HIGH TEMPERATURE HIGH VELOCITY DIRECT POWER EXTRACTION USING AN OPEN-CYCLE OXY-COMBUSTION SYSTEM

AOI: ADVANCE TOPPING CYCLES TO IMPROVE POWER PLANT PERFORMANCE

SUBTOPIC 7-A: COMPONENT LEVEL DEVELOPMENT TO ENABLE DIRECT POWER EXTRACTION

Manuel Hernandez, Luisa Cabrera, Brian Lovich, Omar Vidana, Jad Aboud, Norman Love and Ahsan Choudhuri

MIRO NASA Center for Space Exploration and Technology Research
Department of Mechanical Engineering
The University of Texas at El Paso

Innovative Energy Concepts

DE-FE-0024062

2016 CROSSCUTTING RESEARCH & RARE EARTH ELEMENTS: PORTFOLIOS REVIEW

APRIL 18-22, 2016, PITTSBURGH, PA

THE UNIVERSITY OF TEXAS AT EL PASO
CENTER FOR SPACE EXPLORATION TECHNOLOGY RESEARCH

NASA

U.S. DEPARTMENT OF
ENERGY

MHD Research Group at the University of Texas at El Paso

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

- ME Ph.D. Research Assistants and Project Leads
  - Manuel Hernandez
  - Luisa Cabrera

- ME MS research assistants
  - Brian Lovich
  - Jad Aboud
  - Omar Vidana

- ME UG Research Assistants
  - Analuisa Garcia
  - Gabriella Enriquez

Presentation Outline

- Introduction
- Project Overview
- Background
  - Previous work in LOX/CH4 Torch Igniters
  - Previous work in Oxy-Combustion HVTS guns
- DPE Component-level Developments
- System Integration in MHD DPE Experimental Facility
- Future work
- Impacts
- Summary and Conclusions
- Acknowledgements

Introduction

Introduction

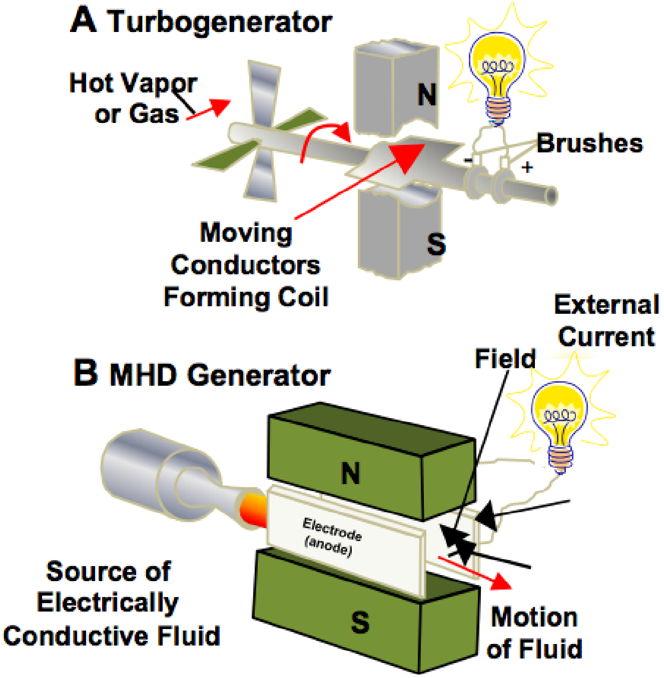
- The development of Advanced Energy Systems (AES) is critical to our future.
- Combustion processes empower our world and our modern society. However, combustion devices of today exhibit low conversion efficiencies, despite significant progress in the last decades

This opportunity for enhanced efficiencies motivates advances in combustion theory and in practical combustion devices.

Combustion researchers are faced with

  - Creating more efficient combustion systems
  - Reducing the impact to the environment

AESs, such as MHD direct power extraction, may enhance conversion efficiencies of current power cycles.



Introduction

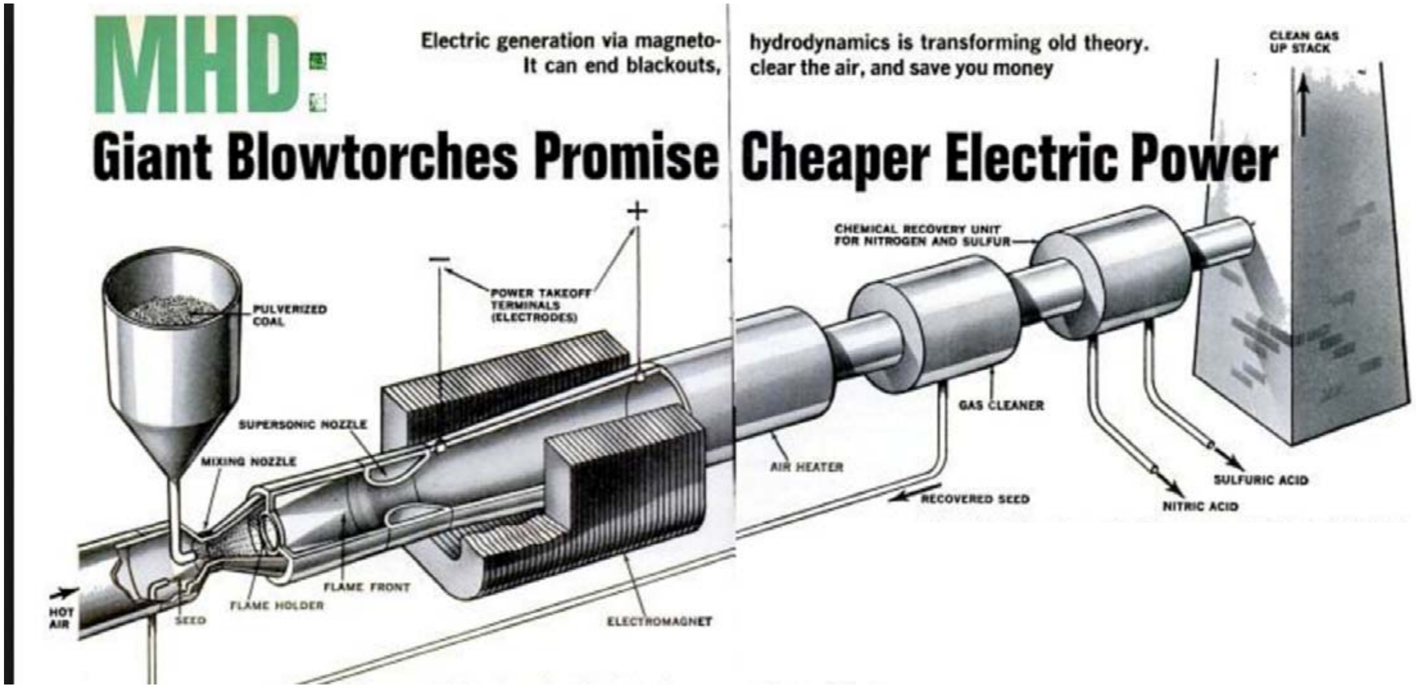
- **Early and more recent MHD research has focused on subsonic MHD flows of oxy-enriched preheated air and pulverized coal combustion**
- **The exception is the work of natural gas MHD in Russia**

MHD characteristics	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.

