCrAlY bond coat will be optimized to extend the lifetime of the TBC system. Reactive elements such as Y + hafnium (Hf) or Y + zirconium (Zr) will be co-doped into the MCrAlY coatings by modifying the composition of the CrAlY alloy powder. The composition of the CrAlY+ alloy (where "+" equals Hf or Zr, etc.) will be carefully designed, based on the literature data for model MCrAlY alloys and other types of MCrAlY coatings. Other parameters of the electrolytic codeposition process will be systematically studied using a design-of-experiment approach to provide a fundamental understanding of their synergistic effects and to optimize the coating composition and microstructure.

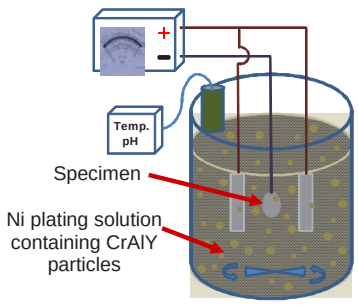

Figure 1. Laboratory electro-codeposition process.

Goals and Objectives

The goal of this project is to develop and optimize MCrAlY bond coats for syngas/hydrogen turbine applications using a low-cost electrolytic codeposition process. The coating performance will be improved by reducing the impurity levels in the coating and by employing reactive-element co-doping. The oxidation resistance of the new bond coat will be assessed in water vapor environments with various water levels. The failure mechanism of the new TBC/bond coat architecture will be studied to provide a knowledge base needed for further extending the TBC lifetime.

Specific objectives include:

- Exploring a sulfur-free plating solution (to replace conventional sulfate or sulfamate plating bath) with the aim of reducing impurity levels (particularly sulfur) in the MCrAlY coatings. This is expected to improve the oxidation resistance.
- Co-doping reactive elements (e.g., Y+Hf or Y+Zr) into the bond coats via engineering the composition of the CrAlY-based powders to further enhance their oxidation performance.
- Optimizing the electro-codeposition parameters using a design-of-experiment approach to provide a fundamental understanding of the synergistic effect of multiple variables on coating microstructure/composition and coating quality.

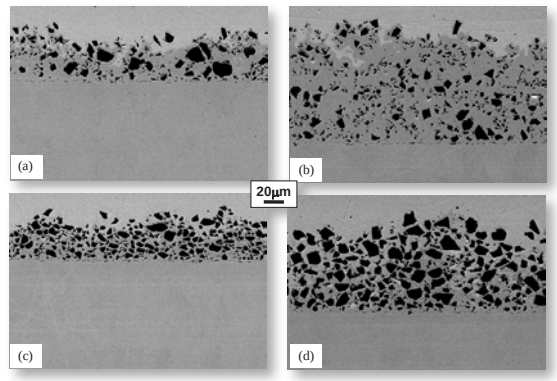

Figure 2. SEM cross-sectional images of the coatings codeposited with 10 g/L Cr-Al-Y particles in the solution. The current density and stirring speed were: (a) 20 mA/cm2, Stir #3, (b) 60 mA/cm2, Stir #3, (c) 20 mA/cm2, Stir #7, and (d) 60 mA/cm2, Stir #7.

Accomplishments

- Established a well-controlled laboratory process of fabricating Cr-Al-Y powder using arc melting followed by ball milling.
- Employed two electro-codeposition configurations, i.e., vertical and horizontal (also known as sediment codeposition) arrangements in synthesis of composite coatings consisting of the Ni matrix and the embedded Cr-Al-Y particles.
- Studied the effects of electro-codeposition parameters on Cr-Al-Y particle incorporation in the coating using a Design-of-Experiment approach.
- Investigated the potential of using a sulfur-free fluoborate-based nickel plating solution for electro-codeposition of MCrAlY coatings

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. Successful application of the proposed electrolytic codeposition process will offer an alternative, economical fabrication route, with advantages such as non-line-of-sight deposition and capabilities for producing dense and oxide-free coatings, as compared with current low-cost thermal spray processes.

FE0007332 July 2013

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PROJECT FACTS

Hydrogen Turbines

Mechanisms Underpinning Degradation of Protective Oxides and Thermal Barrier Coatings in High Hydrogen Content-Fueled Turbines—University of California, Irvine

Background

Thermal barrier coatings (TBCs) and components in the hot section of gas turbines are degraded by coal-derived high hydrogen content (HHC) synthesis gas (syngas). In this project the University of California, Irvine (UCI) will provide an improved mechanistic understanding of the degradation of critical turbine system materials in HHC-fueled systems and guide the development of more robust material sets.

This project is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from HHC fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment. This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers.

Project Description

This project will evaluate the potential impacts of coal-derived syngas and HHC fuels on the degradation of turbine hot-section components through attack of protective oxides and TBCs. The primary focus is to explore mechanisms underpinning the observed degradation processes and connections to the combustion environments and characteristic non-combustible constituents.

This work addresses turbine materials stability concerns by conducting tests in simulated syngas and HHC environments to evaluate materials evolution and degradation mechanisms. Thermally grown oxide (TGO) development and TBC failure unique to HHC environmental exposures will be assessed. High-resolution imaging and microanalysis will be used to explain the evolution of surface deposits (molten phase, formation, and infiltration). Electron beam physical vapor deposition coating will be used to fabricate test coupons with idealized microstructures for comparison with thermal spray systems. Representative syngas and HHC fuels with realistic levels of impurities and contam-inants must be determined in order to explore differences in heat transfer, surface degradation, and deposit formation. Experiments will be executed to study the melting and infiltration of simulated ash deposits. Reaction products and evolving phases associated with molten phase corrosion mechanisms will be identified.

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PARTNERS

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PROJECT DURATION

Start Date	End Date
09/01/2010	08/31/2013

COST

Total Project Value
$625,000

DOE/Non-DOE Share
$500,000/$125,000

AWARD NUMBER

FE0004727

U.S. DEPARTMENT OF ENERGY

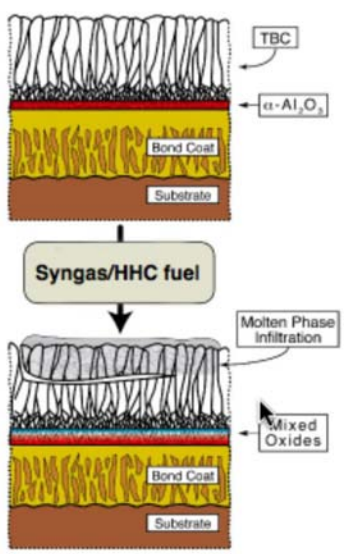
New material systems for laboratory testing will be developed and thermal gradient and combustion rig testing of material test coupons will be facilitated. Information on the resulting combustion environments will be correlated to properly assess materials exposure conditions and guide the development of lab-scale simulations of material exposures.

Goals and Objectives

The goal of this project is to derive a mechanism-based understanding of protective TGO layer and TBC system degradation modes associated with turbine operation with syngas and HHC fuels, and develop a knowledge base upon which the design of coatings more resistant to the observed attack mechanisms may be based.

Specific objectives:

- Evaluate the unique impacts of utilizing coal-derived syngas and HHC fuels on the degradation of turbine hot-section components, and develop an improved mechanistic understanding of the observed degradation processes in relation to the fuel-dependent combustion environments.
- Develop material design protocols that maximize the lifetime of protective oxides and TBCs in syngas and/or HHC combustion turbine exposures.
- Procure baseline materials representative of overlay and bond coat materials, and begin assessing oxide growth and phase development (at 1,125 degrees Celsius [°C]) as a function of simulated combustion by-product stream composition and water vapor content.
- Explore the fundamental mechanisms by which water vapor affects non-ideal oxide growth and TBC system lifetime by (1) utilizing novel specimen exposure protocols, (2) carrying out selected experiments on a burner rig test system, and (3) applying advanced microscopy and spectroscopic methods to quantitatively evaluate oxide development in relation to varying exposure environments.



Schematic of potential modifications to materials degradation with syngas/ HHC Fuels.

- Synthesize and/or procure representative fly ash compositions resulting from combustion of coal-derived syngas and HHC fuels and initiate evaluations of thermo-chemical interactions with baseline TBC systems.

Accomplishments

- Completed modifications to furnace-based test rigs to facilitate extended oxidation experiments (up to 1,000 hours) in controlled water vapor content environments.
- Obtained bulk cast versions of (1) idealized nickel-aluminum (Ni-Al) alloy compositions, (2) two commercial M-chromium aluminum yttrium alloy (MCrAlY; where M is one of several different metals) bond-coat compositions including a cobalt (Co)-rich composition and a Ni-rich composition, and (3) several commercial bond-coat on Ni-based super-alloy substrate systems for studies of oxide growth in varying simulated combustion environments.
- Initiated characterization of oxide growth and phase development under 1,125 °C exposures in dry and elevated water vapor environments. The resulting oxide growth and phase development were assessed using (1) x ray diffraction, (2) high-resolution microscopy, (3) site-specific cross-sectional analysis by focused ion beam sectioning, and (4) energy dispersive spectroscopy analysis by focused ion beam sectioning.
- Demonstrated enhanced oxide formation (specifically, of Ni-based spinels) with increasing water vapor content, suggesting a direct role of water vapor pressure (pH_2O)-dependent species on the activities and transport of positive ions (Ni, etc.) through developing thermally grown oxides.
- Synthesized laboratory versions of syngas-derived fly ash and initiated studies of thermo-chemical interactions in yttria-stabilized zirconia (YSZ) TBC material reactions with baseline TBC systems.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This project will support an increase in the life of turbine hot-section components, which will increase maintenance intervals and ultimately the life of the power system.

Tests of a combustor leveraged for materials exposure studies.

FE0004727 January 2012

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Low Thermal Conductivity, High Durability Thermal Barrier Coatings for IGCC Environments—University of Connecticut

Background

Improved turbine materials are needed to withstand higher component surface temperatures and water vapor content for successful development and deployment of integrated gasification combined cycle (IGCC) power plants. Thermal barrier coatings (TBCs) in particular are required to have higher surface temperature capability, lower thermal conductivity, and resistance to attack at high temperature by contaminants such as calcium-magnesium-alumina-silicate (CMAS) and water vapor. There is also a concurrent need to address cost and availability issues associated with rare earth elements used in all low thermal conductivity TBCs.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

The University of Connecticut, in cooperation with Pratt & Whitney and Siemens Energy, will use a novel solution precursor plasma spray (SPPS) process (Figure 1) to deposit low thermal conductivity, high durability yttria stabilized zirconia (YSZ) TBCs and to utilize surface protective layers (SPLs) to provide high temperature contaminant resistance and increased surface temperature capability, while minimizing the use of rare earth elements. The SPPS process provides a unique TBC microstructure that consists of through-thickness vertical cracks for strain tolerance, ultra-fine splats for spallation crack resistance, and the ability to produce very low thermal conductivities. The low thermal conductivities, or low-K (with K representing heat conductivity), will result from planar arrays of fine porosity called inter-pass boundaries (IPBs) and the ability to vary porosity content over wide ranges. The IPBs are generic conductivity lowering features that can be implemented for any TBC. Pratt & Whitney and Siemens Energy will contribute valuable specimens and will test the down-selected low-K TBCs.

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PARTNERS

Pratt & Whitney
Siemens Energy

PROJECT DURATION

Start Date	End Date
10/01/2011	09/30/2014

COST

Total Project Value
$657,212

DOE/Non-DOE Share
$498,886/$158,326

AWARD NUMBER

FE0007382

U.S. DEPARTMENT OF ENERGY

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The low-K YSZ TBC structure will be created using the SPPS process. Taguchi methods for design of experiments will be used to systematically determine the deposition parameters to minimize the thermal conductivity. Cyclic durability tests of the low-K TBC will be conducted to verify that the excellent durability of the SPPS TBC is preserved. A protective surface layer of gadolinium-zirconium will be added to the low-K YSZ TBC to increase the maximum allowable surface temperature by at least 100 degrees Celsius (°C) and improve its CMAS resistance, while minimizing the heavy use of rare earth elements. This improved contaminant resistance will be verified by testing in CMAS and moisture. Contaminant resistance will be further enhanced by employing two novel approaches, one using aluminum-titanium additions to the YSZ, and the other by deliberately adding calcium sulfate, shown to block CMAS when deposited by natural processes in service engines. The spallation failure mechanisms of the low-K TBC will be defined to provide guidance for subsequent improvements and a sound basis for life prediction methodologies.

Goals and Objectives

The goal of this project is to develop low-K, high durability TBCs for IGCC environments.

- Fabricate very low-K SPPS YSZ TBCs. The low thermal conductivities will result from planar arrays of fine porosity (also called IPBs) and the ability to vary the porosity content over wide ranges.
- Improve the maximum allowable surface temperature of the low-K TBC by at least 100 °C and dramatically improve its high-temperature contaminant resistance by adding an SPPS SPL.
- Improve the high contaminant resistance of the SPL coating by using two novel approaches to dope YSZ with minor elements.
- Define the spallation failure mechanisms of the low-K TBC to provide guidance for subsequent improvements and a sound basis for life prediction analyses.

Accomplishments

- SPPS YSZ TBCs were deposited with a thermal conductivity of 0.6 watts per meter kelvin, a 50 percent reduction compared to air plasma spray (APS) YSZ. This breakthrough accomplishment achieved the prime goal of the program by introducing planar arrays of porosity, called inter-pass boundaries (IPBs). The IPBs are a unique microstructural feature of the SPPS process. Other low thermal conductivity TBCs rely on expensive rare-earth elements and exhibit poorer fracture toughness and erosion resistance (Figure 2).
- Preliminary thermal cycling tests were performed and showed that SPPS YSZ with IPBs had a cyclic life equal to that of standard SPPS YSZ TBCs and better than that of APS YSZ TBCs.
- A preliminary erosion test on low conductivity YSZ TBCs with IPBs showed erosion resistance as good as or better than standard YSZ TBCs (Figure 4).
- Successfully created a CMAS precursor solution suitable for use in subsequent CMAS testing.
- Successfully applied a protective surface layer consisting of a rare earth element based CMAS resistant higher temperature material (Figure 3).
- Purchased and installed a tube furnace for future high humidity testing.
- Successfully sprayed new YSZ-based TBCs with additional contents of Alumina and Titanium oxide, aiming to achieve advanced CMAS resistance as reported in Nitin Padture's work. The thermal conductivity of these new TBCs was measured using laser-flash (Figure 5).
- Demonstrated that calculated thermal conductivity based on micrographs are not reliable and replaced this method with laser flash measurements.

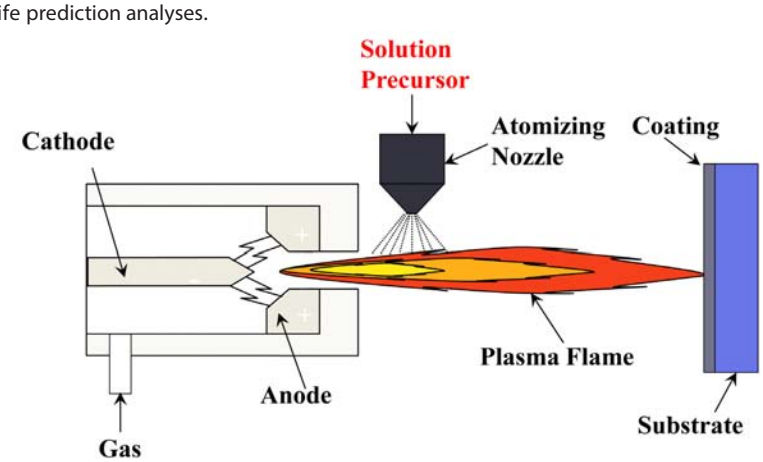

Figure 1. Solution Precursor Plasma Spray Process.

Benefits

This USTR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This work will support the development and deployment of IGCC power plants through the development of improved turbine materials capable of withstanding higher component surface temperatures.

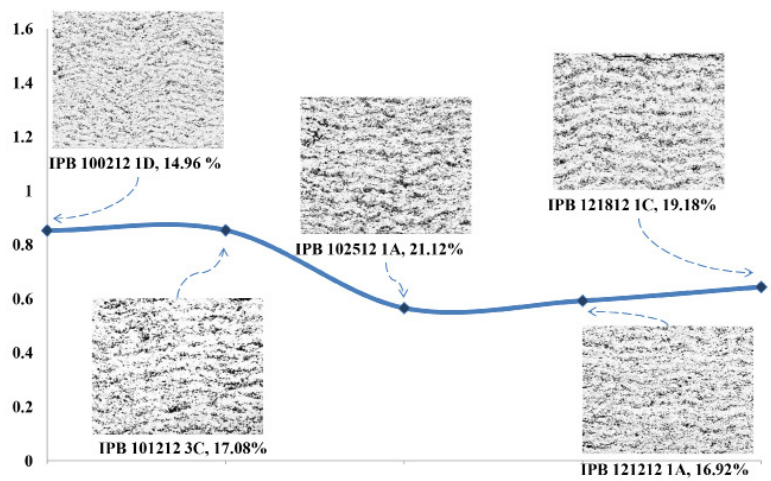

Figure 2. Thermal conductivity of SPPS YSZ reduced 50% compared to APS YSZ using planar arrays of porosity (IPBs). The more prominent the IPB structure, the lower the thermal conductivity.

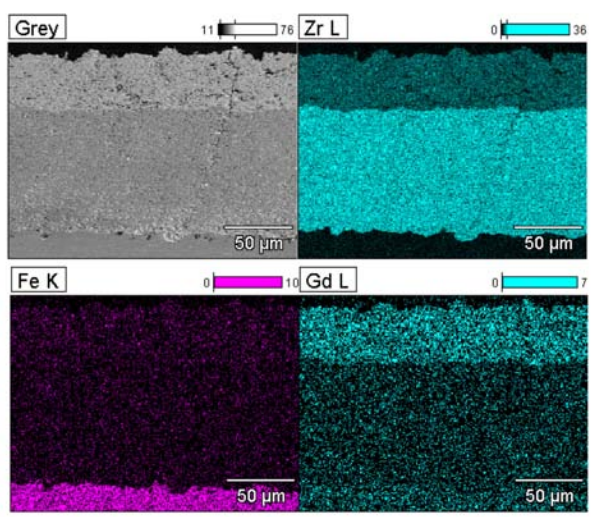

Figure 3. Gadolinium Zirconate (GdZr) protective surface layer (PSL) successfully applied. Top left image is an electron microscope image of a multi-layer coating with the bottom layer being the substrate, the middle layer is YSZ, and the top layer is GdZr. The other images are chemical maps created with Electron Dispersion Spectroscopy. The GdZr PSL can clearly be seen at the top and there is minimal chemical interaction between the layers.

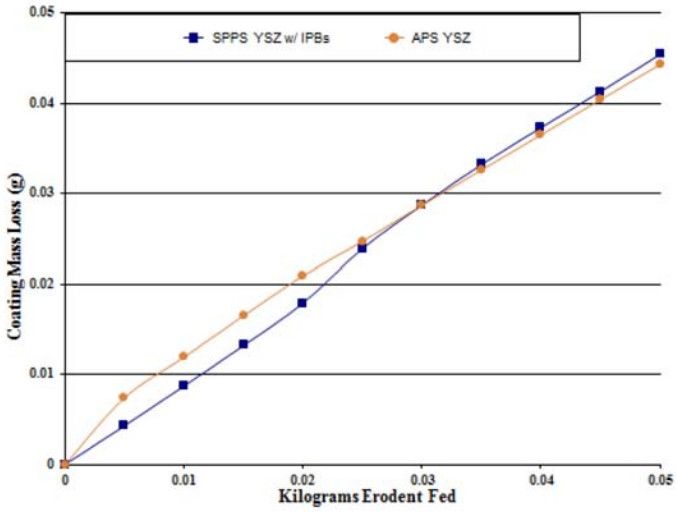

Figure 4. Erosion performance of SPPS YSZ TBCs with IPBs comparable to APS YSZ coatings. The lower the coating mass loss rate, the better the erosion resistance.

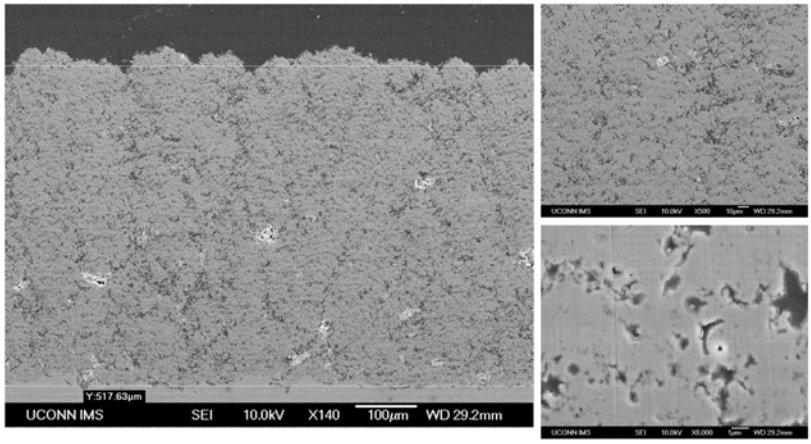

Figure 5. CMAS resistance coating successfully applied using SPPS process for new YSZ-based TBCs with additional contents of Alumina and Titanium oxide.

FE0007382 July 2013

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PROJECT FACTS

Hydrogen Turbines

Preparation and Testing of Corrosion- and Spallation-Resistant Coatings—University of North Dakota

Background

The life of turbine components is a significant issue in gas fired turbine power systems. In this project the University of North Dakota (UND) will advance the maturity of a process capable of bonding oxide-dispersion strengthened alloy coatings onto nickel-based superalloy turbine parts. This will substantially improve the lifetimes and maximum use temperatures of parts with and without thermal barrier coatings (TBCs). This project is laboratory research and development and will be performed by UND at their Energy & Environmental Research Center (EERC) facility and the Department of Mechanical Engineering. Some thermal cycle testing will occur at Siemens Energy (Siemens) in Orlando, FL. UND will also characterize trace fuel contaminants from a pilot-scale gasifier including multiple cleaning processes at EERC to determine more precisely which contaminants are likely to be present in high hydrogen content fuels.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

This project is designed to refine the evaporative metal bonding (EMB) method, then apply the refinements to bonding a layer of corrosion- and spallation-resistant alloy (APMT) to turbine parts composed of two nickel superalloy compositions and test the parts to determine if lifetimes have been increased. The work involves measurement of the temperature-dependent diffusion rates of zinc, the bonding metal used in the EMB process. The component superalloys of interest are CM247LC®, and Rene 80. The corrosion and spallation resistant super alloy layer is advanced powder metallurgy techology (APMT). This information will help the EERC-led project team better design the heat treatments needed to create the bonds between the superalloys and the APMT plating and assure that the zinc completely diffuses out of the

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
10/01/2011	09/30/2014

COST

Total Project Value
$600,000

DOE/Non-DOE Share
$480,000/$120,000

AWARD NUMBER

FE0007325

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turbine components created. The team will also model force distributions in the clamped structures being plated with APMT to assure that the compressive force used to hold the APMT and superalloys together during bonding is adequately distributed over the surfaces being joined. This modeling capability will allow the team to better design the clamping fixtures and force distribution plates (buffers) that will be used to bond plates of the APMT to more complex superalloy turbine parts.

To determine the appropriate conditions for corrosion testing of the bonded parts in simulated turbine conditions, the team will measure trace constituents in combusted syngas produced in the EERC entrained-flow gasifier. This will consist of combusting a slipstream of cleaned coal derived synthesis gas (syngas) produced from the gasifier, quenching the combusted gas with nitrogen, and collecting the submicron particulates on Nuclepore surface filters and gaseous constituents in activated carbon, zeolite traps, or gas impingers. After determining the best heat treatment and clamping methods, the team will bond plates of APMT to the surface of superalloy test samples (buttons) and turbine parts provided by Siemens. Siemens will also apply TBCs to some of the bonded parts and evaluate them. The EERC will perform laboratory hot corrosion tests simulating post-combustor turbine gas compositions, including relevant trace species defined in pilot-scale testing.

Goals and Objectives

The goal of this project is to apply a recently developed method of plating nickel superalloys with protective iron-chromium-aluminum (FeCrAl) layers closer to commercial use in syngas-fired turbines. The project is designed to determine if plating APMT onto nickel-based superalloy turbine parts is a viable method for substantially improving the lifetimes and maximum use temperatures of the parts, both those with TBCs and those without. If successful, the information will help move the protection process close to demonstration testing. In addition, the team will characterize the microcontaminants in combusted higher-hydrogen-content gas. This information will be used to best simulate actual corrosion conditions but can also be used by other researchers studying deposition and gas flow in turbines.

