High Temperature High Velocity Direct Power Extraction Using an Open-Cycle Oxy-Combustion System

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A Giant Leap Forward
research.utep.edu/cSETR

Project Overview

Research Objectives

The overarching goal is to demonstrate the feasibility of a GCH_4/GO_2 combustor and nozzle to enable supersonic direct power extraction via MHD.

Phase 1 (November 2014 to December 2015)

Research Objective 1: Design and fabricate a laboratory-scale combustor and nozzle facility for open-cycle MHD.

Milestone 1: Complete design of system cooling

Milestone 2: Complete design of components (injector, combustor, nozzle)

Milestones 3 and 4: Fabrication of finalized system components

Phase 2 (December 2015 to December 2016)

Research Objective 2: Investigate partially premixed flame stability characteristics

Milestone 5: Flame testing to characterize injector and combustor performance

Milestone 6: Systematically characterize flame stability characteristics

Ongoing (January 2017 to June 2017)

Design and development of a 1MW scale MHD combustor

Presentation Outline

- **Project Overview**
- **Research Team**
- **Introduction**
- **Technical Approach**
- **Results**
- **1-MW Combustor Development**
- **Future work**
- **Impact**
- **Summary and Conclusions**
- **Acknowledgements**

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Research Team

Principal investigators
- Dr. Norman Love
- Dr. Ahsan Choudhuri

Ph.D. Research Assistants
- Luisa Cabrera (Accepted a position at Intel)
- Manuel Hernandez (GE Power)

MS Research Assistants
- Jad Aboud (Currently pursuing PhD at UTEP)
- Omar Vidana (Toyota)
- Brian Lovich

ME UG Research Assistants
- Analuisa Garcia (LMC)
- Gabriella Enriquez (Chrysler)

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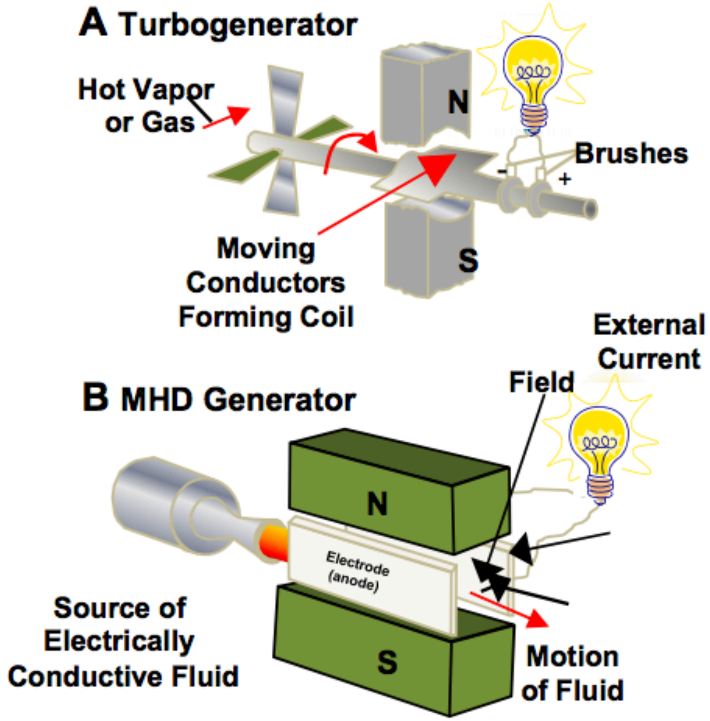
Introduction

- Development of Advanced Energy Systems (AES) is critical

- Combustion processes empower our world. However, combustion devices exhibit low conversion efficiencies and emit CO_2 into the atmosphere

- Combustion researchers are faced with
  - Creating more efficient combustion systems
  - Reducing the impact to the environment, which includes CO_2 emissions

- MHD shows promise of making Oxy-Combustion (a CCS technique) an advantageous technology for power generation



Introduction

MHD direct power extraction may enhance conversion efficiencies of current power cycles.

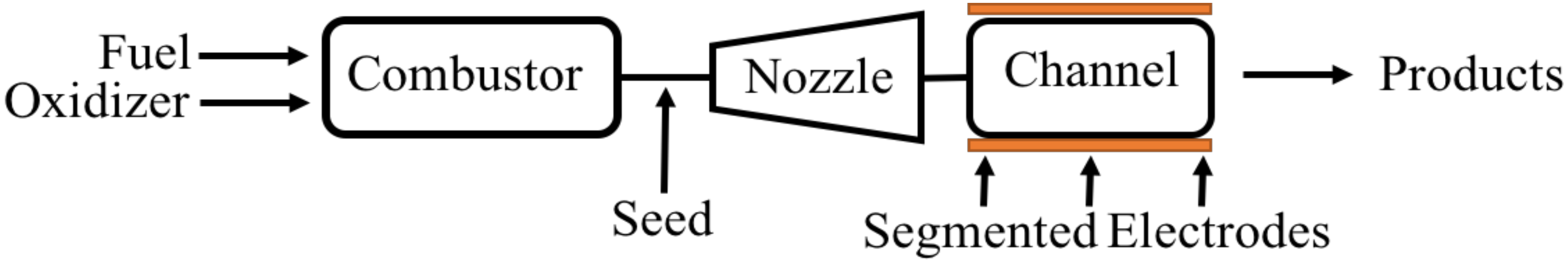
$$P \propto \sigma B^2 V^2$$

Parameter	Symbol
Conductivity	σ
Plasma/Gas Velocity	V
Magnetic Field Strength	B

<u>**In this project the following is used:**</u>

Oxy-Fuel combustion: Enhances electrical conductivities due to higher flame temperatures

Integration of supersonic nozzle: Energy extraction potential increases with Mach number up to 2.5



Introduction

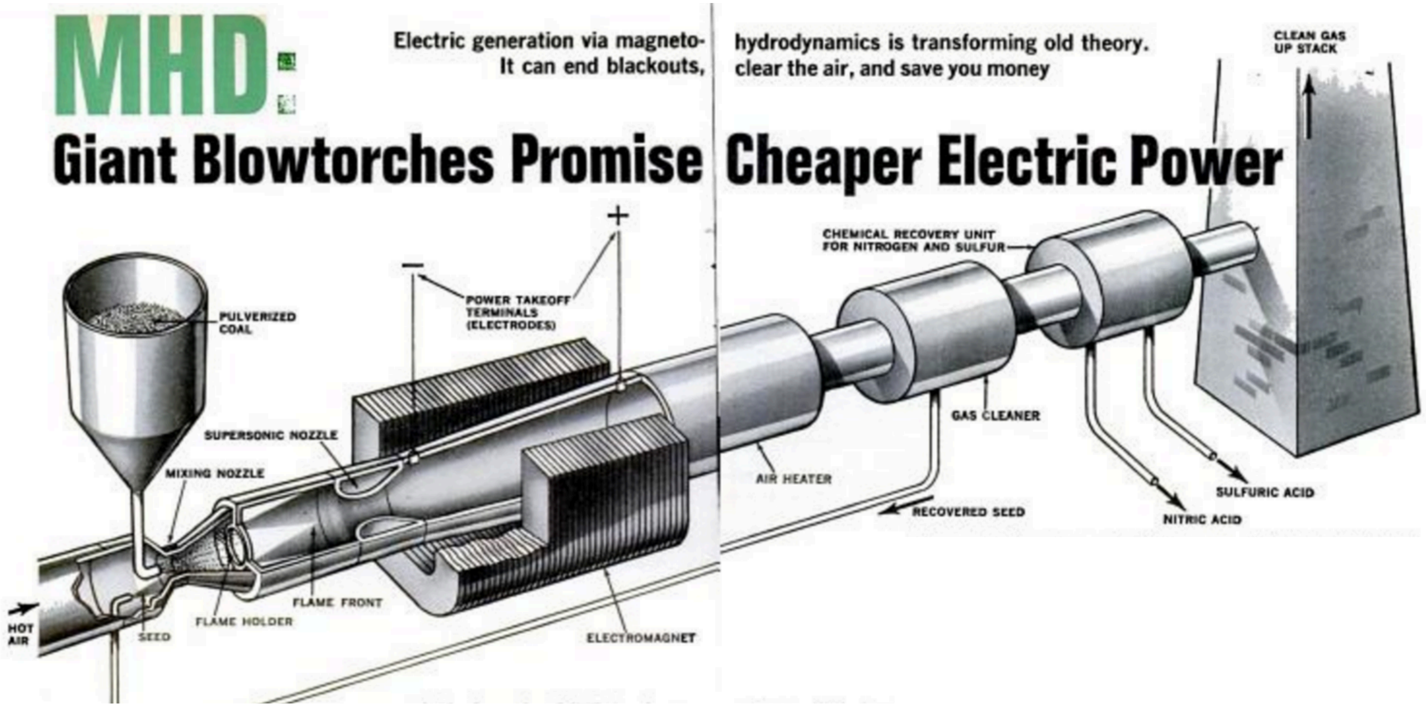
- Early and more recent MHD research has focused on subsonic MHD flows of oxy-enriched preheated air and pulverized coal combustion