In the 1970s, MHD power cycles used preheated oxy-enriched air and pulverized coal

Now, our aim is to use methane-oxygen combustion



MHD: Giant Blowtorches Promise Cheaper Electric Power

Electric generation via magnetohydrodynamics is transforming old theory. It can end blackouts, clear the air, and save you money

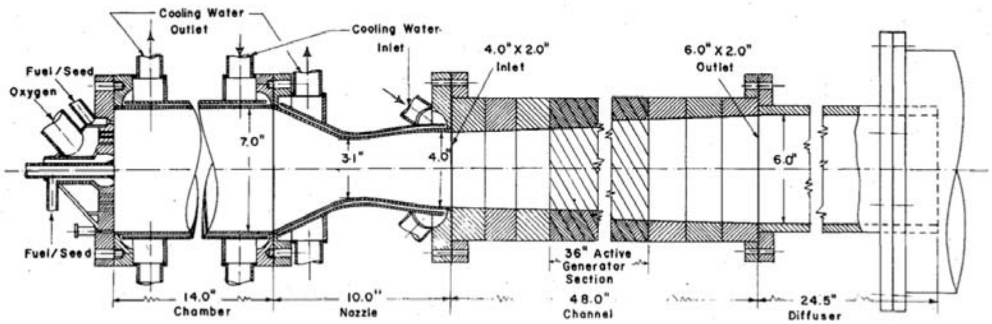
A. Freese. MHD: Giant blowtorches promise cheaper electric power. Popular Science, Vol. 194, No. 6, 1969.

Introduction

Research focus

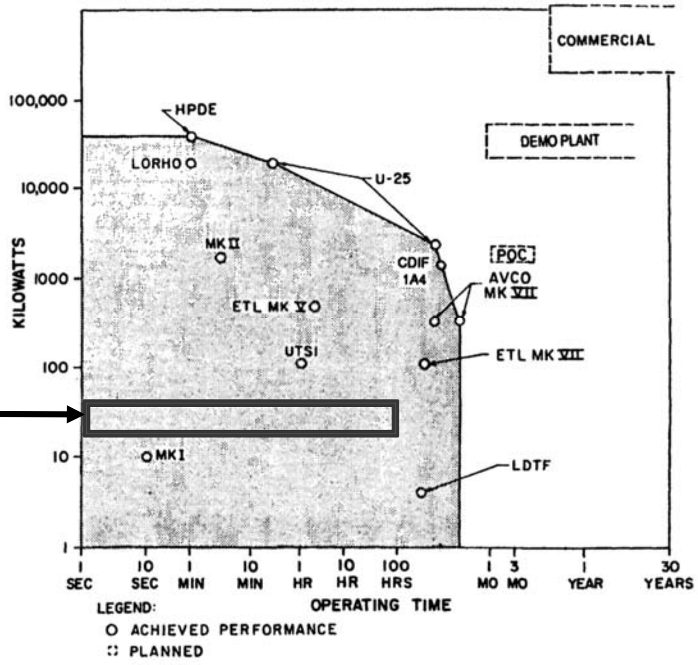
- We are developing a coaxial swirl injector, combustor and nozzle system to generate high temperature gas moving at Mach 2.
- Supersonic velocities of seeded combustion plasmas may lead to enhanced power output in MHD generators.

- **Proposition: Methane oxygen combustion may enhance electrical conductivities**
  - Higher flame temperatures
  - Copper structures were prevalently used in previous studies.
    - This is shown in Roy and Wu's work on MHD generation
    - Nickel-based super alloy structures are implemented in our design
    - Nickel based super alloys exhibit higher strength properties at elevated temperatures and distinct thermal conducting behavior than copper structures, and are prevalently used in launch vehicle propulsion systems.
  - Scaling of the turbulent combustion phenomena is an interest of this work since it affects the combustion dynamics.
  - Combustion stability problems are fundamental to the progress of AESs of large-scale MHD oxy-fired systems and these problems are addressed by investigations of fuel injection methods.



G. D. Roy and Y. C. L. Wu. "Study of Pressure Distribution Along Supersonic Magnetohydrodynamic Generator Channel", AIAA Journal, Vol. 13, No. 9 (1975), pp. 1149-1153.

- **We will discuss the design and the system integration of a laboratory-scale prototype for advanced topping cycles of MHD direct power extraction.**



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

Project Overview

Project Overview

Research objectives

- The overarching goal is to demonstrate the feasibility of a GCH4/GO2 combustor and nozzle to enable supersonic direct power extraction via MHD.
- Phase 1 (Nov., 2014-2015)
  - Research objective 1: Design and fabricate a laboratory-scale combustor and nozzle facility for open-cycle MHD.
- Phase 2 (Dec., 2015-2016)
  - Research objective 2: Investigate partially premixed flame stability characteristics

Project Overview

Tasks

Year 1

- Task 1: Design a DPE system for high temperature flows
  - Early considerations focused on LN2 coolant delivery as in space propulsion systems
  - 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

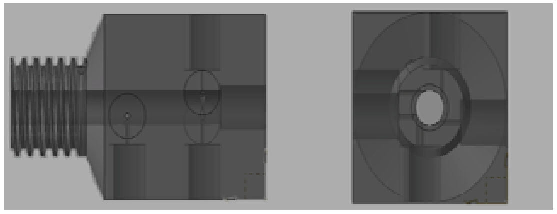
- Task 3: Component and System Level Testing
- Task 4: Systematically Characterize Flame Stability Characteristics

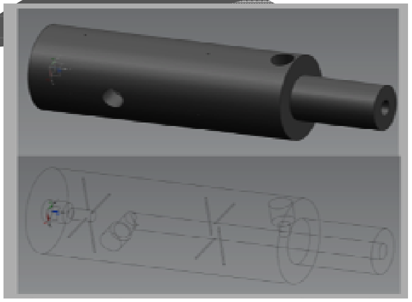
Background

Background

GOX/GCH4 AND LOX/CH4 Torch Ignition

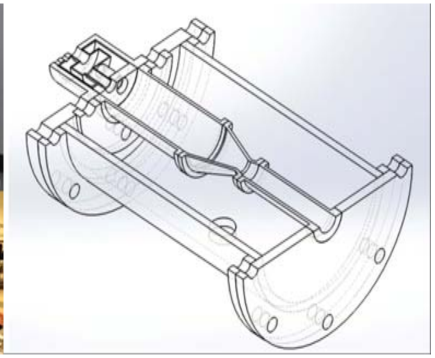
- Flores et al. "An Experimental Evaluation of a Torch Ignition System for Propulsion Research", AIAA 2013-4152
- Flores et al. "Experimental Studies of Uni-element Shear Coaxial Injectors for LOX/CH4 Propulsion Research", AIAA 2013-3851





HVTS

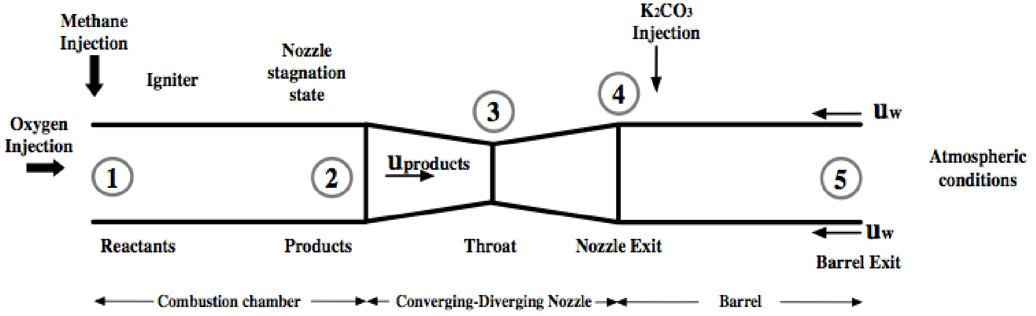
- Mohamed et al. "High Velocity Oxy Fuel Thermal Spray Gun Design", AIAA 2014-0854.
- Mohamed et al. "Flow Characterization of High Velocity Oxy-Fuel Thermal Sprays", AIAA 2014-3417).

