

2016-01-01

# Design and Experimental Investigation of an Oxy-Fuel Combustion System for Magnetohydrodynamic Power Extraction

Manuel Johannes Hernandez

University of Texas at El Paso, [manuel.johannes.hernandez@gmail.com](mailto:manuel.johannes.hernandez@gmail.com)

Follow this and additional works at: [https://digitalcommons.utep.edu/open\\_etd](https://digitalcommons.utep.edu/open_etd)

 Part of the [Aerospace Engineering Commons](#), [Art and Design Commons](#), and the [Mechanical Engineering Commons](#)

---

## Recommended Citation

Hernandez, Manuel Johannes, "Design and Experimental Investigation of an Oxy-Fuel Combustion System for Magnetohydrodynamic Power Extraction" (2016). *Open Access Theses & Dissertations*. 665.  
[https://digitalcommons.utep.edu/open\\_etd/665](https://digitalcommons.utep.edu/open_etd/665)

This is brought to you for free and open access by DigitalCommons@UTEP. It has been accepted for inclusion in Open Access Theses & Dissertations by an authorized administrator of DigitalCommons@UTEP. For more information, please contact [lweber@utep.edu](mailto:lweber@utep.edu).

DESIGN AND EXPERIMENTAL INVESTIGATION OF AN OXY-FUEL  
COMBUSTION SYSTEM FOR MAGNETOHYDRODYNAMIC POWER  
EXTRACTION

MANUEL JOHANNES HERNANDEZ  
Doctoral Program in Mechanical Engineering

APPROVED:

---

Norman Love, Ph.D., Chair

---

Ahsan Choudhuri, Ph.D.

---

Yirong Lin, Ph.D.

---

Bill Tseng, Ph.D.

---

Charles H. Ambler, Ph.D.  
Dean of the Graduate School

Copyright ©

by

Manuel Johannes Hernandez

2016

## **Dedication**

I dedicate my dissertation to two influential people in my life. An influential person was my grandfather, Manuel Hernandez Guerrero. My fiancé, Laura Cecilia Ruiz, was the other influential person in my life. Cecilia has provided unconditional support and sacrifices during my doctoral studies. There are no words that can express my sincerest gratitude. They both supported my professional growth with their words, actions, presence, and confidence while I pursued my doctorate degree. I sincerely thank them for their continuous support, which will never be forgotten.



DESIGN AND EXPERIMENTAL INVESTIGATION OF AN OXY-FUEL  
COMBUSTION SYSTEM FOR MAGNETOHYDRODYNAMIC POWER  
EXTRACTION

by

MANUEL JOHANNES HERNANDEZ, BSME, MSME

DISSERTATION

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

Department of Mechanical Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

December 2016

## **Acknowledgements**

First and foremost, I acknowledge the most supportive person in my life, my fiancé, Laura Cecilia Ruiz. My Fiancé provided remarkable bolstering support in all of my work. Many sacrifices have been made since the beginning of my doctoral degree in order to move forward with my professional goals and endeavors. Laura Cecilia was an important person that provided constant confidence and patience during my doctorate degree and research.

I would like to thank other immediate family members, such as my parents and grandparents, for their lifelong support.

Regarding research, this dissertation was funded and supported by the U.S. Department of Energy, under the award DE-FE-0024062, wherein the Project Manager is Jason Hissam. However, any opinions, findings, conclusions or recommendations expressed herein are those of the author and do not necessarily reflect the views of the Department of Energy.

Invaluable mentorship was provided by the Department of Mechanical Engineering in support of my doctoral work. I wish to acknowledge my research advisors, Dr. Norman Love and Dr. Ahsan Choudhuri, who both have provided excellent opportunities to build my research network, professional development, and the support to present my work on a national and international framework.

My research team and our group dynamics have also provided countless support during my research. I acknowledge each one of them for their individual contributions and their hard work.

## **Abstract**

A general consensus in the scientific and research community is the need to restrict carbon emissions in energy systems. Therefore, extensive research efforts are underway to develop the next generation of energy systems. In the field of power generation, researchers are actively investigating novel methods to produce electricity in a cleaner, efficient form. Recently, Oxy-Combustion for magnetohydrodynamic power extraction has generated significant interest, since the idea was proposed as a method for clean power generation in coal and natural gas power plants. Oxy-combustion technologies have been proposed to provide high enthalpy, electrically conductive flows for direct conversion of electricity. Direct power extraction via magnetohydrodynamics (MHD) can occur as a consequence of the motion of “seeded” combustion products in the presence of magnetic fields. However, oxy-combustion technologies for MHD power extraction has not been demonstrated in the available literature. Furthermore, there are still fundamental unexplored questions remaining, associated with this technology, for MHD power extraction.

In this present study, previous magnetohydrodynamic combustion technologies and technical issues in this field were assessed to develop a new combustion system for electrically conductive flows. The research aims were to fully understand the current-state-of-the-art of open-cycle magnetohydrodynamic technologies and present new future directions and concepts. The design criteria, methodology, and technical specifications of an advanced cooled oxy-combustion technology are presented in this dissertation. The design was based on a combined analytical, empirical, and numerical approach. Analytical one-dimensional (1D) design tools initiated design construction. Design variants were analyzed and vetted against performance criteria through the application of computational fluid dynamics modeling. CFD-generated flow fields permitted

insightful visualization of the design concepts. Therefore, numerical computational fluid dynamics (CFD) models were developed to design and optimize the combustion flow fields of oxy-fuel combustion systems. These models were analyzed to understand the boundary layer and heat transfer profile and qualitative behaviors in the product designs. Advanced materials for high-temperature applications were assessed for their possible implementation in the product design. A trade-off analysis indicated that this scheme may incur elevated product cost and a difficulty in manufacturing. Active cooling strategies were considered for product development. A rocket-based cooling scheme, regenerative cooling, was implemented to provide active cooling. In the hot gas path (HGP) cooling design, CFD models were developed to predict the variation of heat removal along the oxy-combustion wall for various operating conditions. The oxy-combustion technology was manufactured using electrical discharge machining (EDM). The product development lifecycle in this dissertation encompassed preliminary design, detailed design, and demonstration and validation of the product. Towards the final stages of the product development, Fuel-rich oxy combustion experiments were carried out to demonstrate and observe flame characteristics from the designed technology and to predict heat transfer loads. The demonstration findings of oxy-combustion flames are presented in this work to contribute the developing field of MHD direct power extraction, which lacks oxy-combustion design data and qualitative combustion datasets.

The findings show that this oxy-combustion concept is capable of providing a high-enthalpy MHD environment for seeding, in order to render the flow to be conductive. Based on previous findings, temperatures in the range of 2800-3000 K may enable magnetohydrodynamic power extraction. The combustor hardware design was developed to contribute to engineered systems rated less than 100 kW for demonstration. The product hardware was designed to produce

gas velocities of 2000 m/s gas and temperatures within the following range of 2800-3000 K. In the injection system, the momentum flux ratio (MFR) was estimated to be 16. The heat loss fraction in this oxy-combustion system, based on CFD and analytical calculations, at optimal operating conditions, was estimated to be less than 10 percent. Furthermore, the heat transfer design removed approximately 7 MW/m<sup>2</sup>. The experimental performance of oxy-combustion systems demonstrates promise for advanced power generation applications.

## Table of Contents

Acknowledgements .....	v
Abstract .....	vi
Table of Contents .....	ix
List of Tables .....	xi
List of Figures .....	xii
Chapter 1: Introduction .....	1
1.1 Motivations .....	1
1.2 Dissertation Research Question .....	6
1.3 Structure of Dissertation .....	8
Chapter 2: Background and Literature Review .....	11
2.1 Theory of Magnetohydrodynamics .....	12
2.2 Charged Species In Flames .....	19
2.3 Combustion Magnetohydrodynamics .....	24
Chapter 3: Methodology .....	51
3.1 Product Development Methodology .....	51
3.2 Computational Fluid Dynamics (CFD) Modeling of Combustion .....	60
3.3 Computational Fluid Dynamics (CFD) Modeling of Cooling Design....	62
3.4 Magnetohydrodynamic Generator Analysis .....	65
3.5 Experimental Methodology .....	71
Chapter 4: Results and Discussion.....	74
4.1 Introduction .....	74
4.2 Product Design and Experimental Hardware Testing Facility .....	74
4.3 Oxy-Fuel Combustion Modeling Results .....	83
4.4 Coolant Channel Flow Modeling Results .....	87
4.5 Magnetohydrodynamic Generator Analysis .....	88
4.6 Experimental Results of Slightly Fuel Rich Oxy-Methane Flames .....	92

Chapter 5: Conclusions and Future Work.....	99
References.....	103
Vita.....	110

## **List of Tables**

Table 1: Sub-models and implemented conditions in the 3D non-premixed combustion model.	61
Table 2. The sub-models and boundary conditions for the coolant jacket fluid domain.....	64
Table 3. Oxy-combustion system and subsystem design characteristics for MHD applications .	77
Table 4. Boundary conditions and model setup for the 2D/3D modeling of oxy-combustion.....	85
Table 5. Design constraints on combustor, nozzle, and MHD Generator characteristics for a conceptual MHD generator analysis.....	90



## List of Figures

Figure 1. Probable orbits of electrons that describe ionization mechanisms. <sup>16</sup> .....	13
Figure 2. MHD physics described in a one-dimensional form in the above schematic. <sup>16</sup> .....	16
Figure 3. The design of a water-cooled rocket engine configuration for liquid-fuel and air combustion. <sup>38</sup> .....	30
Figure 4. Way and Hundstad's MHD combustor and results of electrical conductivity. <sup>34</sup> .....	31
Figure 5. Characteristics of MHD research experiments, which were conducted at AVCO, General Electric, and Westinghouse, during the early progression in the MHD field. <sup>16</sup> .....	32
Figure 6. A T-s diagram and a schematic of a general open-cycle MHD generator in the early designs. <sup>34,40</sup> .....	33
Figure 7. Boundary layer development under the influence of a non-uniform magnetic field. <sup>44</sup> ..	35
Figure 8. Generator design options and their associated MHD performance values for three advanced MHD power plant designs for large-scale. <sup>61</sup> .....	41
Figure 9. Representative schematic of the insulator gap problem in slag-laden large-scale MHD generators. <sup>71</sup> .....	44
Figure 10. MHD secondary flow problem in an illustrative schematic. <sup>74</sup> .....	47
Figure 11. The current state-of-the-art conceptual design of a diagonally-connected coal- combustion MHD generator, from the work of Pian et al. <sup>75</sup> .....	48
Figure 12. The research opportunities in MHD generators regarding scale and long-duration time. <sup>23</sup> .....	49
Figure 13. Seeded coal-air MHD combustor and generator from the work of Roy and Wu. <sup>117</sup> ...	52
Figure 14. Design schematic for the oxy-fuel combustor for Magnetohydrodynamic Power Extraction. ....	58
Figure 15. The discretized mesh for the PDF-based, non-premixed combustion model. ....	62
Figure 16. The small-scale MHD Combustor cooling jacket and a two-dimensional schematic are shown in mm units above, specifically, in Windows A and C. The MHD cooling jacket flow domain and mesh are shown in windows b and d. ....	64
Figure 17. Reference frame and schematic used in this simplified analysis of a constant-velocity MHD generator. ....	67
Figure 19. Assembly of the MHD Combustor (Top). Coaxial swirl injector cross-section (bottom left) and an exploded view of the fuel ring manifold and individual ports in the fuel injector (bottom right). ....	78
Figure 20. Two-dimensional drawing of the exterior shell components of the cooling jacket structure. ....	79
Figure 21. Two-dimensional drawing of the main combustor body, profile, and cooling jacket component systems. ....	80
Figure 22. MHD combustor experimental facility at the University of Texas at El Paso. ....	81
Figure 23. MHD Combustor experimental setup: reactant and water cooling systems and other instrumentation .....	82
Figure 24. Photographs of the experimental setup (left) and a demonstration test with the following combustion conditions: O/F 3.5, theoretical chamber pressure of 110 psi, and 30 seconds of operating time. ....	83
Figure 25. The MHD combustor prior to welding. These photographs show the detail and surface finishing of the EDM manufactured parts for the MHD oxy-combustion system. ....	83