	Avco Mk I	Avco Mk II	General Electric Research Laboratory	General Electric Research Laboratory	General Electric Research Laboratory	Westinghouse Model 2	Westinghouse Model 1
Working fluid	Argon and arc heater	Ethanol or keosene and oxygen	Nitrogen and plasma jet heating	Propane and oxygen	Hydrogen and air	Diesel and oxy-enriched air	n-Heptane and oxy-enriched air
Temperature, K	2800	3000	3200	2300	2550	2800-3000	2570
Gas velocity	Mach 0.7	1000 m/s	700 m/s	568 m/s	Mach 0.8	500-860 m/s	757 m/s

Source: Sutton, G., and Sherman, A. Engineering Magnetohydrodynamics, McGraw-Hill, New York, 1965.

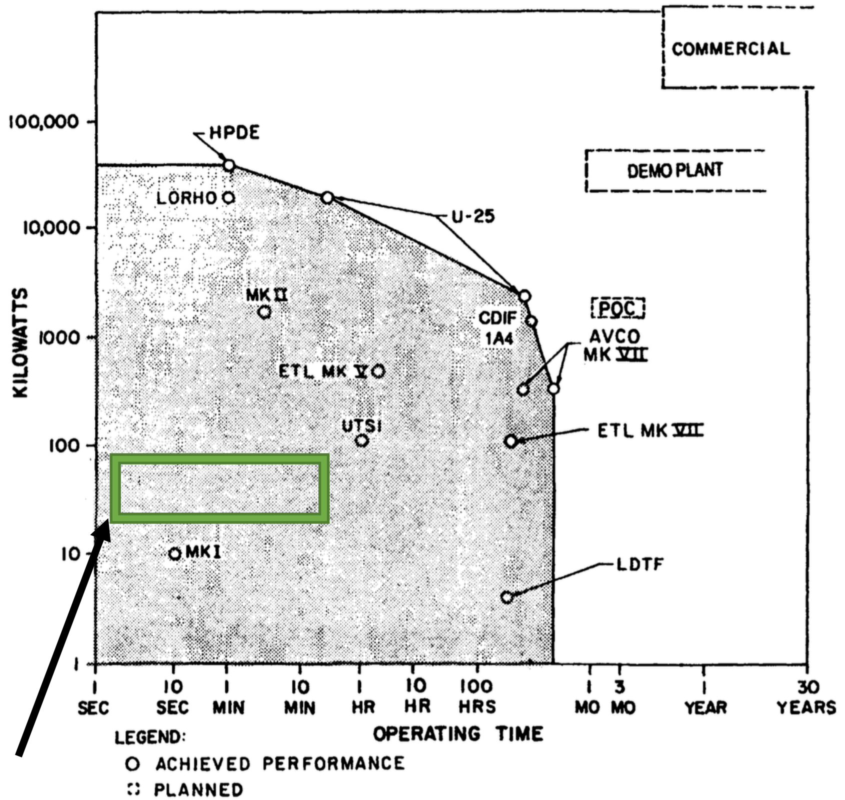
Introduction

- In the 1970s, MHD power cycles used preheated oxy-enriched air and pulverized coal
- Our aim is to use methane-oxygen combustion



Introduction

- Design and the system integration of a laboratory-scale prototype
- Combustor uses a coaxial swirl injector, combustor and nozzle system to generate high temperature gas moving at Mach 2
- Supersonic velocities of seeded combustion plasmas may lead to enhanced power output in MHD generators



60 kW Lab-Scale Region

Carlson C. P. Pian and Robert Kessler. "Open-Cycle Magnetohydrodynamic Power Generators",Journal of Propulsion and Power, Vol. 15, No. 2 (1999), pp. 195-203

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Technical Approach

Year 1

- Task 1: Design a DPE system for high temperature flows
  - Water cooled convective cooling jacket
  - Milled cooling channels
  - Wall material considerations: copper or aerospace-grade super alloy structures

- Task 2: Design a DPE system for supersonic flows of M > 1.8
  - Investigate cryogenic LOX/LCH4 igniter injector: coaxial swirl injection with tangential orifices
  - Extend nozzle geometries to meet the above supersonic criterion
  - Generate underexpanded jet flames

Year 2

- Task 3: Component and System Level Testing
- Task 4: Systematically Characterize Flame Stability Characteristics

Technical Approach

Combustor Design
- Design Requirements
- Characteristic Geometry

Swirl Coaxial Injector
- Orifice geo.
- Interfaces
- Optimization

Numerical models
- FEA
- Combustion CFD
- Coupled Heat Transfer Model

Interface Development
- Feed System integration
- Combustor manufacturing

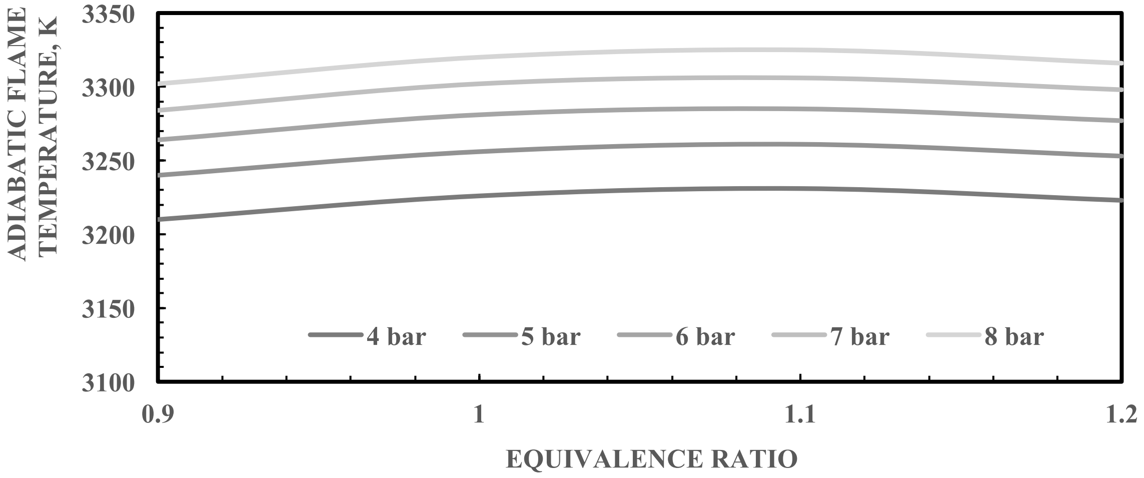
Testing Operations
- Safety checks
- Experiments
- Data post Processing