Accomplishments

- All materials, equipment, and clamps assembled for preparation of bonded parts.
- Analysis of the diffusion rates of zinc through the three alloys has been completed at 700 ° and 1214 °C.
- At 700 °C, the diffusivity in APMT is slightly higher (~4 vs. ~2 μm^2/min) than in CM247LC.
- The diffusion rate in the Rene 80 at 700 °C was below UND detection limits.
- The diffusion rate in APMT is approximately 20 times higher than in CM247LC or Rene 80 (~120 vs. ~8 μm^2/min) at 1214 °C.
- The ANSYS finite element model of the clamping system has been completed, including the measured expansion data for the alloys. It is shown in Figure 1.
- A sample calculated stress distribution in APMT at 1214 °C using the present clamping system is shown in Figure 2.

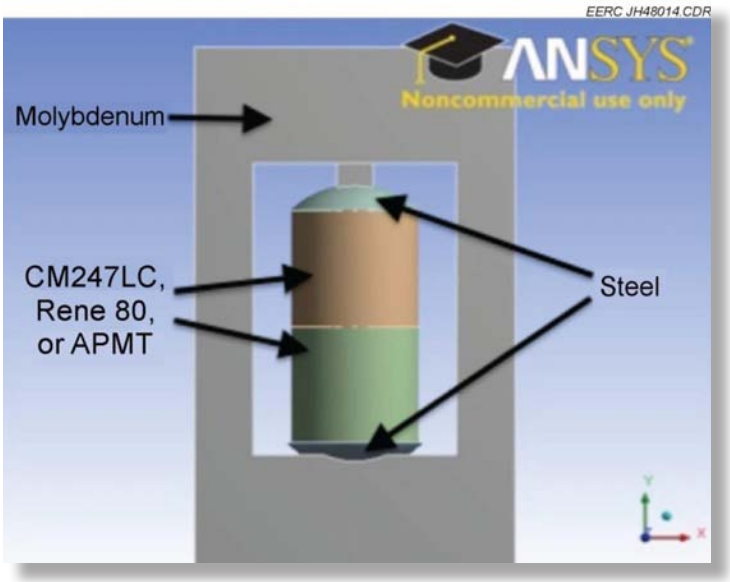

Figure 1. Finite element model used to study stress distributions during bonding.

- Sampling of vapor and particulate matter present in filtered syngas created in pilot-scale gasification systems continues.
- The particles collected after the system warm-gas filter are typically 0.2 to 0.5 µm in diameter, as shown in Figure 3.
- After the syngas is combusted, the particles appear slightly larger and much more spherical, as shown in Figure 4.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This work will advance the method of plating nickel superalloys with protective FeCrAl layers toward commercial use in syngas-fired turbines and will greatly increase the life-times and maximum-use temperatures of nickel superalloy turbine components.

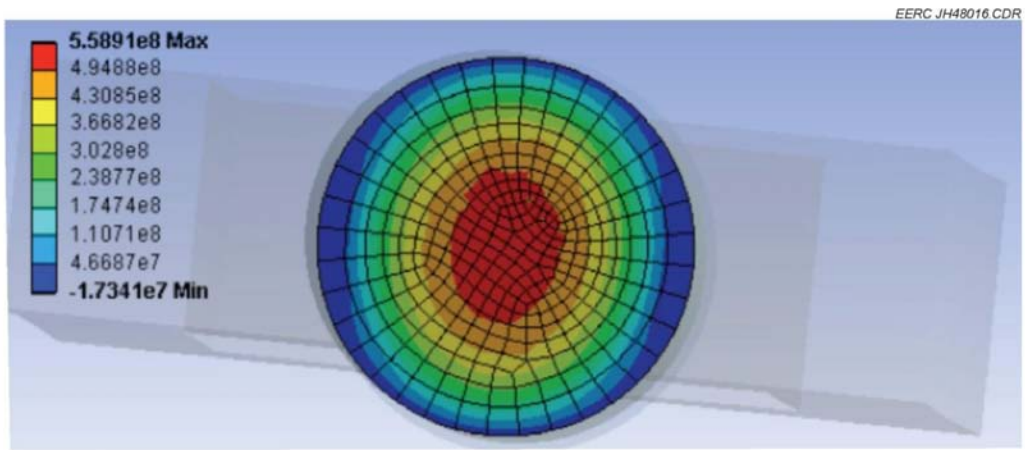

Figure 2. Normal stress distribution at bonding interface during bonding of APMT at 1214 °C.

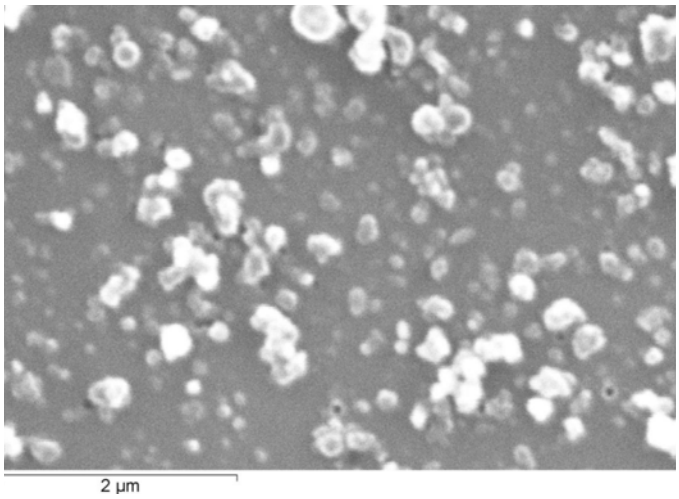

Figure 3. Particles collected at the thermal oxidizer inlet from scrubbed and filtered syngas.

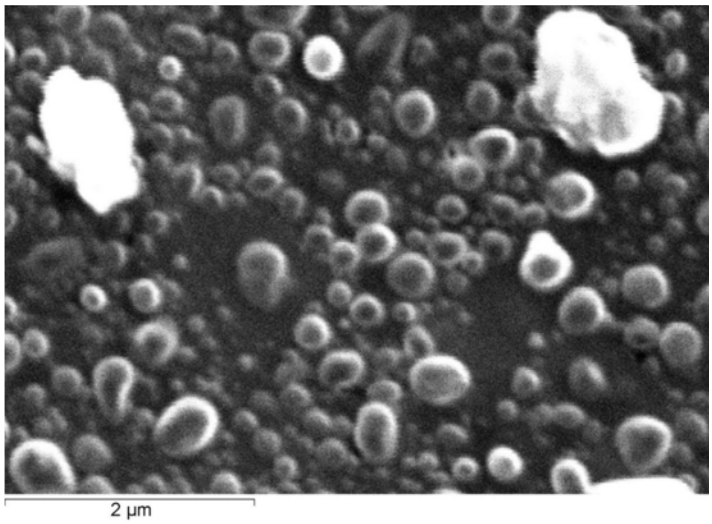

Figure 4. Particles collected from the thermal oxidizer outlet after burning syngas that had been filtered and scrubbed.

FE0007325 August 2013

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PROJECT FACTS

Hydrogen Turbines

Degradation of TBC Systems in Environments Relevant to Advanced Gas Turbines for IGCC Systems—University of Pittsburgh

Background

The conditions inside integrated gasification combined cycle (IGCC) systems, such as high steam levels from hydrogen firing, high carbon dioxide steam mixtures in oxy-fired systems, and different types of contaminants, introduce complexities associated with thermal barrier coating (TBC) durability that are currently unresolved. In this work the University of Pittsburgh will team with Praxair Surface Technologies (PST) to determine the degradation mechanisms of current state-of-the-art TBCs in environments consisting of deposits and gas mixtures that are representative of gas turbines using coal-derived synthesis gas (syngas).

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content (HHC) fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

This project will determine the degradation mechanisms of current state-of-the-art TBCs in environments comprised of particulate matter and gas mixtures which are representative of gas turbines using coal-derived synthesis gas (syngas). The observed degradation processes will be used to guide the development of improved coatings for hot section components in the potentially harsh gas turbine environments in which fuels derived from coal and even perhaps biomass are burned. The unresolved complexities associated with TBC durability include enhanced attack of yttria-stabilized zirconia (YSZ) top coating by chemical reaction, physical damage of the topcoat by molten deposit penetration, and accelerated bond coat corrosion. This work is investigating how the interaction between the ash and oxidants affect TBC degradation by using lab-scale testing. Important outcomes from this study will include understanding TBC degradation; modeling IGCC environments to develop better coatings; and extending the service life of TBCs by mitigating degradation.

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PARTNERS

Praxair Surface Technologies

PROJECT DURATION

Start Date	End Date
10/01/2011	09/30/2014

COST

Total Project Value
$562,702

DOE/Non-DOE Share
$434,324 / $128,378

AWARD NUMBER

FE0007271

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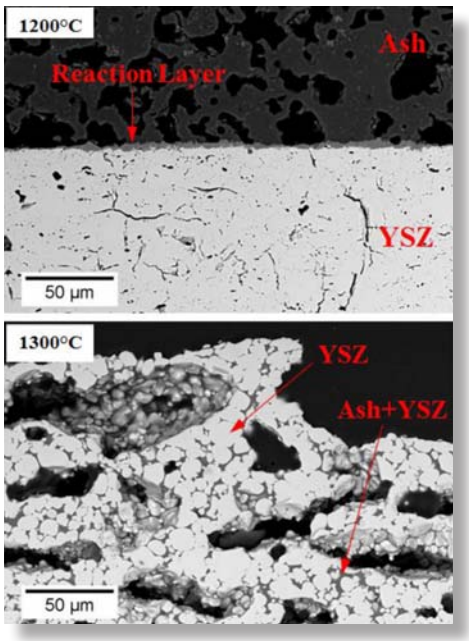
This research is using the high-temperature corrosion testing facilities at the University of Pittsburgh. The deposits currently being used are based on fly ash, and accordingly, consist of calcium oxide (CaO), aluminum oxide (Al_2O_3), silicon dioxide (SiO_2) and iron oxides (FeO_x). Additions of potassium sulfate (K_2SO_4) and iron sulfide (FeS) are used to simulate other ash constituents. The tests are being conducted on two different TBC system types provided by PST of Indianapolis, Indiana. PST will also conduct thermal gradient tests for assessing TBC durability with and without deposits. Both exposed and unexposed test samples are being extensively characterized using the suite of capabilities available at the University of Pittsburgh.



Free-standing YSZ coupons reacted with commercial fly ash. A thin reaction layer formed at 1200 °C, while the ash melted and severely degraded the YSZ at 1300 °C.

Goals and Objectives

The main goal of this project is to use lab-scale testing to systematically reveal the interplay between prototypical deposit chemistries (i.e., ash and its constituents, K_2SO_4 and FeS) and environmental oxidants (i.e., oxygen, water, and CO_2) on the degradation behavior of advanced TBC systems. Specific objectives are as follows:

- To characterize and determine the main factors governing the degradation of a state-of-the-art nickel-cobalt-chromium-aluminum-yttrium (NiCoCrAlY) bond coats and two differently processed YSZ TBCs in gaseous atmospheres that are increasingly relevant to IGCC systems.
- Add to the complexity by including synthetic surface deposits based on coal fly ash, with particular emphasis on the fly-ash components calcium oxide and silicon dioxide.
- Establish an effective experimental procedure for assessing high-temperature, deposit-induced degradation in IGCC-relevant environments.
- Study the further complexity of adding K_2SO_4 or FeS to the synthetic ash deposit.

The fundamental relevance of these objectives lies in the need to better understand the chemical, physical, and kinetic factors that can lead to accelerated degradation of TBCs used in IGCC systems. The practical significance lies in the guidance provided for predicting TBC degradation behavior and for designing TBCs that exhibit adequate degradation resistance.

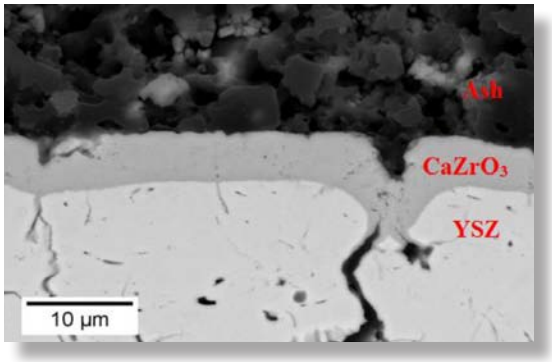
Accomplishments

- Commercial fly ash was found to cause extensive degradation of the YSZ top coat material at temperatures above 1300 °C. At relatively lower temperatures, a solid-state reaction occurred between the YSZ and ash which was less detrimental, but still relevant to TBC durability.
- Synthetic fly ash of varying compositions was used to assess TBC degradation at the lower temperatures. Solid-state reaction to form calcium zirconate ($CaZrO_3$) was found to occur only if a minimum level of CaO was present in the ash.
- Realistic synthetic fly-ash compositions with additions of K_2SO_4 and FeS caused extensive damage, resulting in thicker reaction layers and much deeper infiltration into cracks within the YSZ. Using synthetic mixtures will provide an understanding of the specific role(s) of each ash constituent in accelerating the degradation process.
- Testing done in CO_2+20%H_2O environments showed very little difference in the formation of the $CaZrO_3$ layer as compared to experiments in dry air. These initial results suggest that this particular attack on YSZ may not depend greatly on the gas atmosphere.
- The presence of CO_2 or H_2O in the reacting atmosphere was not found to alter the protective oxidation of state-of-the-art NiCoCrAlY bondcoat alloys at 1100 °C.
- A study of the reactive element level in NiCoCrAlY alloys revealed that while harmless in air, slightly excessive Y doping is detrimental in the presence of commercial fly ash, as Y-rich oxide inclusions in the scale act as initiation sites for rapid alloy degradation.
- Upon exposure of various NiCoCrAlY alloys to commercial fly ash, as well as synthetic ash mixtures (oxides with/without FeS or K_2SO_4) in air and in O_2-SO_2, the extent of metal loss could be directly related to the relative amounts of β-NiAl and γ-Ni phases in the alloy structure.

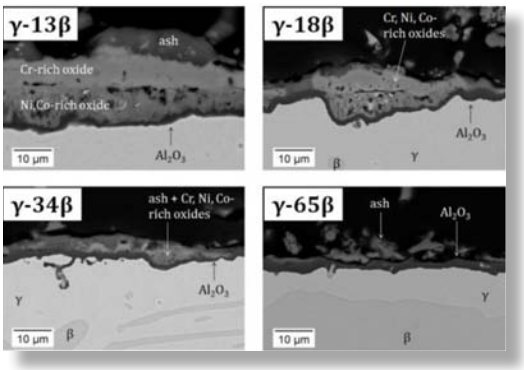
- Exposure of selected alloys to individual oxide deposits (CaO, MgO, Al_2O_3, SiO_2, Fe_2O_3, Cr_2O_3) in air showed that, while all oxides altered the extent of Al_2O_3 growth, only CaO caused significant alloy degradation.
- CaO was shown to react preferentially with the Al-lean γ phase through the formation of a liquid calcium chromate. The β-γ phase distribution was found to be critical to the establishment of a continuous Al_2O_3 layer, which effectively mitigates alloy degradation. These observations provide an understanding for the better resistance of β-rich alloys in the presence of more complex ash deposits, and offer guidance for coating design.

Benefits

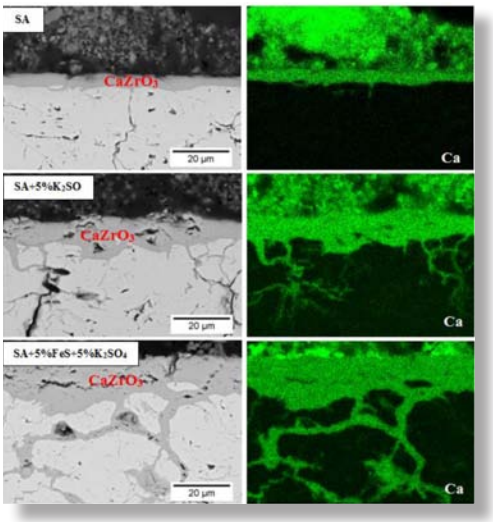
This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The outcome of this study will help define cost-effective IGCC specifications, performance modeling, and directions for new coating/blade alloy compositions.



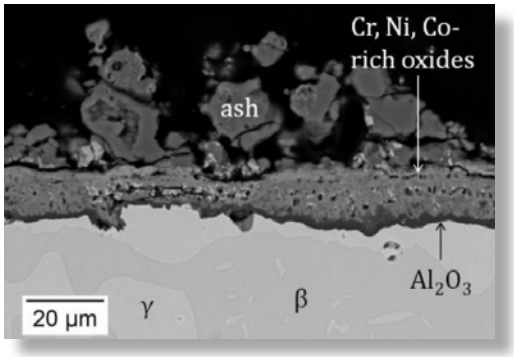
YSZ reacted with a synthetic ash at 1100 °C for 72 hours showing a continuous reaction layer. Synthetic ash mixtures with lower amounts of CaO did not form this reaction product, showing that there is a minimum CaO activity necessary in the ash to react with the YSZ.



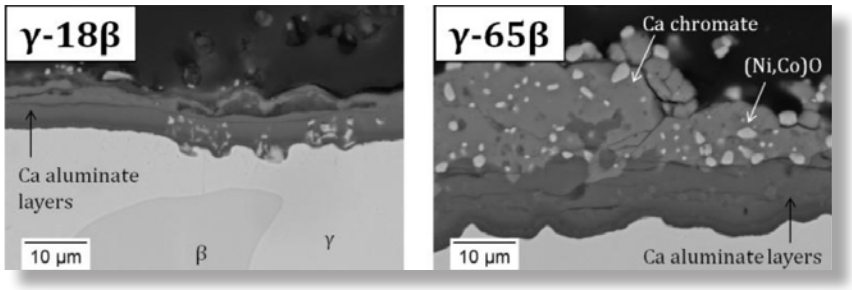
NiCoCrAlY alloys after 50 hours exposure to class C fly ash in CO_2-H_2O at 1100 °C. Alloy degradation is mitigated when increasing the β phase fraction.



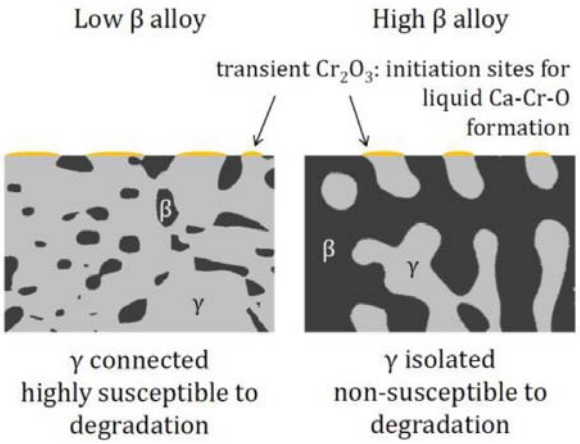
YSZ reacted with synthetic ash (SA) with and without additions of K_2SO_4 and FeS. The reaction product formed with only synthetic ash does not infiltrate the cracks in the YSZ. The degradation is more aggressive with the additives: the reaction product is thicker and the infiltration is more significant.



Ni-19Co-15Cr-24Al-0.3Y (atomic %) after 50 hours exposure to class C fly ash in CO_2-H_2O at 1100 °C. Excessive doping caused extensive alloy degradation.



NiCoCrAlY alloys after 50 hours exposure to CaO in air at 1100 °C. Reaction of CaO with the Cr-rich γ-phase to form a calcium chromate causes extensive alloy degradation.



Role of phase distribution in CaO-induced degradation of β-γ NiCoCrAlY alloys.

FE0007271 August 2013

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PROJECT FACTS

Hydrogen Turbines

Novel Hafnia-Based Nanostructured Thermal Barrier Coatings for Advanced Hydrogen Turbine Technology—University of Texas at El Paso

Background

Thermal barrier coatings (TBCs) are protective layers of low thermal conductivity ceramic refractory material that protect gas turbine components from high temperature exposure. TBCs improve efficiency by allowing gas turbine components to operate at higher temperatures and are critical to future advanced coal-based power generation systems. Next generation gas turbine engines must tolerate fuel compositions ranging from natural gas to a broad range of coal-derived synthesis gasses (syngas) with high hydrogen content. This will require TBCs to withstand surface temperatures much higher than those currently experienced by standard materials. In this project the University of Texas at El Paso (UTEP) will investigate TBC materials capable of tolerating a minimum 1,300 degree Celsius (°C) surface temperature for long-duration operations.

This project was competitively selected under the University Turbine Systems Research (UTSR) Program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

This project will vary growth conditions and target/ingot materials to study their influence on the coatings' phase, microstructure, mechanical, thermal, and chemical properties. The project will derive qualitative and quantitative models for failure mechanisms, lifetime, and performance of the nanostructured yttria-stabilized hafnia (YSH), gadolinia-stabilized hafnia (GSH), and yttria-stabilized zirconium dioxide–hafnium dioxide (YSZH) ceramic TBCs from all these studies. The models will be used to predict pathways to further improve the microstructure, properties, and, ultimately, performance of these coatings. The central theme of the microstructure evaluation and various characterizations is to provide feedback to fabricators to enable production of materials with superior stability, high-temperature tolerance, thermal durability, and sensitivity.

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PROJECT DURATION

Start Date	End Date
10/01/2009	01/31/2013

COST

Total Project Value
$491,081

DOE/Non-DOE Share
$381,233/$109,848

AWARD NUMBER

FE0000765

U.S. DEPARTMENT OF ENERGY

The specific approach for this project is to provide a large number of interconnected surface nano-grains while maintaining the columnar structure. This will lead to a large interfacial thermal resistance and extremely low thermal conductivity. There are several types of material structure improvements that will also be specifically addressed, including morphology/geometric uniformity, crystal structure and phase, microstructure quality, doping profiles, and material composition. Fundamental thermo-mechanical and thermo-chemical properties and performance will be measured and correlated to the microstructure. The thermal conductivity and size-dependent surface reactivity of the ceramic coatings will be measured. Finally, laboratory experiments in accelerated test environments will be performed to investigate the relative importance of various thermo-mechanical and thermo-chemical failure modes of TBCs. Effects of thermal stress cycling, oxidation degradation, and their complex interaction with respect to TBC failure, will be evaluated using a syngas combustor rig. The parametric relationship between turbine environments containing high hydrogen content fuels and thermo-mechanical cracking in the ceramic layer will be developed.

Goals and Objectives

The goal of this project is to develop nanostructured hafnia-based coatings for advanced hydrogen turbines. A fundamental understanding of TBCs will be acquired and a knowledge database of next-generation TBC materials will be created with data on high-temperature tolerance, durability, and reliability.

The proposed nanostructured TBCs will have superior heat resistance, thermal insulation, oxygen barrier qualities, hot-corrosion and erosion resistance, and resistance to adverse coating/substrate interactions. Specific objectives include:

- Engineer hafnia-based TBCs.
- Deliver TBC materials that meet the DOE required performance target of reliable surface temperature tolerance of 1300 °C for a minimum of 8,000 hours.
- Investigate the physical and mechanical properties of YSH, GSH, and YSZH coatings and demonstrate the high-temperature stability of the coatings' composition.
- Understand the substrate-coating structure and stability.

Accomplishments

- Deposited varying coating compositions of YSH, GSH, and YSZH on various substrate materials.
- Evaluated the crystal structure, surface morphology, and substrate-coating interface structure of the coatings.
- Determined mechanical properties of the YSH and YSZH coatings.
- Investigated chemical stability of the YSH and YSZH coatings at higher temperatures.
    - Evaluated the durability of YSH coatings for extended hours under hot gas exposure in a laboratory combustor test rig.
    - Performed analysis of residual stress in the YSH, GSH and YSZH coatings before and after hot gas exposure.
    - Evaluated the thermal oxidation resistance of the YSH coatings.

Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. TBCs that will tolerate higher surface temperatures will improve the efficiency of advanced hydrogen turbines in coal-based power generation systems.

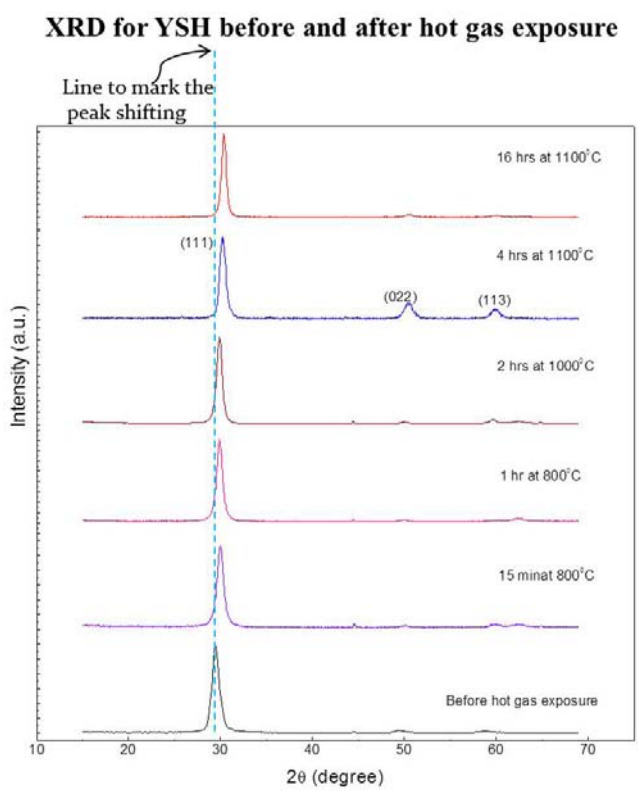


Figure 1. X-ray diffraction (XRD) patterns of YSH coating before and after exposure to hot gases.