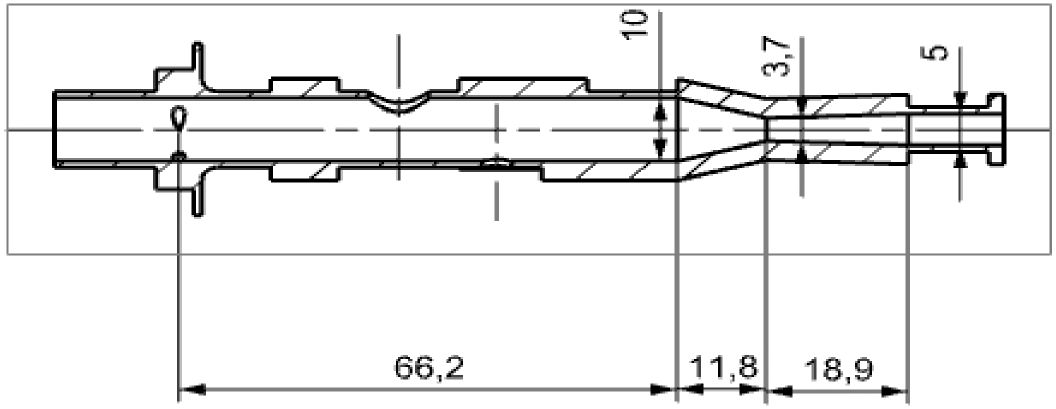


DPE Component Developments

DPE Component Developments

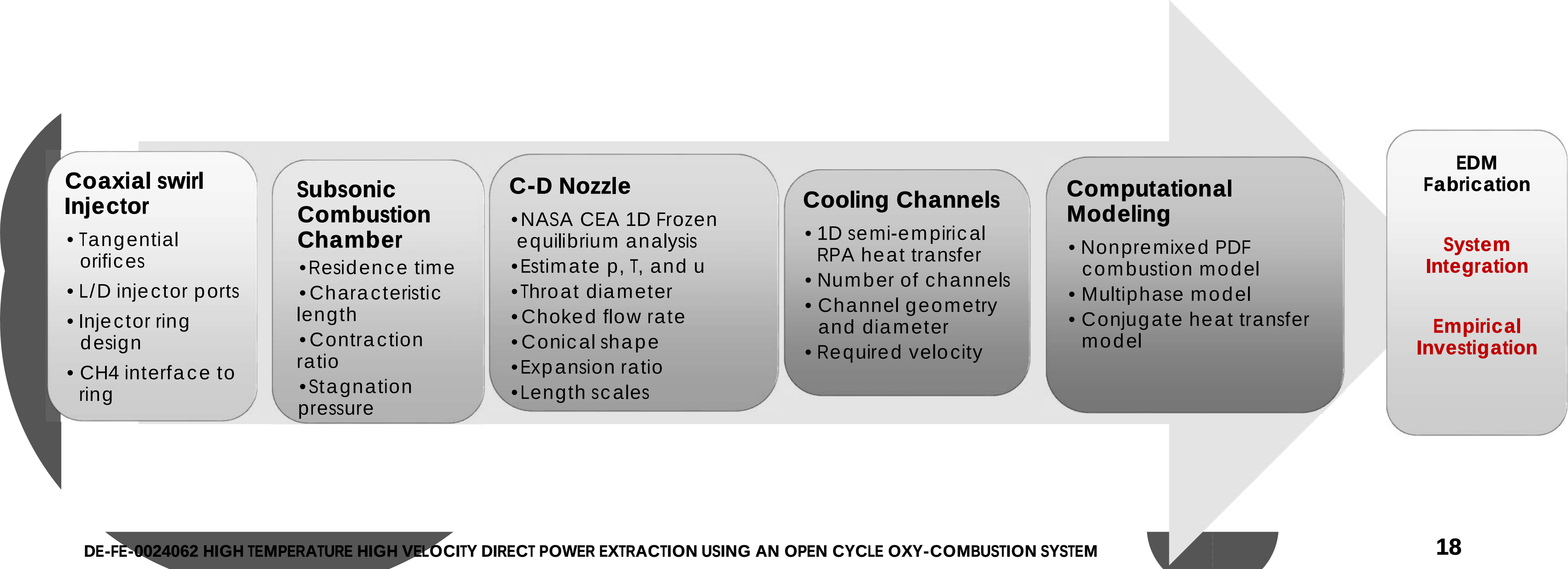
- System-level requirements for a GCH_4/GO_2 DPE Combustor
  - Coaxial tangential swirl injector
  - Fuel-rich stoichiometric conditions
  - Combustion pressures: 5-9 bar
  - Nozzle exit conditions of supersonic velocities (near Mach 2) and 3000 K
  - Cooling channels for long-burn times
  - Inconel 718 material





DPE Component Developments

- Design workflow and methods



Coaxial swirl Injector
- Tangential orifices
- L/D injector ports
- Injector ring design
- CH4 interface to ring

Subsonic Combustion Chamber
- Residence time
- Characteristic length
- Contraction ratio
- Stagnation pressure

C-D Nozzle
- NASA CEA 1D Frozen equilibrium analysis
- Estimate p, T, and u
- Throat diameter
- Choked flow rate
- Conical shape
- Expansion ratio
- Length scales

Cooling Channels
- 1D semi-empirical RPA heat transfer
- Number of channels
- Channel geometry and diameter
- Required velocity

Computational Modeling
- Nonpremixed PDF combustion model
- Multiphase model
- Conjugate heat transfer model

EDM Fabrication

System Integration

Empirical Investigation

DPE Component Developments

Computational models were used to predict combustion properties, fuel injection, and coolant flow

Method

- Used a one-dimensional compressible reacting flow analysis
- Turbulent GO2/GCH4 reactive flow fields were modeled by a non-premixed PDF method
- A multiphase model of air/methane was used to assess several coaxial-swirl fuel injections
- A k-epsilon turbulent flow model exposed to steady heat transfer was implemented