Figure 26. A standard k-epsilon viscous model was investigated to understand the non-premixed combustion and flow field in three-dimensions. The figure is separated by zone to describe the following: (a) mass fraction path lines for methane; (b) mass fraction path lines for coaxial oxygen injection; (c) static temperature contours in Kelvin; and (d) flow velocity contours. ....	85
Figure 27. Two-dimensional k-epsilon model with non-premixed oxy-combustion. The results of interest are the contours of velocity magnitude, static temperature, and absolute pressure. ....	87
Figure 28. Static temperature contours of the MHD Cooling Jacket in Kelvin. <sup>118,119</sup> .....	88
Figure 29. Area ratios for various outlet-inlet pressure ratios in a constant-velocity MHD generator. ....	91
Figure 30. Transverse Faraday current densities for various gas flow velocities at the inlet of a constant-velocity MHD generator.....	91
Figure 31. The field of small and large-scale MHD generator experiments are shown as of 1999. <sup>23</sup> .....	95
Figure 33. Oxy-combustion flame structure for constant pressure combustion at 7.58 bar, O/F 3.5, and an operating time of 10 seconds.....	97
Figure 34. Oxy-combustion flame structure for constant pressure combustion at 7.58 bar, O/F 3.5, and an operating time of 30 seconds.....	97
Figure 35. Oxy-combustion flame structure for constant pressure combustion at 7.58 bar, O/F 3.5, and an operating time of 120 seconds.....	98
Figure 36. Rendering of both Oxy-Combustion Energy Systems (60 kW and 1 MW) for MHD applications. ....	102

# **Chapter 1: Introduction**

## **1.1 MOTIVATIONS**

Modern society is dependent on hydrocarbon combustion, a predominant source of energy and power.<sup>1</sup> Combustion converts over 75 percent of primary energy sources.<sup>1,2</sup> Hydrocarbon combustion sustains a majority of the electricity generation portfolios in many nations, and it enables transportation. Major primary energy sources in the United States are natural gas and coal. A general focus of research today is attentive to developing advanced power cycle technologies that use coal and natural gas. Current goals of the combustion communities are to improve efficiencies of combustion systems and reduce emissions of certain pollutants, mainly carbon dioxide, in power generation applications. These product design goals are global priorities, which may evolve by political and investment structures in the near future. Today, certain technologies are being developed to restrict emissions from hydrocarbon-air flames in state-of-the-art energy systems. The state-of-the-art engine systems include aviation engines, automotive internal combustion engines, and land turbines.

The topic of electrical power generation engines is a vast subject. However, this dissertation is focused on the product development and testing of advanced combustion methods. These methods are part of a new class of advanced fossil power cycle technologies, which underscore the development of higher-efficiency stationary, heavy-duty gas turbines and combined cycles.

Stationary gas and steam turbines are the current state-of-the-art electrical power generation technology. Research in these technologies targets many areas including: blade advancements (i.e. thermal barrier coatings, cooling strategies to increase inlet turbine temperature, and compression designs), lean, multistage combustion techniques<sup>3</sup>, and the implementation of numerical computations of higher-order approximations in flames to optimize burner designs<sup>4</sup>.

Advancements in each of the listed fields have led to gas turbine advancements. The research has aimed to resolve the major limitation in turbo machinery, design of hot gas path (HGP) components. HGP components in gas turbines are multi-stage turbine airfoil blades, nozzles, shrouds, and casing structures. The facet of direct contact with high-temperature combustion gases from hydrocarbon-air flames is an area that has received substantial research, in addition to combustion research. Since the aim is to increase efficiency by increasing temperatures in these systems, this direct contact gas path must be resolved by creative cooling and design solutions. The cause of this design constraint in turbines is associated with the heat release from combustion flames. Therefore, combustion processes must be designed to specific temperature limits in turbines. This is the current trend in the evolution of advanced gas turbines.

Different power generation strategies are being developed as alternative lines of research, which may augment current gas turbine systems and combined hybrid power cycles. The proposed idea is that you may add high-temperature rocket-based systems ahead of gas turbine cycles, in order to increase the potential for additional electrical power generation. This idea describes a magnetohydrodynamic power generator, which operates at temperatures above 2500 C in the absence of rotating machinery. A research area that may capitalize on rocket-based technologies is the development of magnetohydrodynamics.

Magnetohydrodynamics is a unique form of energy conversion. Direct energy conversion in these systems is based on ionized, electrically conductive gas flows. In general, magnetohydrodynamics (MHD) is the study of electrically-charged fluids in the presence of magnetic fields. MHD is a widely studied field, spanning many contexts. Magnetohydrodynamics of fully conductive gases are studied in both astrophysics and in thermonuclear fusion devices. However, the discussion is limited to magnetohydrodynamics of combustion gases.

Magnetohydrodynamics have been investigated for other magnetic interactions on particular gases, such as systems that use cold air (Hypersonic MHD systems) and inert gas (Closed-cycle MHD systems).

Combustion magnetohydrodynamics is a potential field that has demonstrated potential for advanced power generation applications. This concept has been studied for many years, but the idea is to pass an electrically conductive combustion gas flow in a uniform magnetic field and cause Lorentz forces. These Lorentz forces may interact to cause changes in velocity in combustion MHD technologies. In the case of power extraction, Lorentz forces may decelerate the flow as a consequence of current density formation. In the opposite sense, Lorentz forces can also impart energy (electrical in form) to increase the velocity. Lorentz force direction is the critical determining factor. From the general physics, a major question in this research field is how can we achieve a stable ionized flow with high electrical conductivity properties, which may then cause MHD forces to generate electrical currents? In the past, the majority of the research concentrated on answering this research question with combustion flames.

Past research on the subject of magnetohydrodynamics was conducted within a specific time frame, 1960-2004. However, after more than 40 years of research, hydrocarbon air flames resulted in slagging issues and low electrical conductivity values. Recently, based on several review articles,<sup>5-9</sup> Oxy-fuel combustion flames may be a viable option to solving this research question and it may further advance magnetohydrodynamics research. Recent interests in magnetohydrodynamics are based on the idea that oxy-fuel flames exhibit higher flame temperatures, on the order of 3000 C, in the chemical reaction zone or flame front. These higher temperatures are required for MHD systems. This high-temperature facet is what distinguishes MHD combustion systems from current state-of-the-art gas turbines. However, the definition of

an oxy-fuel combustion system at any thermal scale has not been defined for MHD power extraction, based on several survey of the literature on the subject.<sup>8,10</sup> Furthermore, analytical, numerical, or experimental studies of oxy-fuel MHD systems have not been published in the available literature. Therefore, a focus of this work is to contribute a design methodology that leverages computational modeling and experimental studies of oxy-fuel combustors to the field of combustion magnetohydrodynamics. However, certain questions have scoped this dissertation research in this topic. For instance, scoping questions include:

- What are the design criteria, system requirements, and the physical architecture of oxy-fuel combustion MHD systems?
- Furthermore, can stable oxy-fuel flames provide the temperatures required to ionize seed materials and render the flow to be electrically conductive?

These questions motivated research into charged species, ionization mechanisms, and electrical conductivity studies in flames and a survey of combustion magnetohydrodynamics technology research to answer the posed questions.

A major concern in magnetohydrodynamic research is the conductivity state of the gases. Electrical conductivity is a major parameter that governs if magnetohydrodynamic forces can occur. Electrical conductivity is a function of the ion and electron densities per unit volume and a strong function of temperature. The relationship between electrical conductivity and ionization fraction is critical to the feasibility of MHD power generation from combustion gases. How ionization processes occur in oxy-flames must be understood for magnetohydrodynamic applications. How ionization occurs in particular chemical systems, either with natural gas or gasified coal gases, may impact the effectiveness of MHD interactions.

Various techniques have been used in past research, mainly through alkaline metal reactions in hydrocarbon air flames. This technique is referred to as called seeded flame ionization. However, other ionization techniques have been studied within other context in the field of MHD power extraction. Non-thermal ionization techniques, such as electron beams and nanosecond discharges, have been studied for hypersonic flight applications of MHD. The findings, experimental results, and numerical modeling of Hypersonic MHD systems may be used in the future to cross-transfer knowledge to improve Combustion MHD design practices. General ionization concepts may be used in conjunction with seeded combustion gases in MHD systems, since there is a drive to solve conductivity problems associated with seeded coal flames. Non-thermal techniques for MHD propulsion applications have been investigated by a number of researchers.<sup>11-15</sup> The mechanisms of ionization in oxy-fuel flames is not well understood. A more detailed investigation into these non-thermal techniques in conjunction with oxy-fuel magnetohydrodynamics may be of future interest and it outside of the scope of this dissertation. A brief discussion of these ideas and their role in MHD systems is discussed in the conclusions of the dissertation.

Research gaps in previous research is the study of hydrocarbon-oxygen combustion at various thermal rating scales for MHD systems. Further study of this research gap is merited to rectify the inadequacies of the electrical conductivity in seeded combustion. A collection of research has been reviewed to understand the past trends and findings that constitute the field of conventional MHD. This particular field, “Conventional Combustion MHD”, is being revisited due to promising advantages with using Oxy-methane or Oxy-coal Combustion for power extraction. The progression of MHD research began after researchers studied ionization in rocket flames and led to diverse collection of works, which were focused on demonstration studies, MHD

system design studies, and slagging and other non-uniformity effects in seeded coal flames. Subsequently following this work, the most recent research, namely within the last decade, has focused on MHD systems for hypersonic aviation. A survey of this recent field has not been conducted, as of late. However, these systems are not targeted to develop power generation applications. Therefore, the focus of this dissertation is delimited to answer certain research questions, and the structure of the dissertation is explained in the next sections.

## **1.2 DISSERTATION RESEARCH QUESTION**

The dissertation is focused on understanding of oxy-fuel combustion for magnetohydrodynamics applications. In particular, methane-oxygen combustion is being developed for MHD extraction. The focus is to define, develop, and demonstrate an oxy-fuel combustion engine system for magnetohydrodynamic applications. In order to achieve this objective, this dissertation research was intended to answer specific research questions. The research questions addressed in this dissertation include:

- What are the research opportunities in the field of combustion magnetohydrodynamics?
- Could methane-oxygen combustion flames and their structure provide an adequate high-temperature flow-field, if seeded with potassium, for Lorentz forces to act on charged particles?

These questions have not been addressed in other recent works, according to the most recent review papers. The novelty of this work is that rocket-based technologies could demonstrate and permit MHD power extraction. In addition, the targeted use of computational modeling to scope and produce combustion technologies is evaluated for clear visualization of the high-temperature flow fields in power generation systems.



The objectives of this research is to design, develop, and demonstrate a methane-oxygen combustor (rated less than 100 kW) for flame characterization, in order to address the research questions within the field of MHD research. The hypothesis in this work is that Oxy-methane Combustion may provide the necessary temperature, and hence electrical conductivity, requirements for advanced Oxy-Combustion MHD product designs. The cold and hot gas path components (HGP) was devised to test the feasibility of oxy-combustion for this direct conversion method, MHD. The HGP nozzle device was designed to provide velocities above 2000 m/s and gas temperatures near or above 2800 K. Partially premixed flames were targeted as the flame classification in this system. These flames could, in theory, be stable and interact with a magnetic field near 1.5-5 Tesla in a Faraday magnetohydrodynamic device. The hypothesis, methane-oxygen flames may provide sufficient temperatures to promote unprecedented levels of electrical conductivity properties, by thermal ionization in the hot boundary layers and in the core flow, is tested in this computational design and experimental work.

The experiments are aimed to demonstrate flames under various pressures and burn times. A thermal rating class of 100 kW, or below, was the design point for the proof-of-concept (POC) design in MHD systems. POC is confirmed in order to develop the proposed oxy-combustion rocket-based technology for larger thermal rating scale oxy-fuel combustors for MHD applications. Analytical and numerical analysis were carried out to predict the static temperature profiles, pressure distribution, and velocity variation in the hot-gas path (HGP) components to understand the feasibility of oxy-fuel combustion gases, in chemical equilibrium, flowing through the experimental combustion chamber and nozzle.