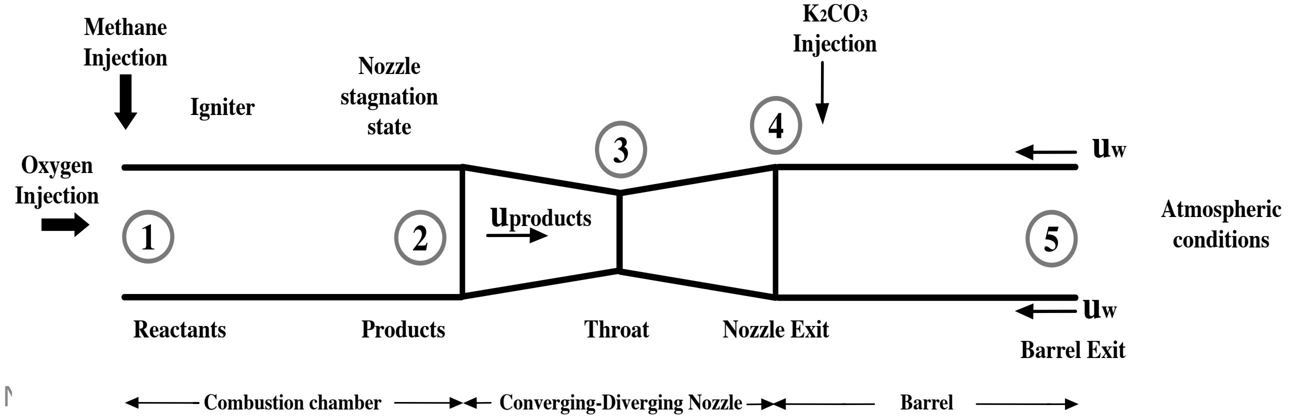
Combustor Scaling Study

Technical Approach

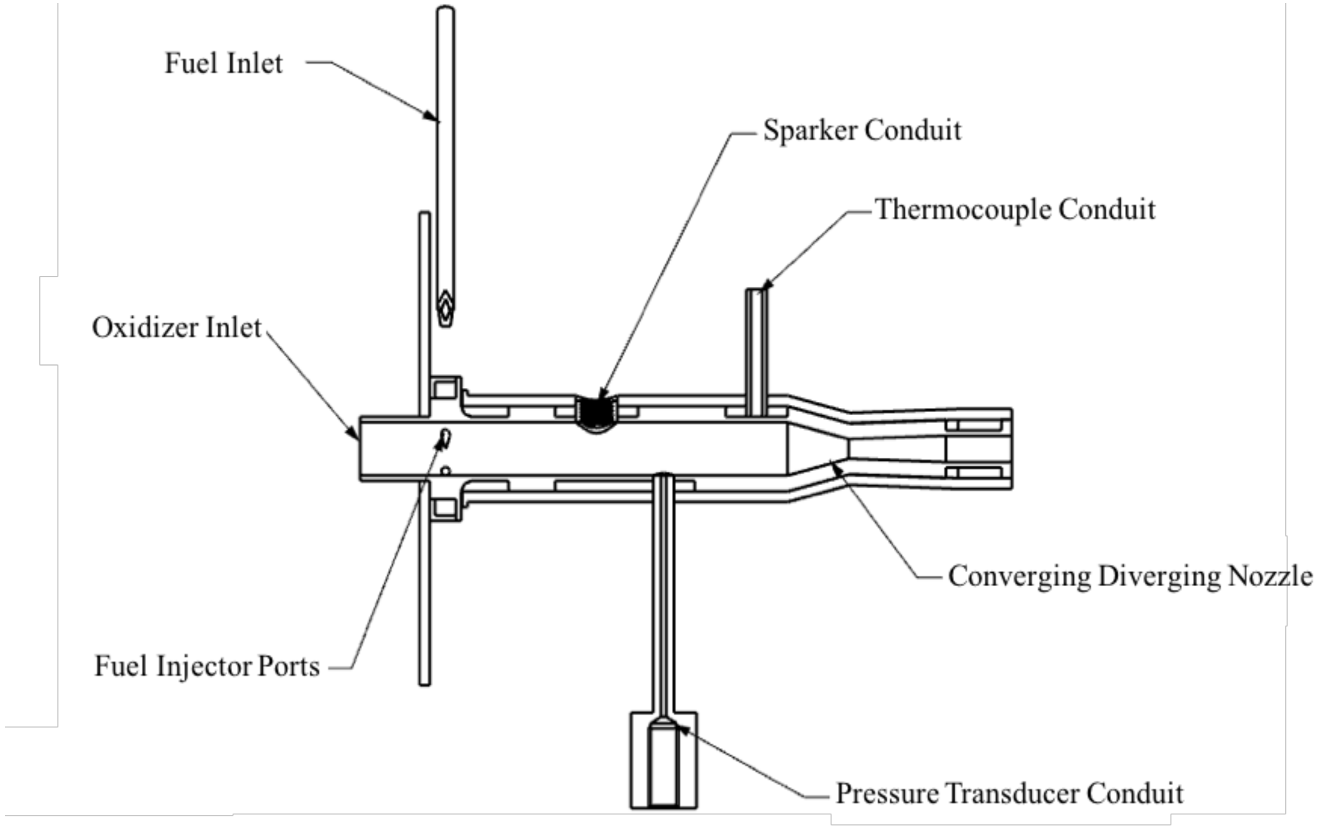
60 kW Combustor

- Flame temperature/combustion pressure study yielded operational parameters of 4-8 bar
- Thermal protection system based on regenerative cooling in rocket engines
- Models developed for swirl-coaxial injector optimization
- Computational combustion model compared exit parameters to isentropic flow equations
- Finite element study using superalloy Inconel 718
    - Higher strength of material/ 3D printing cap.