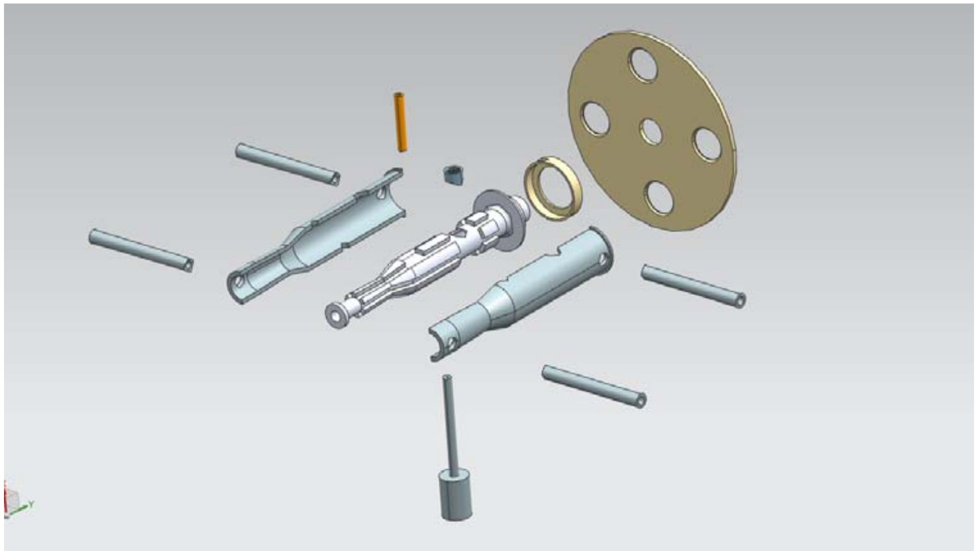
Findings

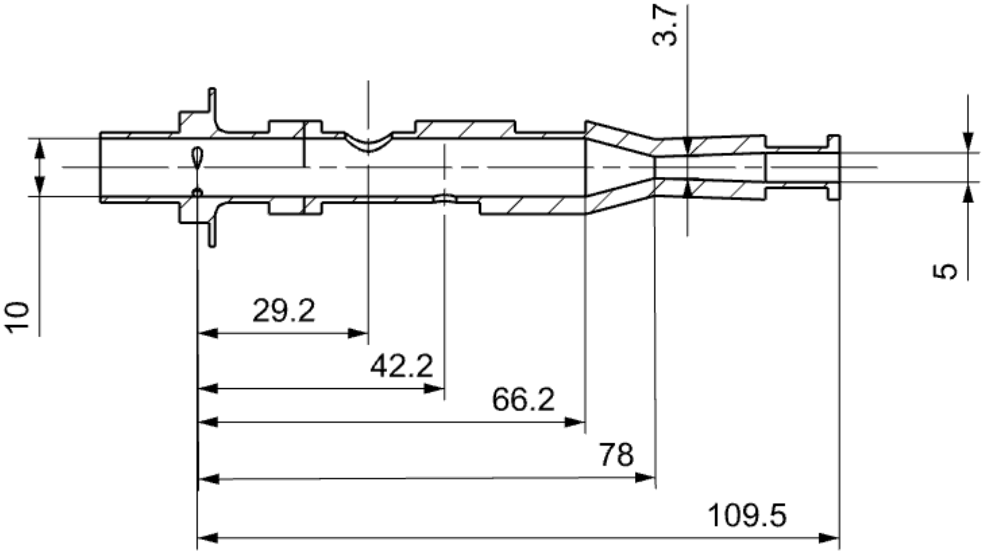
- The PDF Nonpremixed Combustion model showed close agreement of the predicted properties at the nozzle throat and exit sections and those generated by NASA's CEA code.
- Volume fraction contours from the multiphase model showed enhanced flow field using a fuel injection inlet oriented at 115 degrees in comparison with that of a 45 and tangential (180 degree) from horizontal.
- The k-e model with variable heat transfer predicted maximum static temperatures of 441 K on the cooling structure.

Vidana et al. "Component and System Modeling of a Direct Power Extraction System", AIAA 2016-0990

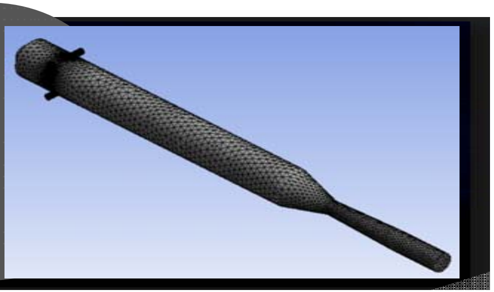
DPE Component Developments

- Schematic of the 60 kW combustion chamber and nozzle

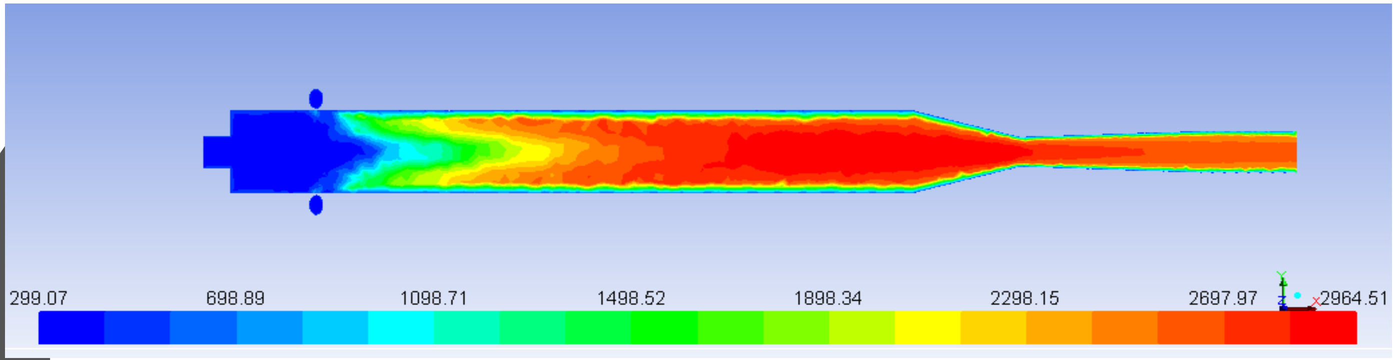


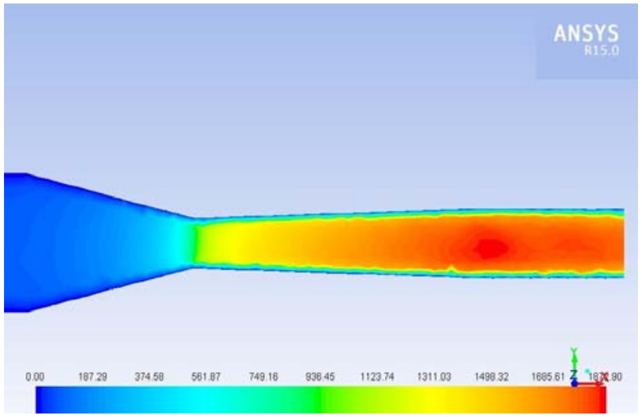


DPE Component Developments



- Turbulent non-premixed PDF combustion model

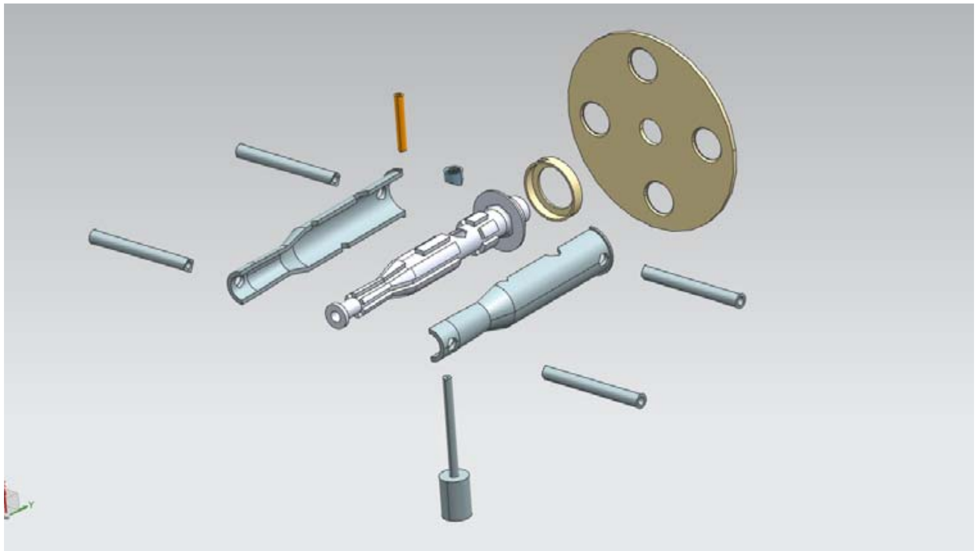


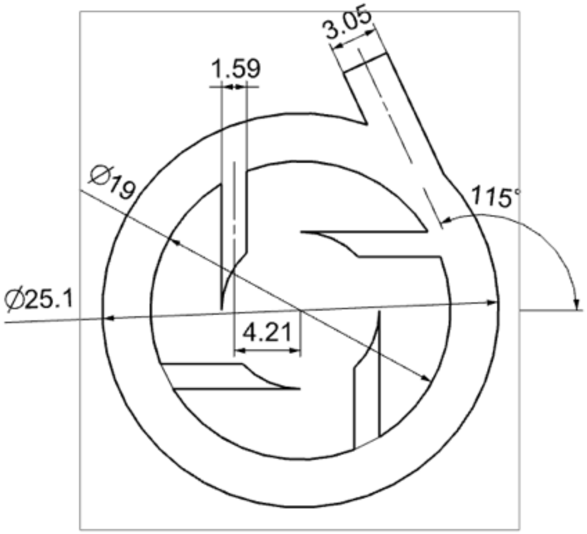


Vidana et al. "Component and System Modeling of a Direct Power Extraction System", AIAA 2016-0990