### **1.3 STRUCTURE OF DISSERTATION**

The dissertation structure is described for clarity. Chapter 2 presents the pertinent background and literature review. In Subsection 2.1, the general theory of magnetohydrodynamics is discussed. In Subsection 2.2, original papers and reviews of charge species in unseeded and seeded flames, measurement of electrical conductivities in flames, and ionization processes are discussed. These collections are directly related the critical role of flame electric properties. Therefore, an understanding of the impactful properties that promote or decrease MHD performance was imperative. This subsection discusses electrical properties alkaline-metal flames. In Subsection 2.3, the progression of combustion MHD studies is detailed. This progression led to pronounced changes in the direction of MHD research, and opened ideas for other MHD applications. In the final subsection, the most recent literature in the field of magnetohydrodynamics – cold air hypersonic magnetohydrodynamics – is discussed briefly.

Chapter 3 describes the methodology, formulations, and computational methods used in this dissertation investigation. The first subsection describes the analytical and empirical approach to create the Oxy-Combustion system. This process begins with definition of design criteria, translation to engineering requirements, followed by subsystem definition and design. In the design process, the subsystems that make up the oxy-fuel combustion system include the fuel port-injection, combustion section, sonic and supersonic nozzle, and an advanced cooling jacket. Subsection 3.2 describes the subsystem computational modeling approach. A three-dimensional computational modeling effort was performed the properties of non-premixed combustion gases in contact with the HGP components. The findings of this work included contours of the static pressure, static temperature and velocity. Subsection 3.3 describes the computational modeling of a water cooling jacket, comprised of rectangular cooling channels, subjected to empirical and numerical boundary conditions for the interior wall surface and a uniform, local heat-transfer

coefficient for the exterior cooling channel surfaces. Subsection 3.4 delineates the experimental setup used to conduct oxy-fuel hot-fired experiments and a description of the design of experiments. Subsection 3.5 is a description of the methods used in a theoretical study of oxy-methane gases in a MHD generator. This study was conducted to solve the area ratio of the generator and the current variation with a uniform electrical conductivity.

Chapter 4 presents results and discussion in regards to the product development lifecycle. Subsection 4.1 describes the design criteria and specifications of the injector, combustion chamber, nozzle, and cooling jacket for the nominal design point. Subsection 4.2 details the computational modeling and its associated results, specifically the non-premixed port-injection, combustion gas path loads in the combustor sections and sonic and supersonic nozzles. Subsection 4.3 describes the computational modeling of the cooling jacket, which is subjected to empirical boundary conditions, based on nozzle heat transfer studies in cryogenic rocket engines, for the local gas-side heat-transfer coefficient and a uniform local coolant heat-transfer coefficient. The maximum heat load, which occurs where the nozzle cross-section is a minimum, was the parameter that governed the heat transfer design of the system.

Subsection 4.4 describes the experimental setup required to demonstrate fuel-rich and slightly-fuel rich oxy-fuel flames for a variety of burn times. Subsection 4.5 addresses the experimental results of slightly-fuel-rich oxy-fuel flames, corresponding to an O/F ratio of 3.5, for “long-duration” experiments. In this subsection, long-duration experiments are delineated. These “long-duration” experiments were considered as combustion residence time above 10 seconds. Transient and fuel-rich experiments, characterized as “short-burning times”, were tested and demonstrated in the scope of this research. However, since realistic MHD conditions was the dissertation, only the results of near-stoichiometric flames are provided in the dissertation.

Therefore, select oxy-fuel flame data for an MHD environment is shown. The experimental data described in this section includes the static temperatures of the combustor at a point on the exterior surface and high-speed ICCD photography of the flames for 10, 30, 60, 120, and 300 seconds. The heat loss fraction, based on the uniform heat flux and the higher heating value (HHV) of methane, is evaluated. A selected topic of discussion is an analysis of the empirical local heat-transfer coefficient in the nozzle and the effects of combustor throat diameter, or thermal rating, on heat flux for magnetohydrodynamic generators. This is discussed in brief in this section. This topic is discussed in detail since it is critical loss parameter in MHD systems.<sup>5</sup> Subsection 4.6 discusses a conceptual theoretical analysis of combustion gases in a linear Faraday MHD system, and its effects on estimating the electrical conductivity.

Chapter 5 provides concluding remarks of the dissertation. While Chapter 6 discusses future opportunities in the study of oxy-fuel flames for magnetohydrodynamics.

## **Chapter 2: Background and Literature Review**

Magnetohydrodynamics is a subject that has received extensive interests in engineering for many applications. Researchers, at the Department of Energy and other university institutions, have interests in solving particular combustion-related problems with gaseous magnetohydrodynamics. MHD power extraction in stationary power cycles may be a transforming, disruptive technology. The study of MHD to address other issues is evident in the literature. Authors examined MHD systems for hypersonic flight applications, a separate field on its own. Hypersonic problems, such as high-heat flux shielding, flow field regime conversion from hypersonic to supersonic flows, and flow field control applications, were studied in the field called Cold Air MHD Hypersonics. Researchers have studied this particular problem of reducing heat flux during planetary re-entry and scramjet operations with magnetohydrodynamic technologies. These are only some instances where MHD has received attention in the aerospace and combustion research communities.

Chapter 2 is a survey of the pertinent literature on the general theory of magnetohydrodynamics. Following this topic, the origins of magnetohydrodynamics trace back to seeded flames. Previous research concerned with charged species, ions, in flames and the importance of measuring the electrical conductivity measurements. Individual studies on this subject, charged species in flames, clearly state the motivations for their work is the study of gaseous combustion magnetohydrodynamics. Three overarching themes of MHD research adequately describes the progress in this field. These topics outline the following: demonstration or proof-of-concept studies, MHD system design studies, and relatively recent investigations concerning slag and other non-uniformity effects in seeded coal MHD generators. Pertinent review articles are cited in this Chapter from particular viewpoints on the advances in MHD generators.

## 2.1 THEORY OF MAGNETOHYDRODYNAMICS

The theory of Magnetohydrodynamics is described in many select texts.<sup>16,17</sup> These books describe the method from two perspectives, from either a physical particle viewpoint or by kinetic theory. The theory is extensive because of its multi-physics nature. It encompasses aspects from a variety of fields. Magnetohydrodynamics can occur by a fully-conductive gas or a partially ionized gas. The subject touches upon areas of plasma physics, two-body and three-body collisions, ionization and recombination mechanisms, Lorentz forces, etc. In general, the “fluid” is a collection of individual charged species, such as heavy ions, neutrals, and electrons, which make up an ionized gas. Therefore, the dynamics of ionized gases or plasmas, the working fluids in combustion MHD flows, is the subject of magnetohydrodynamics (MHD). A question arises when considering MHD interactions. How these charged species behave in magnetohydrodynamic phenomena has been studied by many researchers? The facets of ionization are essential in the study of MHD systems.

Atoms or compounds undergo ionization to make MHD interactions possible. The possible states of an electron include the stable, excited, or escaped states, as illustrated in Figure 1. In MHD theory, the important parameter that governs the feasibility of MHD forces is the electrical conductivity. This parameter characterizes electrically conductive fluids; it is a property that expresses a relationship between number density of ions and electrons and temperature. The ionization fraction is a ratio that defines the state of the ionized fluid. In combustion MHD systems, the electrons are a consequence of low-ionization from alkaline metals, such as cesium or potassium. Seed materials, alkaline metals, are injected into flames for ionization reactions to occur in the chemical reaction zone (CRZ). In the past, seed materials were inserted into the fuel-flow path. Ionization reactions and techniques vary depending on the MHD gas flow, as mentioned

in the Introduction Chapter. Therefore, the general ideas of ionization mechanisms and electrical conductivity, are major concerns in the design and analysis of MHD technologies.

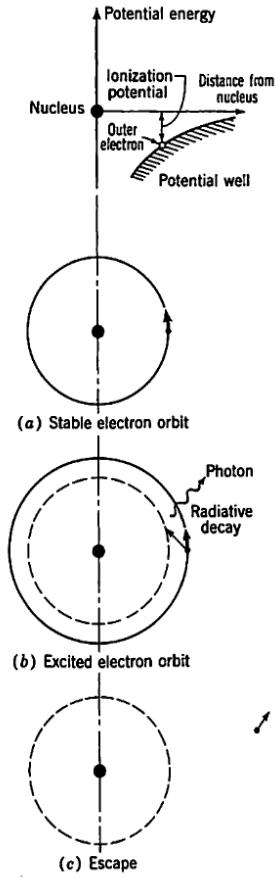


Figure 1. Probable orbits of electrons that describe ionization mechanisms.<sup>16</sup>

A presentation of the theory of magnetohydrodynamics can be segmented into constituent elements. The idea of ionized gases is a good starting point in the study of MHD. Ionized gases are the crux of MHD applications. Ordinary gas molecule behavior is distinctly different ionized behavior. This distinction is what makes MHD applications unique. The term plasma, made up of multi-component constituents in gases, is the origin of this discussion. However, in addition to understanding plasma chemistry, knowledge of electromagnetic forces is crucial to the study of

MHD systems. Since charged particles have a statistical behavior, this collisional behavior must be accounted for in this theory. Following these concepts, conduction and diffusion of ionized gases are critical to MHD interactions. For instance, this subject details collision cross sections, electrical conductivity properties, thermal conduction and diffusion in partially ionized gases.

MHD equations, and their derivations from a continuum modeling perspective, can be found in a monograph written by Sutton and Sherman.<sup>16</sup> MHD equations have exact solutions for specific simplified MHD geometries. A simplified model is Hartmann flow. Hartmann flow is the original mathematical investigation of MHD applications. Hartmann investigated this problem in 1937.<sup>18</sup> Couette flow, subjected to a uniform magnetic field, is another mathematical problem that has an exact solution.

In addition to the basic equations, specific aspects require consideration when analyzing MHD effects for product development. A major aspect that is frequently considered is the Hall effect. Hall effects in MHD flows may be accounted for in the basic equation formulation by modifying the electrical conductivity relation in the set. This quantified effect may be necessary if the magnetic field is of sufficient strength. Another critical area is the effect of the boundary layers involved in MHD interactions. Boundary layers have been a subject of intense scrutiny in MHD research, since it is a primary zone for electrode damage, arcing, heat transfer, and MHD power extraction. In the context of MHD power generation, many other subtopics must be considered in the study of MHD. These subtopics include, but are not limited to the following: device geometries, inviscid or viscous analyses, seed materials, mechanisms of thermal ionization, and compressible flow behavior. Each of these subtopics were broadly investigated to an extent for this dissertation. These subjects form the foundation of MHD interactions and govern its subsequent application in power generation applications.



A formulation of MHD flow equations, as seen in many texts, is derived from a continuum modeling approach.<sup>16,17</sup> Detailed theoretical treatments can be found in books authored by Sutton and Sherman and others by Rosa. From these references, the governing equations merge Maxwell's equations and viscous fluid mechanics equations. The complexity of this coupled set of equations justifies the need for simplifications, in order to define product specifications for MHD hardware. In accordance with these two authors, many approximations may be made, which hold as valid under certain conditions and flow regimes. Simplifications are delineated here for clarity. For instance, in Maxwell's equations, according to Sutton and Sherman, certain approximations hold true in the context of magnetohydrodynamic flow, these include:

- Neglect displacement current
- Conduction current magnitude may be considered larger than excess charge transport;
- Electrostatic body forces may also be neglected in the equations of motion if the contribution is small compared to the Lorentz force.<sup>16</sup>

For product development, reduced MHD equations were analyzed. MHD equations may be considered for one-dimensional variation to resolve engineering problems. The use of similarity parameters can also lead to other simplified descriptions, according to Sutton and Sherman. Definite similarity parameters, or non-dimensional numbers, have been implemented in many MHD design papers to reduce the complexities in the design of MHD systems. The most common dimensionless ratios, which may define MHD flows, include the following: Reynolds number, Magnetic Reynolds number, Mach number, Hall parameter, Magnetic force number, and the Prandtl number.

A quasi-one-dimensional approximation is a common practice when designing fluid dynamic devices. MHD devices or other combustion devices can be designed from this low-order approximation method. In the design of jets, rocket engines, inlets, combustion chambers, nozzles, and turbine blade passages are designed using this approach. For a more-detailed discussion of the one-dimensional approach, authors describe this method in Fluid Mechanics texts. Although this method has its limitations, it can be used to understand fundamental flow changes in these devices with rational accuracy. A quasi-one-dimensional treatment of an MHD flow is shown in Figure 2.