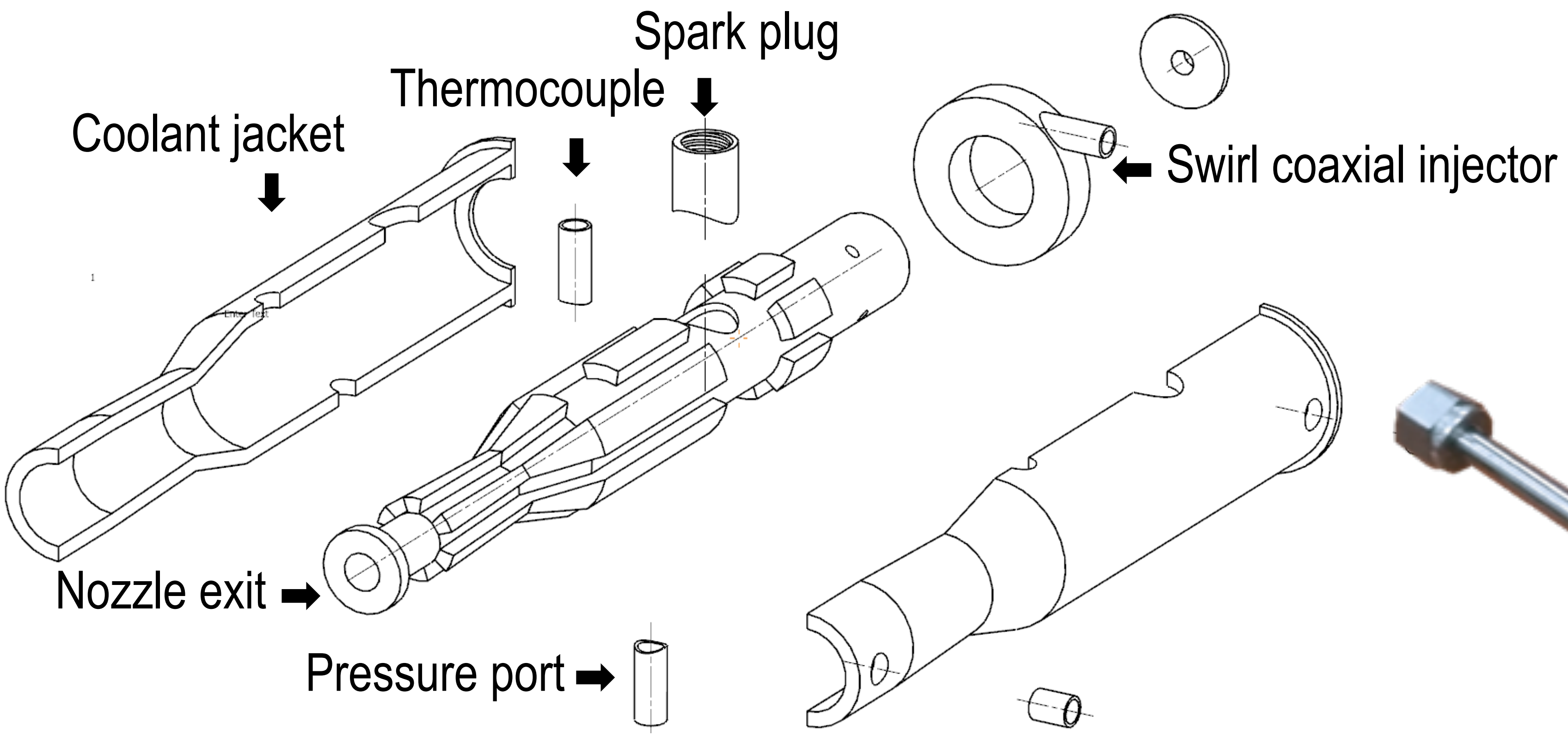


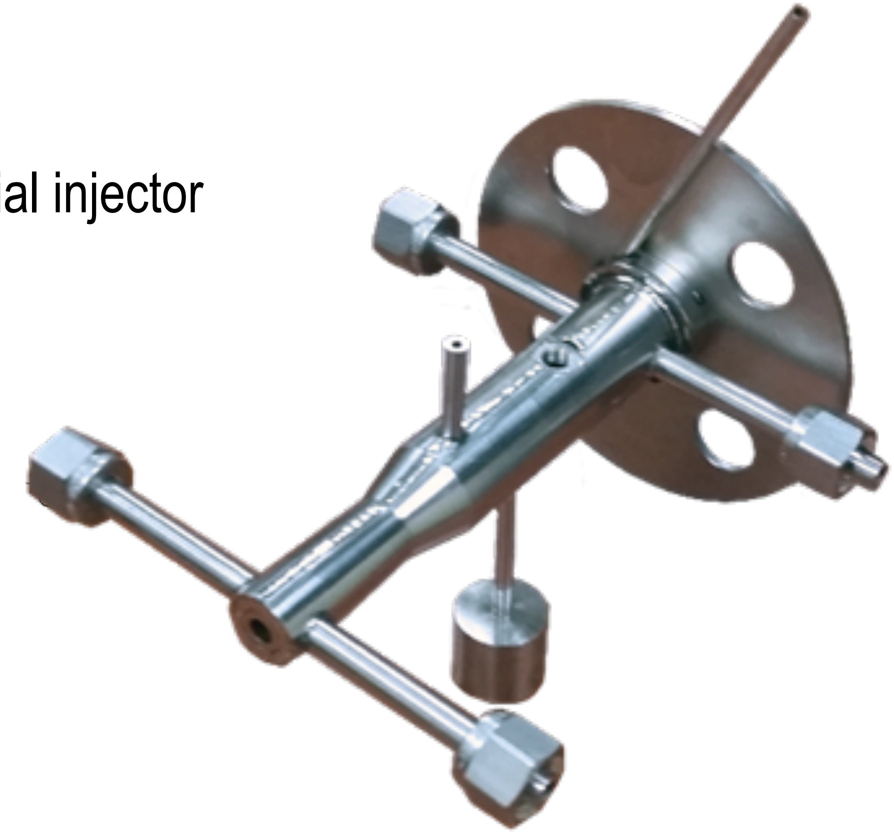
Technical Approach



- **CH_4/O_2 DPE Combustor**
  - Coaxial tangential swirl injector
  - Fuel-rich to stoichiometric conditions
  - Combustion pressures: 5-9 bar
  - Nozzle exit conditions of supersonic velocities (near Mach 2) and 2800 K
  - Cooling system for long-burn times
  - Inconel 718