The figure indicates no phase change after exposure to hot gases.

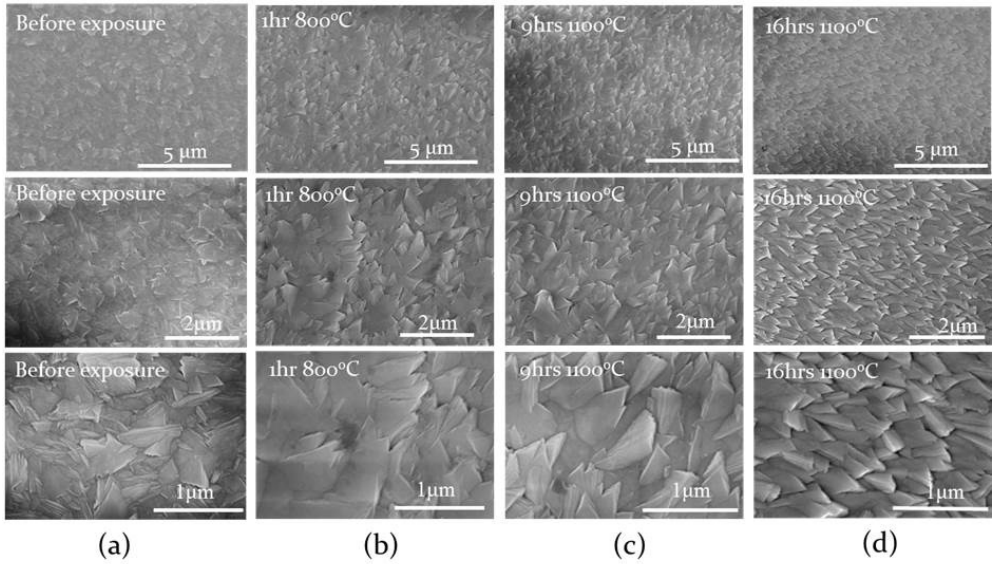


Figure 2. Scanning electron microscope (SEM) images of YSH sample after exposure to hot gases showing the dense triangular grains.

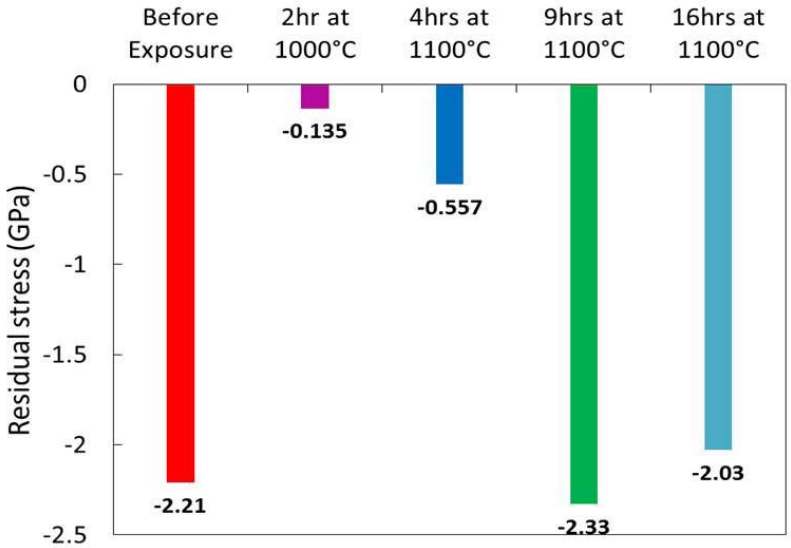


Figure 3. Residual stress in YSH coatings before and after exposure to hot gases.

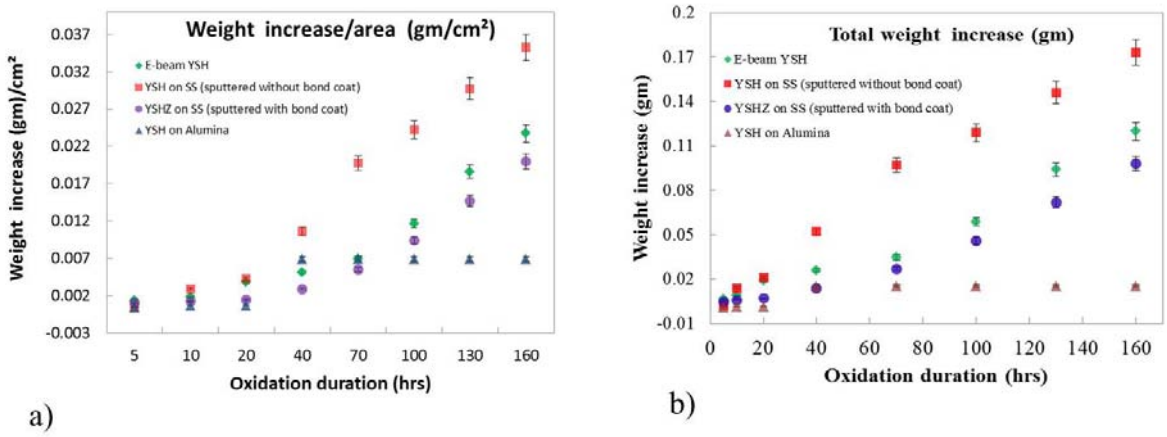


Figure 4. The weight increase against the exposure time after thermal oxidation a) weight increase per unit area against exposure time and b) total weight increase against exposure time.

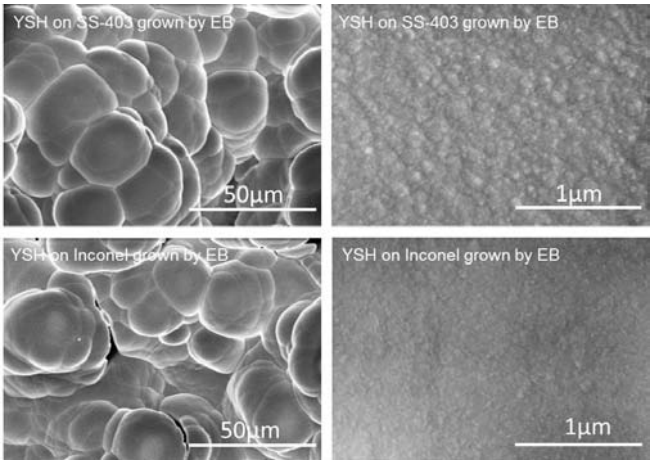


Figure 5. Surface morphology of YSH coatings grown by electron beam physical vapor deposition (EBPVD).

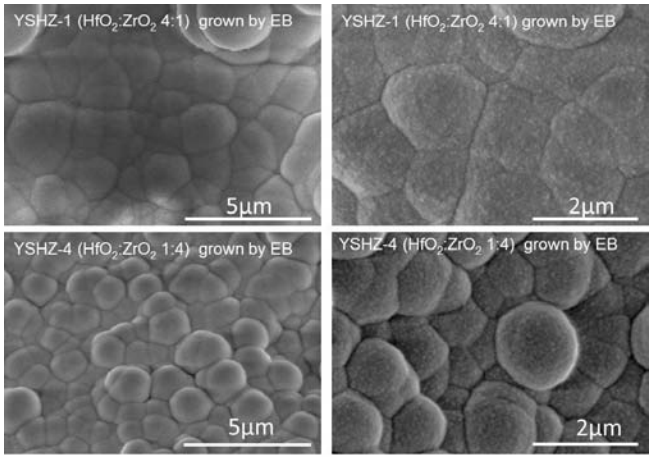
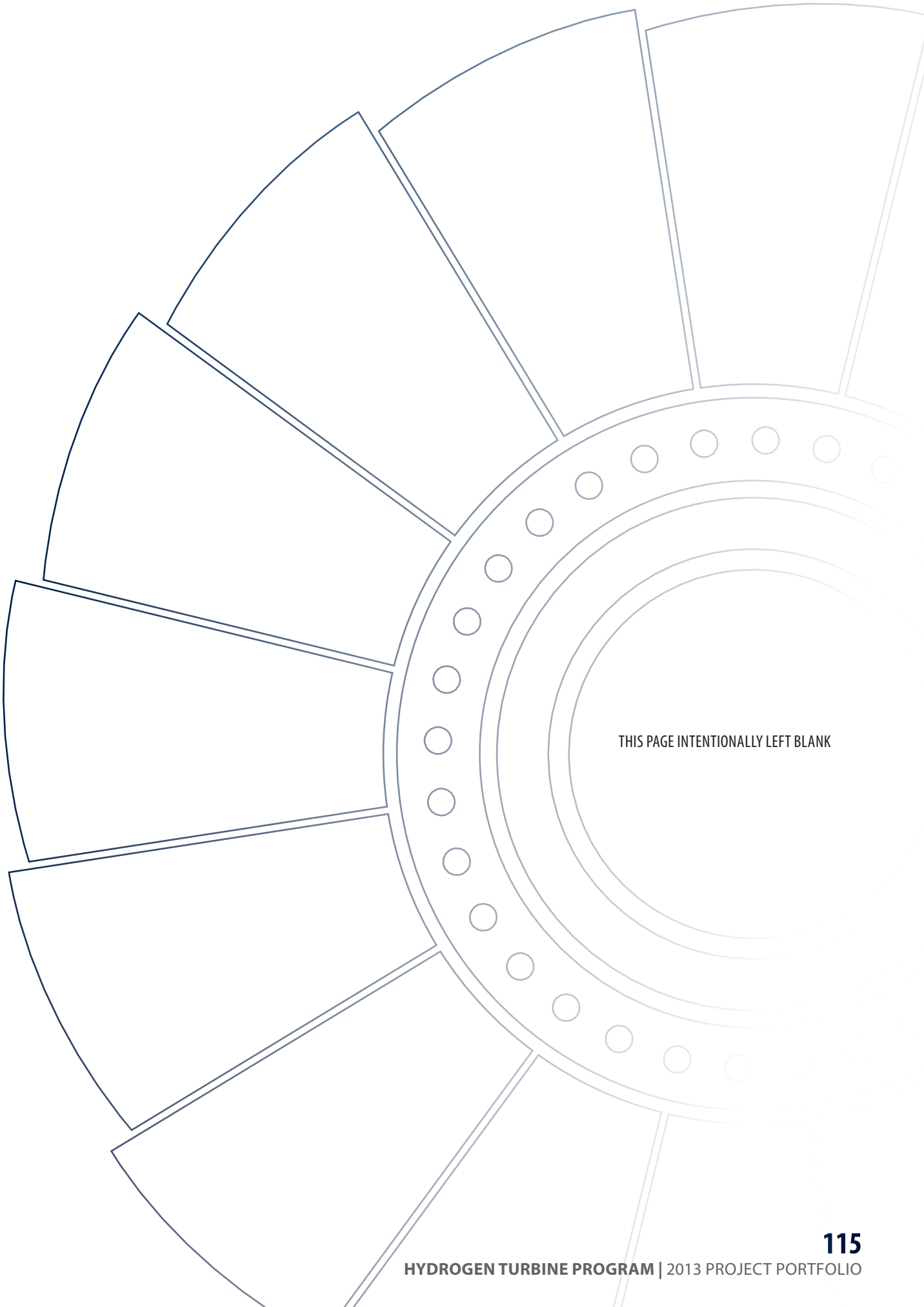


Figure 6. Surface morphology of YSHZ-1 and YSHZ-4 coatings grown by EBPVD.

FE0000765 July 2013



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SECTION 7: ADVANCED RESEARCH

The Advanced Research key area under the Hydrogen Turbine program is conducted with corporate partners, universities, and Government laboratories to advance the goals of the program. The selected institutions are uniquely qualified to perform research and address specific areas that complement ongoing efforts to develop advanced turbine technology. The Advanced Research area also supports the development of new and innovative manufacturing techniques and addresses fundamental understanding in materials, heat transfer, and combustion research.

The NETL-RUA Turbine Thermal Management effort supports the Hydrogen Turbine program through conduct of novel, fundamental, basic and applied research in the areas of aerothermal heat transfer, coatings development, and secondary flow control. This research project utilizes the extensive expertise and facilities readily available at NETL, participating universities, small business organizations as Mikro Systems and Coatings for Industry, as well as Ames Laboratory. The research approach includes explorative studies based on scaled models and prototype coupon tests conducted under realistic high-temperature, pressurized, turbine operating conditions. This research is expected to render measurable outcomes that will meet the DOE's Hydrogen Turbine program development goals of a 3–5 percentage point increase in power island efficiency and a 30 percent power increase above hydrogen-fired combined cycle baseline. In addition, knowledge gained from this project will further advance the aerothermal cooling and TBC technologies in the general turbine community. The program has been structured to address development and design of aerothermal and materials concepts in FY 2012–13; design and manufacturing of these advanced concepts in FY 2013; and high-temperature, pressurized, prototype coupon testing of these concepts under conditions replicating modern gas turbine engines in FY 2013–15. In addition, a world-class test facility is being developed for studying leakages, secondary flows, internal heat transfer, and advanced airfoil aerodynamics under high-speed rotating conditions.

Research being conducted at Ames Laboratory is improving the tools used to study heat transfer issues in the design of turbine components. The understanding of cooling flows is important for the development of advanced cooling techniques that seek to increase effective cooling rates while lowering cooling fluid flows. The work examines both CFD-based analysis tools used for heat transfer study and the experimental methods that are used to develop those tools. The CFD analysis tools that are improved or developed will then be applied to support the development of advanced turbine technologies for near-zero-emission type coal-based power systems.

Oak Ridge National Laboratory is evaluating issues related to extending the lifetime of bond coatings in TBCs by applying mechanistic understanding of the factors that contribute to their degradation in syngas/hydrogen-fired turbines. The environment within these turbines will contain more contaminants and water vapor than the natural gas counterparts. Maintaining turbine availability with current alloys and coatings may require a reduction in turbine inlet temperature, thereby reducing efficiency. Researchers are investigating the effects that different levels of water vapor will have on the coating lifetime. Coating performance and spallation resistance have been improved with modified sprayed bond coatings. This research will lead to more robust bond coatings that will extend the service life of hot gas components under harsher environments and higher temperatures.

The factsheets in this section provide more details on the projects being performed in the Advanced Research area of the Hydrogen Turbine program.

AERO-HEAT TRANSFER

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Analysis of Gas Turbine Thermal Performance—Ames Laboratory

Background

Developing turbine technologies to operate on coal-derived synthesis gas (syngas), hydrogen fuels, and oxy-fuels is critical to the development of advanced power gener-ation technologies such as integrated gasification combined cycle and the deployment of near-zero-emission type power plants with capture and separation of carbon dioxide (CO_2). Turbine efficiency and service life are strongly affected by the turbine expansion process, where the working fluid's high thermal energy gas is converted into mechanical energy to drive the compressor and the electric generator. The most effective way to increase the efficiency of the expansion process is to raise the temperature of the turbine's working fluid. However, the higher temperatures exceed the maximum temperature the state-of-the-art turbine material systems can withstand while maintaining structural integrity and operational reliability. Thus, cooling—such as internal, film, and impinge-ment—is essential for all parts of the turbine whose surfaces contact the hot gases.

Ames Laboratory (Ames Lab) and Purdue University are exploring advanced cooling strategies to respond to the challenging nature of turbine hot gas path component design. Today's turbines are designed to operate very close to the maximum allowable temperatures of their materials of construction and must meet current industry goals to greatly reduce cooling flows to further increase system efficiency. These cooling com-ponent designs are further challenged by the combustion of high-hydrogen fuels and oxy-fuels, which increase turbine heat transfer characteristics due to the increase water vapor content, elevated erosion and deposition tendencies, and much higher hot-gas mass flow rates. These combined aero-thermal challenges illustrate the importance of maximizing the available cooling within the application of advanced cooling strategies.

This project is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these tech-nologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes CO_2 emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

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PARTNERS

Purdue University

PROJECT DURATION

Start Date 10/01/2004
End Date 09/30/2013
(annual continuations)

COST

Total Project Value
$995,000

DOE/Non-DOE Share
$995,000/$0

AWARD NUMBER

ALO5205018

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Customer Service: 1-800-553-7681

Project Description

Ames Lab and Purdue University are developing cooling strategies through the following tasks:

- Develop and evaluate computational fluid dynamics (CFD)-based analysis tools that can be used to study heat transfer issues in the design of turbine components and develop guidelines and best practices for their use.
- Examine the basis of the experimental methods used to validate CFD design and analysis tools.
- Apply CFD analysis tools to support the development of turbine technologies for advanced, near-zero emission-type coal-based power systems. The analysis tools of interest are those that can properly account for the steady and unsteady three-dimensional heat transfer from the hot gas in the turbine blade/vane passages through the turbine material system (thermal barrier coating and superalloy) to the internal cooling passages as a function of the cooling strategy as well as a function of the hot-gas and coolant compositions, mass flow rates, and temperatures.

Goals and Objectives

The goal is to develop an analysis tool that can be used to examine and explore heat transfer design issues of turbine components to support the development of turbine technologies for advanced coal-based power systems. The tool will consider heat transfer from the hot gases to the turbine material system as a function of the cooling strategy, fuel used, amount and nature of diluents used to control combustion and formation of nitric oxides, mass flow rate, firing and turbine inlet temperatures, and the thermodynamic cycle.

Accomplishments

- Performed CFD simulations that showed that if the Biot numbers of two geometrically similar configurations are nearly the same in magnitude and distribution on both the hot and cold sides of a turbine material, then the magnitude and contours of the normalized temperature and heat flux within the turbine material would be nearly the same. This analogy enables experimental studies of turbine cooling designs at near room temperatures and pressures with greatly scaled-up geometries to allow for more detailed interrogations that provide insight into turbine cooling performance (as if the experiment was conducted under realistic turbine operating conditions with high temperatures, high pressures, and the correct dimensions).
- Examined three approximations for bulk temperature that are widely used in experimental measurements of the heat transfer coefficient. The work showed that linear interpolation only gives accurate results in straight ducts with an error of less than 3 percent if the flow is turbulent, the two planes where the bulk temperatures are measured are taken in the fully-developed region (i.e., not in the entrance transition region), and the distance between the two planes where linear interpolation is employed is 20 duct hydraulic diameters or less. Other approximations based on the inlet temperature or an averaged bulk temperature give grossly inaccurate results.
- Performed initial CFD studies to understand how 'pin fins' clearance height-to-diameter ratio and height-to-diameter ratio affect surface heat transfer and stagnation pressure.
- Performed a study on the flow and heat transfer in the entrance region of a smooth circular duct and the entrance region of a rectangular duct lined with an array of pin fins.

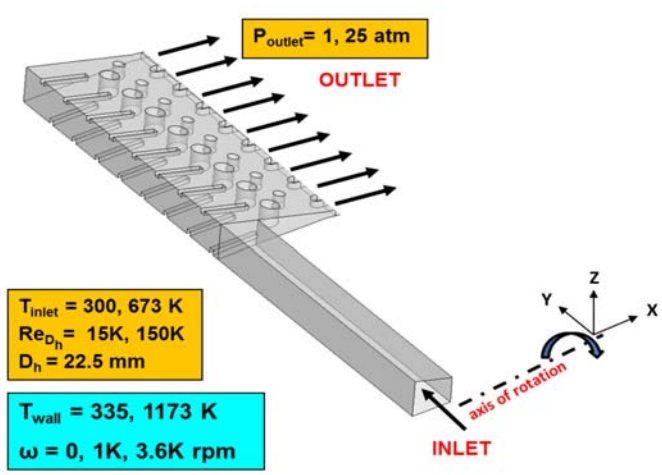

Figure 1. Schematic of the wedge-shaped duct with ribs and pin fins for the trailing edge of a turbine vane/blade.

During this effort a new nondimensional parameter, called the SCS number was proposed and contrasted with the traditional Nusselt number (Nu). The SCS number has the advantage of not requiring the bulk temperature, which is difficult for the experimentalist to measure. For Nu, the history is embedded in the bulk temperature (Tb). For SCS, the history is built into the SCS number itself. Thus, the magnitude of SCS is also a measure of the "capacity" of the fluid to cool or heat the wall. The SCS may be preferred for quantifying heat-transfer measurements since there will no ambiguity in the Tb used to define heat-transfer. However, when designing heat exchangers, Nu is preferred because Tb is clearly defined. Thus, a formula was developed to convert SCS to Nu and vice versa.

- Performed a time-accurate conjugate CFD study to understand the unsteady flow and heat transfer in and about a nickel-based super alloy plate heated on one side by a specified heat flux and cooled on the other side by an array of impinging cooling jets with varying heating and cooling loads. Though the cooling supplied ensures that the maximum temperature in the plate is equal to the maximum allowable material temperature when steady state is reached, it was found that the maximum temperature in the plate exceeded the maximum allowable temperature for a substantial amount of time. The duration of over temperature is a strong function of the heat capacity in the material and the variation of the heat-transfer coefficient along the cooled side of the plate.
- Performed CFD simulations based on steady RANS (Reynolds-averaged Navier-Stokes) closed by the shear-stress transport turbulence model to study the compressible flow and heat transfer in a wedge-shaped duct for the trailing-edge region of a turbine vane/blade under rotating and non-rotating conditions. The objective is to understand the flow mechanisms by which ribs and pin fins in the wedge-shaped duct turn radially outward flow of the coolant from the hub to flow uniformly in the axial direction to cool the entire duct. Results obtained show that pin fins can greatly reduce the size of the separated region when the coolant emerges from the inlet duct to enter the wedge-shaped duct. Also, pin fins provide flow resistance to control the uniformity of the flow along the cross section of wedge-shaped duct in addition to enhancing surface heat transfer via horseshoe vortices about each pin fin. A staggered array of square ribs that extend from the exit of the inlet duct to the tip of the wedge-shaped duct in the radial direction was found to create two sets of spiraling flows that causes the radial flow exiting from the inlet duct to spiral in the axial direction with one created by the stagnation region upstream of each rib and the other created by the separation downstream of each rib. When there is rotation, the staggered array of ribs was found to mitigate the adverse effects of centrifugal buoyancy by confining flow separation to be between the ribs on the leading face.

Benefits

This project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. Studies by Ames Lab and Purdue University will increase the reliability of CFD-based analysis tools and thereby allow designers to minimize the critical heat transfer issues in the design of their turbine components.

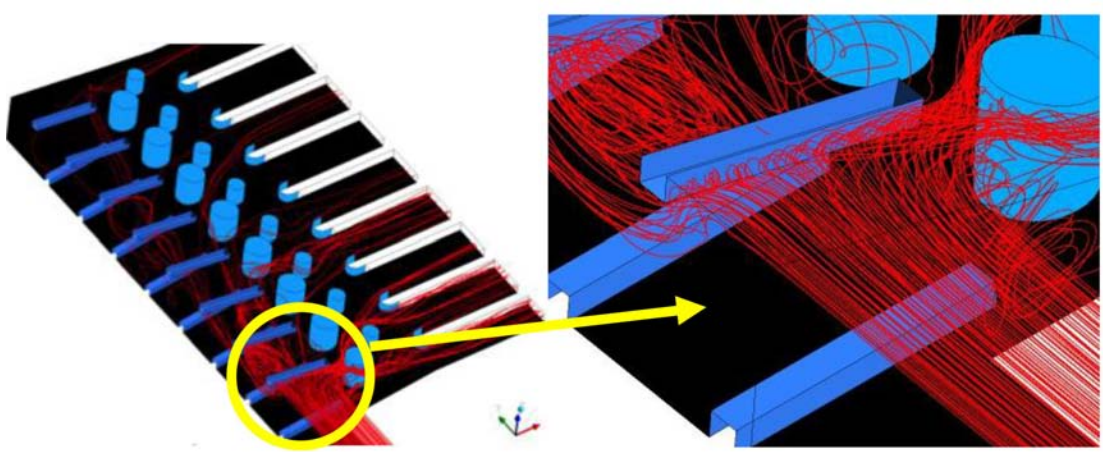

Figure 2. Streamlines showing how the ribs turn radially outward flow towards the axial direction.