DPE Component Developments

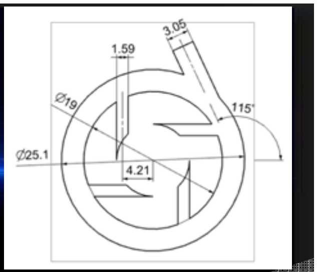
- Schematic of coaxial swirl injector



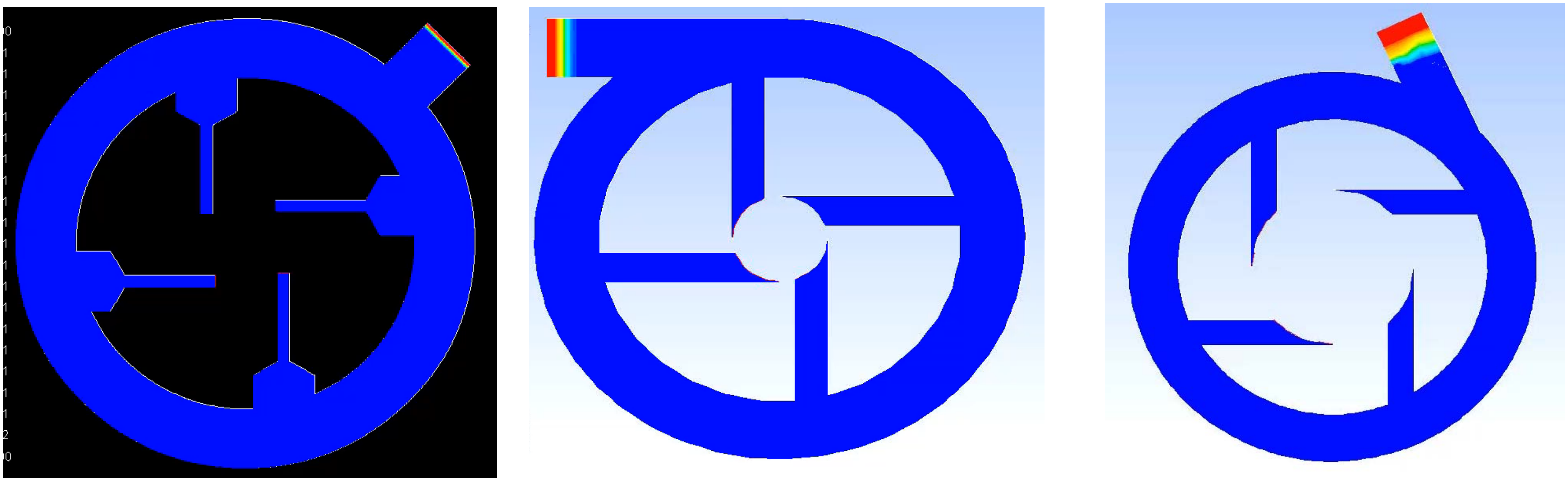


Vidana et al. "Component and System Modeling of a Direct Power Extraction System", AIAA 2016-0990

DPE Component Developments



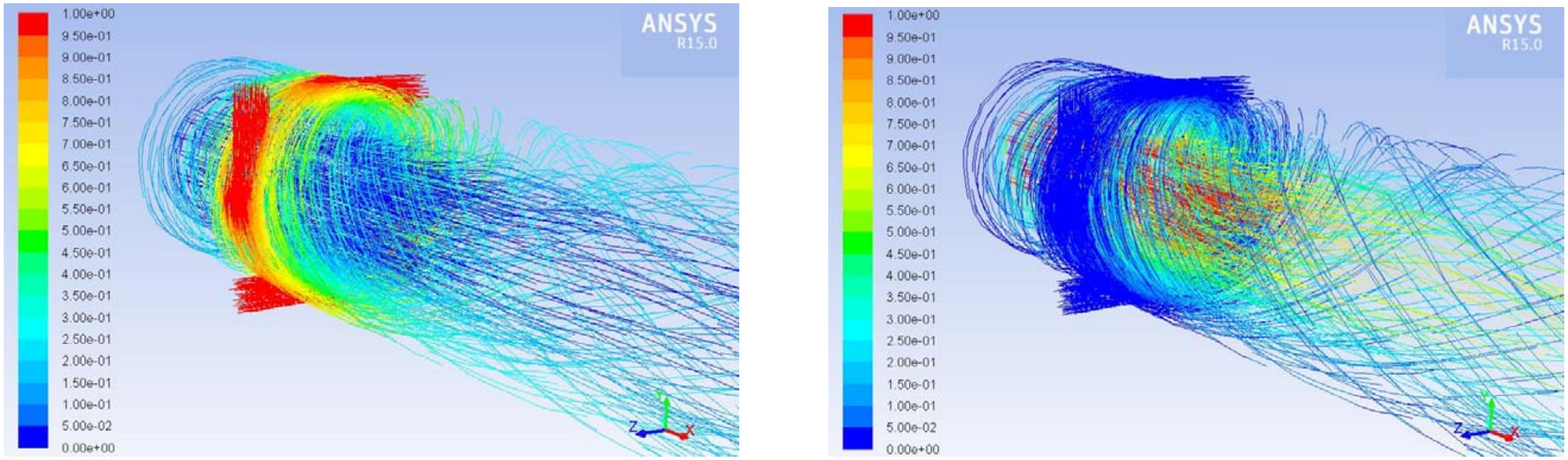
- Multiphase models of air/methane for the optimization of the fuel manifold and injection



Vidana et al. "Component and System Modeling of a Direct Power Extraction System", AIAA 2016-0990

DPE Component Developments

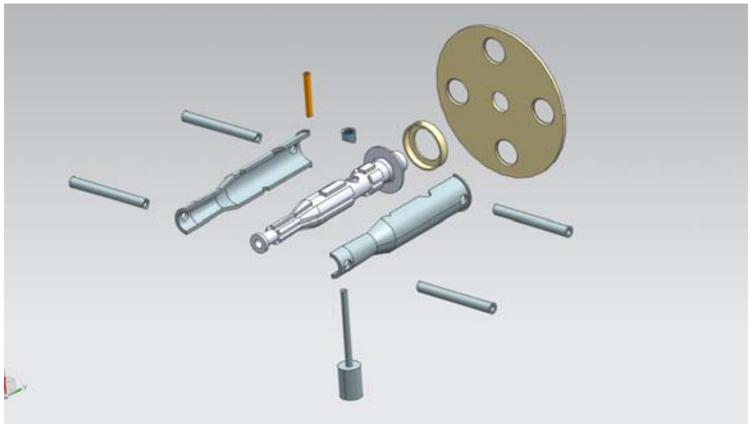
- Mass fractions of CH4 and O2 shown by pathlines from the nonpremixed combustion models

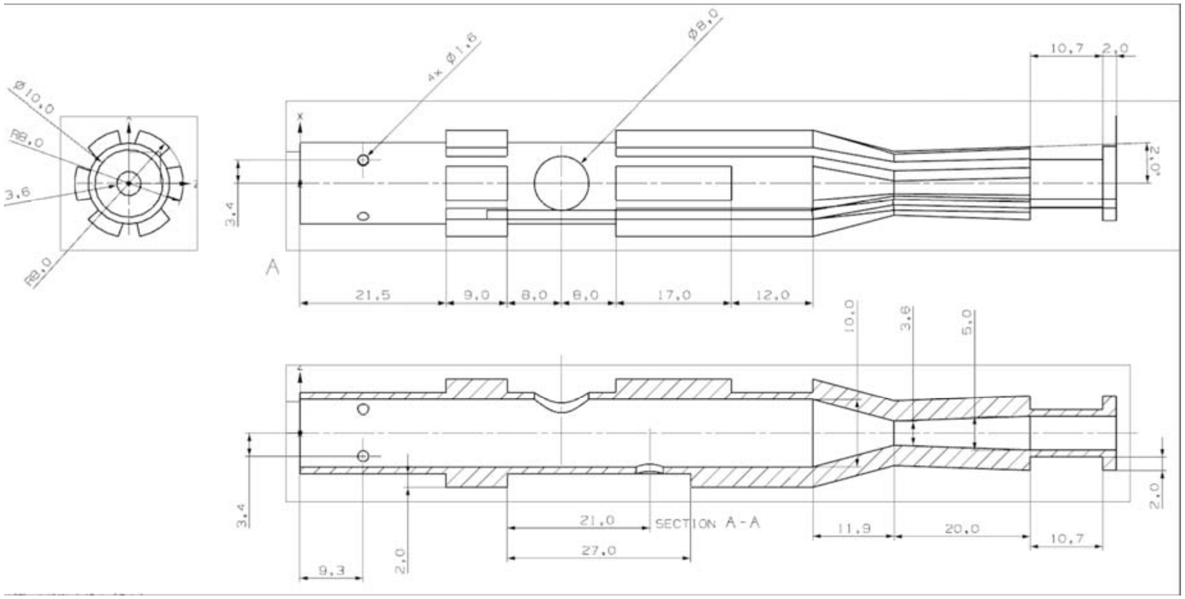


Vidana et al. "Component and System Modeling of a Direct Power Extraction System", AIAA 2016-0990