Technical Approach

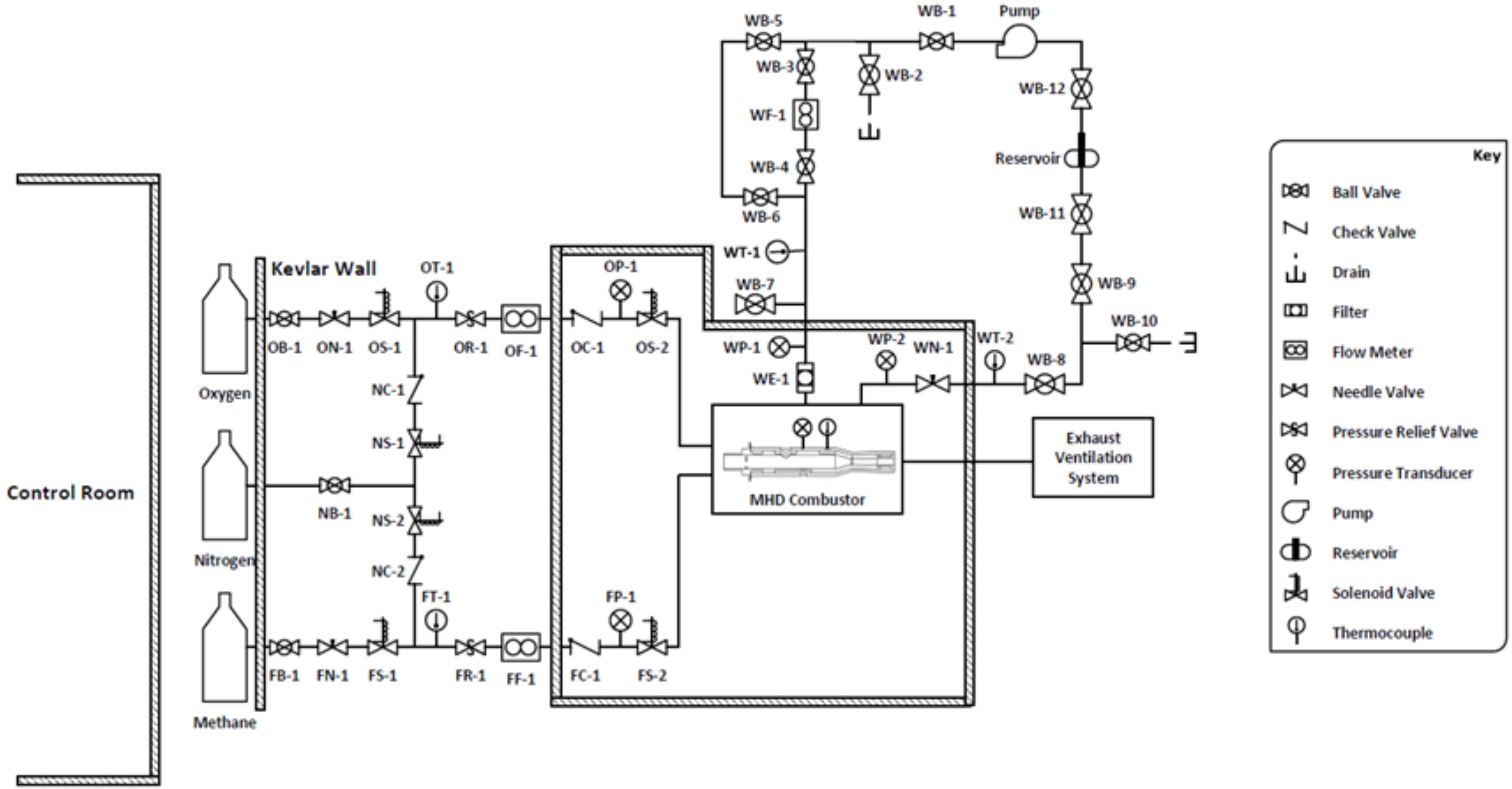




Exploded View

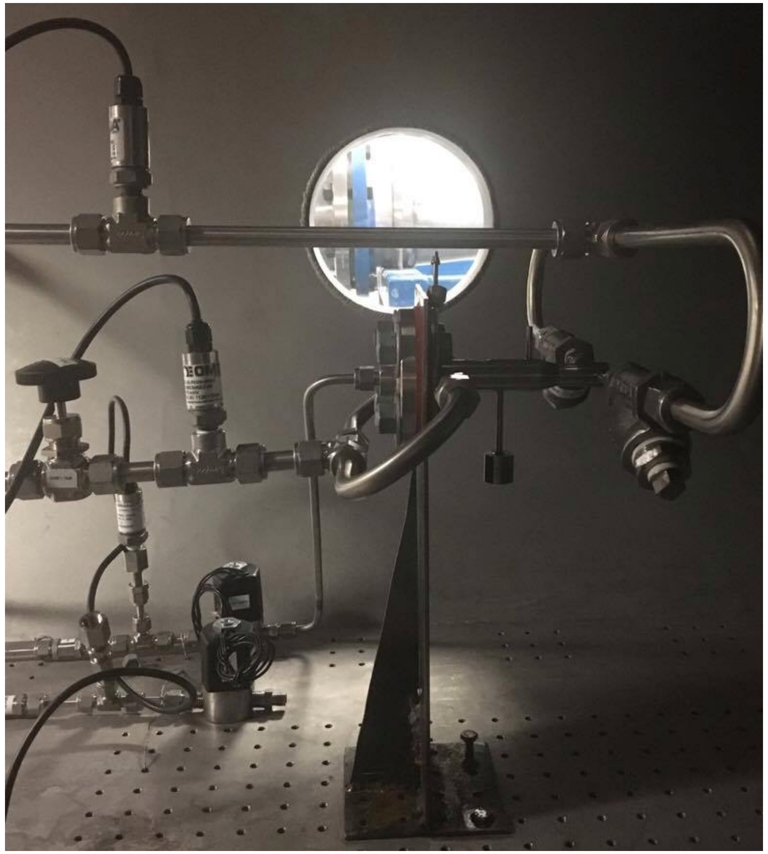
Final Product

Technical Approach



Technical Approach

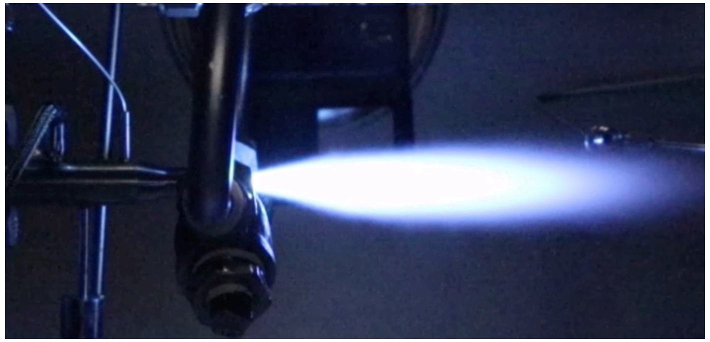
Feed System



Combustor Setup

Technical Approach

Test Parameter		Units
Chamber Pressure	760	kPa
Mass Flow Rate	4.5	g/s
Minimum test time	2	s
Maximum test time	300	s
Minimum O/F	2	-
Maximum O/F	4	-
Total Tests	60	-
Total burning time	1750	s



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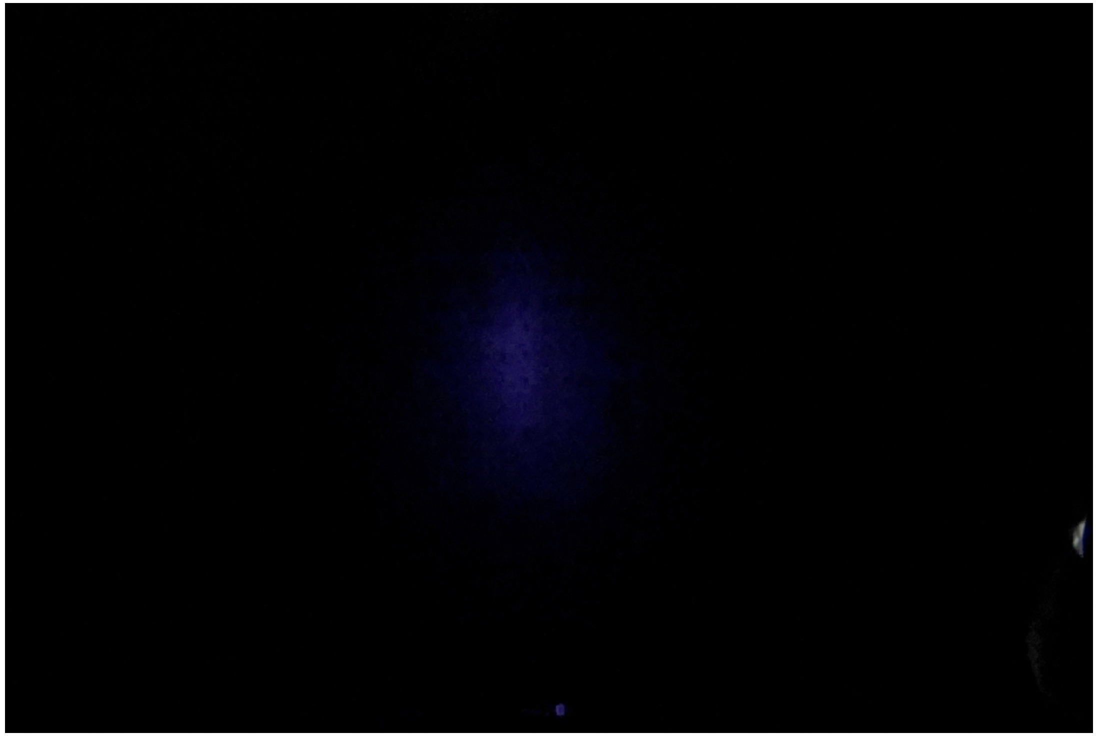
Results

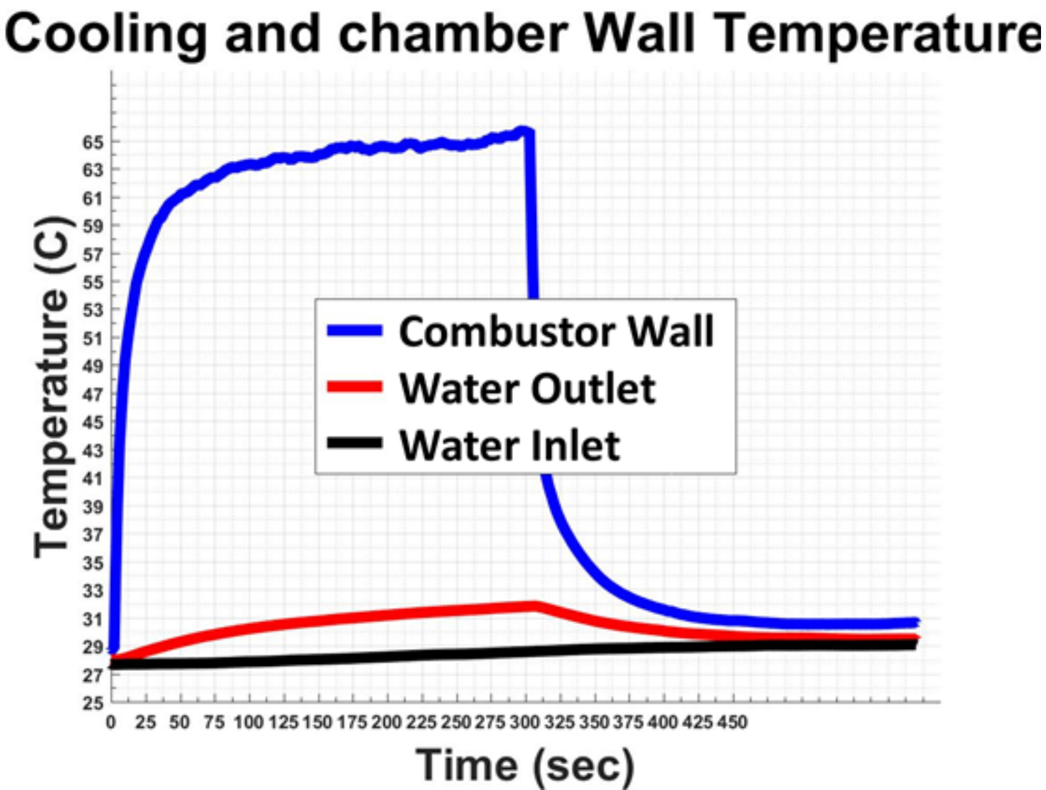
O/F = 4

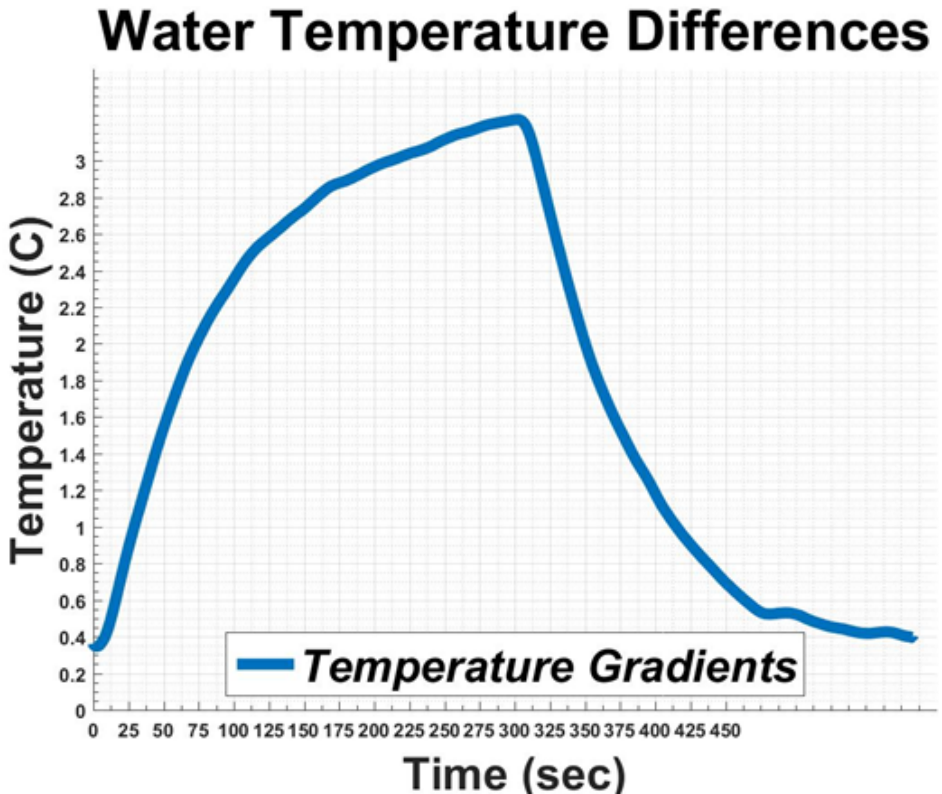


O/F = 4

Results

Test Parameters	
Operating chamber pressure (psi)	110
Test time (s)	300
Oxidizer to Fuel Ratio	4