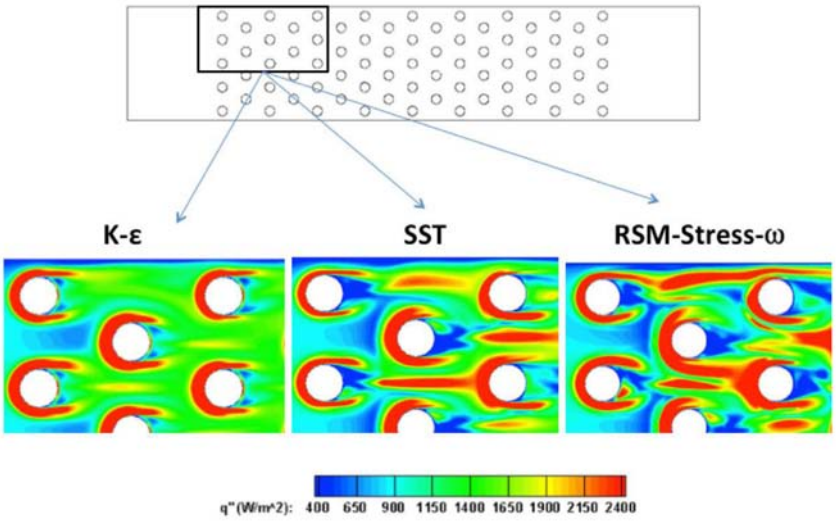

Figure 3. Heat Flux on the Wall Induced by Pin Fins as obtained by using the following turbulence models: realizable k-ε, shear-stress transport (SST), and full Reynolds stress model (RSM) with stress-omega in the near-wall region.

ALO5205018 July 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Demonstration of Enabling Spar-Shell Cooling Technology in Gas Turbines — Florida Turbine Technologies

Background

The Florida Turbine Technologies (FTT) spar-shell gas turbine airfoil concept has an internal structural support (the spar) and an external covering (the shell). This concept allows the thermal-mechanical and aerodynamic requirements of the airfoil design to be considered separately, thereby enabling the overall design to be optimized for the harsh environment these parts are exposed to during operation. Such optimization is one of the major advantages of the spar-shell approach that is not possible with today's conventional monolithic turbine components.

The proposed design integrates a novel cooling approach based on Advanced Recirculating Total Impingement Cooling (ARTIC™) to improve heat transfer and allow higher turbine operating temperatures and/or a reduction in cooling flow. Taken together, the optimization of higher operating temperatures and better cooling with less flow will lead to turbines that are more efficient, have longer life, and consequently generate power at a lower cost of electricity.

This project was competitively selected under the Small Business Innovative Research (SBIR) Program. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine eqipment.

Project Description

The scope of this SBIR Phase III project includes the design, analysis, fabrication, assembly, installation, and testing of prototype spar-shell turbine airfoils and associated hardware, culminating in the validation of performance and functionality in a commercial gas turbine.

Goals/Objectives

The objective of this project is to develop and test–at a commercial prototype scale–first-stage, spar-shell turbine airfoils requiring significantly less cooling flow than the current state-of-the-art. The benefits of this technology are compelling,

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PARTNERS

Siemens Energy

PROJECT DURATION

Start Date	End Date
07/08/2011	12/31/2013

COST

Total Project Value
$1,707,140

DOE/Non-DOE Share
$1,310,845/$396,295

AWARD NUMBER

FE0006696

U.S. DEPARTMENT OF ENERGY

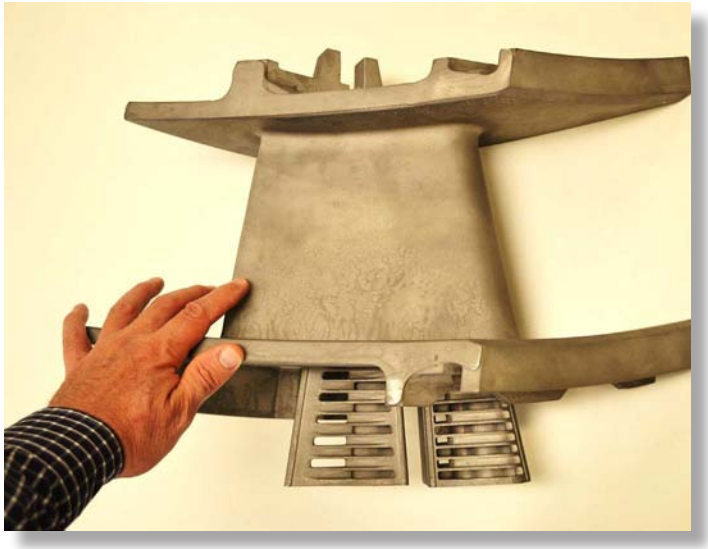
with studies indicating the combined cycle efficiency of current F-frame gas turbine-based power plants could be increased one percent (i.e.: from 60 to 61%) with the incorporation of this technology within the first three rows of airfoils in the gas turbine. Successful engine test validation of spar-shell airfoils in this project will open the door to commercialization of this new technology in both F-frame and other highly-cooled turbine airfoil applications. FTT's commercialization plan includes production of saleable components for new and retrofit applications.

Accomplishment

- Produced a viable design concept which continues to be developed within the detailed design phase.
- Completed extensive engineering calculations and analysis of the feasibility of the mechanical design, including cooling and structural aspects.
- Conducted failure modes and effects analyses (FMEA's) to identify the pertinent technical risks and to define mitigation plans to counter these risks.
- Established an agreement with Siemens Energy, Inc., to participate in this project.
- Identified a suitable test vehicle, and a target date for insertion of spar-shell turbine components into thatvehicle was defined.
- Performed high-fidelity thermal and structural analyses to support the feasibility of the detailed design.
- Completed the detailed design of a spar-shell vane.
- Released casting details to production.
- Completed design verification and validation testing of the heat transfer and sealing aspects of the design.
- Completed detailed design reviews.
- Facilitated fabrication feasibility and cost assessments with FTT manufacturing and procurement support.
- Completed product definition (drawings, computer-aided design (CAD) models, etc.).
- Fabricated prototype models to demonstrate/illustrate the design concept and to prove the manufacturing feasibility of the concept.
- Completed definition of instrumentation requirements and wrote instrumentation specification.
- Completed manufacture of airfoil (shell) castings.
- Completed manufacture of internal spar castings.

Benefits

This SBIR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The SBIR program is positioned to leverage the agility and innovative competencies of small businesses. It is through this program that a small company, Florida Turbine Technologies, has developed a potential breakthrough technology for turbine airfoils with significantly improved cooling efficiency. Continued investment in this small business will likely result in U.S. engineering and manufacturing jobs.



FTT Spar-Shell Vane under Construction for Test in a Large-Scale Industrial Gas Turbine Engine.

FE0006696, July 2013

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PROJECT FACTS

Hydrogen Turbines

Phase III Xlerator Program: Rapid Commercialization of Advanced Turbine Blades for IGCC Power Plants—Mikro Systems

Background

Mikro Systems, Inc. is developing their proprietary TOMO℠ manufacturing technology to produce turbine blades with significantly improved internal cooling geometries that are beyond current manufacturing state-of-the-art, thus enabling higher operating temperatures. Funding from the American Recovery and Reinvestment Act (ARRA) under the Small Business Innovation Research (SBIR) Phase III Xlerator Program will be directed towards accelerating commercial adoption of TOMO℠ technology by leading turbine manufacturers through the demonstration of superior manufacturability, cost, and performance. Ultimately, this technology will lead to improved efficiency and cost of gas turbines for coal-based integrated gasification combined cycle (IGCC) and natural gas combined cycle (NGCC) power applications.

This project is managed by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Mikro Systems has developed a unique ceramic core casting technology — TOMO℠ — that uses precision, three-dimensional, lithographically-derived tooling that permits the intricate design and casting of enhanced heat transfer features for gas turbine blades. The Mikro Systems approach allows new internal cooling features that are not possible with current casting processes. It is envisioned that this replacement core casting technology will seamlessly integrate with established casting processes used by the industry, minimizing new capital investment requirements and quickly revolutionizing the industry's ability to enhance both existing and future turbines with new blade designs.

This project addresses the need for rapid, cost effective manufacturing of advanced turbine blades that will improve the performance of and reduce the cost of electricity produced by IGCC power plants. Mikro Systems will scale up the TOMO℠ process and produce casting cores for a row one blade in a commercial Siemens (SGT5-501F) gas turbine. Concurrently, Siemens will redesign the 501F blade to improve the

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PARTNERS

Siemens Energy
Precision Castparts Corp.

PROJECT DURATION

Start Date	End Date
10/01/2010	12/31/2012

COST

Total Project Value
$1,508,479

DOE/Non-DOE Share
$1,508,479 / $0

Government funding for this project is provided in whole or in part through the American Recovery and Reinvestment Act.

AWARD NUMBER

FE0006220

U.S. DEPARTMENT OF ENERGY

cooling properties, and new blades will be cast using Mikro Systems' core casting technology. Produced test blades will be evaluated through engine testing to qualify the TOMO process for commercial core production.

Goals/Objectives

The overall goal of this project is to demonstrate that Mikro's TOMO℠ technology can produce advanced turbine blade cooling features economically without disruption to current production methods and facilities. These objectives will also demonstrate the competitiveness of the technology, including cost, quality, and ability to produce advanced cores, and to foundry certify the production readiness of cores using an existing blade design from Siemens.

Accomplishments

Under a prior agreement with DOE, Mikro Systems demonstrated that the TOMO℠ process can lead to revolutionary new turbine cooling designs that can be developed faster and at significantly lower cost than current techniques allow. This new phase of ARRA funding enabled Mikro Systems to develop the technology to a point of maturity where it was licensed to Siemens Energy, Inc. (SEI).

- Issued a purchase order to PCC (Precision Castparts Corp.) for engineering support and initial casting trials.
- Completed CAD models and other foundry requirements.
- Mikro Systems' TOMO Lithographic Molding technology for producing industrial gas turbine (IGT) investment casting turbine blade cores was licensed to SEI. Mikro Systems and SEI signed a collaborative technology license agreement in April 2011. SEI has since established a full-time staff of 10 people in Charlottesville, Virginia, and is working closely with Mikro Systems at the low rate initial production (LRIP) facility to learn and refine the core fabrication technology. SEI has leased a facility in Charlottesville for producing IGT cores and wax patterns using TOMO technology beginning in late 2012.
- Received 501F core tooling. Mikro Systems received the baseline core tooling and has used it to produce the first 16 prototype cores for metal casting trials.
- Completed the LRIP facility expansion. The LRIP facility is fully complete and in production.
- Produced prototype cores and completed metal casting trial. The metal casting trial and results were provided to Mikro Systems.
- SEI/Mikro Systems focus teams formed for Casting improvement, Material development, and Finishing improvement.
- All casting automation/improvement equipment and sequences were individually tested for impact on the part and the material quality.
- Rescaled and remade the core tooling to compensate for changes from process improvements.
- During the production run for the first pre-production qualification (PPQ) inspection, Mikro Systems achieved a 50% overall process yield that meets the target goal for fiscal year 2012.
- Defined schedule of PPQ trials with PCC foundry, and first lot of 16 PPQ trial cores produced and inspected and accepted by PCC.
- Due to time constraints, only 6 of the final 16 cores were metal cast. The parts showed 100% clean interior with no core defect or movement.

Benefits

The SBIR program is positioned to leverage the agility and innovative competencies of small businesses. It is through this program that a small company, Mikro Systems in Charlottesville, Virginia, has developed a way to revolutionize the investment casting process of the gas turbine industry. The Mikro Systems approach is breakthrough technology for both development and manufacturing of ceramic casting cores. It enables faster and lower-cost development of advanced gas turbine blades, and the process can be scaled-up for volume production. Further, Mikro Systems technology supports design features that are not possible with conventional core casting technology. ARRA investment in this small business will likely result in more US jobs as well as gas turbines for the electric power generation industry that are more efficient, cost less, and have lower emissions of criteria pollutants and CO_2, which support DOE's Hydrogen Turbine Program.

The TOMO process allows cast turbulation features not possible to create by conventional fabrication methods.

FE0006220 August 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Turbine Thermal Management—NETL-RUA

Background

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of technologies to achieve power production from high-hydrogen-content fuels derived from coal that is clean, efficient, and cost-effective, and minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

The NETL Regional University Alliance (RUA) is an applied research collaboration that combines NETL's fossil energy expertise with the broad capabilities of five nationally recognized regional universities, of which three are participating in this project: Pennsylvania State University (Penn State), University of Pittsburgh, and Virginia Polytechnic Institute and State University (Virginia Tech). In addition, there are several industry collaborators, and URS is the NETL site support coordinator.

The NETL-RUA Turbine Thermal Management project supports the Hydrogen Turbine Program through conduct of novel, fundamental, basic, and applied research in the areas of aerothermal heat transfer, coatings development, and secondary flow control. This research project utilizes the extensive expertise and facilities available at NETL and the participating universities. The research approach includes exploratory studies based on scaled models and prototype coupon tests conducted under realistic high-temperature, pressurized turbine operating conditions. This project has been structured to address design, manufacturing and bench-scale performance assessment of aerothermal and materials concepts, and incorporation of these concepts into prototype airfoil configurations.

Project Description

The Turbine Thermal Management project is focused on basic and applied technology development in the areas of heat transfer, materials development, and secondary flow control. Specific objectives are as follows:

Aerothermal and Heat Transfer: Identify internal and external airfoil cooling concepts that provide composite benefit for reduced cooling flow and heat management, and which can be commercially manufactured. At least one new turbine cooling technology concept will be developed and demonstrated under realistic engine

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PARTNERS

Regional University Alliance
Coatings For Industry
Mikro Systems Inc.
Corrosion Consultants Inc.
Ames Laboratory
Pratt & Whitney
URS

PERFORMANCE PERIOD

Start Date	End Date
10/01/2011	09/30/2013

(annual continuations)

COST

Total Project Value
$3,240,000

DOE/Non-DOE Share
$3,240,000 / $0

AWARD NUMBER

FWP-2012.03.02

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operating conditions. Concepts include NETL-RUA's near-surface embedded micro-channel concept, porous media thermal barrier coatings (TBCs), and/or tripod-hole film cooling configurations.

Coatings and Materials Development: Develop bond coat, diffusion barrier, and extreme temperature TBCs as an integrated composite-architecture for utilization in next generation land-based engines. Expand NETL-RUA's programmatic direction and focus through initiation of research on ceramic matrix composites and oxide dispersion strengthened material systems for use at temperatures exceeding 1400 °C. The performance and extended durability of these materials systems are being assessed through bench-scale isothermal and thermal cycling/flux testing.

Design Integration and Testing: Utilizing enhanced heat transfer internal and film cooling designs, commercially cast coupon test articles for heat transfer assessment at near room temperature and at high temperature under pressurized combustion gas conditions generated in NETL's aerothermal test facility in Morgantown, WV.

Secondary Flow Rotating Rig: Design and construct a world-class test facility for testing new cooling improvement strategies for the turbine rotating blade platform, and develop performance data relevant to initial concept designs and/or platform modifications. The primary focus of the turbine test facility is to increase turbine efficiencies by using disruptive new designs in sealing the interfaces between stationary and rotating airfoil components. The main driver of this effort is development of new designs that will lead to reduction in fuel usage by an order of magnitude or more. The facility will include a section of a turbine including a vane/blade/vane (i.e., 1.5-stage turbine), which will be operated at conditions replicating those in a modern gas turbine engine.

In 2014, the Turbine Thermal Management project will begin to explore pressure gain combustion and advanced supercritical CO_2 cycles as a possible means to contribute to overall improved plant operating efficiency.

Goals and Objectives

The Turbine Thermal Management project is being conducted as an NETL-RUA team effort to initially solidify new concepts and innovation, followed by scaled model testing to quantify the efficiency benefits of the conceptual innovations, and completed with technology demonstration under realistic, bench-scale, turbine operating conditions for validation. Technical expertise and facilities needed for this research are available at NETL and participating univer-sities. Major technical goals of this research effort include:

- Development of novel, manufacturable, internal airfoil cooling technology con-cepts that achieve a cooling enhancement factor of approximately five over that of smooth, internal airfoil cooling channel passages.
- Development of advanced, manufacturable airfoil film cooling concepts that achieve a 50 percent reduction in required cooling flow.
- Design, construction, and operation of a world-class t est facility for testing advanced sealing improvement strategies for the turbine rotating blade platform to ultimately reduce fuel burn.
- Development of advanced material system architectures that permit operation of turbine airfoils at temperatures at least 50–100 °C higher than current state-of-the-art components.

FY13 Accomplishments

Aerothermal and Heat Transfer:

- Detailed experimental studies were conducted at the University of Pittsburgh using detached circular pin-fin arrays arranged in a 2-D configuration to demonstrate enhanced heat transfer over smooth cooling channel surfaces. Pin-fin arrays with smaller inter-pin spacing in the span-wise direction were shown to perform as a row of jets which induce high heat transfer at the region immediately behind the pins (Figure 1). Current test data indicate comparable heat transfer enhancement to that of a typical fully-bridged circular pin-fin array.
- Detailed experimental and numerical studies were conducted on jet impingement channels with staggered and angled jets for NETL-RUA's near surface embedded micro-channel cooling concept. High heat transfer was observed at the upstream region caused by the impingement effects from the first, second and third jets. The heat transfer at the downstream region decreased substantially as the result of crossflow effects. By staggering and having inclined jets, better mixing and additional vortices result, with an 20% heat transfer enhancement in the channel.
- Numerical studies using ANSYS CFX were conducted on dimpled and hemispherical protrusion trailing edge zig-zag channel designs. Qualitative comparisons indicated that the zig-zag channels with dimples and hemisperical protrusions have lower heat transfer performance in comparison to the zig-zag channels that contain ribs. The design/configuration of zig-zag channel with dimples and hemisperical protrusions is being revised and further evaluated using ANSYS CFX to down-select the optimized geometry for further experimental testing.
- Heat transfer and pressure loss testing conducted with a triple impingement trailing edge coupon at near-room temperature indicated that with the presence of 90 ° inlet and impingement at the upstream region, the total heat transfer enhancement was 20% higher than previously considered cooling configurations.

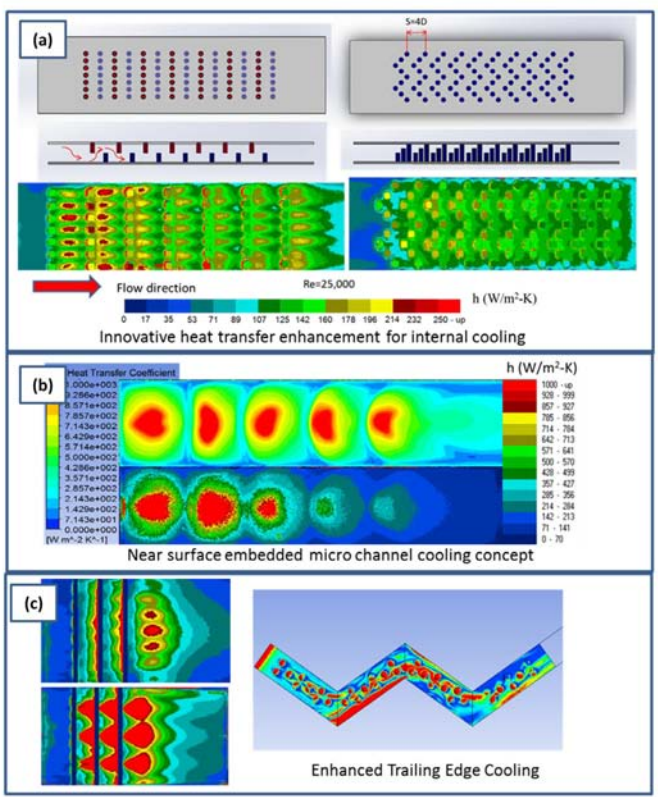

Figure 1. Results from Heat Transfer Enhancement Studies Conducted at the University of Pittsburgh for Advanced Internal Airfoil Cooling Concepts.

- The effects of blowing ratio, density ratio and hole geometry were studied at Virginia Tech to provide a clear understanding of parametric effects on tripod hole film cooling geometries. The 15° layback antivortex hole design was shown to be an optimal design in terms of overall performance (Figure 2). These designs were tested in a flat plate wind tunnel and on a low speed vane cascade. In all cases, the tripod hole configuration provided over 50% improvement in cooling effectiveness while using 50% less coolant mass even while operating at extremely high blowing ratios of 4.0.

- Thermal stress distribution analyses were conducted for Haynes 230 coupons containing film cooling tripod holes. Major stress concentrations within the Haynes 230 coupon were not identified, and static thermal gradients are not considered to be an issue for the tripod hole configuration. This effort is being expanded to address similar stress within CM247 tripod hole coupons which will be commercially cast and subsequently tested in NETL's high temperature, pressurized, aerothermal test facility in Morgantown, WV.

Coatings and Materials Development:

- Efforts were focused at NETL, CFI, and the University of Pittsburgh on the application of NETL-CFI's wet slurry diffusion bond coat system on CM247, MarM247, IN939, PM2000, Hayne 230, and Ni-ODS substrates. All coatings consisted of a β-NiAl matrix with distribution of (Cr, Ta, W)-rich precipitates that were dependent on the substrate alloy. Initial isothermal oxidation testing for 100 hours at 1100 °C led to the formation of an external layer of alumina. The aluminide coating that formed from the slurry on the Fe-based PM2000 alloy from the AID coating-deposition process contained an extensive amount of Kirkendall voids, which detrimentally affected the coating integrity during subsequent thermal exposure.

- Development of a thin film ODS-layer on channeled nickel-based superalloys at Ames Laboratory was directed to production of NETL-RUA's near surface embedded micro-cooling channel effort. Ni-ODS powder composition and size fractions were analyzed with respect to oxygen content. Removal of powder particulates 25 µm greatly reduced the oxide content in the resulting coating. Selection of the appropriate deposition process was undertaken to generate dense ODS architectures. HVOF processing was selected for minimal oxidation during deposition while maintaining coating density.

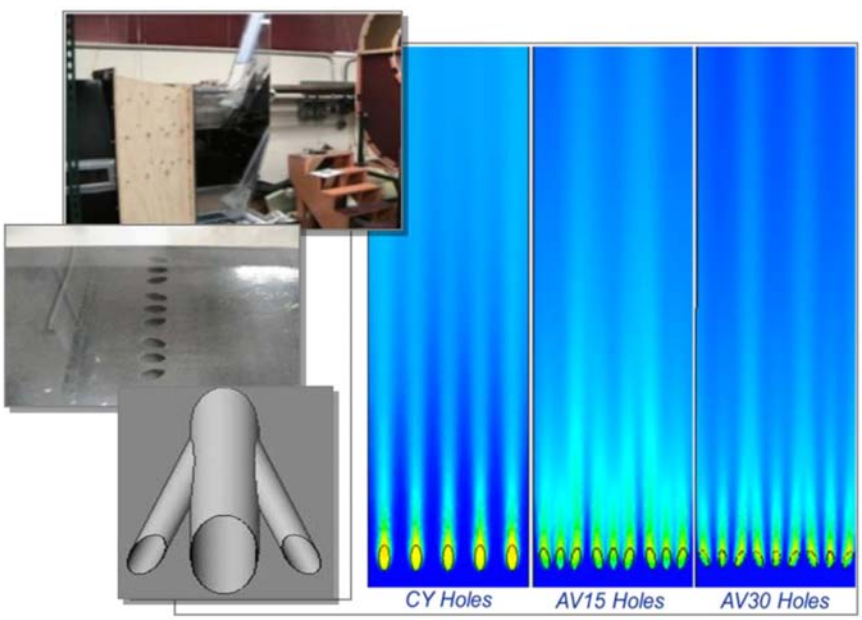

Figure 2. Virginia Tech's Tripod Hole Film Cooling Configuration, Laboratory Test Equipment and Recent Experimental Results Demonstrating Enhanced Cooling Effectiveness over Current State-of-the-Art Film Cooling Configurations.

- Efforts were also focused on determining the appropriate processing conditions for application of HVOF Ni-ODS. Reduced temperature combustion conditions were found that generated a dense coating with minimal oxidation. Liquid nitrogen substrate cooling was also effective for reducing oxidation similar to direct HIP'ing. XRD analyses of the heat-treated HVOF coupons confirmed that oxygen-exchange reaction capability of precursor Ni-ODS powders was maintained through thermal spray deposition (Figure 3).
- A thermoset matrix composite (TSMC) was selected as a viable sacrificial channel filler material for deposition of Ni-ODS on nickel-based superalloys (Figure 4). The filler material consisting of alumina was identified to be ideal for ease of manufacturing, and which withstood both the thermal and mechanical requirements of HVOF. Removal of the TSMC post Ni-ODS deposition via full decomposition was shown to occur at 500-600 °C.