DPE Component Developments

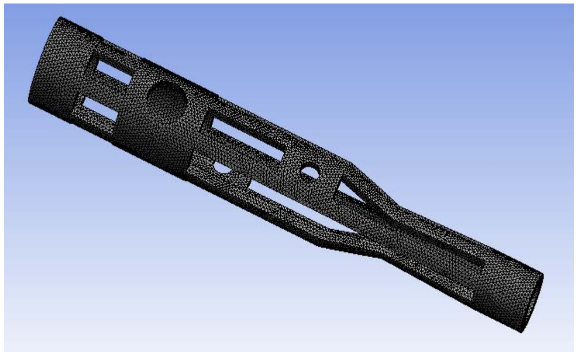
- Schematic of the cooling structure on the combustor body

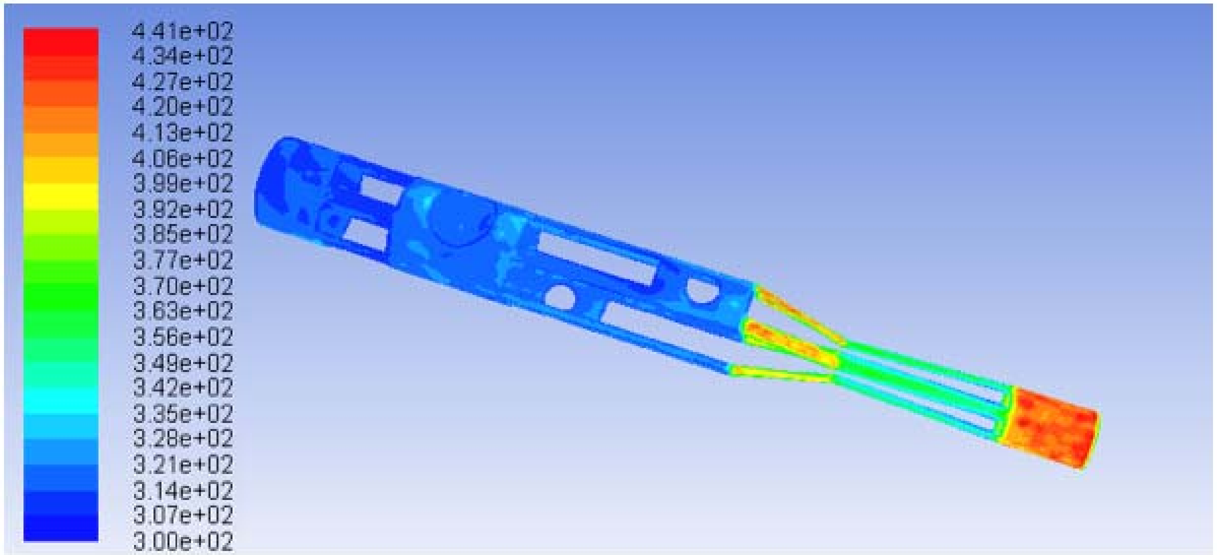




DPE Component Developments

- Standard k-e modeling with conjugate heat transfer of the cooling structure

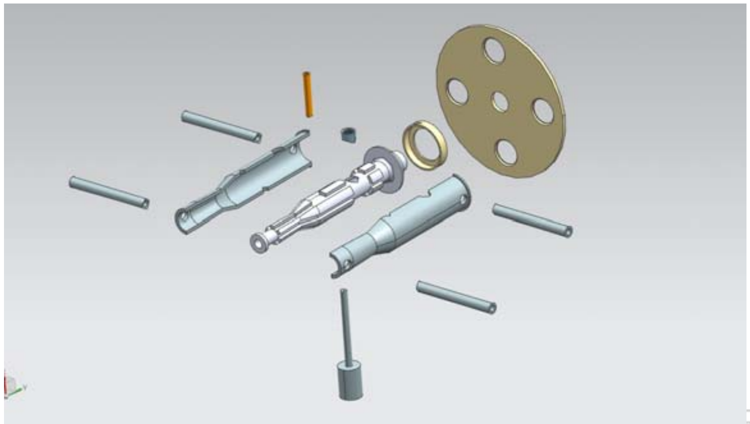


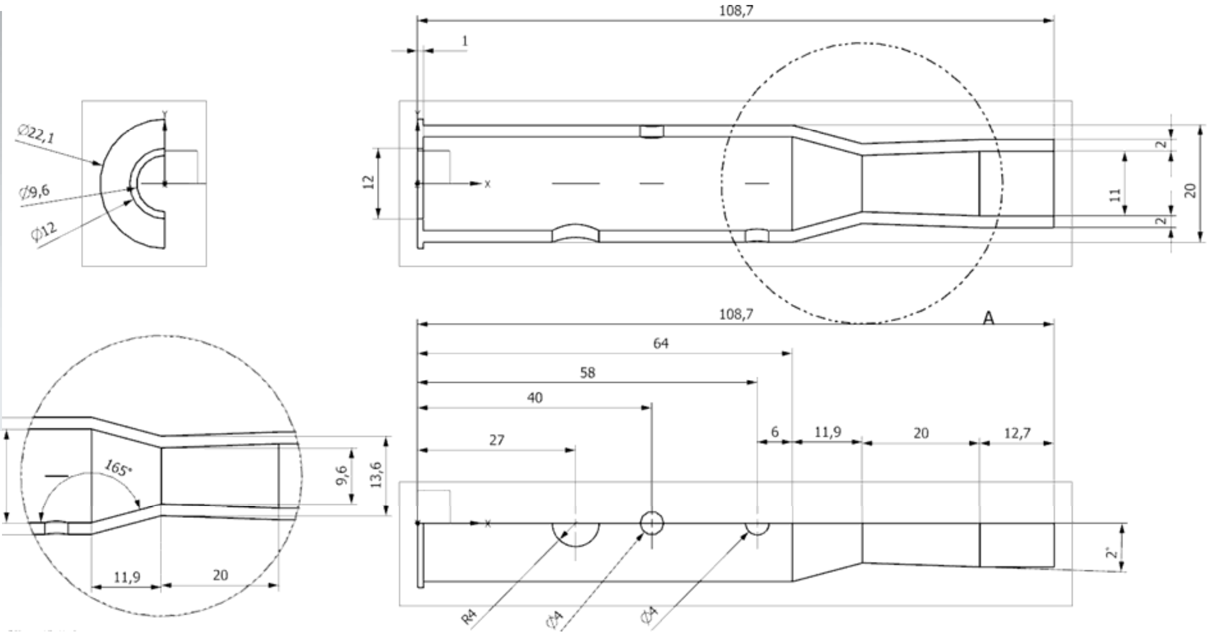


Reference: Vidana et al. "Component and System Modeling of a Direct Power Extraction System", AIAA 2016-0990