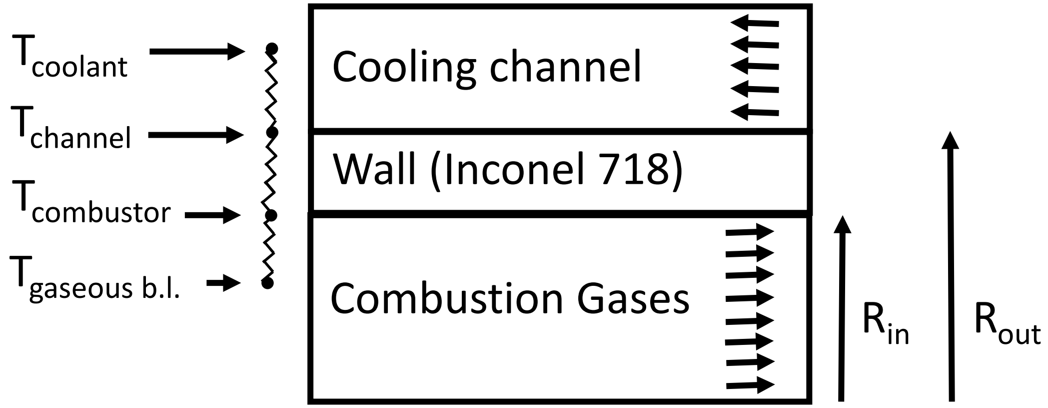
Results

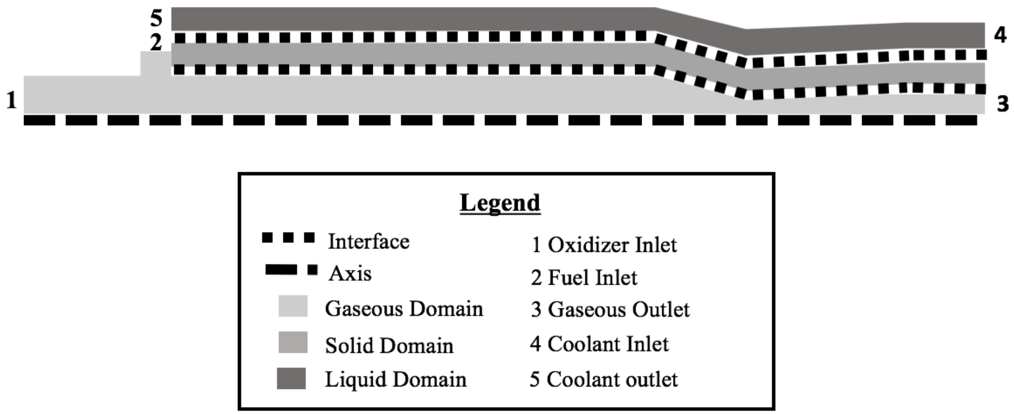
Thermal Model
- Purpose: Establish design methodology for high heat flux systems (1 MW combustor)

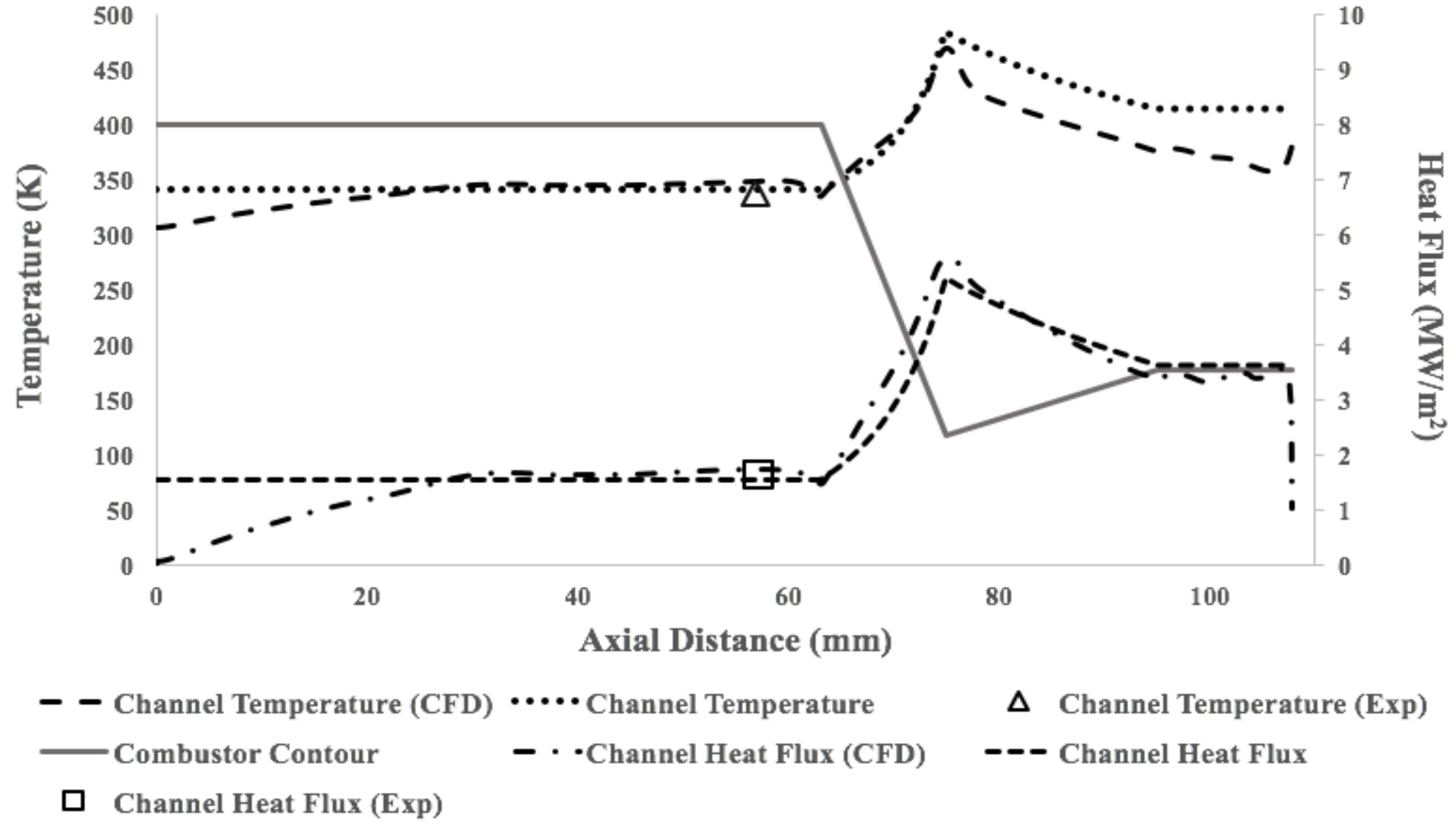
Analytical
- 1-D approach to conduction equation
- Thermal resistance system

Numerical
- Fully-coupled 2-D CFD model
  - Non premixed combustion
  - Wall conduction
  - Channel flow

- Results compared to experimental data







Parameter	2-D CFD	Experimental	Analytical	Units
Temperature gained by coolant	2	3.2	4.2	K
Localized chamber temperature	346	338	338	K