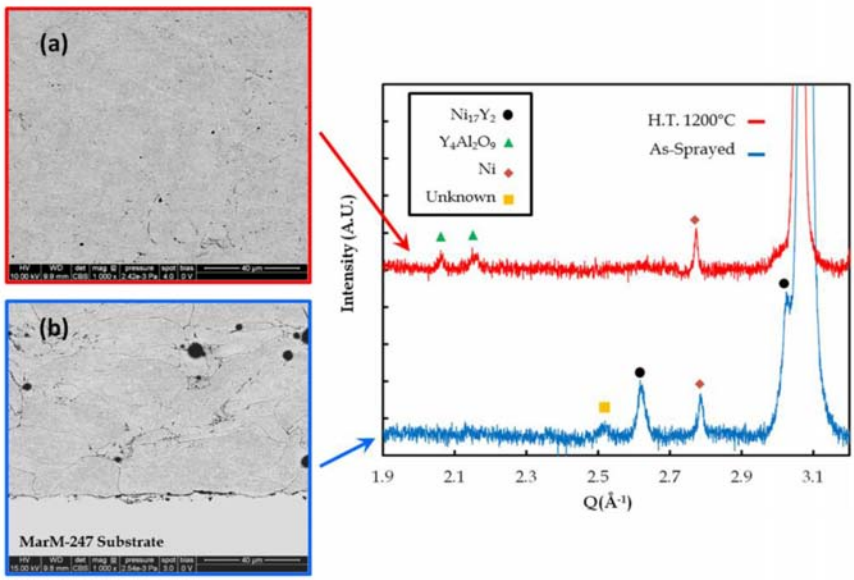

Figure 3. Microstructure of the Ames University HVOF Ni-ODS Overlay Coating on MarM-247 in the (a) Heat-Treated and (b) As-Sprayed Condition along with Corresponding X-Ray Spectra Indicating The Oxygen-Exchange Reaction and Precipitation of Oxide Dispersion Phase ($Y_4Al_2O_9$).

Figure 4. Ames Laboratory Grit Blasted Near Surface Embedded Micro-Channel Concept after Impregnation with Fugitive Thermoset Filler along the External Channels.

Design Integration and Testing:

- CM247 test coupons containing fully-bridged pin-fin internal cooling arrays, as well as zig-zag trailing edge cooling architectures were successfully cast at Mikro Systems Inc (Figure 5). Computer tomography (CT) scans of the internal configurations at NETL identified the robustness of the TOMO fabrication techniques used by Mikro Systems Inc., for production of complex parts. Similar efforts are underway for production of the first set of CM247 cast coupons containing tripod hole film cooling architectures.

- Optical pyrometer methods were developed at NETL to measure spatially resolved temperatures on test coupons within NETL's high temperature, pressurized aerothermal test facility. The accuracy of the optical measurements was determined to be within 8 °C of thermocouple readings. Additional testing was conducted to characterize incident radiation on the coupons during high temperature exposure. Spatial variation in the incident radiation was characterized which ultimately led to improvement in temperature measurement accuracy.

- Testing was additionally conducted in NETL's aerothermal test facility using test coupons with fan-shaped cooling holes over a range of pressures and blowing ratios. The measured overall effectiveness variations with pressure and blowing ratio amounted to engine metal temperature variations of 50 °C. When compared to testing conducted with a coupon that did not contain cooling holes, locally measured net heat flux reduction was shown to increase with an increase in blowing ratio to a value of 0.5, meaning that fan-shaped film cooling holes could reduce heat flux by 50%. Figure 6 shows the area-average overall effectiveness variation with pressure and blowing ratio for test coupons with fan-shaped film cooling holes.

- Modifications to the NETL high temperature, pressurized aerothermal test facility included the capability of controlling cooling air temperature. Elevated cooling air temperatures can now be achieved to generate more realistic coolant-to-mainstream density ratios which can be held constant through a range of operating conditions.

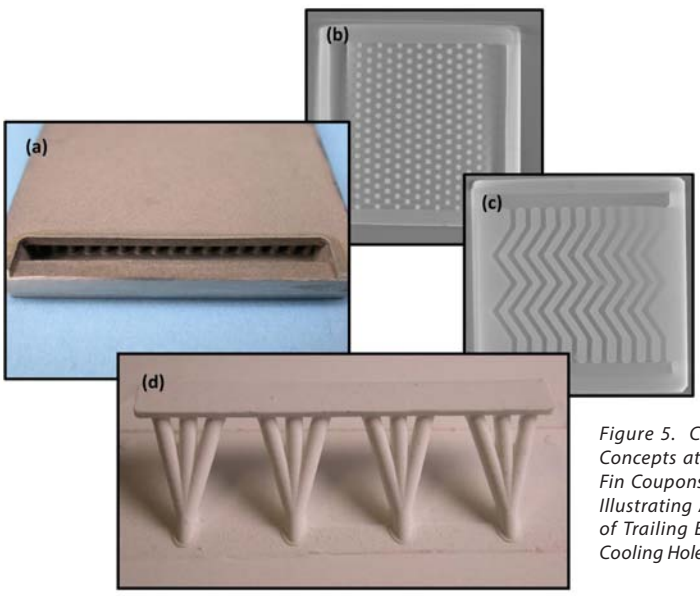

Figure 5. Commercial Production of NETL-RUA's Advanced Cooling Concepts at Mikro Systems Inc. (a) First Cast CM247 Fully Bridged Pin Fin Coupons; (b) CT Scan of Cast CM247 Fully Bridged Pin Fin Coupon Illustrating Absence of Blockage within the Pin Fin Array; (c) CT Scan of Trailing Edge Zig-Zag Cooling Configuration; (d) Tripod Hole Film Cooling Hole Core.

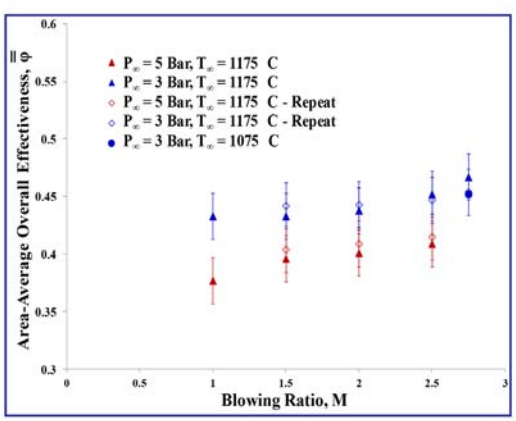

Figure 6. Area-Average Overall Effectiveness Illustrated as a Function of Blowing Ratio during Testing of Haynes 230 Coupons Containing Fan-Shaped Film Cooling Holes in NETL's High Temperature, Pressurized Aerothermal Test Facility.

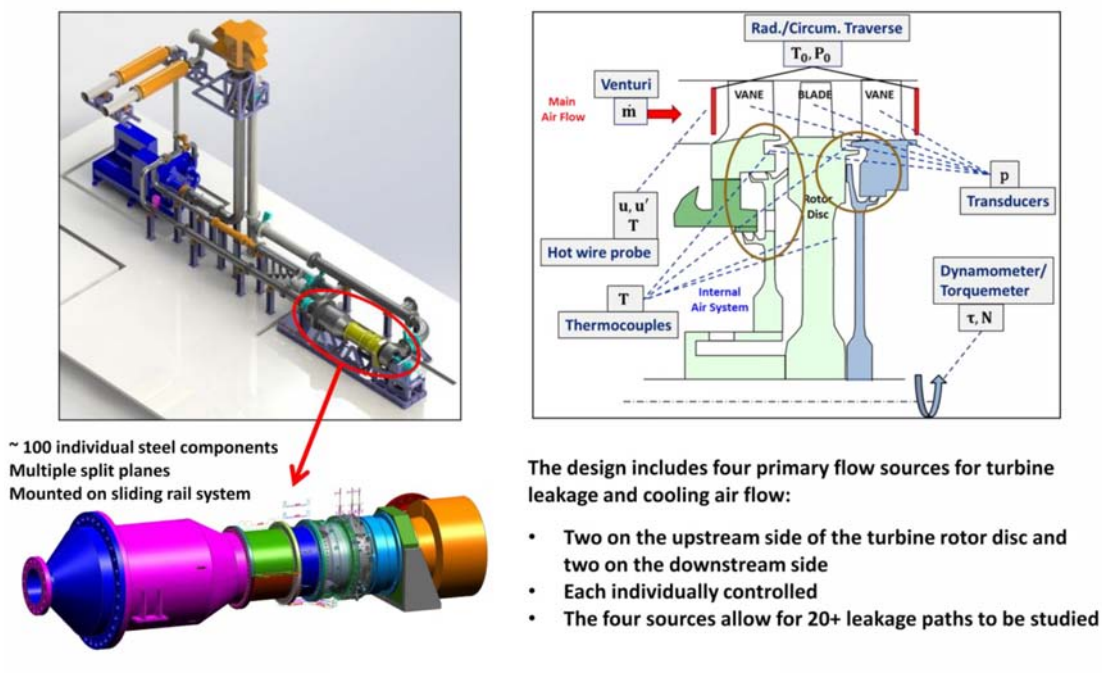

Figure 7. The New Secondary Flow Rotating Rig Design at Penn State has been Completed and Is Currently Being Manufactured and Assembled.

Secondary Flow Rotating Rig:

- The research team at Penn State officially moved into laboratory rooms and offices of the secondary flow rotating rig facility (Figure 7). Simultaneously, the electrical infrastructure and outdoor substation was completed for supplying power to two 1500 HP compressors.
- The compressor cooling system, turbine cooling system, dynamometer and water break system, telemetry system, pipe and air flow ductwork system, and magnetic bearing system were procured.
- Individual part drawings and 3-D solid modeling were completed for all facility and rig parts including all primary and secondary systems. Design reviews of all parts were conducted. The pipe ductwork system was designed in accordance with ASME B31.3-2002 Process Piping - Code for Pressure Piping. An overall facility and rig instrumentation plan was developed. Phase 1 (2014-2015) and Phase 2 (2015 - 2016) test conditions were identified and developed into the design package.
- Additive manufacturing methods/vendors for turbine vane construction were investigated and used to fabricate the airfoil vanes with integral instrumentation features. Example trial vanes were procured to allow evaluation of the integral instrumentation features. Over sixty Pratt & Whitney cast blades were also procured. A purchase order was issued for turbine disk forging and machining. Manufacturing has begun at multiple vendors on all steel hardware components that comprise the turbine test section.
- With respect to the pipe ductwork system, request for vendor quotes, competitive bidding, bid awarding, and purchase orders were completed. Manufacturing, plant visit and process reviews were conducted. Outdoor cooling system components were installed. Design and integration of programmable logic control system is in progress. Facility roof penetration locations were identified and prepared/framed. Facility roof platform equipment was acquired. Instrumentation acquisition is in progress (small sensors and large meters). Flow control valves were investigated, vendor bids were obtained, and procurement is in progress. Construction of the two steel chambers located upstream and downstream of the turbine test section is on-going. These chambers serve to condition the pressurized air flow.

- The gas tracer system has been identified (CO_2 injection into purge and leakage flow paths), acquired and benchmarked using a bench-top test stand. The PLC system design is in progress with Penn State's Applied Research Laboratory to design, build, and test the facility PLC control system by December 2013. PLC hardware has been identified and price quoted. The input and output specifications (electrical and physical) are currently being cataloged for all facility equipment items and facility operational instrumentation to help in the design of both the PLC system and the data acquisition system. In addition, calibration standard equipment was procured.

Benefits

This NETL-RUA project supports DOE's Turbine Program that is focused on development of gas turbines that can be operated on coal-based hydrogen fuels, while increasing the combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This research is expected to render measurable outcomes that will help meet these goals plus a 30 percent power increase above the hydrogen-fired combined cycle baseline. In addition, knowledge gained from this project will further advance aerothermal cooling and TBC technologies in the general turbine community.

FWP-2012.03.02 RUA August 2013

COMBUSTION

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Low-Swirl Injectors for Hydrogen Gas Turbines in Near-Zero Emissions Coal Power Plants—Lawrence Berkeley National Laboratory

Background

The U.S. Department of Energy Hy(DOE) Lawrence Berkeley National Laboratory (LBNL) is leading a project in partnership with gas turbine manufacturers and universities to develop a robust ultra-low emission combustor for gas turbines that burn high hydrogen content (HHC) fuels derived from gasification of coal. A high efficiency and ultra-low emissions HHC fueled gas turbine is a key component of a near-zero emissions integrated gasification combined cycle (IGCC) clean coal power plant.

This project is managed by the DOE National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from HHC fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Low-swirl combustion technology was conceived at LBNL to help industrial natural gas turbines achieve ultra-low emission targets. This project is a logical extension to adapt a low-swirl injector (LSI) for HHC fuels and to scale up the sizes for large utility gas turbines. Most commercial gas turbines are developed for use with natural gas. Adapting these gas turbines to HHC fuels brings about complex combustion engineering issues and additional safety risks due to the higher reactivity and different combustion properties of the HHC flame compared to natural gas.

The LSI is a novel combustion technology that has the potential to meet the operational and emissions goals for HHC-fueled gas turbines. Its basic premise is to produce a detached and freely propagating flame. The idea is fundamentally different from the conventional approaches to trap or hold the flame by physical means or by strong vortices. Laboratory experiments have verified that the basic LSI concept is amenable to operate on natural gas, synthesis gas (syngas), and hydrogen while meeting the aggressive emission target of <2 ppm NO_x (less than two parts per million oxides of nitrogen). The current focus is on developing a conceptual LSI prototype for adaptation to utility-size gas turbine combustors. As an essential aspect of this effort, laboratory studies on premixed turbulent flames are also pursued.

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University of California, Irvine

PERFORMANCE PERIOD

Start Date	End Date
10/01/2006	09/31/2013

(annual continuations)

COST

Total Project Value
$5,289,800

DOE/Non-DOE Share
$5,289,800 / $0

AWARD NUMBER

FWP7-678402

U.S. DEPARTMENT OF ENERGY

Goals and Objectives

The current goals of the project are to advance the core technology support research pertaining to fundamental hydrogen combustion issues while concurrently pursuing the development of a fuel-flexible LSI that operates on natural gas, syngas, and HHC fuels in a utility-size gas turbine of 100 to 250 megawatt (MW) power output. Project objectives are as follows:

- Develop a reduced-scale LSI combustor assembly for fuel-flexible operation and evaluate its performance at simulated gas turbine conditions.
- Define the size and configuration of the LSI for an industrial-size high-efficiency gas turbine operating on natural gas.
- Analyze lean premixed turbulent CH_4 and H_2 flame structures to support turbulent modeling development.
- Gain better understanding of turbulent H_2 flame structures and LSI flame acoustics.

Accomplishments

- Rig-tested a reduced-scale fuel-flexible LSI combustor at simulated gas turbine conditions and demonstrated the potential of the LSI technology to meet the aggressive emissions and operational program goals.
- Developed the basic layout of a multi-LSI combustor system for a high-efficiency ultra-low emissions 4 MW gas turbine.
- Characterized the instability behaviors of CH_4 and HHC flames and showed the influence of the outer shear layer on flame oscillations.
- Previously conducted laboratory experiments at atmospheric conditions demonstrating that a LSI with a modified flared nozzle extends its operability with HHC fuel to an adiabatic flame temperature (Tad) of 1,700 K without inciting flame flashback.
- Demonstrated that the LSI performance is insensitive to variations in its geometric configurations and showed that the size of the swirl annulus can be increased to lower aerodynamic drag.
- Measured the local displacement flame speed for natural gas and hydrogen and gas turbine relevant conditions.
- Developed a unify method to define heat release density for lean premixed turbulent hydrogen and methane/hydrogen flames.

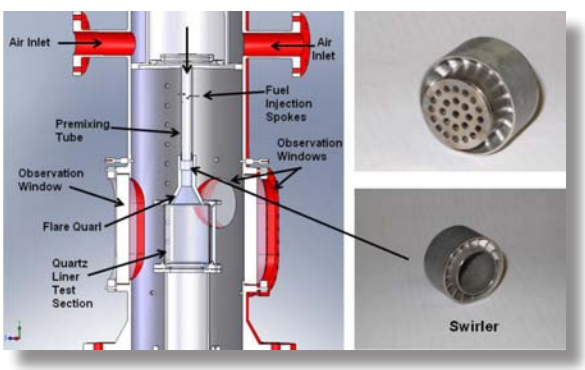

Figure 1. A high pressure chamber with a reduced scale LSI prototype simulating the combustor of a gas turbine.

Benefits

The DOE's Hydrogen Turbine Program is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This project's ultra-low emission LSI combustion technology is paramount for producing a clean and efficient energy source with near-zero emissions using gas turbine technology. LSI technology operates on lean premixed combustion that is the foundation for the dry-low-NO_x (DLN) technologies for almost all advanced low-emissions gas turbines.

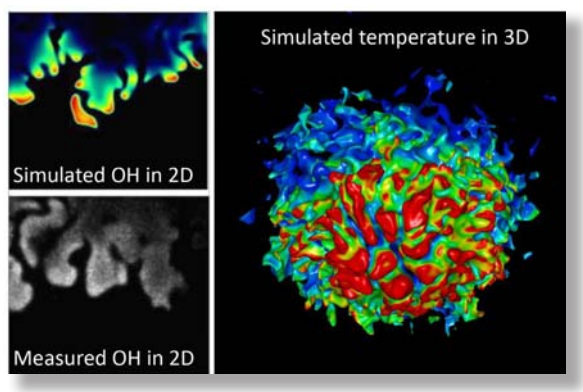

Figure 2. Due to high diffusivity of H_2, burning is non-uniform as shown in 2D by the gaps of the OH radicals for the numerical simulation of and measurement on a lean premixed turbulent hydrogen/air flame generated by a low-swirl injector. The local hot-spots, shown in red on the 3D numerical simulation results, also affects the emissions of pollutants such as oxides of nitrogen (NO_x). To capture the non-uniform burning process in a combustion model, a flowpath diagnostics has been developed to sample the time-dependent 3D simulation results. The sampling results also helped to interpret the experimental measurements and gain more insights into the heat release density of H_2 flames.

Project FWP7-678402, July 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Thermophysical Properties of CO_2 and CO_2-Rich Mixtures—National Institute of Standards and Technology

Background

Carbon capture and storage (CCS) technologies associated with fossil fuel power generation require the handling of significant quantities of carbon dioxide (CO_2) under a range of application-specific pressure and temperature conditions. These systems typically involve a stream that is mostly CO_2, with a variety of minor components, including water (H_2O). Optimization of compressors and other machinery for handling the CO_2 requires knowledge of the thermophysical properties of such mixtures with some precision in order to ensure safe and predictable operation; for example, the H_2O dew point of the mixture (conditions where liquid water drops out) is significant in order to avoid process conditions where liquid H_2O condenses in unwanted places, causing mechanical and/or corrosion problems.

There is also growing interest in the use of supercritical CO_2 as a working fluid in power cycles. In this case, it is primarily the properties of pure CO_2 that are of interest. While an equation of state (EOS) exists that describes the thermodynamic properties of pure CO_2 with good accuracy over the relevant range of conditions, the existing correlations for viscosity and thermal conductivity were developed over 20 years ago and have large uncertainties at the high temperatures and pressures relevant for supercritical CO_2 power cycles. In the case of the viscosity, sufficient experimental data are available (or will soon become available) to produce an improved correlation. In the case of the thermal conductivity, experimental data at high temperatures and pressures are largely lacking, and the few data that exist have relatively large uncertainties, so new data are needed in order to produce an improved correlation.

To this end, the National Institute of Standards and Technology (NIST) will develop accurate data and correlations for the dew point of H_2O in CO_2/ H_2O mixtures and for viscosity and thermal conductivity for pure CO_2. This project is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

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None

PROJECT DURATION

Start Date	End Date
10/01/2011	09/30/2014

COST

Total Project Value
$600,970

DOE/Non-DOE Share
$600,970/$0

AWARD NUMBER

FE0003931

U.S. DEPARTMENT OF ENERGY

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Project Description

NIST will execute experimental and modeling work on the thermodynamics of the CO_2/ H_2O system, modeling work on the viscosity of pure CO_2, and experimental and modeling work on the thermal conductivity of pure CO_2. Specific activities include:

- Perform measurements of dew point for H_2O in CO_2 at temperatures from approximately 10 degrees Celsius (°C) to approximately 85 °C, at pressures up to about 7 megapascals (MPa). Analyze data to extract thermodynamic parameters such as mixture virial coefficients.
- Develop algorithm for reliable vapor-liquid equilibria (VLE) calculation in CO_2/H_2O and similar mixtures. Fit mixture model to available experimental data. Incorporate model and algorithm into NIST REFPROP software.
- Develop new standard viscosity correlation valid to at least 1273 Kelvin (K) and 1000 MPa.
- Using existing apparatus at NIST, measure pure CO_2 thermal conductivity up to 750 K and 70 MPa.
- Develop new standard thermal conductivity correlation valid to at least 1273 K and 100 MPa.

Goals and Objectives

The overall objective of this effort is to address the critical need to experimentally obtain accurate thermodynamic and physical property data for CO_2 and CO_2/H_2O mixtures under specific conditions relevant to advanced power systems (e.g., super-critical CO_2 power cycles) and CCS and, through analysis, develop models based upon the obtained experimental data. The ultimate goal is to provide a standard, validated, high-accuracy set of properties for incorporation into existing public databases.

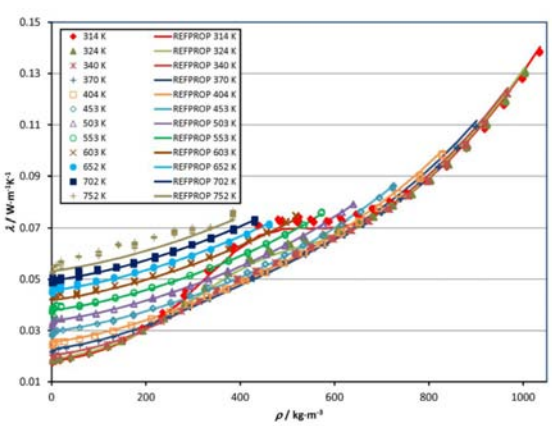

Figure 1. Data obtained in this project for thermal conductivity of pure CO_2 compared with current state-of-the-art correlation.

Accomplishments

- Completed thermal conductivity measurements of pure CO_2 at temperatures from 220 K to 752 K and pressures up to 69 MPa in the liquid, vapor, and supercritical gas phases with lower uncertainty than existing literature data in most of the region.
- Measurements underway for dew point of H_2O in compressed CO_2 with four isotherms measured between 10 °C and 40 °C. Uncertainty is much smaller than existing literature data.
- Completed evaluation of literature data for viscosity of pure CO_2 and developed preliminary gas-phase correlation.

Benefits

This project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. Experimental and modeling work by NIST's Thermophysical Properties Division will contribute to the advancement of CCS and facilitate the adoption of novel power cycles and turbomachinery that have the potential to reduce emissions and increase efficiency.

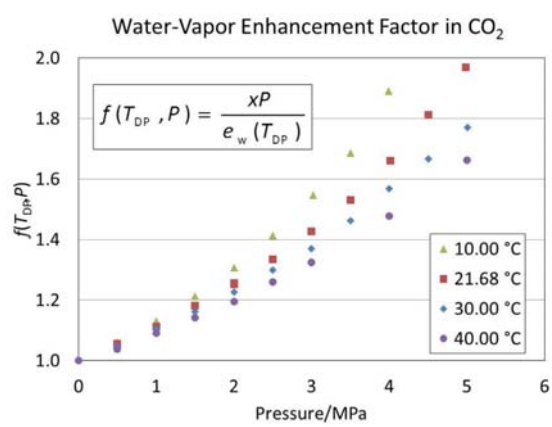

Figure 2. Data obtained so far in this project for enhancement factor, which is the ratio of dew-point water content in the gas to that given by the pure-water vapor pressure alone.

FE0003931 July 2013

MATERIALS

the ENERGY lab
PROJECT FACTS
Hydrogen Turbines

Coating Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines—Oak Ridge National Laboratory

Background

The Department of Energy (DOE) Oak Ridge National Laboratory (ORNL) is leading research on the reliable operation of gas turbines when fired with synthesis gas (syngas) and hydrogen-enriched fuel gases with respect to firing temperature and fuel impurity levels (water vapor, sulfur, and condensable species). Because syngas is derived from coal, it contains more carbon and more impurities than natural gas. In order to achieve the desired efficiency, syngas-fired systems need to operate at very high temperatures but under combustion conditions necessary to reduce nitrogen oxide (NO_X) emissions. ORNL's current project is focused on understanding the performance of high-temperature, corrosion-resistant coatings that protect superalloys, particularly in light of the high water contents expected for high-hydrogen-fired turbines. ORNL will define and address materials issues to maximize service lifetime of bond coats and thermal barrier coatings (TBCs).

