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

CONTACTS

Richard A. Dennis
Technology Manager, Turbines
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4515
richard.dennis@netl.doe.gov

Mark C. Freeman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-6094
mark.freeman@netl.doe.gov

James F. Driscoll
Co-Principal Investigator
Aerospace Engineering
University of Michigan
3004 FXB Building
Ann Arbor, MI 48109
734-936-0101
jamesfd@engin.umich.edu

Matthias Ihme
Co-Principal Investigator
Mechanical Engineering
Stanford University
488 Escondido Mall, Bldg. 500, Rm. 500A
Stanford, MI 94305
650-724-3730
mihme@stanford.edu

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

PROJECT DURATION

Start Date 10/01/2011

End Date 09/30/2014

COST

Total Project Value
$570,537

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

AWARD NUMBER
FE0007060

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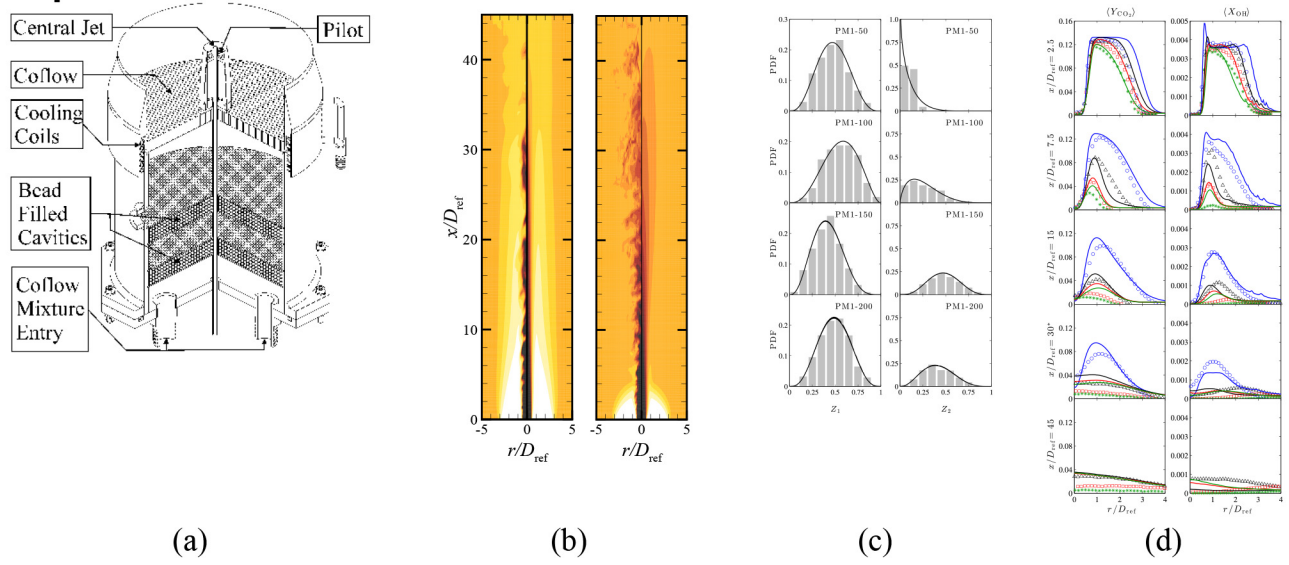
Figure 1. Large-eddy simulation of a piloted partially-premixed burner, showing (a) experimental configuration, (b) comparison of temperature fields between two operating conditions, (c) comparison of modeled and experimental probability density function of scalar field quantities (mixture fraction and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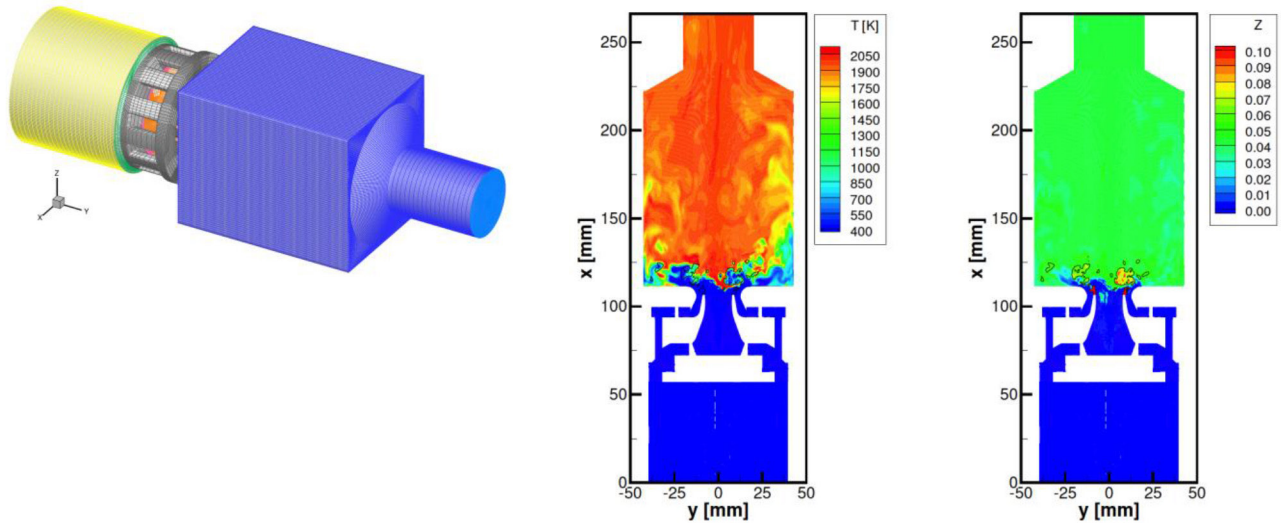