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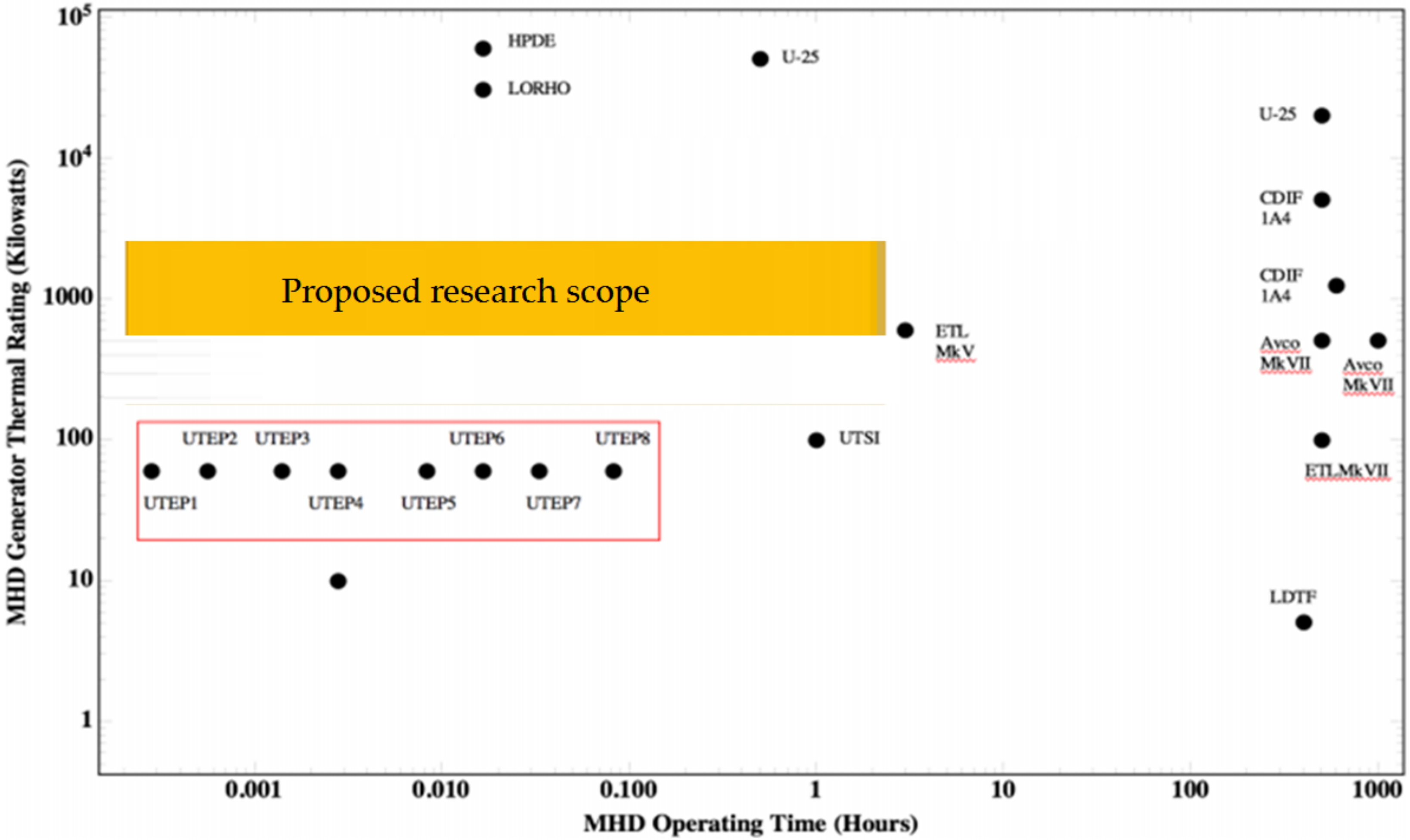
1-MW Combustor Development

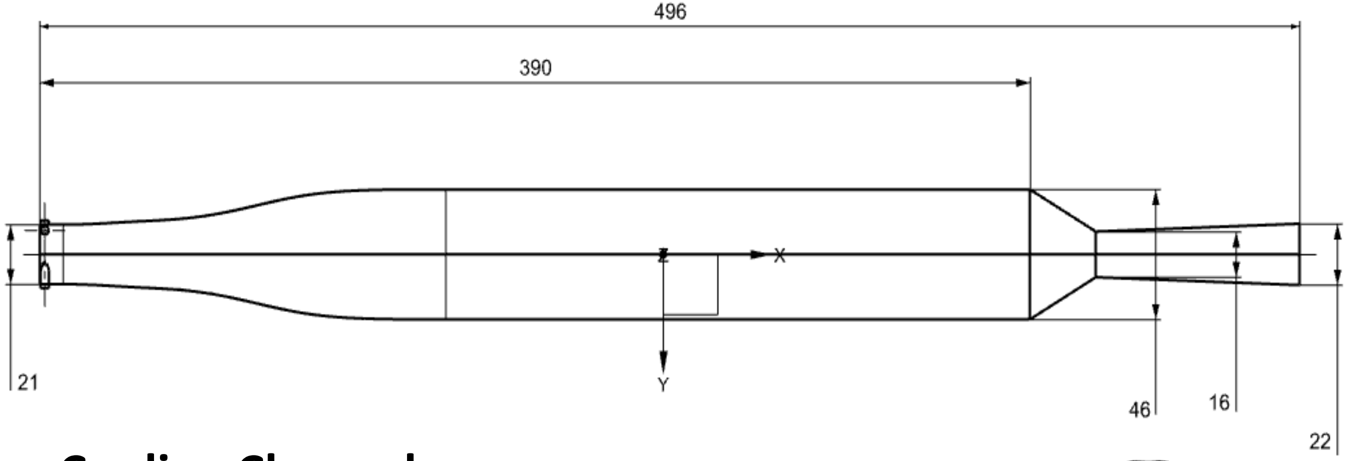


1-MW Combustor Development

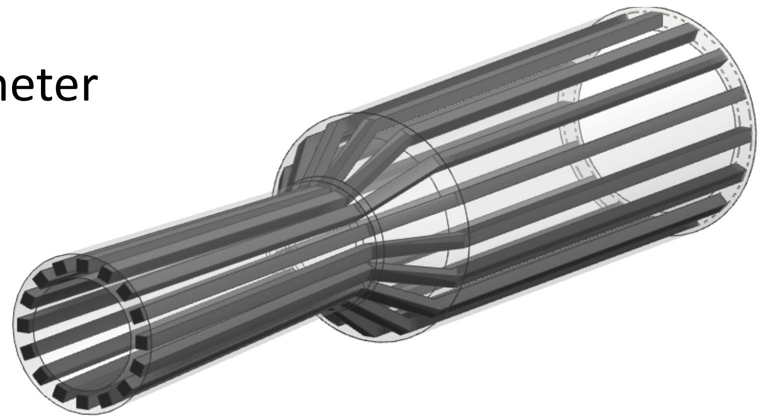
Requirements
2800 K (exit)
Mach 1.9 (exit)
1 MW thermal input

Scaling Non-Dimensional Parameters
Schmidt number
Prandtl number
Nusselt number
Mach number
Specific heat ratio
Momentum Flux Ratio

Preliminary Design
(units in mm)



Cooling Channels
2 mm hydraulic diameter



1-MW Combustor Development

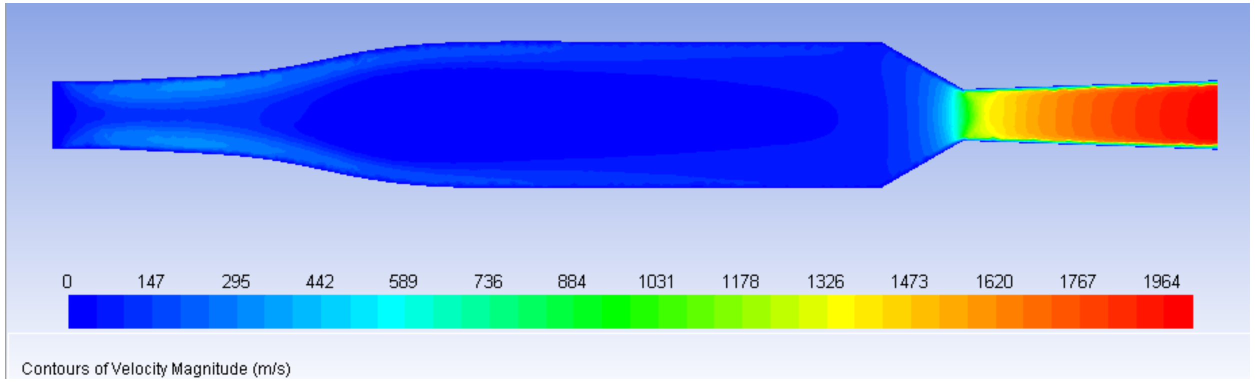
Parameter name	Symbol	Value	Units
Equivalence ratio	φ	1.1	
Total mass flow rate	$\dot{m}_{total}$	0.083	kg/s
Minimum total injection pressure	p_{inj}	123	psi
CH_4 temperature	T_f	298	K
CH_4 density	ρ_f	0.67	kg/m^3
CH_4 mass flow rate	$\dot{m}_f$	0.0180	kg/s
CH_4 volumetric flow rate	$\dot{V}_f$	1610	slpm
O_2 temperature	T_{ox}	298	K
O_2 density	ρ_{ox}	1.297	kg/m^3
O_2 mass flow rate	$\dot{m}_{ox}$	0.0653	kg/s
O_2 volumetric flow rate	$\dot{V}_{ox}$	3000	slpm