This project is managed by the DOE National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

For this project, ORNL has three tasks. The first task is to study the effect of higher water vapor contents during thermal cycling. Figure 1 shows the average TBC lifetime data for three specimens of each coating type at 1,150 degrees Celsius (°C) in dry oxygen (O_2) and air with 10, 50, and 90 percent by volume water vapor for two different types of diffusion bond coatings. Lifetime is being defined as the time to 20 percent spallation of the low thermal conductivity yttria-stabilized zirconia (YSZ) top coating of the TBC. The addition of water vapor had a dramatic effect on the platinum (Pt)-modified aluminide coating, especially with 10 percent water vapor, but no statistical effect on the average lifetime of Pt-diffusion coatings.

The second ORNL task is to quantify the benefit of adding yttrium (Y) and lanthanum (La) dopants to nickel (Ni)-base superalloys on TBC lifetime. Superalloy coupons were coated with nickel-cobalt-chromium-aluminum-yttrium (NiCoCrAlY) and NiCoCrAlY-hafnium-silicon (NiCoCrAlYHfSi) bond coatings using a thermal spray high velocity oxygen fuel (HVOF) process. Ten percent water vapor had a negative effect on coating lifetime at 1100 °C, but similar lifetimes were observed for the substrates with and without Y and La.

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
10/01/2004	09/30/2013

(annual continuations)

COST

Total Project Value
$3,512,000
Base
DOE/Non-DOE Share
$3,512,000 / $0

AWARD NUMBER

FEAA070

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The third task is characterization of the microstructure and microchemistry of these TBC systems to assist in mechanistic understanding of the roles of dopants and water vapor on coating lifetime. The initial results have demonstrated that titanium (Ti) from the superalloy can diffuse through the NiCoCrAlYHfSi coating and become incorporated into the thermally-grown alumina (aluminum oxide) scale.

Goals and Objectives

The primary goal of this project is to evaluate high-performance airfoil coating architectures based on Y- and La-containing superalloys. Another key goal is to quantify and understand the role of elevated water contents on airfoil degradation. Advanced characterization techniques are being used to obtain a better mechanistic understanding of these phenomena.

Accomplishments

- Laboratory evaluations at ORNL are focusing on evaluating TBC specimens in different environments containing water vapor and CO_2 to determine their effect on performance.
- A CO_2-10% water vapor environment was not detrimental to TBC lifetime for diffusion bond coatings tested at 1150 °C. Thus, the lower CO_2 levels found in conventional or syngas-fired turbines are not likely to impact TBC performance.
- The effect of as-sprayed coating surface roughness on thermally-sprayed (metal) MCrAlYHfSi coatings was evaluated at 1100 °C. Rougher coatings (Ra~8) showed similar TBC lifetimes in 1-hour cycles in air with 10% water vapor as coatings with Ra~5. The performance in 100-hour cycles is now being evaluated.
- The TBC test matrix has included lower cost single-crystal superalloy substrates being implemented in current turbines including low-Rhenium (Re) second-generation alloys (N515) and Re-free first-generation alloys (1483). The higher Hf content in N515 resulted in longer TBC lifetimes, while the lower Al content in 1483 may have reduced their performance compared to conventional 3% second-generation alloys X4 and N5.
- Current alloy development is evaluating cast MCrAlYX compositions before fabricating coatings. Recent work has shown that combinations of Y and Hf or La and Hf result in improved oxidation resistance with less internal oxidation and no detrimental effect of Ti additions was identified.
- High-resolution analytical electron microscopy has been used to study the segregation behavior of Y, La, Hf and Ti as well as study the minor effects of water vapor on the thermally-grown alumina on the surface of coatings and model alloys.
- A characterization methodology was developed where the same 500 by 670 µm area was characterized as a function of exposure time to determine changes in the surface roughness and residual stress in the thermally-grown alumina scale. The technique was also used to track the location of transient metastable alumina phases on aluminide bond coatings and these phases did not appear to contribute to increased oxide thickness or higher stress levels.

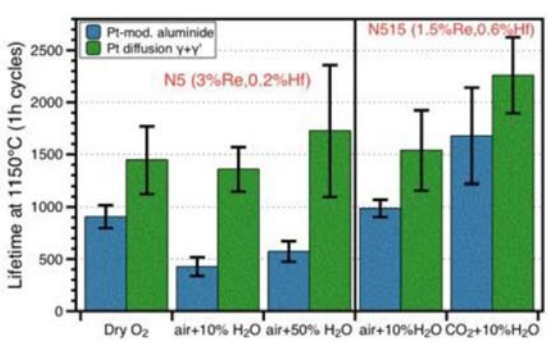


Figure 1. Average lifetimes (number of 1-hour cycles to failure) for EB-PVD (electron-beam, physical vapor deposition) yttria-stabilized zirconia (YSZ)-coated superalloy specimens with two different platinum-containing diffusion bond coatings exposed in 1-hour cycles at 1150 °C in several environments. Two different superalloy substrates were evaluated. The bars note the standard deviation for 3 specimens of each type.

Benefits

This project supports DOE's Hydrogen Turbine Program, which is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. ORNL's research is advancing mechanistic understanding of factors that contribute to airfoil degradation and extends cycle efficiency with an increased temperature capability of the hot gas path components by maximizing the service lifetime of bond coats and TBCs.

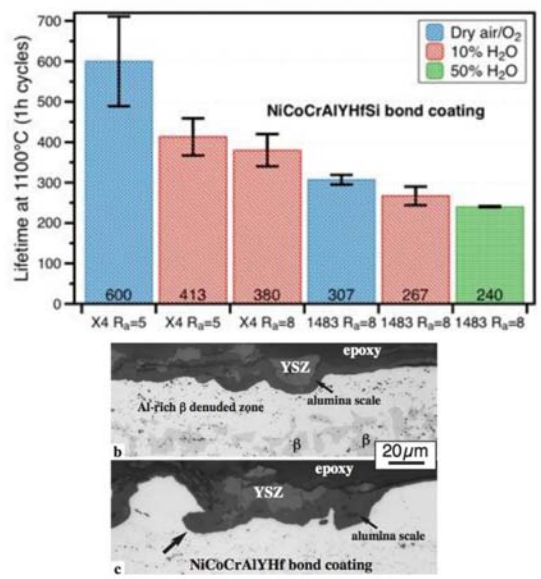
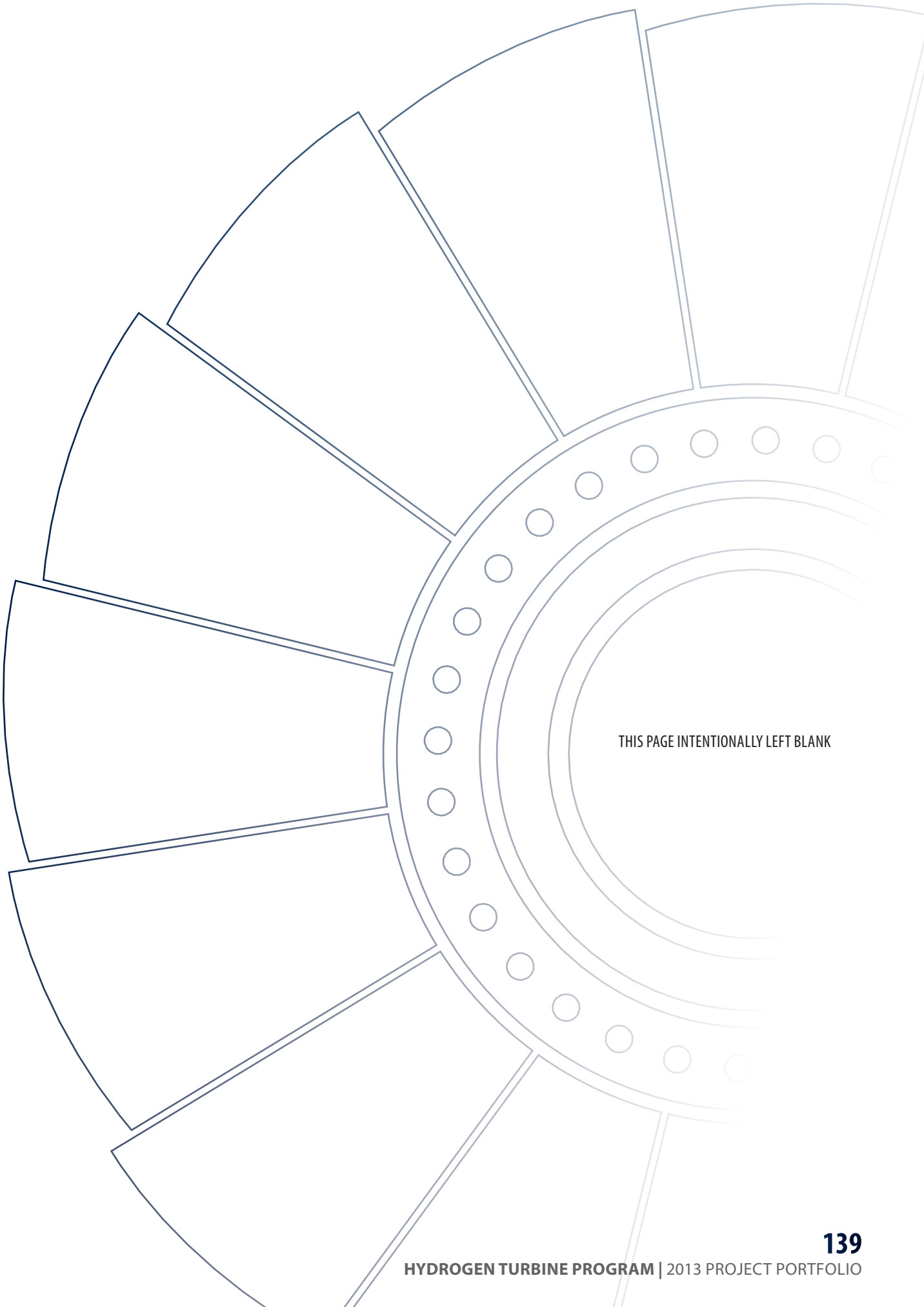


Figure 2. (a) Average coating (number of 1-hour cycles to failure) lifetimes for APS (air plasma sprayed) YSZ coated alloys X4 and 1483 16mm diameter superalloy coupons with HVOF NiCoCrAlYHfSi type bond coatings with two different average roughness (Ra) values exposed in 1-hour cycles at 1100 °C in dry and wet environments. Bars note one standard deviation for three specimens of each type. Light microscopy of polished cross-sections of failed X4-coated specimens exposed in 10% water vapor (b) R_a=5 after 440 cycles and (c) R_a=8 after 380 cycles. The arrow in (c) shows where thermally grown aluminum oxide is beginning to undercut an asperity in the higher roughness coating.

FEAA070 July 2013



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SECTION 8: SMALL BUSINESS INNOVATION RESEARCH

The Office of Fossil Energy participates in DOE's Small Business Innovation Research and Small Business Technology Transfer (STTR) programs. SBIR and STTR are highly competitive U.S. Government programs that encourage domestic small businesses to engage in Federal R&D that has the potential for commercialization. Federal agencies with large R&D budgets set aside funding for competitions among small businesses only. Small businesses that win awards in these programs keep the rights to any technology developed and are encouraged to commercialize the technology. By including qualified small businesses in the Nation's R&D arena, high-tech innovation is stimulated and the United States gains entrepreneurial spirit as it meets its specific research and development needs.

The SBIR/STTR program seeks to:

- Stimulate high-tech entrepreneurial innovation
- Utilize small business to meet the Nation's R&D needs
- Foster and encourage participation by minorities and disadvantaged persons in technological innovation
- Increase private sector commercialization

The projects that are organized under the Hydrogen Turbine program SBIR key area support the program goals by developing innovative concepts that will improve turbine system performance. The research focus areas for FY 2013 SBIR projects are Innovative Cooling Concepts, Manufacturing, and Thermal Barrier Coatings.

Mikro Systems, Inc., (Charlottesville, VA) is utilizing its TOMO℠ manufacturing process to develop ceramic cores used in investment casting that will allow advanced cooling geometries that cannot be produced any other way. This process will reduce lead times, lower tooling costs, and allow more rapidly adaptable designs. This revolutionary process will allow airfoil developers to rapidly and cost-effectively test new cooling geometries that will lead to improved plant efficiency.

Physical Sciences Inc., (Andover, MA) is refining its water guided laser drilling system to develop high-speed drilling process for cooling holes in gas turbine components. Advanced cooling designs call for a very large number of holes in the airfoils for effective cooling improvement which is cost prohibitive without the development of high-speed manufacturing techniques.

Florida Turbine Technologies, Inc., (Jupiter, FL) is developing air-riding seal technology that will reduce leakage within the turbine, which will reduce the amount of cooling air needed from the compressor and increase turbine throughput. This technology will be able to be retrofit to existing turbines at a low cost, leading to improved performance and increased revenue for turbine operators.

In FY 2013, the following activity occurred in the SBIR key area:

- HiFunda (Salt Lake City, UT) was awarded a Phase II continuation of their ultra-high-temperature TBC development project.
- QuesTek Innovations (Evanston, IL) was awarded a Phase I project on computational materials design of castable single crystal Ni-based superalloys for industrial gas turbine blades.
- Mikro Systems was selected for a Phase I rapid manufacturing project.
- Florida Turbine Technologies and Mikro Systems were both recommended for Phase II continuation of their projects.

The factsheets that follow provide more information on these projects as well as additional SBIR projects that have been awarded under the Hydrogen Turbine program.

INNOVATIVE COOLING CONCEPTS

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Air-Riding Seal Technology for Advanced Gas Turbine Engines—Florida Turbine Technologies, Inc.

Background

Advanced gas turbine engines have many engineered gaps and clearances to permit relative movement between stationary and rotating parts, and relative thermal expansion between adjacent parts that operate at different temperatures. Reduction of the leakage flows associated with these critical hot gas path component interfaces—through the use of highly efficient sealing technologies—will result in a significant improvement in overall turbine performance, efficiency and power output.

Florida Turbine Technologies, Inc (FTT) is developing an innovative design approach to provide a highly durable contactless air-riding seal (ARS). This rotating-to-static sealing approach may permit dramatic improvement in steady-state clearance control and cooling air requirements. The reduced running clearance of the ARS as compared to a knife-edge seal increases efficiency and total power output.

This turbine project was competitively selected under the Small Business Innovative Research (SBIR) Program. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Many of the rotating-to-static sealing techniques applied commercially today have capabilities limited by the worst-case transient gap conditions. More specifically, gaps are set based on the pinch point within the transient response to prevent rubbing and or damage to the sealing device of the rotating and stationary components. This passive approach to clearance setting results in larger steady-state operating clearances and efficiency-robbing air leakage.

FTT is proposing an active sealing technique to allow for the tightest clearances at the steady-state operating condition. The contactless ARS technology utilizes a pressure balancing system, permitting the seal to "follow" the target surface through axial and radial transient excursions. This results in reduced running seal clearances with no degradation over time, as the seal does not rub at any point in the mission cycle.

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
06/28/2012	08/13/2015

COST

Total Project Value
$1,149,847

DOE/Non-DOE Share
$1,149,847 / $0

AWARD NUMBER

SC0008218

U.S. DEPARTMENT OF ENERGY

In this project, an ARS rig will be created at FTT will be modified to operate at similar speeds and pressure ratios as those expected in a gas turbine engine. Seal operating data will be recorded and used to calibrate a computational fluid dynamics (CFD) model. The CFD model will be used to predict seal performance at off-design points (e.g., start-up transient, shutdown). Test results will also be used to compare flow leakage against the current state-of-the-art static-to-rotating seal (the knife-edge seal).

Goals and Objectives

The goal of this SBIR project is to gain understanding and advance the development of the ARS concept with the ultimate goal of introducing this technology into a gas turbine engine. The Phase II project aims to build upon the technology feasibility demonstrated in Phase I by considering real world anomalies and testing the ARS in an engine like environment. Phase II objectives include the following:

- Design work for implementation of the ARS technology into industrial gas turbine engines.
- Creation of analytical models (one-dimensional [1D], CFD, and fluid structural interactive [FSI]) to predict seal performance of various design concepts.
- Creation of system model to address seal response characteristics.
- Generation of a rig design capable of testing the design concepts and evaluating their performance.
- Evaluate seal design concepts through testing.
- Correlate analysis predictions with test data.

Accomplishments

- Proved the ARS's functionality to operate with significantly reduced leakage rates over a range of pressures.
- Matched analytical results, 3D CFD and 1D hand calculations, to test data demonstrating understanding of the physical behavior of the technology.
- Developed technology maturation concepts based upon analytical models rooted to test data.
- Created engine performance models to illustrate the potential benefit of $7.2 million per year for a single utility scale engine with the ARS technology installed.
- Awarded Phase II SBIR to take the technology from technology readiness level (TRL) 2/3 to 5/6.

Benefits

This SBIR project supports DOE's Hydrogen Turbine Program, which is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The SBIR program is positioned to leverage the agility and innovative competencies of small businesses. Accordingly, FTT will advance the development of air-riding seals that will reduce leakage, improve durability, and ultimately, increase turbine efficiency.

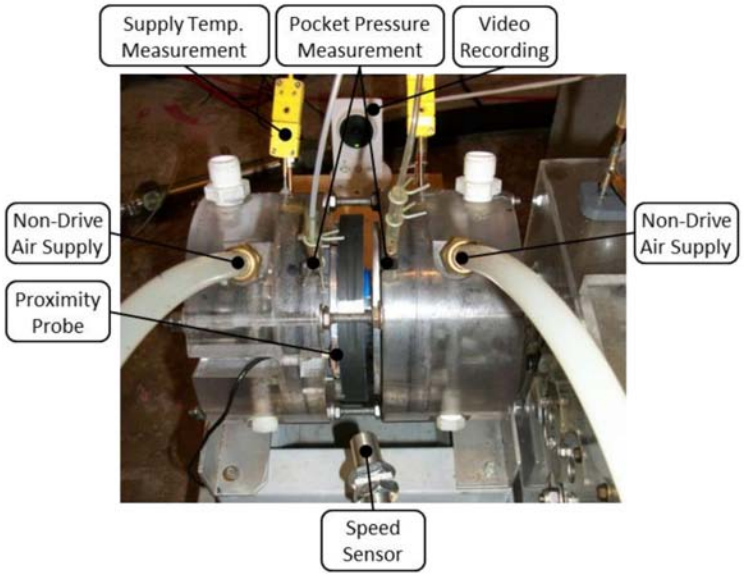

Figure 1. ARS Phase I Test Rig Showing Instrumentation Locations.

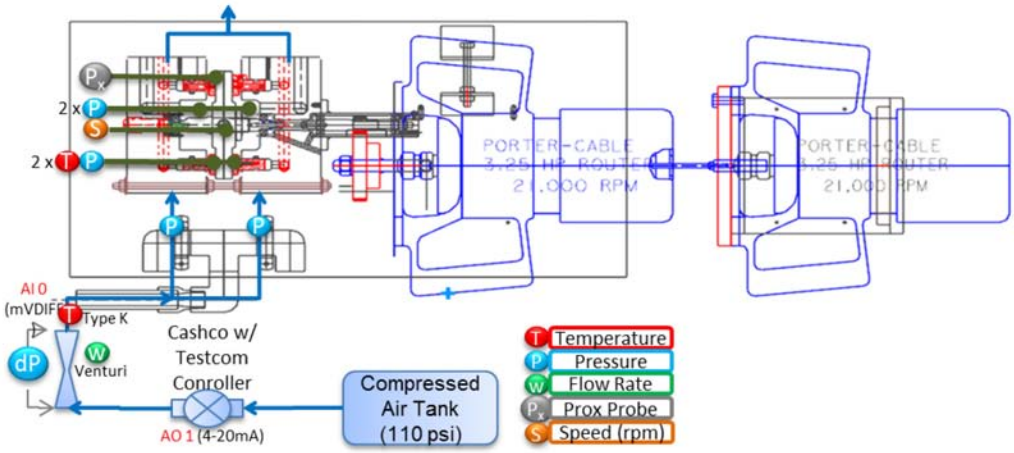

Figure 2. Facility Layout of the ARS Phase I Test Rig.

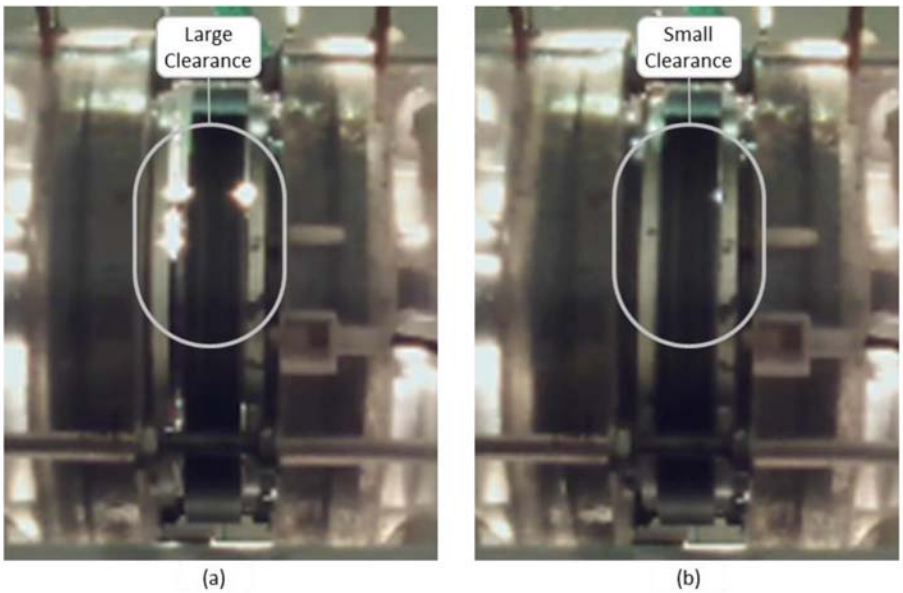

Figure 3 . Video Screen Captures of the Seal in the Unpressurized/Open State (a) and Pressurized/Closed State (b) During the Phase I Rig Operation.

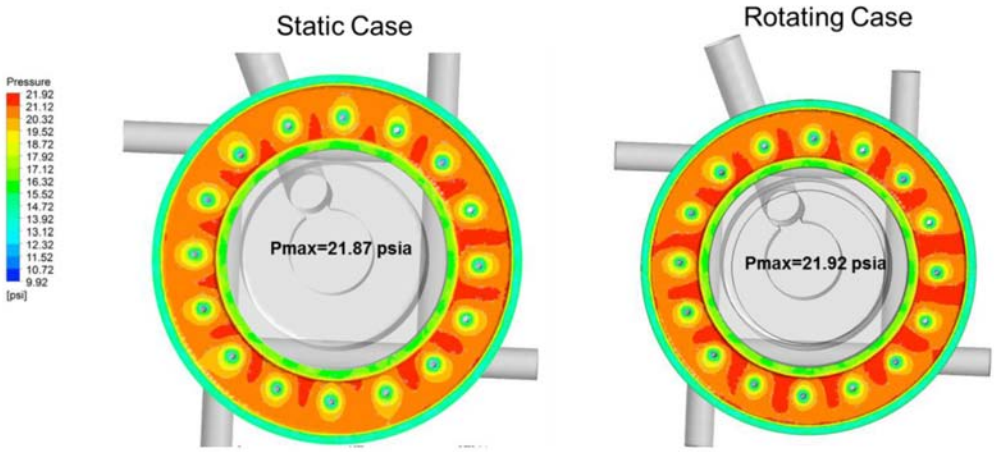

Figure 4. 3D CFD Results Detailing the Effects of Rotation at 80 psi Inlet Pressure.

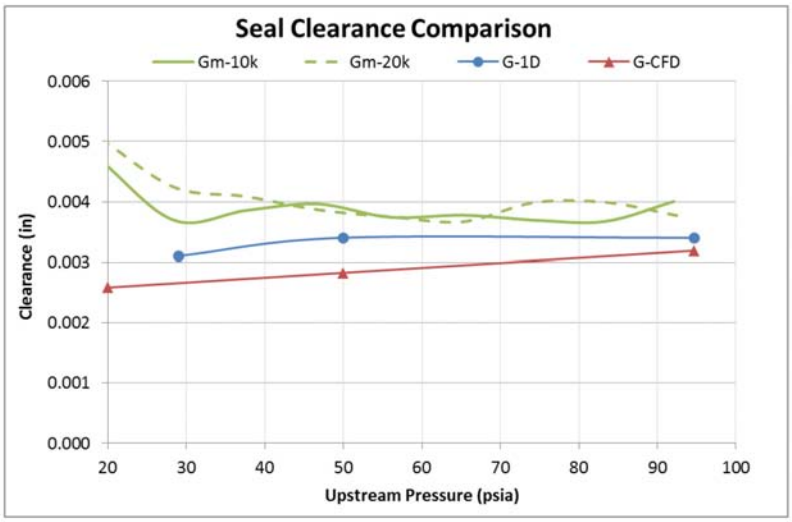

Figure 5. Seal Clearance Analytical Predictions Compared to Test Data.