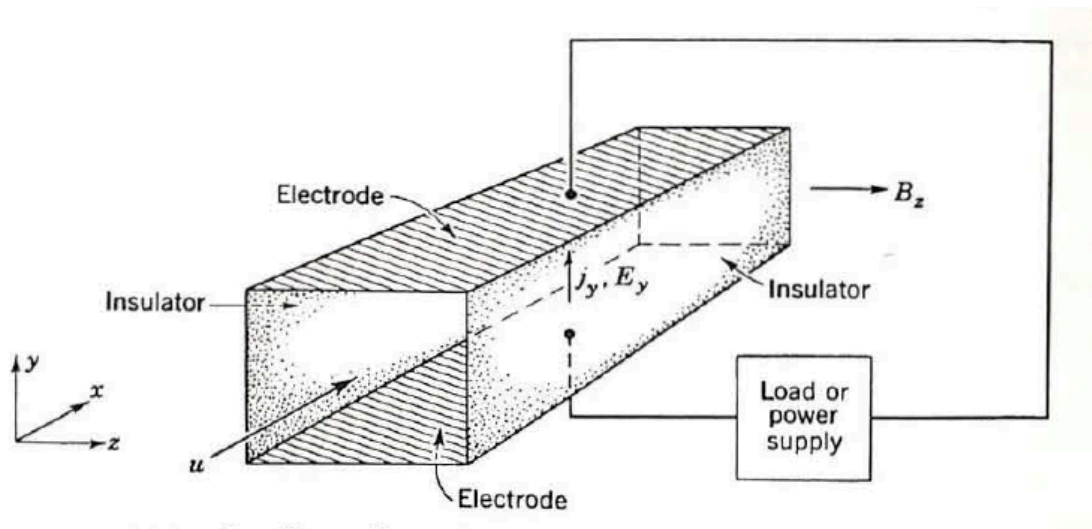


Figure 2. MHD physics described in a one-dimensional form in the above schematic.<sup>16</sup>

This approximation provides first-order differential equations as a description for the MHD device. The pressure and temperatures, in addition to specific heats, can be assumed to be uniform over the cross-section in question. MHD theory is applied to specific geometries. Various authors examined multiple cross-sections for magnetohydrodynamic generators. However, the basic geometry of hydrocarbon combustion devices in MHD generators is the rectangular cross-section,

as shown in Figure 2. When considering a Rectangular-Faraday MHD generator, assumptions may be invoked to solve MHD problems, according to Sutton and Sherman. These conditional assumptions are listed here for brevity, which includes the following conditions: Magnetic Reynolds number is significantly small, less than 1; gradual variation in cross-sectional area; a transverse pressure variation that is small; and channel dimensions should have large length-to-height ratios.

A quasi-one-dimensional formulation is presented here per the documented theory in Sutton and Sherman's text. The formulation begins with the governing physical laws of conservation of mass, momentum, and energy. Conservation of mass is written by assuming steady, a dominant dimensional variation in properties along the x-direction only, and constant thermo-physical properties across the cross-section, in differential form. This relation is expressed as

$$\frac{d}{dx}(\rho u A) = 0 \quad (1)$$

The next governing equations is the Conservation of Momentum for the equation of motion and the Conservation of Energy, which can be written as

$$\rho u \frac{du}{dx} = -\frac{dp}{dx} + j_y B_z \quad (2)$$

$$\rho u \frac{dh}{dx} = j_y E_y + j_x E_x \quad (3)$$

Ohms law and its relationship to the individual Faraday and Hall current densities is written by Equation 4 and 5.

$$j_y = \frac{\sigma}{1 + (\omega\tau)^2} (E_y - uB_z + \omega\tau E_z) \quad (4)$$

$$j_x = \frac{\sigma}{1 + (\omega\tau)^2} \left( E_x - \omega\tau (E_y - uB_z) \right) \quad (5)$$

Properties of the flow, namely the enthalpy and electrical conductivity, is necessary for closure.

However, in addition to these parameters, other unknowns are found in MHD problems. These other parameters include the following:

- Fluid properties: density, static pressure, static enthalpy, and velocity
- Cross-sectional area
- Current densities (Hall and Faraday)
- Electric fields
- Magnetic field

Per Sutton and Sherman, the MHD equations can be approximated by first-order ordinary differential equations. Certain conclusions can be drawn when analyzing MHD equations. Specifically, this set should consider an ideal, isentropic gas behavior. Furthermore, there are two identifications of MHD problems.<sup>16</sup> The first MHD problem prescribes the electric field, magnetic field, and cross-sectional area. This problem then resolves flow velocity and electrical conductivity. While, in contrast, a second mathematical problem involves the prescription of the fluid in a uniform magnetic field and addresses the electric fields and cross-section. In general, this reduced theory of MHD equations is a summary the general multi-physics in MHD. Only an abridgment of this formulation was necessary for the dissertation. The dissertation was scoped to understand the basic application principles of MHD only.

Therefore, this description of MHD principles was sufficient. However, for further discussion of the theory, a discourse of choice can be found in Sutton et al.<sup>15</sup> For a one-dimensional analysis of MHD Power Extraction, this one-dimensional theory was analyzed.

The next section discusses an introduction to the relevant aspects of charged species in flames.

## **2.2 CHARGED SPECIES IN FLAMES**

Ions in flames is a vast subject. Many fundamental and applied investigations have been carried out by numerous researchers, in order to understand the fundamentals of combustion flames in applications. Ions in flames have specific roles in practical applications today, of which the chemistry is still not completely well known today. Research in the areas concerning ion formation, ion mechanisms, and practical applications of ions in flames have been documented.<sup>19</sup> In magnetohydrodynamics, forces may be imparted to ions in flames to produce certain effects. In other words, magnetic forces can lead to acceleration or deceleration of charged species or ions in flames. Magnetic field deceleration provides a method to extract kinetic energy from flow particles to create electrical currents. This subsection is focused on reviewing the methods used to investigate charged species in flames, general characteristics of flame electrical properties, and ionization in hydrocarbon flames without and with metal additives. Its noteworthy to mention, that the choice to include ionization of metal additives in flames is due to its integral role in magnetohydrodynamic devices. Furthermore, most investigations of ions in flames were performed circa 1960s, since there were interests at the time in understanding ionization in combustion processes from rocket engines and developing high-temperature magnetohydrodynamic devices.

Certain methods have been studied to gain insight into the electric properties from flames. Both intrusive, and non-intrusive, methods have been evaluated to define various electric characteristics in flames. Today, a selection of these methods are still in active use to investigate low-ionization-fraction or partially ionized gases (known as low-temperature plasmas). For magnetohydrodynamic devices, a critical property of investigation is the conductivity which is a required facet of hydrocarbon flames in these applications.

Conductivity properties are directly connected to the performance of magnetohydrodynamic devices. In addition, conductivity can may provide information about the detection of flame appearance. Conductivity can be expressed in a mathematical relationship which relates the number density (concentration) and mobility of ions and electrons, assuming certain provisos. A majority of the literature on ionization and conductivity in flames cannot be summarized in this dissertation alone. Research on ionization and conductivity of flames can be traced to the early 1900s. However, this dissertation cites the most relevant articles in reference to the development of MHD devices.

Selected papers in the literature have studied conductivity in flames. The highlighted papers will be discussed further. Tufts investigated conductivities in various locations in Bunsen flames.<sup>20</sup> In this work, Tufts concluded that the conductivity at the inner cone was relatively higher in magnitude than the outer cone.<sup>20,21</sup> In addition, after a review of the earlier works, Tufts suggested that a general hypothesis could be deduced. Tufts hypothesized that a majority of ionization in flames possibly occurred near the electrode surface.<sup>20</sup> This work clearly indicated a need for a more detailed description of ion profiles in flames.<sup>21</sup> Following these studies, subsequent investigations were concerned with mapping conductivities in different parts of flame geometries. Gold studied velocity of negative ions in flames in order to estimate the mobility and hence

conductivity at the inner cone of a flame. Gold provided estimates of the conductivity, mobility, and electron concentration, at this location in the flame using a mathematical model.<sup>22</sup> Gold predicted the electrical conductivity to be near  $7 \times 10^{-6}$  mhos/cm.<sup>19</sup> Fialkov discussed how other experimental flame measurements of conductivity may be estimated by current- voltage drop ratios. The use of Langmuir probes, and probe theory, are a common methodology to investigate the so called volt-ampere characteristics in flames. If an extensive discussion of the Langmuir probe method is necessary, the interested reader can be directed to articles like Fialkov or other references such as H. Wilson. A drawback of using Langmuir probes for quantifying conductivity in flames is the resolution size and that the probe theory is complex. There are difficulties with this measurement technique. Probe measurements are dependent on an array of certain parameters associated with the probe surface environment. In flames, the probe sheath is a critical zone, which is sensitive to the convective high-temperature, high-velocity flow field.

### **2.2.1 Rates, ion concentrations, and mobility in flames**

In flames, electric properties must be investigated to understand how conductivity in flames can vary in magnetohydrodynamic systems. The rates of ionization and recombination are parameters that define the concentration profiles of charged species in specific flame structures.<sup>19</sup> These profiles are different for various mixture conditions, such as fuel rich, stoichiometric, and lean flames. The chemical reaction zone, which resides at the flame front, is the location where the ion concentration is said to be maximum. After passage through the reaction zone, recombination effects dominate in this region of the flame structure. Recombination rates decrease the overall concentration of ions in the colder regions of the flame due to energy loss. Profiles can capture the formation and destruction of ions in flames. This behavior, however, is not clearly captured for very rich concentration flames. Fuel rich flames near the stoichiometric condition is characteristic

of the maximum flame temperatures. These profiles have been investigated experimentally by researchers to understand soot formation, but have had limited results thus far. Molecular beams, in conjunction with Langmuir probes, is a method to resolve ion concentrations in flames. The rates of ion formation and recombination are a subject in question, which remains to be answered in the context of combustion magnetohydrodynamics. These rates stipulate how long the conductive gas remains conductive. Therefore, this is an active area of research for oxy-fuel combustion. In specific stoichiometric hydrocarbon flames, without low ionization elements, positive ion concentrations may range near  $10^{10}$  to  $10^{11}$  ions per cubic centimeter.<sup>19</sup> On the other hand, fuel-rich flames may have ion concentrations for a specific fuel on the lower end of the spectrum, near  $10^9$  ions  $\text{cm}^{-3}$ .<sup>22</sup>

The concentration of negatively charged ions, electrons and heavier ions, in flame have also been studied. However, difficulties exist with identifying the individual contributions between electron ions and heavier negative ions. For instance, electron attachment is problematic from the chemistry point of view. Methods to acquire information on the total negative ions are available, but certain assumptions must be assumed. For instance, a major assumption that is commonly made is that the number of positive ions are equal to the negative ion concentration. Negative ion formation is attributed to three mechanisms, in general. These mechanisms include three-body attachment, dissociative attachment, and chemi-ionization processes. Published data is available on negative ion concentrations for atmospheric flames, both flat and conical shapes. However, negative ion concentration is not readily available for high-velocity pressurized oxy-fuel flames or flames used in conventional magnetohydrodynamic devices.

Ion mobility is characteristic that must be understood in MHD devices. Ion mobility expresses how the ion velocity, i.e. drift velocity, relates to the electric field.<sup>19</sup> This parameter is



also very difficult to determine experimentally since the spatial distribution of concentrations can vary along the flow field and its highly time-dependent. Average values of ion mobility in flames, however, can be acquired using a first order approximation – Blanc’s law. For further analysis, previous research on mobility measurements can be found in several articles cited by Fialkov.<sup>22</sup>

### **2.2.2. Ionization mechanisms that are relevant to MHD applications**

Many ionization mechanisms are present in flames. Particular mechanisms are chemi-ionization and thermo-ionization, which are prevalent processes in flames. The ionization processes are sensitive to the stoichiometry of the flames. Ion concentrations in hydrocarbon flames were attributed to mostly thermal ionization and excited species collisions in early works on flames. However, as the science progress other mechanisms were observed, shifting this original theory. A thorough review of this early progress is the work conducted by Calcote. Arguments against thermo ionization have contested the idea of thermal ionization as the predominate source of ionization. A question, in combustion science, that has received substantial effort was if ionization in a flame was of thermally-induced origin or if other aspects have a role?