DPE Component Developments

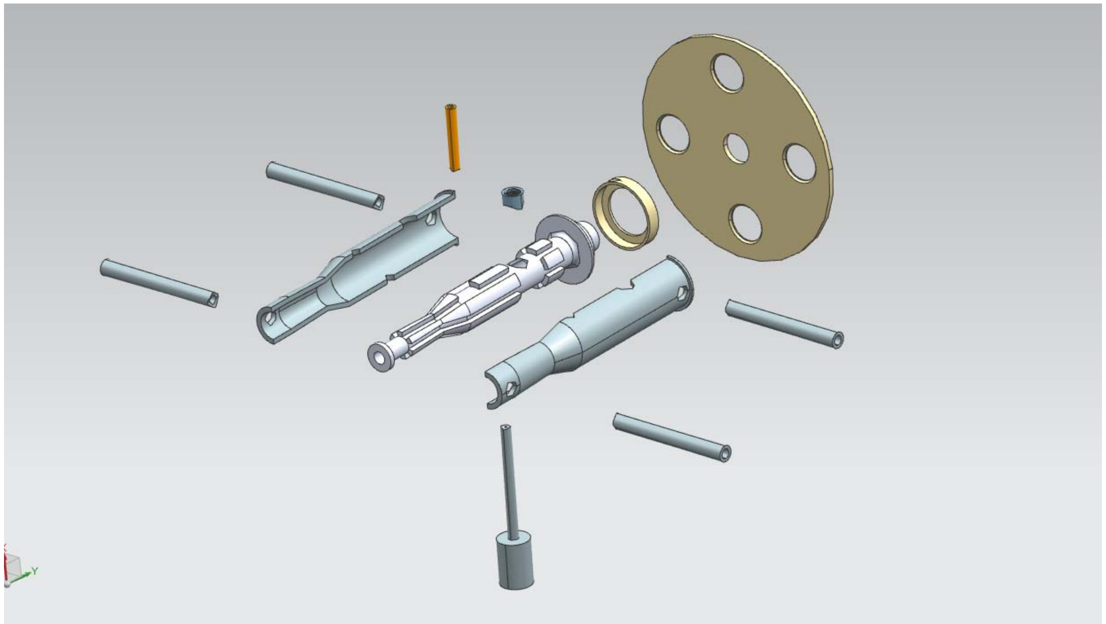
- Schematic of the cooling structure enclosure units





DPE Component Developments

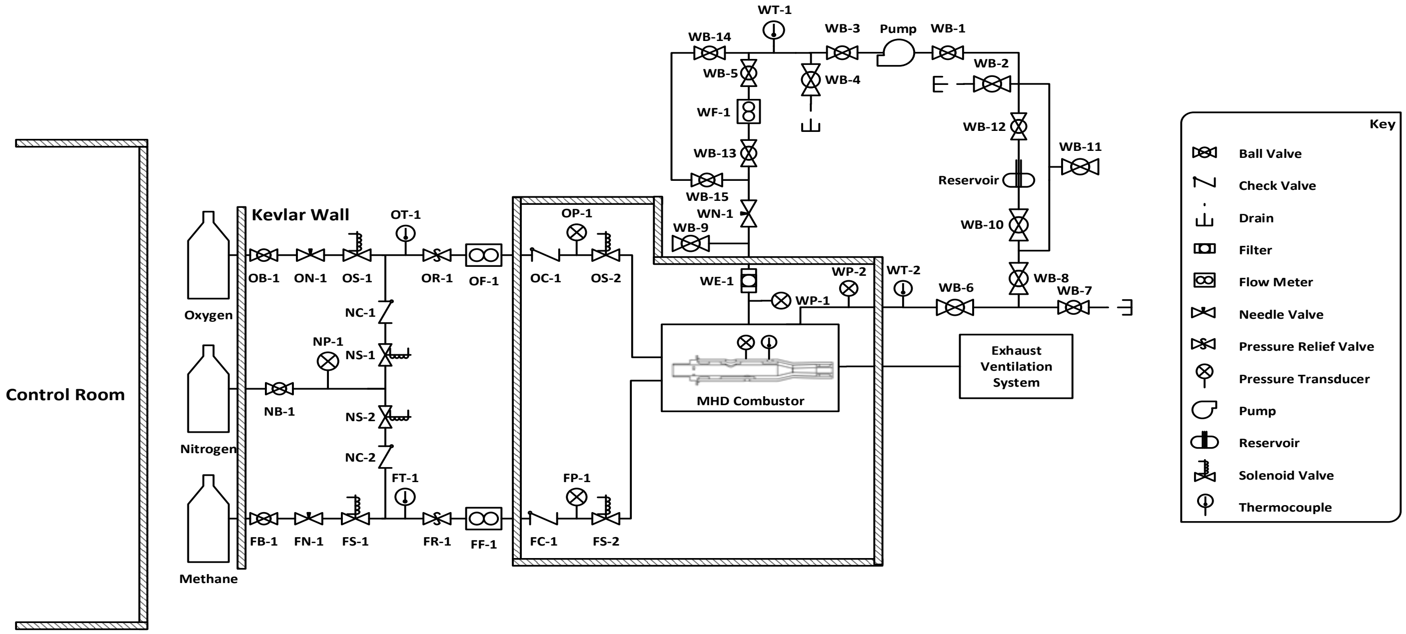
- Exploded view of the 60 kW MHD DPE Combustor System



System Integration in the MHD DPE Experimental Facility

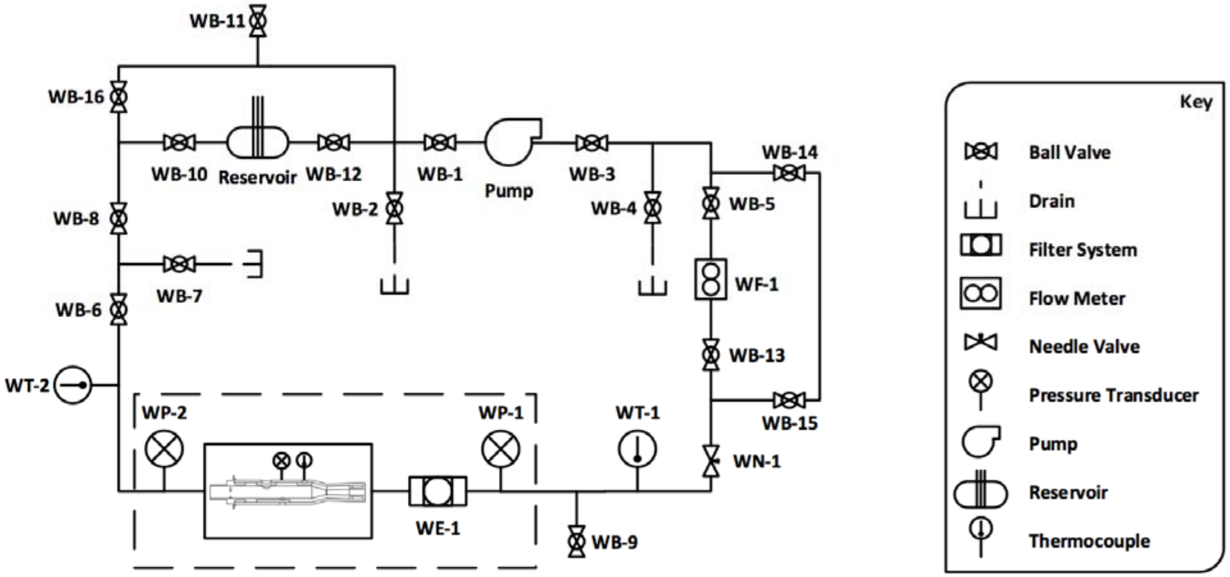
System Integration in MHD DPE Experimental Facility