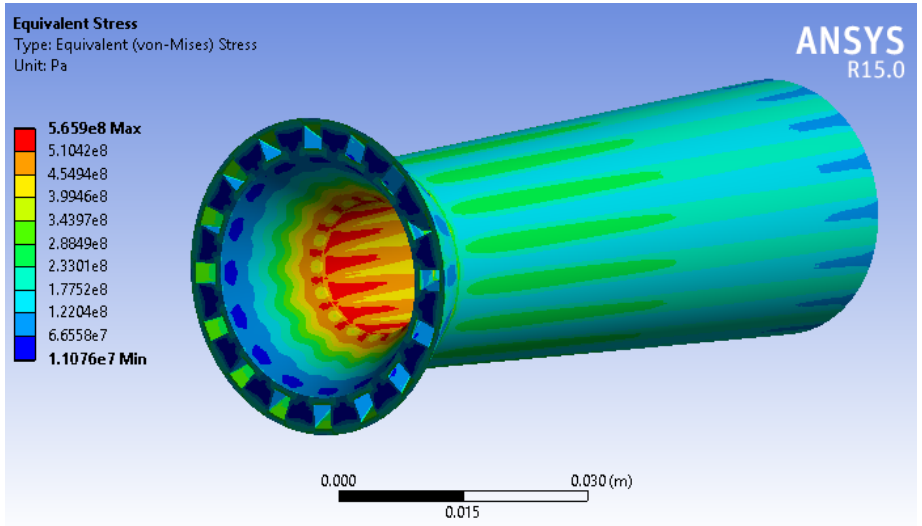
1-MW Combustor Development

CFD Investigation

Velocity
CEA: 1980 m/s
ANSYS: 1950 m/s
Error: 1.5%

Temperature
CEA: 2920 K
ANSYS: 2810 K
Error: 4.1%





FEA Stress Investigation
Thermal + Mechanical

Analytical Method: 570 Mpa (maximum)
Numerical Method: 565 Mpa (maximum)

Factor of Safety
1MW: 1.75
60 kW: 1.5

$$S_t = \frac{(p_{co} - p_g)r}{t} + \frac{Eaqt}{2(1-v)k}$$

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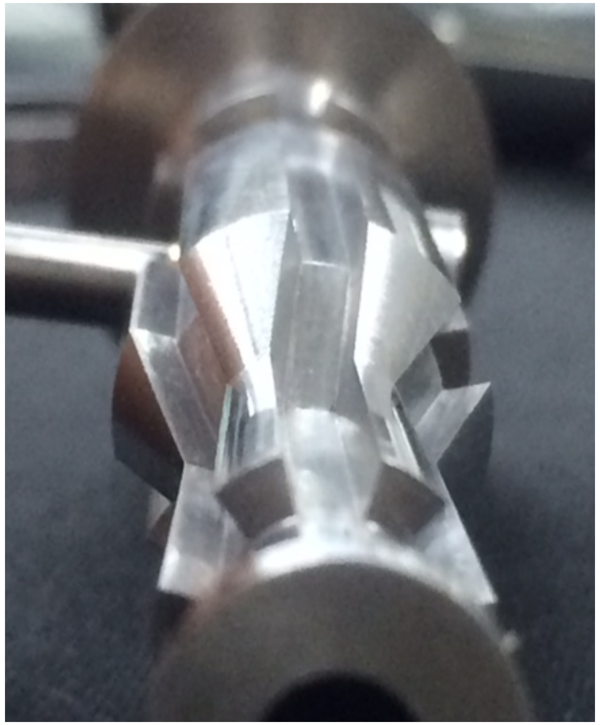
Future Work

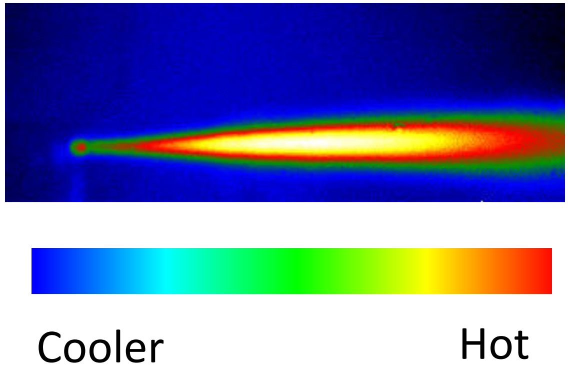
- **1-MW combustion system**
  - Cooling channel aspect ratio optimization
    - CFD
  - Placement of temperature/pressure sensors
  - Manufacturing
  - Analysis of combustion stability
  - Seed injection parameters
  - Design of feed system interfaces



Future Work

- **Flame Temperature Measurement**
  - Heat flux estimate and verification
    - Thermal Camera
    - High Temperature Pyrometer
  - Integration of monochromator
  - Estimation of flame emissivity

Image from the thermal camera



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Impact

Collaborative experiences at NETL in Albany, OR

- Manuel J. Hernandez (Summer 2015)
- Brian Lovich (Summer 2016)

Awards and Honors

- Selected for AIAA Sci-Tech 2016 Terrestrial Energy Best Paper Award
- Ph.D. Research Assistants attended the 2016 Combustion Energy Frontier Research Center Combustion Summer School at Princeton University

Students Graduated

- Manuel J. Hernandez (PhD in Mechanical Engineering)
- Jad G. Aboud (MS in Mechanical Engineering)
- Omar Vidana (MS in Mechanical Engineering)

Impact

Publications

- Cabrera, L., Choudhuri, A., and Love, N., ”Heat Transfer Characterization Methodology for an Oxy-Fuel Direct Power Extraction Combustion System,” (Under Review)

- Luisa A. Cabrera, Jad G. Aboud, Manuel J. Hernandez, Brian Lovich, Ahsan Choudhuri and Norman D. Love. “Heat Transfer Characterization of a High Heat Flux Oxy-Fuel Direct Power Extraction Combustor”, 55th AIAA Aerospace Sciences Meeting, Grapevine, TX, (AIAA 2017-1606)

- Manuel J. Hernandez, Luisa A. Cabrera, Omar Vidana, Mariana Chaidez, and Norman D. Love. "Design of a Supersonic Oxy-Methane Combustor for Direct Power Extraction", 54th AIAA Aerospace Sciences Meeting, San Diego, CA, AIAA 2016-0243

- Omar Vidana, Mariana Chaidez, Brian Lovich, Jad Aboud, Manuel J. Hernandez, Luisa A. Cabrera, andNorman D. Love. "Component and System Modeling of a Direct Power Extraction System", 54th AIAA Aerospace Sciences Meeting, AIAA SciTech, (AIAA 2016-0990)

- M. Hernandez, L. Cabrera, A. Choudhuri, and N. Love. Flame stability of Supersonic Oxy-Methane Flames for Direct Power Extraction, 2016 AIAA Propulsion and Energy Forum and Exposition.

- 2015 and 2016 Southwest Emerging Technologies Symposiums Technical papers (4)

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Summary and Conclusions

- A coaxial swirl injector, 60 kW combustor, and nozzle have been developed and constructed for use in direct power extraction systems
  - Component and system modeling efforts of the 60kW combustor has been documented
  - System integration in the MHD experimental facility was completed

- Computational models for heat transfer characterization were developed and compared to experimental data

- Preliminary design parameters and analysis for 1-MW combustor have been developed
  - Heat transfer optimization of 1-MW combustor are underway

Acknowledgements

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Thank you