In hydrocarbon flames, thermal ionization in flames can occur as a result of the following interactions:

- Alkali metals and other impurities,
- Intermediate chemical pathway reactions
- Carbon species interactions
- Kinetic energy transfers through collisions with neutral species
- “Hot” non-equilibrium electrons
- Energy transfer by electronically excited species

All of these interactions can play a role in oxygen flames in a gases traveling a high-speed. Certain causes of thermal ionization are relevant to MHD. With regard to magnetohydrodynamics, alkali metal impurities which are easily ionized are added to the flame. Therefore, impurity effects in flames were investigated for this dissertation. This collection is described in more detail in the MHD literature subsection. Authors have claimed that if certain impurities are added to the flame, the ion concentration can be as high as 14 times larger than that of thermal ionization alone.<sup>19</sup> Hot electrons, which were investigated previously by von Engle and Calcote may be of importance. Hot electrons may alter ionization processes in flames, which have not been investigated for MHD applications. Therefore, this subject is still an ongoing area of investigation in the field of MHD and in other fields as well. However, there is a general consensus excited electrons can be harnessed for high-temperature combustion MHD studies. Another ionization process that is relevant to MHD applications is residence or life of short-lived electronically excited species. More details on the flame chemistry and or ionization processes can be found in classical combustion science texts, such as those by C.K. Law, I. Glassman, and K. Kuo, and original articles by Calcote and Fialkov, to name a few.

These subjects of charged species merit further investigation, especially in the case of oxygen-based hydrocarbon flames. Therefore, many aspects of oxy-combustion chemistry remain to be studied for power generation. Thus far, particular subjects were reviewed to understand the most critical areas of combustion gases and its interactions with electric and magnetic fields. The next section discusses the progress in combustion magnetohydrodynamics.

## **2.3 COMBUSTION MAGNETOHYDRODYNAMICS**

Combustion magnetohydrodynamics is an interdisciplinary field. Gaseous conductors have shown promise for power generation technologies. The idea is based on creating electrical

discharges as a consequence of the motion of electrically conducting gases. Many facets of combustion magnetohydrodynamics has been studied in an effort to develop magnetohydrodynamic technologies for the production of electricity. The progression of this subject has not been fully documented in a text. The most recent reviews<sup>10,23</sup> in combustion magnetohydrodynamics have specific focuses. The major reviews of this subject clearly define the needs in this field. Kayukawa and Pian and Kessler have suggested possible future directions in this field.<sup>10,23</sup> However, these reviews have discussed research opportunities that focused on two areas: loss mechanisms in coal magnetohydrodynamics research and open-cycle magnetohydrodynamic generator design issues. Although a comprehensive review has not been presented in the available literature, from these recent surveys, the next steps in the field is presented. These future research needs are directed toward the evolution of systems to use oxygenated flames, among other areas. Other areas of need are the development of advanced electrode materials and superconducting magnets. Probable enhancements to the electrical conductivity properties motivates renewed research in this field. Oxy-combustion systems may provide promising impacts to the electrical conductivity properties in MHD systems because of the relatively hot flame temperature. An additional motivation for researching oxy-combustion is the system's capacity to permit carbon capture in power generation.

The progression of magnetohydrodynamic power extraction research has had a difficult time-dependent path. The early studies of combustion magnetohydrodynamics can be traced to the early works in the 1950s. Significant research contributions involved findings over a span of approximately six decades. In general, the progression evolved from small-scale investigations, which were aimed to understand MHD devices at a scale for proof-of-concept. MHD studies progressed from these small-scale developments to large-scale developments on the basis of

promising findings. This movement to develop larger-scale MHD investigations was prompted by the need to design advanced power generation plants. Therefore, the research objectives in past studies targeted commercial-scale demonstration and evaluation of MHD technologies. After technical progress in coal combustion MHD systems, and an analysis of the state-of-the-art MHD performance, MHD research programs were terminated in the early 1990s due to technical limitations. Problems associated with the flow train, design of electrodes, air preheaters, coal combustors, seed processing, magnetic field strength, and electric current flow problems ultimately terminated further interests in the field. However, a particular problem was the electrical conductivity in flames, which has inhibited further investment in the technology for power plants.

### **2.3.1 Progress in combustion magnetohydrodynamics**

Combustion magnetohydrodynamics research can be traced to a single subject, electromagnetic induction. The nature of magnetohydrodynamics was investigated by Michael Faraday in 1832.<sup>24</sup> Faraday attempted to understand magnetohydrodynamics through experimental investigations of liquid mercury. After a century of Faraday's work, magnetohydrodynamics research shifted from liquid metal magnetohydrodynamics to gaseous magnetohydrodynamics. Gaseous conductors in magnetohydrodynamic systems were proposed in a number of patents. Magnetohydrodynamic generator concepts appeared in patents in 1910.<sup>25</sup> Although, the principle of these concepts was correctly characterized, electrical conductivity properties were not completely understood at this time. Furthermore, MHD experiments had not been demonstrated to confirm the physical concept of gaseous magnetohydrodynamics. Gaseous magnetohydrodynamics research, at the time, was purely an idea and it required fundamental advancements in many areas. Therefore, many fundamental questions were unanswered. For instance, a question, is it possible to have electrical discharges from a conducting gas? To answer

this question, several subjects required investigation. Two subjects were of interest, the field of gaseous discharges and combustion flames. Although, both fields, i.e. gas discharges and combustion flames, are independent and have a progression of their own, these studies provided the foundation of advancement in magnetohydrodynamics. The topic of gaseous combustion gases, as conductors, in magnetohydrodynamic applications was the focus of this review.

Many early studies contributed to knowledge and development of magnetohydrodynamics. In the beginning the field of ions in flames, such as ionization mechanisms and electrical conductivity in combustion, was still in its infancy. Electrically conductive properties in flames have been studied since the early works of Volta.<sup>26</sup> Volta, in 1801, studied electric discharges from flames in the presence of a nonconductor. Detonation front effects on electrical gas conductivities were also studied by Turpin in 1893.<sup>27</sup> In a later study, Tufts argued that ions in flames was a result of combustion chemical reactions.<sup>20</sup> Thomson in another study claimed that free-carrier formation was evident in combustion reactions, circa 1909, which may be acted upon by external magnetic fields.<sup>27</sup> Thomson, in this work, argued that external fields could potentially affect flame propagation and be able to produce electrical discharges. J.J. Thomson found that combustion caused negative charged carriers, ions and electrons.<sup>27</sup> This claim stimulated research in the field to study electrons and ions in flames for applications, which included magnetohydrodynamics. Following the work of Thomson in 1909, several studies were carried out to confirm Thomson's hypothesis. In 1958 and onward, a collection of work, by Calcote<sup>28-32</sup>, van Tiggelen<sup>21</sup> and other researchers, reported findings on ions, electrons in flames. In these works, many researchers confirmed that free-electron carrier concentrations were found in flames. Furthermore, Calcote, Sugden, and van Tiggelen each presented findings that supported magnetohydrodynamics research by advancing measurements of electron and ion densities in flames.<sup>27</sup>

While, concurrent research was carried out on ions in flames, particular concepts of gaseous magnetohydrodynamic systems were also being investigated.<sup>16</sup> Several designs of magnetohydrodynamic generator technologies were proposed and investigated in patent documents. The physics of these concepts were not completely understood. Both theoretical and experimental works were required to define working concepts of MHD systems with demonstration data. MHD research in this time could be characterized as developmental in support of gaseous magnetohydrodynamic technologies. For instance, an important theoretical work that occurred in this period was Meghnad Saha's work on thermal equilibrium in plasma chemical systems. Saha provided a relationship that describes ionization fraction as a function of temperature, which is critical for electrical conductivity calculations. Hartmann presented a theory of laminar electrically conductive flows.<sup>18</sup> On the other hand, the pioneering experiments of gaseous combustion magnetohydrodynamics were investigated by Halasz and Karlovitz. Particular research work on non-equilibrium magnetohydrodynamic power generation was also carried out by Halasz and Karlovitz.<sup>33</sup> They studied MHD through numerous from 1938 to 1946.<sup>34</sup> In their experimental system, combustion gases flowed through an annular system in the presence of a radial magnetic field.<sup>34</sup> Halasz and Karlovitz's experiments resulted in low electrical current collection in the MHD system, and suggested that the cause could be due to inadequate ionization. Their findings motivated other approaches for ionization approaches, such as electron beam ionization. Karlovitz and Halasz studied electron beams for magnetohydrodynamic interactions.<sup>16</sup> They concluded that the low current collection could be attributed to negative ion formation, a consequence of recombination reactions. These findings discouraged further investigations of gaseous MHD generators until the beginning of the 1960s.

Rocket engines stimulated research in MHD, since ionization in rocket flames could be used in magnetohydrodynamic generators. Several theoretical papers were written on conductive inviscid flows from a rocket engine nozzle configuration, in support of rocket MHD combustors.<sup>35,36</sup> Another supporting theoretical work was that of Saric and Touryan, which investigated magnetohydrodynamic entrance flow from rockets, and accommodated for the influences of Hall currents and ion slip effects.<sup>37</sup> Rocket engine configurations were suggested as a concept for magnetohydrodynamics by many authors.<sup>34,38,39</sup> Nichol et al. (1961) suggested that seeded flames in rockets exhibited high degrees of ionization, a promising technology for magnetohydrodynamics.<sup>38</sup> Nichol et al. studied ion concentration in water cooled rocket engines using Langmuir probes. A schematic representation of the water-cooled rocket engine, rated at 10-pounds thrust and used in the work of Nichol et al. (1961), is presented for illustrative purposes. Figure 3 shows this early configuration of a rocket engine. In the same year, magnetohydrodynamic power generation from combustion gas flows was also investigated by Way and Hundstad (1961).<sup>34</sup> In their first work, Way and Hundstad<sup>34</sup> presented both a discussion on the dimensions of their experimental combustion-driven magnetohydrodynamic generator and the combustion characteristics in their studies. Particularly, the combustion gases were directed to flow through a rectangular duct, in the presence of an orthogonal magnetic field. The combustor design used in these experiments included a swirl nozzle to inject liquid diesel fuel and a cooling jacket. In their work, combustion experiments were conducted with seeded potassium flames, where the potassium was 10 percent by mass of the fuel. Figure 4 shows a photograph of the combustion chamber and magnetohydrodynamic generator used in the work of Way et al. (1961).<sup>34</sup> Their study contributed to the field in many ways. A MHD combustor design for combustion magnetohydrodynamic power generation was presented. In addition, Way and Hundstad discussed

initial calculations of electrical conductivity from these combustion gas experiments. In this work, they defined magnetohydrodynamic generator tests to occur for 2-4 minutes.<sup>34</sup> The resulting electrical conductivity values are shown in Figure 4.<sup>34</sup> Subsequently, Way and co-workers documented a summary of their experiments in a another paper.<sup>40</sup> A main finding, from both works of Way et al. (1961), was the conclusion that sufficient power generation was possible from MHD experiments. However, a major concern was the insufficient current collection from combustion products.<sup>34,40</sup> Therefore, findings from these investigations described that charged gases in the exhaust of rocket engines could be used to extract electrical current. Although technical difficulties were found, researchers perceived charged gases from high-temperature rocket flames could makeup a useful approach in magnetohydrodynamic technologies. Thermal ionization was the focus of these magnetohydrodynamic experiments, which motivated further research.