Figure 2. Large-eddy simulation of gas turbine model combustor, showing (left) computational mesh, (middle) instantaneous temperature field, and (right) mixture fraction field.
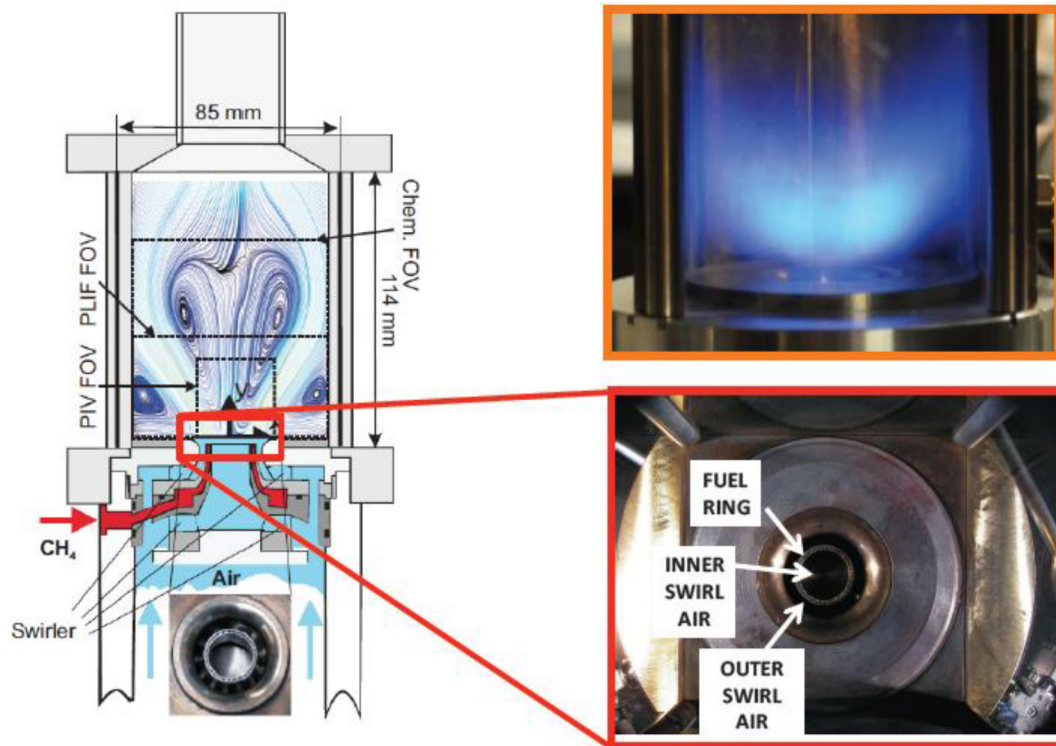
Figure 3. Illustration of Key Features of Dual-Swirl Gas Turbine Combustor with Advanced Diagnostics.