SC0008218, August 2013

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PROJECT FACTS

Hydrogen Turbines

Advanced Cooling for IGCC Turbine Blades—Mikro Systems

Background

Turbine blade and vane survivability at higher operating temperatures is the key to improving turbine engine performance for integrated gasification combined cycle (IGCC) power plants. Innovative cooling approaches are a critical enabling technology to meet this need.

Mikro Systems, Inc. is applying their patented Tomo-Lithographic Molding (TOMO) manufacturing technology to produce turbine blades with significantly improved internal cooling geometries that go beyond the current manufacturing state-of-the-art to enable higher operating temperatures. This project addresses two important aspects. First is the need to increase the quality and reliability of the core manufacturing process capability to enable advanced cooling features to be incorporated into future turbines. Second is the need to rapidly and economically produce tools and prototype hardware whereby advanced designs can be empirically tested and optimized.

This project was competitively selected under the Small Business Innovative Research (SBIR) Program. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

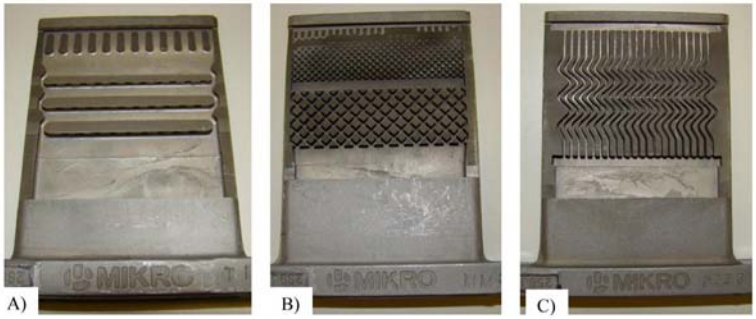

Figure 1. Filleted DS metal castings of the three cooling channel design variants created using Mikro's TOMO technology: (A) triple impingement, (B) multi-mesh, and (C) zig-zag.

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Purdue University
Siemens Energy

PROJECT DURATION

Start Date	End Date
08/27/2009	12/31/2012

COST

Total Project Value
$1,099,896

DOE/Non-DOE Share
$1,099,896/$0

AWARD NUMBER

SC0001359

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Project Description

In order to improve heat transfer and lower cooling air requirements, the advanced blade designs will require more complex internal cooling passages than can be produced using current investment casting techniques. Significant gains can be made, especially on the trailing edge (TE) portion of the turbine blade. Under this project Mikro has produced advanced cooling geometries in TE coupons that could be used on the TE of blades used in IGCC power plants.

Goals and Objectives

The overarching goal of this Phase II effort is to demonstrate that Mikro System's TOMO technology can produce a multitude of designs that have the potential to provide significant improvements in heat transfer for advanced turbine blades. This enables a synergistic relationship between design, manufacturing, CFD modeling, and experimental testing by allowing for design comparisons in a short time period. The program objectives are as follows:

- Refine the TE cooling design produced in Phase I and optimize the design using outputs and results from the Phase I core production and investment casting trials to configure TE coupons.
- Produce two additional design variants by modifying the TE portion of the blade.
- Conduct heat transfer testing focused on the advanced geometries embedded in Phase II coupons.
- Perform CFD testing and analysis on the advanced blades and verify the optimized cooling performance.
- Produce tooling and "foundry ready" ceramic cores that have advanced TE designs on a full-size blade that can be metal cast and tested for improvements in heat transfer for advanced turbine blades.

Figure 2. Eight Blades - 4 Zigzag and 4 Multimesh.

Accomplishments

- Mikro produced models of three TE designs with advanced cooling features for production and CFD analysis.
- Mikro produced ceramic core samples of each design, plus seven additional designs with slight variants. Mikro waxed the cores and the foundry metal cast using directional solidification of CM247.
- Purdue University conducted CFD analysis on three TE designs.
- Siemens completed some initial heat transfer testing on 29 metal cast TE coupons using infrared imaging (10 design variants in all). The infrared imaging results were inconclusive, so the parts were shipped to the University of Pittsburgh for testing.
- NETL-RUA funded the University of Pittsburgh to conduct extensive heat transfer testing on the coupons produced by Mikro using an existing test rig with thermal couples.
- Mikro produced ceramic cores for investment casting of an 8000H row1 blade with two different advanced TE designs (4 blades of each design were produced – eight in all).

Benefits

This SBIR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The SBIR program is positioned to leverage the agility and innovative competencies of small businesses. It is through this program that a small company, Mikro Systems, has developed a way to revolutionize the gas turbine industry's investment casting process. Mikro Systems has created breakthrough technology for both development and manufacturing of ceramic casting cores. It enables faster and lower-cost development of advanced gas turbine blades, and the process can be scaled up for volume production. Further, Mikro Systems technology supports design features that are not possible with conventional core casting technology.

Figure 3. Line-up of blades as in a turbine.

SC0001359 July 2013

MANUFACTURING

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Advanced Filtration to Improve Single Crystal Casting Yield—Mikro Systems

Background

Single crystal (SX) nickel superalloys are a primary material choice for gas turbine hot gas path component castings because of their high resistance to deformation at elevated temperatures. However, the casting yields of these components need to be improved in order to reduce costs and encourage more widespread use within the gas turbine industry. Low yields have been associated with a number of process-related defects common to the conventional casting of SX components. One innovative improvement, advanced casting filter designs, has been identified as a potential path toward increasing the yield rates of SX castings for high-temperature gas turbine applications.

Mikro Systems, Inc. (Mikro) proposes to increase SX casting yields by developing advanced ceramic casting filters that will optimize filtration performance while enabling directional flow of molten alloy during the SX casting process. These performance advantages will be enabled through the geometric design of the filter.

This turbine project was competitively selected under the Small Business Innovative Research (SBIR) Program. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high-hydrogen-content fuels derived from coal that is clean, efficient, and cost effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Mikro will apply their Tomo-Lithographic Molding (TOMO™) manufacturing platform to improve the SX investment casting process through the development of engineered ceramic filters for SX metal casting. Mikro will design an engineered filtration system comprising a primary central filter (located in the pour cup of the mold tree) and a series of secondary in-line filters that are placed before or within each shell within the mold tree. The primary and secondary filters will be designed to work together to effectively control the metal flow for specific airfoil geometries. The filter designs will utilize flow properties (rate and directionality) based on empirical data derived from existing casting production and theoretical data from casting simulation and flow testing. Filtration performance will be baselined using industry standards and optimized through Mikro's ability to form highly engineered surfaces and geometries from ceramics.

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PARTNERS

PCC Airfoils

PROJECT DURATION

Start Date	End Date
06/26/2012	08/13/2015

COST

Total Project Value
$1,149,748

DOE/Non-DOE Share
$1,149,748 / $0

AWARD NUMBER

SC0008266

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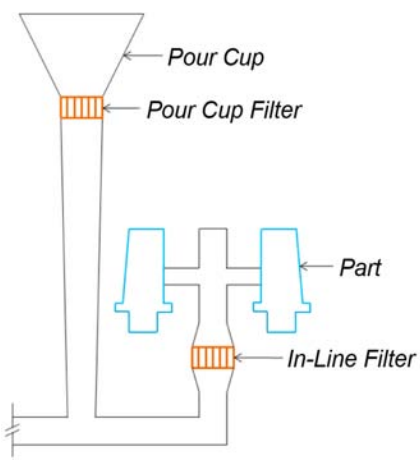
Casting filter designs remain very conventional, with no specific engineering consideration for SX castings. Low yields have been associated with a number of process-related defects, and foundry experts estimate that over $7 million per year in scrap castings are due to inclusions that could be prevented with advanced filtering.

Goals and Objectives

The goal of this project is to increase SX casting yields through the development of engineered advanced geometry ceramic filters for metal castings. During Phase I Mikro demonstrated the technical feasibility of producing advanced designs for pour cup and inline filters using TOMO. Until now, these designs could not be produced due to limitations in current manufacturing methods. Flow tests of Mikro filters demonstrated much lower variability in flow rate and pressure drop from filter-to-filter compared with off-the-shelf filters. The Phase II goal is to build upon Phase I results and further develop/optimize the TOMO process for manufacturing advanced ceramic filters. Phase II objectives include the following:

- Develop a ceramic material system for filters that meets or exceeds foundry requirements for SX casting.
- Further develop and refine the protocols and systems (bench rig and computer simulation) for testing new filter designs for SX foundry casting
- Design, produce and test optimized SX ceramic filters that outperform current state-of-the-art products. SX cast and analyze a small number of complex turbine blades using the Phase II filters
- Develop a business case for producing advanced ceramic filters that are cost competitive with industry standard products.



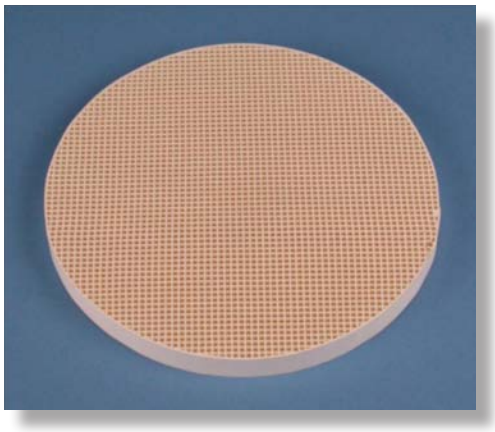
Mold tree schematic.

Accomplishments

- Two types of production secondary filter parts have been obtained from PCC's foundry and examined at Mikro. Neither of the two production options for filtration available to the market today fully satisfies the needs of the foundry. The foam filter is an effective filter with a torturous path and high surface area, but is non-uniform and prone to damage. The extruded filter is robust and uniform, but is not as effective at removing impurities. The cast TOMO filter has the potential of providing the best of both conditions with a uniform engineered complex internal structure.
- Primary filters consisting of three different designs were CAD modeled, tooling was fabricated, and two of each design were produced at Mikro.
- Secondary filters consisting of three different designs were CAD modeled, tooling was fabricated, and two of each design were produced at Mikro.
- Specifications for a water test unit were acquired and constructed by an outside test facility. The rig contained pressure sensors to determine flow resistance, and dye injection points to visually evaluate flow turbulence.
- The in-line (secondary) filters produced at Mikro have been flow tested against two different production filter types. The results show a much greater uniformity of the cast TOMO parts as compared to the standards.
- Awarded Phase II SBIR.

Benefits

This SBIR project supports DOE's Hydrogen Turbine Program, which is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The SBIR program is positioned to leverage the agility and innovative competencies of small businesses. An advanced ceramic filtration system enabled by Mikro's TOMO manufacturing technology will embody internal filtration and flow features that are beyond current state-of-the-art systems. This will improve casting yield, lower the cost, and remove a primary obstacle to more widespread use of SX casting for industrial gas turbines and other critical investment-cast products.

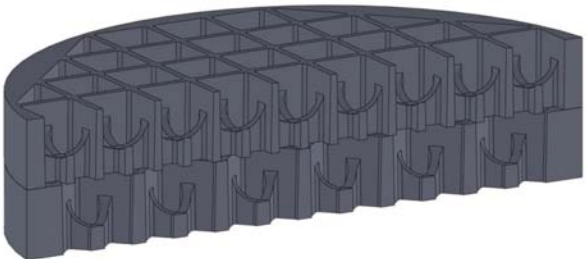


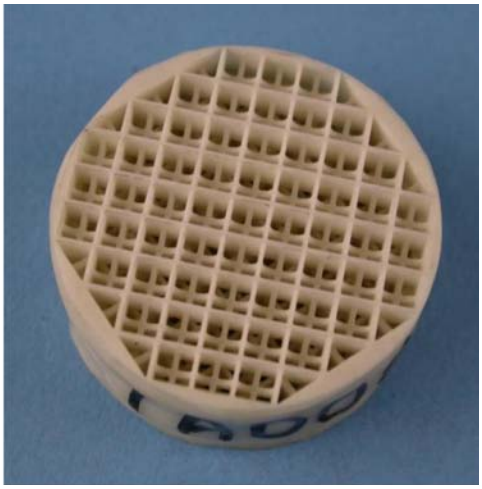
Industry standard flat primary filter.

Conical pour cup (primary) filters produced by TOMO during Phase I.

- *3 filter variants*
- *Can be nested to contain multiple geometries to create tortuous path for effective filtration*
- *Conical shape increases available surface area by 7X over current disc filter*
- *Can contain sidewall features*
- *Point blockage causes less disturbance to output flow pattern*

Industry standard in-line filters – fine structures break and cause incusions in castings





In-line (secondary) filters produced by TOMO during Phase I.

- *Support features are designed into castings*
- *Filter design stronger and less susceptible to thermal shock*
- *Geometric pattern makes flow uniform across filter*

SC0008266 August 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Recovery Act - Advanced Laser Machining Techniques for Cooling Holes in Gas Turbines—Physical Sciences

Background

Physical Sciences Inc. (PSI) has developed a high speed, water guided laser drilling process that will improve the predictability and repeatability of cooling hole performance in gas turbine blades while meeting manufacturing cost objectives. The water guided laser drilling process will also enable cost-effective machining of shaped cooling holes that are desired for next generation turbine cooling strategies. Funding by the American Recovery and Reinvestment Act (ARRA) under the Small Business Innovation Research (SBIR) Phase II Program will further develop the water guided laser drilling process by demonstrating superior flow uniformity compared to holes drilled using current laser or electrochemical methods. A prototype drilling system will be constructed to demonstrate that the technology will meet productivity and cost objectives of turbine manufacturers.

This project is managed by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

PSI will develop a high speed, water guided laser drilling process for creating cooling holes in high temperature metallic alloys used in gas turbine systems. Current drilling technologies produce cooling holes with plus or minus 10 percent (± 10%) air flow variation between identically drilled arrays of holes. This variation requires designers to provide extra holes and extra cooling flow to ensure safe operation, but it results in an excess consumption of cooling air and over cooling in some areas. The novel PSI approach will reduce flow variation to ± 2%, permit more complex cooling hole shapes, and allow for more precise location of cooling holes on turbine blades. In addition, water guided laser drilling will improve the predictability and repeatability of cooling performance and meet manufacturing cost objectives to enable next generation turbine cooling strategies.

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PERFORMANCE PERIOD

Start Date	End Date
02/10/2010	08/31/2013

COST

Total Project Value
$1,148,653

DOE/Non-DOE Share
$1,148,653 / $0

Government funding for this project is provided in whole or in part through the American Recovery and Reinvestment Act.

AWARD NUMBER

SC0003400

U.S. DEPARTMENT OF ENERGY

Goals/Objectives

The program goal is to demonstrate a module that can be attached to a commercial laser drilling head and deliver laser energy to the surface of a work piece through a high pressure stream of water. Objectives of the Phase II program are as follows:

- Design and build a water guided laser drilling head that can be used to drill holes up to 0.050″ (inch) diameter anywhere on the surface of a 12″ x 12″ panel of high temperature alloy—with the head capable of drilling holes at elevation angles from 90° to 20° through a water stream extending up to 1″ from the head.
- Integrate a water guided laser drilling head into a prototype water guided laser drilling system so that all positioning and drilling operations may be performed from a single computer numerical control (CNC) operator interface.
- Develop water guided laser drilling processes that enable arrays of holes to be automatically drilled with user defined diameters and elevation angles anywhere on the surface of a 12″ x 12″ substrate at rates exceeding 3 seconds/hole.
- Demonstrate that the air flow variation of between arrays of holes drilled using water guided laser drilling is less than ±2%.
- Perform metallurgical analysis of the surfaces of water guided laser drilled holes and show that the microstructure of the walls of the holes contain no microcracks, and that debris generated by the drilling process is not deposited on the walls of the holes or forms a ridge on either the entry or exit.
- Define the requirements for a production water guided laser drilling system capable of drilling cooling holes for gas turbine systems.

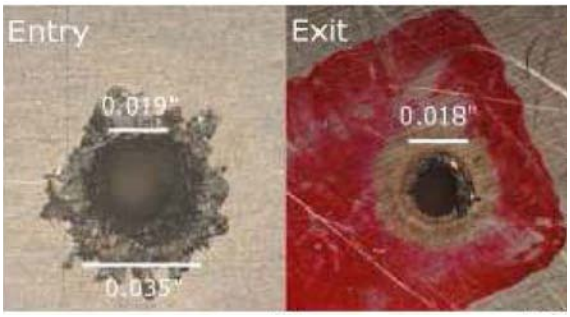

Figure 1. PSI's Phase I water guided laser drilling system was used successfully to drill through holes in 0.050″ Inconel 718 at rates exceeding 3 seconds/hole with small amounts of surface recast on the laser entry and exit.

Accomplishments

- Successfully demonstrated water guided laser drilling of holes between 0.10″ and 0.030″ using a YLS-3000 fiber laser system.
- Successfully drilled holes using water guided laser drilling in Inconel 718, 304 Stainless Steel, and 0.026″ Haynes alloy.
- Achieved better control of the water guided laser drilling process by improving the pressure control on the water stream.
- Improved process reliability by using longer focal length optics to reduce laser power density.

Benefits

This SBIR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The SBIR program is positioned to leverage the agility and innovative competencies of small businesses. It is through this program that a small company, Physical Sciences in Andover, Massachusetts, has developed an advanced technology for drilling precise holes that is critical for building higher efficiency, greener gas turbines and other systems. ARRA investment in this small business will likely result in more U.S. jobs, as well as both the processes and equipment necessary to transition this vital technology to manufacturers of gas turbine systems.

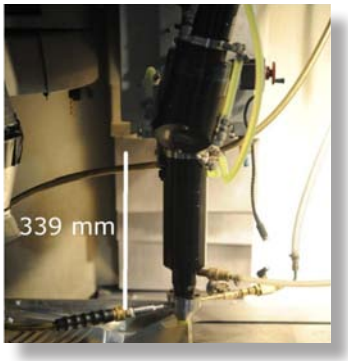

Figure 2. A longer focal length optical system reduces the laser power density injected into the water stream to reduce the likelihood of super-heating the water stream.

Figure 3. Water guided laser drilling of Inconel 718 using longer focal length optical system.

SC0003400 July 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Computational Materials Design of Castable SX Ni-based Superalloys for IGT Blade Components—QuesTek Innovations

Background

Higher inlet gas temperatures in industrial gas turbines (IGTs) enable improved thermal efficiencies, but creep—the tendency of materials to deform gradually under stress—becomes more pronounced with increasing temperature. In order to raise inlet temperatures of IGTs, turbine blade materials are required to have superior creep rupture resistance. Nickel (Ni)-based single crystal (SX) blades have higher creep strength in comparison with directionally solidified blades and are widely used in aerospace engines. However, their use in IGTs, which require larger-size castings (two to three times the size needed in aerospace applications), is limited due to casting-related defects including freckling, high-angle boundary formation between grains, grain nucleation, and shrinkage/porosity, as well as post-cast defects such as incipient melting and recrystallization during high-temperature solution heat treatment. Current techniques for developing new SX alloys are empirical in nature and are inadequate for identifying unique alloy compositions that can satisfy both the processing and property objectives for gas turbine blades.

QuesTek Innovations LLC (QuesTek), with involvement from Siemens Power Generation and PCC Airfoils, proposes to implement a systematic, science-based approach that calculates optimum composition and processing routes to achieve desired material properties to design new castable SX Ni-based superalloys that can be cast effectively as large IGT blade components.

This turbine project was competitively selected under the Small Business Innovative Research (SBIR) Program. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high-hydrogen-content fuels derived from coal that is clean, efficient, and cost effective, minimizes carbon dioxide (CO_2) emissions, and will help to maintain the nation's leadership in the export of gas turbine equipment.

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PCC Airfoils

PROJECT DURATION

Start Date	End Date
02/19/2013	11/18/2013

COST

Total Project Value
$149,618
DOE/Non-DOE Share
$149,618 / $0

AWARD NUMBER

SC0009592

U.S. DEPARTMENT OF ENERGY

Project Description

QuesTek is a leader in computational materials engineering and will employ a systems engineering design framework based on existing CALPHAD (CALculation of PHAse Diagrams) multicomponent tools. QuesTek will invoke reliable physics-based models to predict intrinsic freckling potency, alloy hot-tearing tendency during casting, and other casting related defects. The computational materials design will consider trade-offs between the blade property requirements such as creep strength, resistance to topologically close-packed phase formation, tensile strength, corrosion resistance, grain-boundary strength, and SX processing requirements such as freckling resistance, hot-tearing resistance, and a solution heat-treat window that avoids incipient melting. The Phase I focus will be on computationally designing candidate alloys that can provide enhanced castability while achieving increased metal temperature capability of 1050–1100 degrees Celsius. The Phase II program will focus on developing the entire systems-based materials design and validation through casting complex blade components with internal cooling passages using actual OEM (original equipment manufacturer) blade tooling.

QuesTek plans to collaborate with key stakeholders to define specific property goals and processing constraints that will enhance QuesTek's process-structure models for castability and structure-property models for superalloy design, sketch out microstructural concepts capable of achieving the program goals, and use the enhanced tools to design SX superalloy compositions incorporating these microstructural concepts. Also, QuesTek plans to fabricate baseline commercial alloy compositions (or variants of these compositions) as demonstration IGT tooling castings to characterize their casting behavior and compare it against QuesTek's model predictions. These model castings and the comparison against predictions will serve as a Phase I concept feasibility demonstration.

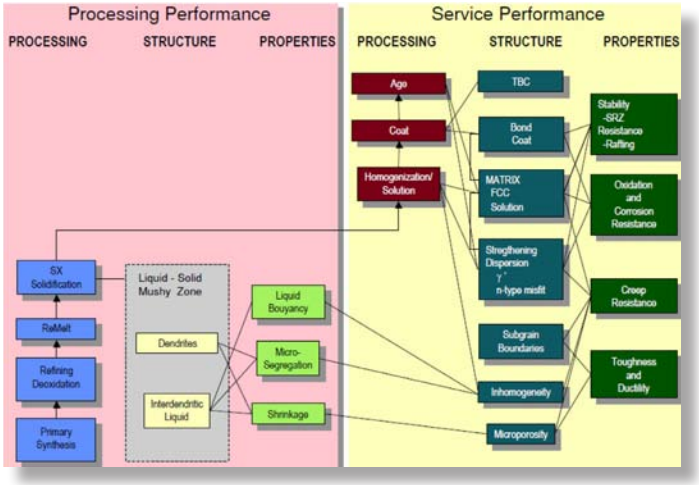
Goals and Objectives

The overall goal of the SBIR program is to design and develop more castable SX Ni-based superalloys that can be cast effectively as large IGT blade components, provide hot corrosion resistance, and provide superior creep performance comparable to state-of-the-art SX aeroturbine blades. The specific objectives of the Phase I program are to utilize QuesTek's models to design such alloys computationally and to demonstrate Phase I concept feasibility by comparing QuesTek's predictions against the casting behavior of certain commercial alloy systems.

Benefits

This SBIR project supports DOE's Hydrogen Turbine Program, which is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The SBIR program is positioned to leverage the agility and innovative competencies of small businesses like QuesTek. IGTs operating at higher temperatures, enabled by new high yield SX castings, can operate at higher efficiency and thus reduce electricity-generation costs and CO_2 emissions. The high yield of the new SX alloys will accelerate their adoption by the IGT community, and their enhanced temperature capability will allow hydrogen-fueled turbines and ultra-high temperature steam turbines to be developed, thus bringing the vision of zero-emission fossil-fuel power plants a step closer to realization.

A single-crystal model blade (length:170mm).



System design chart developed by QuesTek for SX castings that illustrates the links among the performance properties, structure, and processing of the systems engineering approach. The properties are a function of the microstructure which can be achieved by the appropriate processing steps.

SC0009592, April 2013

THERMAL BARRIER COATINGS

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Ultra-High Temperature Thermal Barrier Coatings—HiFunda & University of Connecticut

Background

The U.S. Department of Energy (DOE) has a stated goal to increase the energy efficiency of turbines, and one well recognized method of achieving this goal is through the use of ceramic thermal barrier coatings (TBCs). However, state-of-the-art zirconia-based TBCs have a temperature limit of about 1200 degrees Celsius (°C). New TBC materials that can withstand temperatures of 1300 °C and above are needed to increase turbine operating temperatures and achieve associated gains in energy efficiency.