- MHD Facility Piping and Instrumentation Diagram



System Integration in MHD DPE Experimental Facility

- Cooling Facility Piping and Instrumentation Diagram

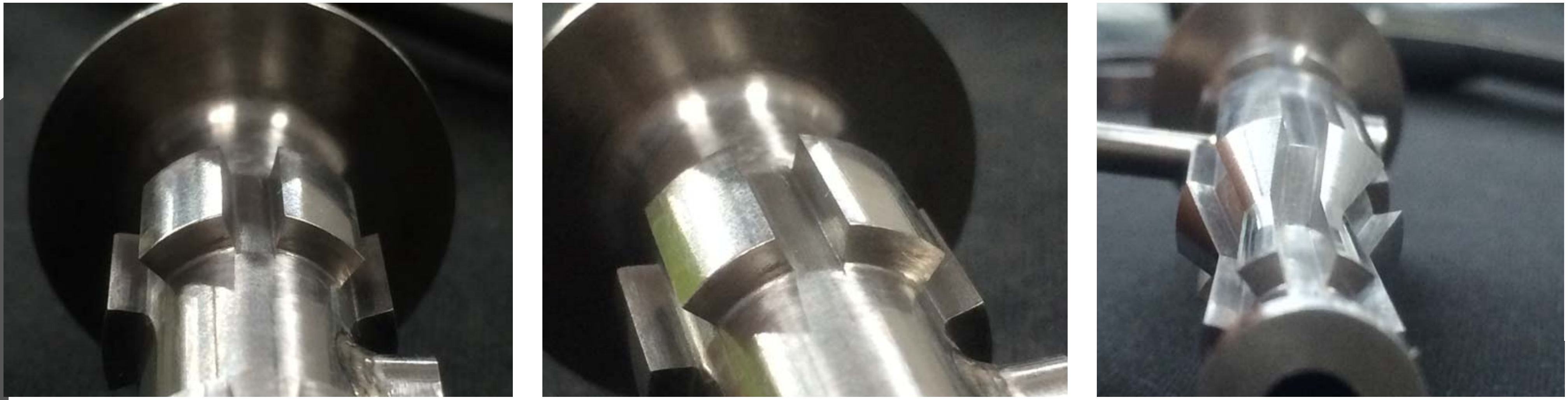


System Integration in MHD DPE Experimental Facility

- Photographs of the EDM manufactured, 60 kW MHD Combustor for supersonic jets

System Integration in MHD DPE Experimental Facility

- Photographs of the EDM manufactured cooling structure

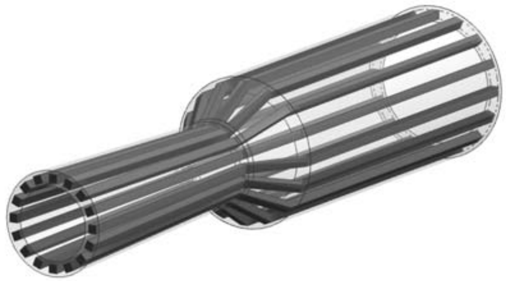


System Integration in the MHD DPE Experimental Facility

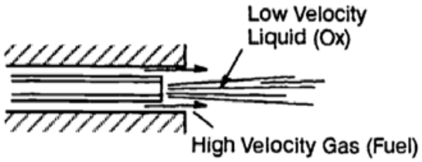
Future Work

Future Work

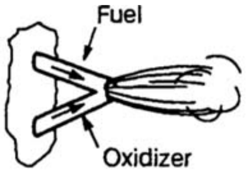
The second prototype is in design for scaling investigations



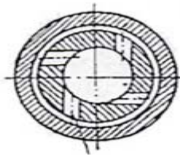
- **This combustor is a 1-MW CH4/O2 AES prototype, which is constructed of Inconel 718.**
- The length scale of the throat diameter has increased 4 times.
- Combustion dynamics and instabilities are a prevalent concern.
  - A particular emphasis is on the fuel injector design for this combustor.
  - **Injector options:**
    - Coaxial-shear injection
    - Coaxial shear
    - Impinging jet fuel injection
  - This AES prototype will include a seed injection port for thermal ionization
  - Optical access is being considered in the design to permit advanced laser diagnostics of combustion fronts.



Coax Element



Unlike Doublet



Coaxial Swirl

Future Work

- **Hernandez et al. “Flame Stability of Supersonic Oxy-Methane Flames for Direct Power Extraction”. AIAA Propulsion and Energy Forum and Exposition 2016. (Submitted Abstract)**

Motivations

- The stability of reacting flows for MHD environments is imperative for reliable conductivities.
- Technical deficiencies of inadequate electrical conductivities prohibited further research in MHD.
- Turbulent flame stabilization theories remain not entirely understood.
- Partially premixed flame propagation is current focus in turbulent combustion research.

Objectives of the paper

- The objective of this paper is to present lift-off and blowout limit data and compare it with correlations for turbulent lifted theories in Section 2.
- A review of empirical lift-off datasets for oxy-methane turbulent jet flames will be shown.
- Section 3 of this article will report schlieren observations of attached, lift-off, and blowout limits for stoichiometric to fuel-rich oxy-methane jet flames.

Impacts

Impacts

- **Collaborative experiences at NETL in Albany, OR**
- **Conference Proceedings and Presentations**
  - 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.
    - Accepted for Fossil Fuel Power Technologies: Lean coal and natural gas power systems, combustion, advanced designs, and microcombustors.
  - 2015 and 2016 Southwest Emerging Technologies Symposiums Technical papers (4)
  - M. Hernandez, L. Cabrera, A. Choudhuri, and N. Love. “Supersonic Underexpanded Jet Flames for MHD Energy Conversion: Component Development”, NASA Glenn Research Center, OH, March 2016.
  - A. Garcia, M. Hernandez, and N. Love. Power generation using magnetohydrodynamics. 2016 University of Texas at El Paso Symposium, El Paso, TX, April 30, 2016.

Impacts

- **Awards and Honors**
  - Selected for AIAA Sci-Tech 2016 Terrestrial Energy Best Paper Award
  - Invited two ME Ph.D. Research assistants to attend the 2016 Combustion Energy Frontier Research Center Combustion Summer School at Princeton University

Summary and Conclusions

- A coaxial swirl injector, 60 kW combustor and nozzle has been developed and constructed for supersonic MHD direct power extraction.
- Component and system modeling efforts of this small-scale combustor has been documented.
- System integration in the MHD Experimental Facility at the University of Texas El Paso has been completed.
- A second 1-MW combustor is being developed for flame stabilization and scaling analysis.

Acknowledgements

- The authors acknowledge the support of the U.S. Department of Energy, under award DE-FE-0024062. The DOE Project Manager is Jason Hissam. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the Department of Energy.

Thank you

Backup

Project Overview

Milestones	Title	Description	Success Metrics	Quarter	Actual Completion
M3	Complete design of cooling system	Design considerations of various cooling techniques	Heat transfer removed. Impact on structural integrity and durability;	Q3	June 30, 2015
M4	Optimize system components	Computational modeling of injector, combustor, and nozzle geometries.	Meet supersonic requirements. Meet near 3000 K in static temperature at exit.	Q4	August 17, 2015
M5	Fabrication of finalized cooling system. Integration of other system components.	Integration with other system components which may include cryogenic delivery unit	Operational facility capable of high heat transfer rate	Q6	March 31, 2016
M6	Fabrication of finalized injector and nozzle systems	Integration and operability analysis of injector and cooled combustor unit	Completed facility capable of high flow exit velocities above 2000 m/s.	Q6	March 31, 2016

Project Overview

Milestones	Title	Description	Success Metrics	Quarter	Estimated Completion
M7	Flame testing using cooling facility and novel injector	Characterize injector and combustor including flame stability	Comparison of flow patterns. Achievement of supersonic flow velocities. Measure heat removed from combustor and impact on structural integrity (i.e. max temperature)	Q7	TBD
M8	Systematically Characterize Flame Stability Characteristics	Finalize flame stability measurements. (Blowout, flashback, flow velocities, heat loads, flame structure, and flame behaviors)	Documented relationship between flame stability, geometry, and fundamental flame properties	Q8	TBD