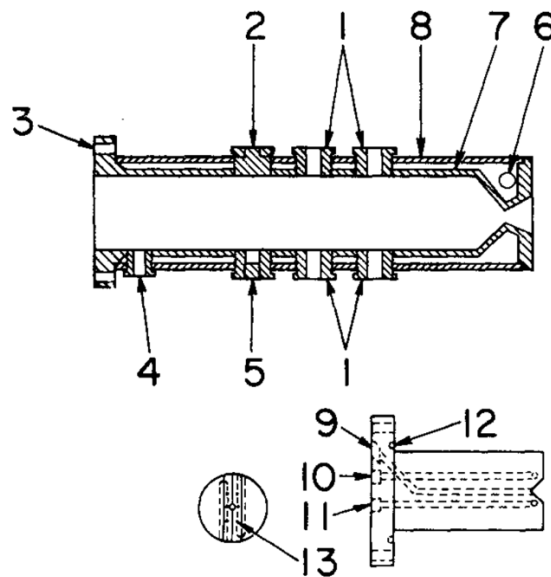


Figure 3. The design of a water-cooled rocket engine configuration for liquid-fuel and air combustion.<sup>38</sup>



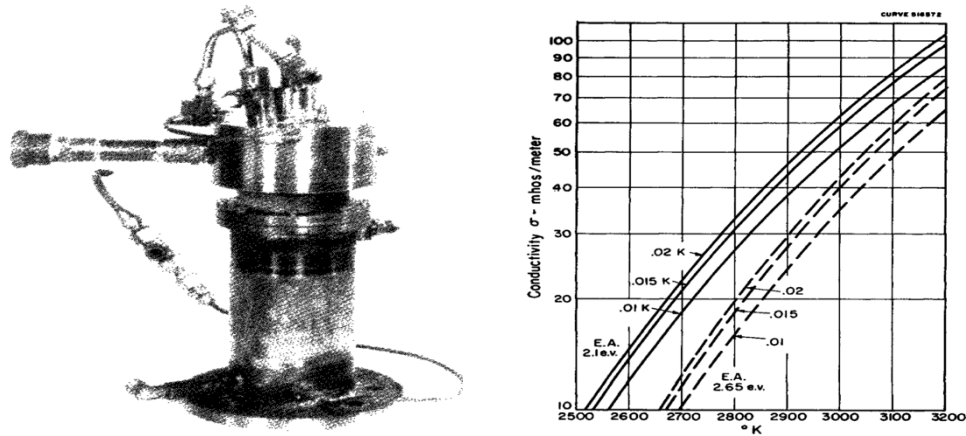


Figure 4. Way and Hundstad's MHD combustor and results of electrical conductivity.<sup>34</sup>

The next phase of research in combustion magnetohydrodynamic power cycles received in-depth attention to resolve specific problems. Following the work of Nichol et al. and Way and coworkers in 1961, monographs documented general aspects of MHD systems. Selected monographs are described. Sutton and Sherman documented a thorough account of engineering magnetohydrodynamics, which includes topics such as MHD propulsion and MHD generator applications.<sup>16</sup> Sutton and Sherman discussed the early concentration and working fluid characteristics associated with combustion magnetohydrodynamic devices. Figure 5 presents this table to describe the working fluids used in the early studies, which were researched at specific research institutions.

Rosa in a monograph described the principles of magnetohydrodynamics and aspects of the current research progress.<sup>17</sup> His work is a detailed discussion that followed his original work, physical principles of magnetohydrodynamic generators, in the field of MHD.<sup>39</sup> Both of these monographs discussed the progress in general terms and their potential applications. In contrast, Bunde's monograph examined MHD power generation from the German MHD research program.

Bunde describes the design of MHD generators, and technical problems in MHD generators.<sup>41</sup> Another major source of literature in this field, in addition to these monographs, many volumes of conference proceedings were held in an effort to understand the physics, systems, and technical issues in MHD systems. However, most conference proceedings are not accessible. It's noteworthy that the bulk of these conference proceedings is archived but not available for review. Therefore, reviews in this field scoped only published journal articles. A similar approach was done here to comprehensively review the progress in the field of MHD from a different perspective. An important finding from these monographs is that subsonic MHD power extraction was evident in the literature.

Characteristic	MHD research	AVCO		General Electric Space Sciences Laboratory	General Electric Research Laboratory	General Electric Research Laboratory	Westinghouse	
		Mark I	Mark II				Model I	Model 2
Working gas...	Kerosene and ethanol (plus oxygen)	Argon with arc heater	Ethanol or kerosene (plus oxygen)	Nitrogen with plasma jet heating	Propane (plus oxygen)	H <sub>2</sub> (plus air)	Diesel oil + octoate soap (plus O <sub>2</sub> + N <sub>2</sub> )	n-Heptane (plus O <sub>2</sub> + 0.47 molar N <sub>2</sub> )
Temperature, °K.....	3000	2800	3000	3200	2300	2550	2800-3000	2570
Gas velocity...	500-1000 m/sec	Mach 0.7	1000 m/sec	700 m/sec	56.8 m/sec	Mach 0.8	500-865 m/sec	757 m/sec
Seeding.....	1 %	K <sub>2</sub> CO <sub>3</sub>	1 % molar KOH powder	K <sub>2</sub> CO <sub>3</sub>	K <sub>2</sub> CO <sub>3</sub>	KOH	1.5 % (molar K in gas) as soap in fuel	0.3 % (molar K in gas) as K <sub>2</sub> CO <sub>3</sub> slurry in fuel
Generator size, in.....	1/2 x 2 x 16	1 x 3 x 20	60 x { 3 x 9 inlet 3 x 13 exit	1/2 x 4 x 29	1 x 2 x 2	2 x 4 x 12	1 1/2 x 4 1/2 x 16	1/2 x 1 x 16
Electrode material....	Tungsten (segmented, 5 electrodes 3 in. long)	.....	Graphite (segmented)	Graphite (4)	Graphite	Silicon carbide	C, ZrO <sub>2</sub> , ZrB <sub>2</sub> , W, etc.	ZrB <sub>2</sub>
Insulator material....	MgO	.....	Nonablating	Zirconia	MgO	MgO	MgO or cooled ZrO <sub>2</sub>	MgO
Magnetic field, gauss.....	20,000	.....	32,000	11,000	4,250	12,000	5,000-14,000	10,000
Emf generated, d-c volts....	50-100	55	Up to 1,400	75-90	0.7	90	30-100 open circuit	7.7 open circuit
Power generated, kw....	1.03	11.6	600	6	0.00002	1.9	1.5-10.4	3 watts per in. of length
Test duration..	30 min	10 sec	10 sec	5 sec	5 min	6 min	3-50 min	40 min
Efficiency (heat to electricity), %..	0.1	.....	3	0.1	.....	.....	~0.3	.....
Reference.....	32	37	25	36	33	35	31	.....

Figure 5. Characteristics of MHD research experiments, which were conducted at AVCO, General Electric, and Westinghouse, during the early progression in the MHD field.<sup>16</sup>

The major design characteristics of early MHD systems is presented in Figure 6, which illustrates a general focus, at the time, on subsonic velocities and temperatures in the range of 2500-3000 K in MHD generators. The architecture of a representative system design that constitutes a regenerative MHD power cycle, from this time period, and a temperature-entropy diagram are presented in Figure 6. In Figure 6, state 0-1 designates the isentropic nozzle process and state 1-2 represents the MHD generator process. MHD generator cycles, subsequently following early designs, indicated a combustion strategy of liquid fuel and preheated air. MHD cycles evolved to a regenerative system architecture that recycles the seed material to generate direct current electricity.<sup>16,34,40</sup> The next phase of research focused on characterizing ionized combustion gases and combustion gas interaction near electrode surfaces.

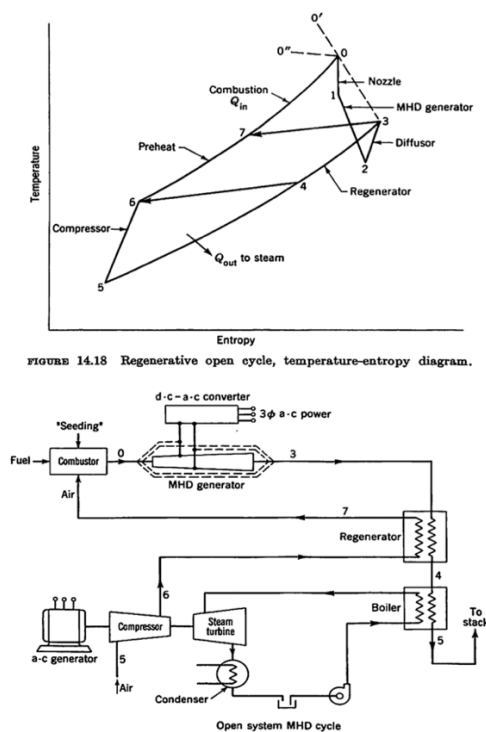


Figure 6. A T-s diagram and a schematic of a general open-cycle MHD generator in the early designs.<sup>34,40</sup>

### **2.3.2 Ionized combustion gases in MHD extraction**

Many studies investigated the characterization of ionized combustion gases in MHD environments. Sutton and Robben<sup>42</sup> carried out preliminary experiments on low-fraction ionized gases. Rosa presented a theoretical discourse on the physics and fundamentals of ionized gases undergoing magnetohydrodynamic power extraction, since many aspects of MHD power extraction were not clearly known.<sup>43</sup> In this work, Rosa wrote about how ionized gases have the potential in many applications, such as military, commercial scale power plants, and in space technologies. Rosa also explained and identified heat loss mechanisms in early MHD systems. These loss mechanisms were attributed to electrical property variations in the ionized combustion gases.<sup>39</sup> His work underscored certain design considerations, i.e. conductivity, ionization mechanisms, and temperature requirements, in magnetohydrodynamic flows, which required more detailed investigations. This paper is important because it described the technical issues that motivated future work in the MHD field in the 1960s. The behavior of viscous boundary layers of laminar electrically conducting fluids were also investigated by Sherman.<sup>44</sup> In MHD systems, the gas dynamics and boundary layer physics impacted the performance in MHD systems significantly. The boundary layer problem studied by Sherman demonstrated that flow separation, caused by an arbitrary magnetic field, was a possible concern.<sup>44</sup> Figure 7 describes this problem in a schematic. The boundary layer problem is still a critical region in MHD flows, which have detrimental impacts on arcing in electrically conducting flows.

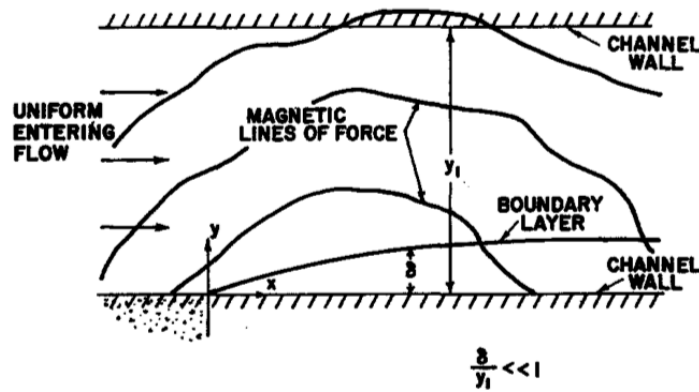


Figure 7. Boundary layer development under the influence of a non-uniform magnetic field.<sup>44</sup>

Certain studies investigated the influence of external electric fields on the combustion gases. The hypothesis was that applied electric fields may enhance on the ionization fraction in combustion gases. The effects of externally applied magnetic and electric fields on the combustion gases were studied by Lapp and Rich, Dimmock and co-workers, and others, which focused on improving ionization. In general, these studies presented advancements regarding the electrical conductivity properties of combustion. For instance, a selected work by Lapp and Rich focused on effects of applied electric fields on the electrical conductivity properties of seeded combustion.<sup>45</sup> Lapp and Rich measured electrical conductivity measurements in seeded hydrogen oxygen flames, with gas temperatures near 2400 K.<sup>45</sup> Dimmock and Kineyko investigated electrical conductivity measurements of seeded low-pressure flames to define the influence of external fields.<sup>46</sup>

### 2.3.3 Electrode interactions

Research in magnetohydrodynamic channels in the presence of electrodes was studied by a number of researchers. Turcott and Gillespie presented findings on the electrical resistance and sheath potentials in the presence of cold electrodes.<sup>47</sup> In addition to the efforts on diagnostics of

combustion plasmas, a thorough review of electrode-plasma interfaces and their associated effects on the design of magnetohydrodynamic systems was studied. Turcotte and Friedman discussed these electrode interfaces with combustion plasmas.<sup>48</sup> They found most of the work in this area, i.e. electrode studies in MHD, were conducted in experiments with shock tubes and in representative MHD system configurations. The combustion system used in the work of Turcotte and Friedman, similar to other studies, is described as a seeded, air combustion system.

Cold electrode surfaces in MHD power extraction environments motivated attention. For instance, the effects of electrode size and segmentation in MHD generators were investigated by Celinksi and Fisher.<sup>49</sup> Eustis and Kessler examined the influences of electrode and boundary layer temperatures on MHD power extraction.<sup>50</sup> Pian and Merk studied boundary-layer separation from electrode walls in MHD generators.<sup>51</sup> Hijikata et al.<sup>52</sup> investigated seeded combustion boundary layers near cold electrodes.