HiFunda LLC and the University of Connecticut (UConn) are teaming to demonstrate an advanced TBC consisting of a new top coat chemistry of yttrium aluminum garnet (YAG) with a unique microstructure, which has higher use temperature, greater erosion resistance, improved sintering resistance, and lower effective thermal conductivity compared to the widely used yttria-partially stabilized zirconia (YSZ) top coats.

This turbine project was competitively selected under the Small Business Technology Transfer (STTR) Program. It is managed by the U.S. DOE National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high-hydrogen-content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help to maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Prior to this project, the use of YAG materials as TBCs has been limited by the difficulty of processing them with a sufficiently compliant microstructure to achieve the required strain tolerance and durability. This project will use a proprietary solution precursor plasma spray (SPPS) process—developed at UConn and demonstrated successfully on other materials such as YSZ—to fabricate YAG-based TBCs with markedly improved temperature characteristics relative to YSZ. In Phase I, the team demonstrated the feasibility of utilizing the SPPS process to deposit TBC coatings of sufficient thickness and desirable microstructures that yielded superior thermal cycling resistance compared with state-of-the-art air plasma sprayed (APS) YSZ coatings. In Phase II, HiFunda and UConn—working closely with major turbine manufacturers and coating service providers—will optimize the process, demonstrate that SPPS YAG TBCs can meet test criteria specified by the turbine manufacturers, and scale up the process to coat components for third party testing.

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PROJECT DURATION

Start Date	End Date
02/20/2012	04/21/2015

COST

Total Project Value
$1,149,988

DOE/Non-DOE Share
$1,149,988 / $0

AWARD NUMBER

DE-SC0007544

U.S. DEPARTMENT OF ENERGY

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Goals and Objectives

The Phase I goal was met by demonstrating, using laboratory tests, that SPPS YAG TBCs have properties that can be tailored to provide superior durability, use temperature, and sintering/erosion resistance, and lower thermal conductivity than YSZ TBCs.

The specific technical objectives for Phase II are as follows:

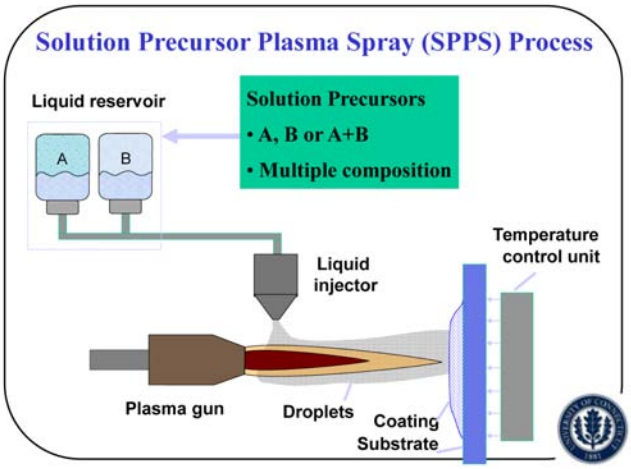
- Establish the HiFunda Incubator Plasma Spray Facility at UConn with staff and equipment.
- Select an optimum precursor that can provide the desirable SPPS YAG TBC microstructure without nozzle clogging.
- Identity optimum SPPS plasma spray processing parameters, using Taguchi Design of Experiments, based on SPPS microstructure (thickness >250 µm, vertical cracks, ultra-fine splats), and with lower thermal conductivity, lower density, and increased hardness (>300 VHN [Vickers Hardness Number]) compared to APS YSZ.
- Demonstrate that SPPS YAG TBCs have a >200 °C temperature capability compared to APS YSZ, along with greater sinter and erosion resistance, superior durability, equivalent or improved CMAS (Calcium-Magnesium-Alumina-Silicate) resistance and lower thermal conductivity.
- Demonstrate a production-capable process for SPPS YAG TBCs.
- Provide cost estimates for SPPS YAG TBCs relative to baseline APS YSZ TBCs.

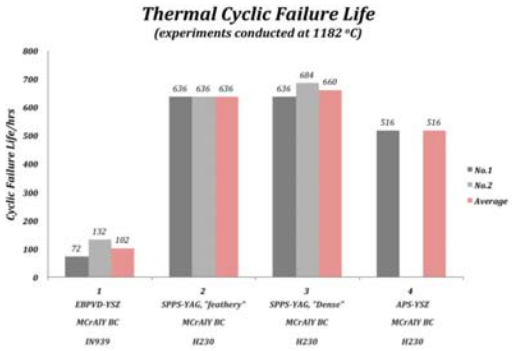
Accomplishments

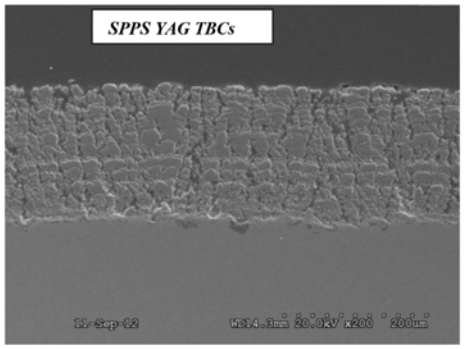
- Identified SPPS processing parameters that could achieve the desirable microstructural features of high porosity and vertical cracking.
- Successfully sprayed coatings of greater than 250 µm thickness that have the desired microstructure.
- Showed that SPPS YAG TBCs have lifetimes that matched or exceeded baseline YSZ TBCs at both standard- and elevated- temperature thermal cycling conditions.
- Established a HiFunda technology incubator at UConn.

Benefits

This STTR project supports DOE's Hydrogen Turbine Program, which is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. The STTR program is positioned to leverage the agility and innovative competencies of small businesses. The novel TBCs developed by the HiFunda team can be an enabling technology for highly efficient next-generation gas turbines.







SC0007544 July 2013

the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

High Temperature Unique Low Thermal Conductivity Thermal Barrier Coating (TBC) Architectures—UES

Background

Gas turbine engines used in integrated gasification combined cycle power plants require higher operating temperatures for enhanced efficiency, lower emissions, and increased performance. Currently, the durability of the turbine engine components is achieved by the use of thermal barrier coatings (TBCs) consisting of yttria-stabilized zirconia (YSZ, six to eight weight percent) and/or by internal/external cooling. The current state-of-the-art TBCs (standard [Std.] YSZ) do not adequately protect the metallic components of turbine engines operating at higher TBC surface temperatures (greater than [>] 1200 degrees Celsius [ºC]).

In order to enhance efficiency of the turbine engines for power generation, there is a need to develop TBCs for higher temperature applications. TBC materials (pyrochlore oxides, highly doped YSZ) having high temperature (>1300 °C) thermal stability, lower thermal conductivity, and sintering resistance do exist. However, these materials possess very low toughness and thereby exhibit higher erosion rates. UES, Inc. and Pennsylvania State University are involved in the development, characterization, and validation of unique TBC designs involving pyrochlore oxides and doped YSZ for high temperature applications.

This project was competitively selected under the Small Business Technology Transfer (STTR) Program and is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

Project Description

Two different materials have been selected for the development of higher temperature TBCs: (1) Pyrochlore oxides (specifically, gadolinium zirconate; $Gd_2Zr_2O_7$ [GZO]) and (2) Modified Std. YSZ through chemistry changes (doping). The overall technical approach of this project is focused on the development and evaluation of novel, multilayered/composite TBC design architectures consisting of GZO and doped YSZ for improved relevant characteristics (reduction in thermal conductivity, erosion rate and sintering rate). The Phase I technical approach involved fabrication, characterization, and performance evaluation of the multilayered and monolayered TBC architectures. Electron beam physical vapor deposition (EBPVD) was utilized to fabricate monolayered and multilayered TBCs of the selected materials. Phase II of the project involves

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PROJECT DURATION

Start Date	End Date
07/12/2010	02/14/2014

COST

Total Project Value
$849,938

DOE/Non-DOE Share
$849,938/$0

AWARD NUMBER

SC0004356

U.S. DEPARTMENT OF ENERGY

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optimization of microstructure and design of the multi-layered TBCs, as well as fabrication and evaluation of composite TBCs fabricated by EBPVD and cost effective atmospheric plasma spray (APS) techniques. Fabricated TBCs are characterized in terms of microstructure, thermal conductivity, erosion resistance, sintering resistance under thermal gradient condition and thermal cycling tests.

Goals and Objectives

The overall goal of this project is to develop novel TBC architectures that provide high thermal insulation (low thermal conductivity) and high erosion resistance without sacrificing strain tolerance.

Accomplishments

Phase I

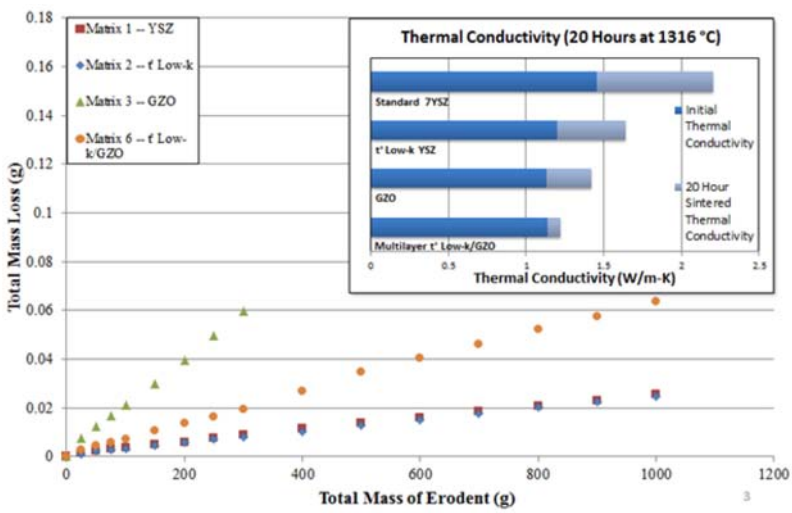
- Successfully fabricated monolayered and multilayered EBPVD TBCs of selected materials namely GZO and doped YSZ. Monolayered Std. YSZ coating was also fabricated for comparison purposes.
- Demonstrated crystalline nature with columnar structure and faceted surface morphology of the as-fabricated mono-layered and multilayered TBCs.
- Demonstrated lower thermal conductivity of the as-fabricated monolayered GZO and doped YSZ TBCs compared to Std. YSZ TBC. It was also demonstrated that the thermal conductivity of GZO can be further lowered by multilayered design. Increase in thermal conductivity after 20 hours of test of the TBCs fabricated from the selected materials was found to be lower compared to the Std. YSZ.
- Demonstrated that the intrinsically higher erosion rate (lower erosion resistance) of GZO can be lowered considerably by the multilayered coating architecture.

Phase II

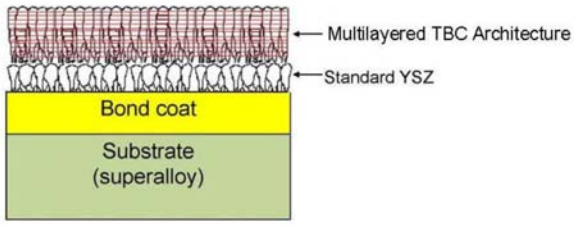
- Microstructural analysis of thermal conductivity samples revealed better high temperature sintering characteristics of selected TBC materials and multilayered coating architectures compared to Std. YSZ.
- Trend in the erosion rate of the high temperature annealed TBCs was found to be similar to as-deposited TBCs. Even for annealed samples, multilayered TBC architecture was able to considerably reduce the erosion rate of GZO.
- Further reduction in thermal conductivity of multilayered EBPVD TBC was achieved by microstructural manipulation.
- Modified multilayered coating design exhibited considerable sintering resistance up to 500 hours at higher temperature (>1300 °C).
- Composite and monolayered TBCs of selected doped materials were fabricated by cost effective APS technique.
- Erosion rates of composite APS TBCs scaled with the composition. Composite TBCs exhibited lower erosion rate than the monolayered coating of highly doped APS TBC.
- Composite TBCs of selected materials were also fabricated by EBPVD technique and are currently being evaluated.

Benefits

This SBIR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This project demonstrates that the multilayered TBC architectures of the pyrochlore oxide GZO and doped YSZ can enable the operation of gas turbine engines at higher temperature for higher efficiency and reduced emission.

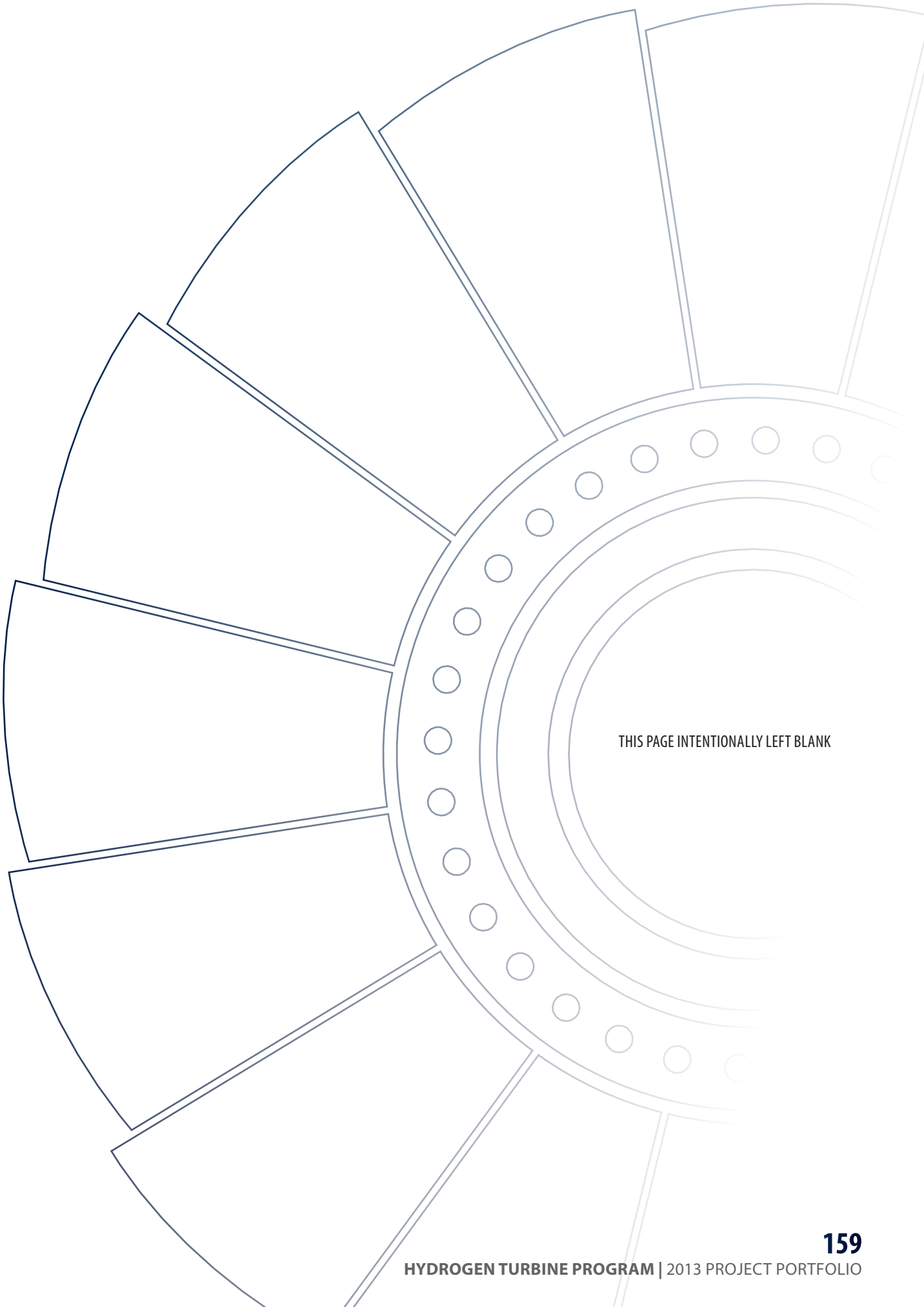


Multilayered (t' low k-GZO) TBCs, as compared to Std. YSZ, can provide lower thermal conductivity with very small increase after 20 hours of test under thermal gradient test at 1316 °C. Multilayered (t' low k-GZO) TBCs can also provide lower erosion rate compared to monolayered GZO.



One of the TBC architectures developed in Phase I.

SC0004356 July 2013



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SECTION 9: **ABBREVIATIONS**

2-D	two-dimensional
ARRA	American Recovery and Reinvestment Act
ARS	air-riding seal
atm	atmospheres
β-γ	beta-gamma
°C	degrees Celsius
C_2H_4	ethylene
C_2H_6	ethane
CaO	calcium oxide
CCS	carbon capture and storage
CFD	computational fluid dynamics
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
COE	cost of electricity
Cr-Al-Y	chromium aluminum yttrium
DOE	U.S. Department of Energy
EERC	Energy & Environmental Research Center
°F	degrees Fahrenheit
FE	Office of Fossil Energy
FY	fiscal year
g/L	grams per liter
GDZ	gadolinium zirconate ($Gd_2Zr_2O_7$)
h	heat-transfer coefficient
H_2	hydrogen
H_2O	water
HHC	high hydrogen content
HO_2	hydroperoxyl
HOCO	hydroxyformyl
IGCC	integrated gasification combined cycle
IGT	industrial gas turbine
kHz	kilohertz
kW	kilowatt
LBNL	Lawrence Berkeley National Laboratory
LES	large eddy simulation
µm	micrometer
m/s	meters per second
mA/cm^2	milliampere per square centimeter
mm	millimeter
MPa	megapascal
MWe	megawatt-electric
MWth	megawatt-thermal
N_2	nitrogen
Na_2SO_4	sodium sulfite/thenardite
$NaTaO_3$	sodium tantalum oxide
$NaVO_3$	sodium metavanadate
NETL	National Energy Technology Laboratory
NGCC	natural gas combined cycle
Ni	nickel
NiCoCrAlY	nickel cobalt chromium aluminum yttrium
NIST	National Institute of Standards and Technology
nm	nanometer
NO_x	nitrogen oxide(s)
Nu	Nusselt number
O_2	oxygen
OEM	original equipment manufacturer
OFT	oxy-fuel turbine
PIV	particle image velocimetry
PLIF	planar laser-induced fluorescence
ppm	parts per million
psig	pound per square inch gauge
R&D	research and development
RANS	Reynolds-averaged Navier-Stokes
RD&D	research, development, and demonstration
rpm	revolutions per minute
RUA	Regional University Alliance
SBIR	Small Business Innovation Research
$S_{L,max,}$	maximum stretched laminar flame speed
SPPS	solution precursor plasma spray
SST	shear stress transport
S_T/S_L	turbulent flame speed/laminar flame speed
STTR	Small Business Technology Transfer
syngas	synthesis gas
Ta_2O_5	tantalum pentoxide
Ta_9VO_{25}	tantalum vanadium oxide
$TaVO_5$	tantalum vanadium oxide
TaYSZ	tantalum pentoxide
T_b	bulk temperature

TBC	thermal barrier coating
TOMO℠	Tomo-Lithographic Molding
u'/S_L	turbulent intensity
UND	University of North Dakota
UTSR	University Turbine Systems Research
V_2O_5	vanadium oxide
vol %	volume percent
W/mK	watts per meter Kelvin
Y_2O_3	yttrium oxide/yttria
YAG	yttrium aluminum garnet
YSH	yttria-stabilized hafnia
YSZ	yttria-stabilized zirconia
YSZH	yttria-stabilized zirconium dioxide/hafnium dioxide
YVO_4	yttrium orthovanadate
ZrO_2	zirconium dioxide/zirconia

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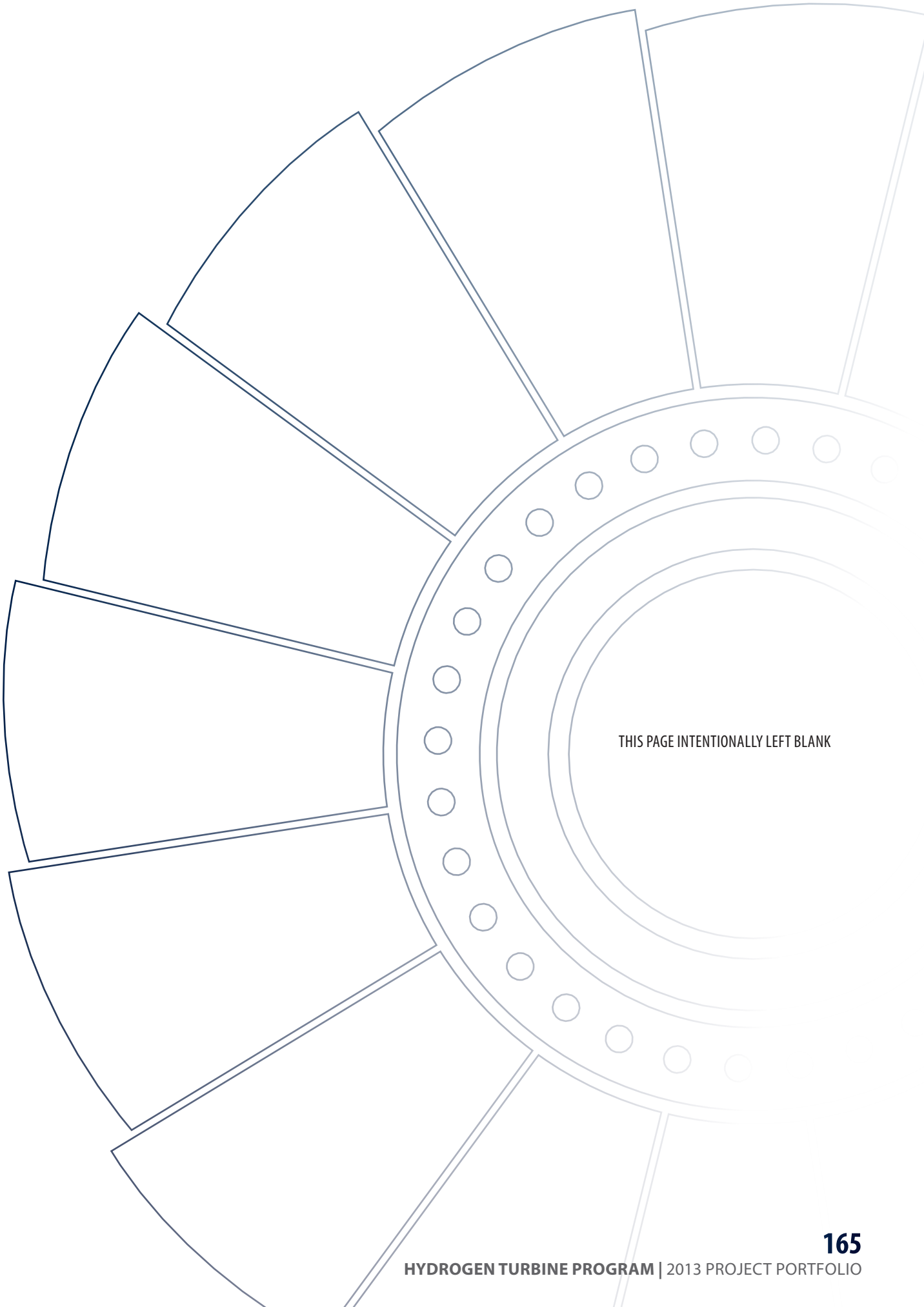
SECTION 11: **RESOURCES**

- **NETL Turbines Website:** The website provides program information, the Project Portfolio, the Program Plan, and other information. netl.doe.gov/technologies/coalpower/turbines/index.html
- **NETL Turbines Reference Shelf:** The reference shelf has links to various reports, presentations, publications, factsheets, key stakeholders, associations and other turbines websites. netl.doe.gov/technologies/coalpower/turbines/refshelf.html
- **The Gas Turbine Handbook:** The NETL Turbine Handbook provides technical information regarding the stationary power-generation gas turbine, and other turbine-based systems that are relevant to the DOE Office of Fossil Energy's Hydrogen Turbine program. netl.doe.gov/technologies/coalpower/turbines/refshelf/handbook/TableofContents.html
- **Hydrogen Turbine Technology Program Plan:** netl.doe.gov/technologies/coalpower/turbines/pdf/Program-Plan-Adv-Turbines-2013.pdf
- **Hydrogen Turbine Program 2012 Portfolio:** netl.doe.gov/technologies/coalpower/turbines/refshelf/turbine_annual_report_2012_web.pdf
- **University Turbines Systems Research Program:** netl.doe.gov/technologies/coalpower/turbines/projects.html
- **Links to Professional Associations/Organizations:**
  International Gas Turbine Institute (IGTI) of ASME: igti.asme.org/
  Gas Turbine Association: gasturbine.org/



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Hydrogen Turbine Program
2013 Project Portfolio