These studies in turn led to investigations concerning other electrical loss mechanisms near electrodes. James and Kruger investigated critical loss mechanisms, such as Joule heating effects, in electrode boundary layers in MHD generators. Gupta and Raju evaluated electrode potential drops across boundary layers in combustion generators.<sup>53</sup> The purpose of their work was aimed toward alleviating electrode erosion by understanding electric current densities in diffuse mode.<sup>53</sup> Electrode potential drops were not readily understood in the diffuse mode, since these effects are distinct for the anode and cathode. Gupta et al. claimed that certain authors focused on this problem in either the anode or the cathode, as the physics are distinctly different in the plasma sheath layers.<sup>53</sup> They contributed an analytical theory to calculate the potential drops due to diffuse current conduction with acceptable accuracy.

### 2.3.4 Large-scale combustion generators

Large-scale combustion generators were researched in many studies, which attempted to answer questions associated with optimal generator designs. The idea of "small-scale" and "large scale" designs was not clear in the context of magnetohydrodynamic power generation. Experimental facilities were designed for large-scale MHD generator experiments. Several researchers studied the effect of system scale and design of generators. For instance, certain researchers focused on the design of rectangular magnetohydrodynamic generators. Blackman et al.<sup>54</sup> studied the performance of combustion MHD interactions in rectangular magnetohydrodynamic channel designs. Rao et al. studied MHD generators that were configured in coaxial cylindrical geometry.<sup>55</sup> A coaxial cross-section geometry was used in the work of Rao et al.<sup>55</sup> Mullaney et al.<sup>56</sup> investigated designs of small-scale magnetohydrodynamic generators. A comprehensive analysis was carried out by Louis, Gal, and Blackburn.<sup>57</sup> The analysis compared theoretical and experimental results from large-scale MHD generators.

Studies have concentrated on large-scale combustor analyses. For instance, Louis et al. (1965) experimentally studied large Reynolds number flows, characterized by mass flow rates within 3-6 lb/s, in a large-scale combustion MHD generator. The details of the MHD generator used in this study can be reviewed in their paper. In brief, the MHD generator operated on combustion products of oxygen and methyl cyclohexane with ethyl alcohol, as the fuel. The purpose of this comprehensive study was to analyze MHD interactions over a range of mass flows within 3-6 lb/s to study pressure ratios, Hall effect, and electrode performance.<sup>58</sup> Louis et al. (1965) desired to understand the internal aerodynamics such as the drag, heat transfer coefficients, and shock locations in MHD generators. Furthermore, they computed theoretical values of conductivity and made a comparison with experimental conductivity data. Their theoretical

analysis, using a one-dimensional, confirmed that the approach described the flow in sufficient detail. From their analysis of electrode performance, they concluded that electrode losses are detrimental to the overall performance of MHD power extraction. MHD flows in the supersonic regime, specifically less than or equal to Mach 1.5, were the focus of this paper. Similar work on large-scale, combustion MHD generators was carried out by Ikeda et al.<sup>59</sup> However, Ikeda et al.<sup>59</sup> studied diesel-oxygen combustion reactions at pressures from 1.46-3.5 atm for MHD generator experiments. The combustor was designed to operate at a mass flow rate of 3 kg/s and produce gas temperatures near 2670 K. These experiments focused on characterizing the heat loss distribution and fraction of thermal input during MHD discharges. Ikeda et al.<sup>59</sup> reported heat losses of 6.4 MW and fractions of thermal input near 24 percent. The heat flux distribution under the influence of MHD extraction discharges was studied for two mass flow rates, i.e. 2 and 3 kg/s. In general, the main finding was the study of MHD interactions for long-duration exposure to MHD interactions.

Simons et al.<sup>60</sup> analyzed pressure and temperature waves in combustion MHD generators to present a model for wave formation in these systems.<sup>60</sup>

Pian and Hals examined advanced MHD powertrains to understand generator performance for systems that could produce 200-1000 MW electrical output.<sup>61</sup> The purpose was to create an advanced generator plan for large-scale demonstration systems.

McClaine et al.<sup>62</sup> focused on subsonic powertrains for combined-cycle power plants, namely MHD-steam systems. At the Avco Everett Research Laboratory, McClaine and co-workers aimed to establish a database for subsonic MHD generator subsystems designs and analyses. MHD generators, under considerations, included both Linear Faraday and Diagonally-connected generators, which interfaced with subsonic combustion flames.



Rosa studied electric arc behavior, a leading cause of generator degradation, in boundary layers for MHD generator development. He argued that the boundary-layer shape and profile, along with current density, affected the size of arcs in MHD systems. Arc shapes have led to decreased component and system life and generator performance, which is strong motivation to explore arcing phenomena in large-scale generators. In MHD devices, Rosa described the boundary layer as a critical region that exhibits steep gradients in temperature and electrical conductivity. His objective was to contribute a theory that related arc size and gradient characteristics to explain observations from experiments at the CDIF.<sup>63</sup>

Another area of investigation considered the flow at the exit of the coal combustion MHD generator, the MHD diffuser. Wilson et al.<sup>64</sup> presented the first laser velocimetry measurements in Coal-Combustion MHD systems. Before this time, no other velocity measurements in MHD combustors or MHD generators were contributed to the literature. The purpose of Wilson and co-workers' paper was to create a database to assist in the design and engineering of MHD components and to validate theoretical modeling efforts.<sup>64</sup> In these experiments, the MHD combustion conditions included preheated air at 1100 K (before combustion), liquid fuel, coal ash and seed material injection. Wilson et al.<sup>64</sup> concluded high-turbulence levels, on the order of 40-50 percent turbulent intensities, were measured in their flow experiments.

### **2.3.5 Magnetohydrodynamic system design studies**

The next research works, namely in the United States, focused on the system-level design of MHD devices exclusively for coal combustion. The subsequent phase of work concentrated on MHD design studies, since particular aspects of magnetohydrodynamics needed to be resolved for larger scale development. Design analyses, preliminary and conceptual in context, were carried out by some authors for the pilot-scale demonstration of MHD power cycles. Designs were tailored

towards larger scale devices the literature progressed by focusing on various needs in the technology. Multiple scales were targeted in this phase. Pian and Hals, in 1985, made a comparative analysis on 200, 500, and 1000 MW power plant configurations as part of the MHD Advanced Power Train development program.<sup>61</sup> Pian and Hals considered MHD devices designed for oxygen-enriched preheated (to 922 K) air and coal combustion. A design criterion in their designs was restricted to fuel-rich flames, to minimize emissions. They provided the results of their generator design analysis and their methodology in this work. Pian and Hals (1985) presented a summary of the design options and relevant data for large-scale MHD devices, which is shown here in Figure 8.<sup>61</sup> This work clearly indicated interests in using supersonic flow trains to improve power extraction in MHD devices.

Other design studies were carried out to improve the system engineering in MHD devices. Other system designs were investigated in subsequent works. Pian, Kessler, and Schmitt (1996) detailed the design of an MHD/steam combined power cycle for demonstration experiments. Design improvements were made to the anode electrode configurations. For instance, Pian, Petty, Schmitt, and Farrar (1995) presented new anode design concepts for a 50 MW magnetohydrodynamic topic cycle prototype. Diagonally-connected electrodes were also proposed to improve the electrical output in MHD devices. In a comparative analysis, Pian (1996) discussed the slag performances in diagonally connected MHD generators, namely the Avco Mk VI and the Component Development and Integration Facility. This relatively large-scale MHD facilities were constructed and analyzed. The major concerns in the performance of these devices were exclusively attributed to the conductive layers of seeded oxygen-enriched air and coal combustion in open cycle magnetohydrodynamic power cycles. This rational led to several new design ideas. The most recent design studies of MHD devices were those of Li et al. (2005) and

Bobashev et al. (2005). Li et al. (2005) provided numerical solutions of electrical current extracted from the flow in diagonally connected magnetohydrodynamic generators. Shock interactions in MHD flows was also an area of study, which affects. Bobashev et al (2005) studied the effects of MHD interactions on supersonic magnetohydrodynamic flows and its shock wave characteristics in these devices. MHD system design studies were completed to achieve increased performance in MHD generators and at larger scales. However, following these design-based studies, detailed investigations on slag-seed interactions in coal combustion gases received interest.

**Table 1 Summary of generator design and performance data for the three recommended plants**

Plant size	~ 200	~ 500	~ 1000
O <sub>2</sub> Enrichment, molar percent	32	32	32
Channel length, m	10	16	18
Mach No.	1.2	1.2	0.885
Pressure ratio	5.19	6.48	7.26
Load parameter	0.7109	0.7400	0.7807
$P_{MHD}$ , MW <sub>e</sub>	84.85	230.22	502.08
$P_{net}^a$ , MW <sub>e</sub>	51.90	149.54	343.75
$Q_{wall}$ , MW <sub>th</sub>	21.37	47.36	77.20
Maximum $E_{yc}$ , kV/m	3.81	3.83	3.98
Maximum $E_{xc}$ , kV/m	2.63	2.17	1.85
Maximum $J_{yc}$ , A/cm <sup>2</sup>	0.77	0.74	0.84
$V_{Hall}$ , kV	22.3	29.4	28.22
Maximum $\beta$	3.94	3.98	3.91
Maximum $B$ , T	4.5	4.5	6.0
Maximum $q_{wall}$ , W/cm <sup>2</sup>	314.0	353.0	406.5
Power density, MW <sub>e</sub> /m <sup>3</sup>	9.62	7.71	7.62
$\eta_{EE}^b$ , %	16.32	19.81	23.52
$\eta_{MHD}^c$ , %	9.98	12.87	16.10
$\eta_{isen}^d$ , %	60.08	64.62	72.45

<sup>a</sup>  $P_{net} = P_{MHD} - P_{comp} - P_{O_2}$ ,  $P_{comp}$  = cycle compressor power,  $P_{O_2}$  = O<sub>2</sub> - plant compressor power. <sup>b</sup>  $\eta_{EE} = P_{MHD}/Q_{in}$ ,  $Q_{in}$  = coal thermal input.

<sup>c</sup>  $\eta_{MHD} = P_{net}/Q_{in}$ . <sup>d</sup>  $\eta_{isen} = P_{MHD}/\Delta H_{isen}$ .

Figure 8. Generator design options and their associated MHD performance values for three advanced MHD power plant designs for large-scale.<sup>61</sup>

### **2.3.6 Non-uniformities in slag-laden combustion gases**

Slagging phenomena, attributed to coal combustion, in MHD systems caused non-uniformities. The effects of slag in coal preheated air flames were studied extensively. This topic in the field of MHD research is a second area that received substantial attention. Many aspects of this phenomena were of interest. For instance, slagging phenomena has been observed to alter the charge distribution in the moving fluid and affect magnetic field interactions. Cathode non-uniformities have devastating impacts on magnetohydrodynamic extraction. These impacts cause non-uniformities as a result of short-circuited electrode interactions. Studies also have focused on understanding the influences of slag layers. Sadovnik and Pian (1986) performed an analytical modeling study of the cathode non-uniformities in slag-laden flows in coal-fired combustion gas generators by a two-dimensional electrodynamics model. The authors made a comparison between the modeled results and experimental data from the AVCO Mk VI and the CDIF generators. Numerical models were carried out by Scott and Simpson to investigate the electrical non-uniformities in commercial scale magnetohydrodynamic generators.<sup>65</sup> Pian and co-workers measured voltage-current characteristics in a slagging magnetohydrodynamic generator, the AVCO Mk VII.<sup>66</sup> In a subsequent study, Pian and co-workers performed other experimental investigations. The objective was to explore slag layer influences on the gas dynamics in slagging generators.<sup>67</sup> Molten-slag induced leakage effects in slagging layers were investigated by Pian and Schmitt.<sup>68</sup> In slag-laden flows, electrical non-uniformities also prompted research into the boundary layers of a magnetohydrodynamic generator, where arcing phenomena also could cause changes in the flow field. Non-uniformities, caused by potassium reactions in coal-air flames, still have many unresolved questions that affect the conductive flow of high-temperature combustion gases.

Luongo and Kruger investigated slag-seed interactions, by a two-dimensional, boundary-layer problem using analytical theory, in coal combustors in MHD generators.<sup>69</sup> The model was used to examine these interactions in a 275 MW<sub>th</sub> MHD generator. Luongo and Kruger argued that the slag layers, which are in contact with relatively colder electrode surfaces, is the main cause of seed absorption in MHD generators.

Pian, a researcher at the Avco Research Laboratory, investigated an analysis of experimental data from two large-scale diagonally-connected MHD generators.<sup>70</sup> The two MHD generators studied in this technical paper included the Avco Mk VI and the Component Development and Integration Facility (CDIF). The objective of this work was to understand the effects of various operating parameters on slag-seed interactions. Pian concluded that an effective slag layer resistance is dependent on combustion operating parameters.<sup>70</sup>

Scott and Simpson<sup>65</sup> examined non-uniformities in commercial-scale MHD generators by formulating a time-dependent model of slag layer development. They emphasized a need to understand the physical mechanisms, slag polarization and slag burnout, in MHD systems. Slag polarization is a major concern since it forms conducting paths near cathodes.<sup>65</sup> This polarization effect was seen as a direct consequence of seed material buildup in the systems. On the other hand, Scott and Simpson also explained slag burnout. Slag burnout is a decrease in electrical conductivity, which is attributed to arcing phenomena near cathodes. Both phenomena led to non-uniformities in flow characteristics in MHD generators and required an in-depth analysis. They developed a model that reasonably predicted inner cathode voltage non-uniformities in large-scale MHD generators, based on experimental data from small-scale magnetohydrodynamic power extraction. This paper is an important paper as it describes the importance of controlling inner cathode-slag conduction paths and hence voltage non-uniformities in slag-laden combustion gases.

Pian et al.<sup>71</sup> investigated, further, the voltage-current properties that occurred at insulator gaps during slag-laden experiments in MHD generators. The purpose of this work was to identify leak resistances and to understand the causes of slag layer development, under various magnetic fields, near anode and cathodes.<sup>71</sup> The conductive behavior of slag coated electrode layers had detrimental impacts on the combustion gas discharges due to MHD interactions. In this work, electrical leakage was studied in a 20 MWth MHD generator, characterized as a liquid fuel, preheated air coal combustion chamber, Mach 1.2 channel entrance, 1-meter channel length, and operated on a mass flux of 2 kg/s.<sup>71</sup> In their experiments, K<sub>2</sub>CO<sub>3</sub>-seeded, fuel-rich combustion at atmospheric pressure and temperatures near 2600 K were the characteristics of the working fluid in question. A representative schematic of the problem they were attempting to understand is shown in Figure 9. They concluded that when the magnetic field was applied, the slag resistance across the insulator gaps decreased from 100 ohms to 0.5 ohms, a critical finding for slagging generators. They interpreted this result as evidence of transverse arcing in the slag layers.<sup>71</sup>

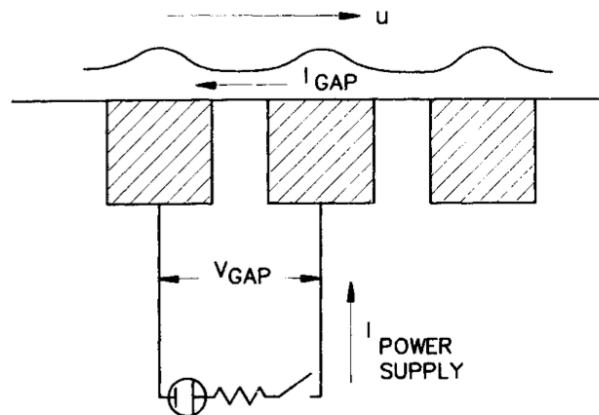


Figure 9. Representative schematic of the insulator gap problem in slag-laden large-scale MHD generators.<sup>71</sup>

The next phase of research of slagging effects in generators concentrated on understanding the cathode wall slag-layer frequency. For instance, Pian, Petty, and McClaine<sup>72</sup> examined cathode wall slag-induced shorting events in MHD generators. This study aimed to define cathode shorting scales with larger combustors and generator channels for MHD power extraction. They argued that many studies were performed in the past to understand slag polarization. However, not many studies examined causes of resegmentation frequency of cathode wall slag. According to Pian et al.<sup>72</sup> cathode wall resegmentation has the capacity to decrease MHD interactions, since the axial current leakage increases as a result of resegmentation. They hypothesized that three problem areas could be the leading cause including

- Hall effects that constrict Faraday currents
- Current reversal as a consequence of shorted slag layers near the boundary layer
- Arcing<sup>72</sup>.

In this work, to understand this process further, Pian et al.<sup>72</sup> experimented with a variety of generator conditions. Pian manipulated conditions to define which parameter affected slag shorting. They concluded that slag resegmentation on the cathode is strongly a function of local Hall electric field and their corresponding Hall voltages. Pian et al.<sup>72</sup> also argued that based on their experiments, Hall parameters, magnetic fields, or gas conductivity presented no effects on cathode resegmentation near the electrode wall. This work motivated further analysis on seeded combustion effects on electrodes.

Ishikawa et al.<sup>73</sup> conducted a numerical analysis on a diagonally-connected, 100 MWth, supersonic MHD generator that operated on coal combustion. Ishikawa and co-workers focused on the mechanisms of slag polarization and its effects on electrical non-uniformities. They found

that external circuits possibly controlled inner anode voltage and current during coal slag polarization events. From this work, they approximated slag leakage power losses of near 20 percent based on their numerical analysis. This claim shows similar results from the latest reviews<sup>10,23</sup> of open-cycle magnetohydrodynamic generators. Specifically, that electrical losses, among heat losses, must be resolved to develop more-efficient MHD power extraction.

Goforth and Kruger<sup>74</sup> studied secondary flows, which have been postulated to impact velocity fluctuations, conductivity profiles, heat transfer fluctuations, and boundary layer voltage characteristics in MHD generators. Their interest in secondary flows stemmed from inconsistencies in boundary-layer temperature profiles and analytical predictions. MHD secondary flows, according to Goforth and Kruger, affected turbulence and axial velocities and heat transfer in slagging MHD generators.<sup>74</sup> A representative problem of MHD secondary flow effects is shown for an infinitely-segmented Faraday generator in Figure 10. Goforth and Kruger contributed to the field by presenting experimental measurement data for MHD secondary flows. The importance of this study was that the authors believed that hot, conductive gas flows in the core were shifted away from the core, a detrimental impact on core flows and MHD generator performance. These secondary flows occurred throughout the MHD channel and therefore required further study.



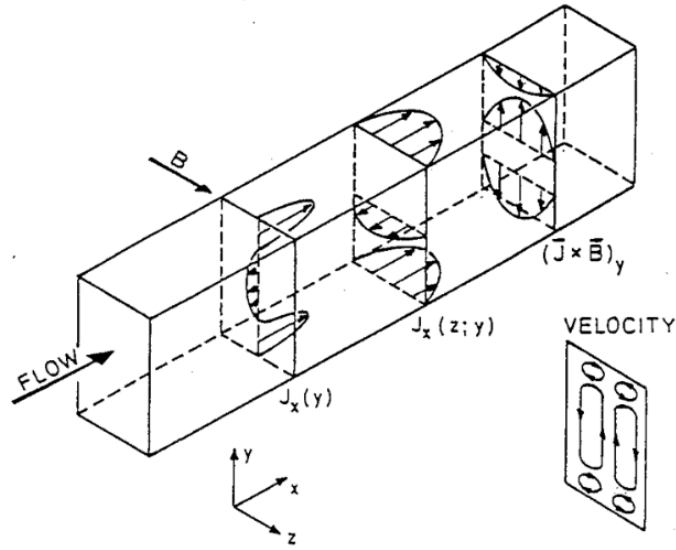


Figure 10. MHD secondary flow problem in an illustrative schematic.<sup>74</sup>

The progression of large-scale MHD generators was redesigned for the next phase of research in the 1990s. Pian et al.<sup>75</sup> presented a paper that described prototypic MHD anode designs and experimental results for the Integrated Topping Cycle MHD power generator. This particular generator design was aimed for 50 MWth proof-of-concept and demonstration. This MHD system accumulated over 500 hardware-exposure hours to verify design reliability. The concept for the prototype designs in this MHD combustor/generator is shown for a context in Figure 11. Figure 11 depicts the direction of the combustion gas flow and the current and ion flow directions in the diagonally-connected MHD generators. Specifically, the prototype designs incorporated water-cooling jackets over a copper material structure, a boron nitride inner anode material for insulation, and aluminum nitride materials for the anodes. The design was based on the current understanding and knowledge of slag induced non-uniformities, secondary flows, and other material impacts that occurred in MHD generators. Pian et al.<sup>75</sup> concluded that localized wear was evident on the anode and cathodes, and they argued that this was due to slag coverage and electrode interactions. Slag

proximity to electrodes required additional research from a materials perspective. Furthermore, alternatives to seeded combustion gases may be needed to avoid slagging effects in MHD generators. However, following this work, although many questions remained in the field of MHD, future experiments in MHD were terminated.<sup>75</sup> This end was confirmed by a later review paper, written by Kayukawa in 2004.<sup>10</sup>

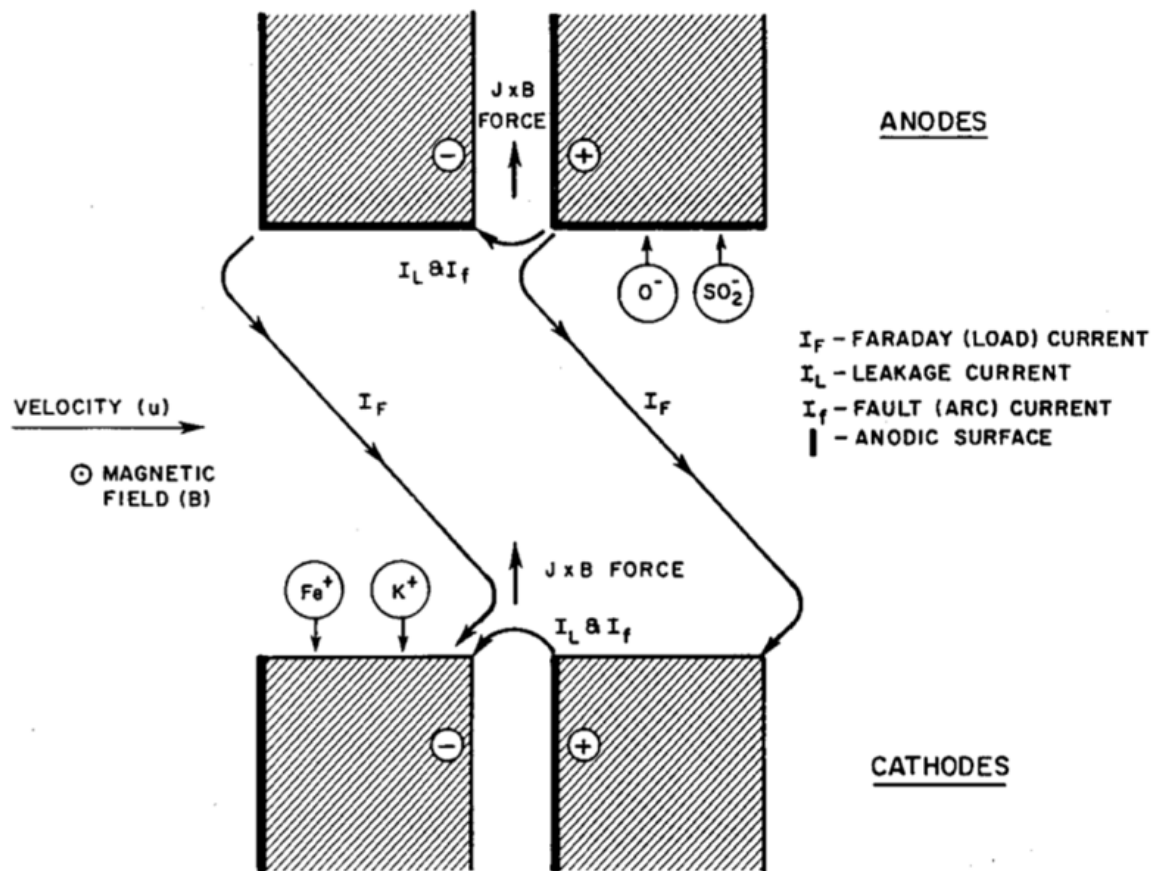


Figure 11. The current state-of-the-art conceptual design of a diagonally-connected coal-combustion MHD generator, from the work of Pian et al.<sup>75</sup>

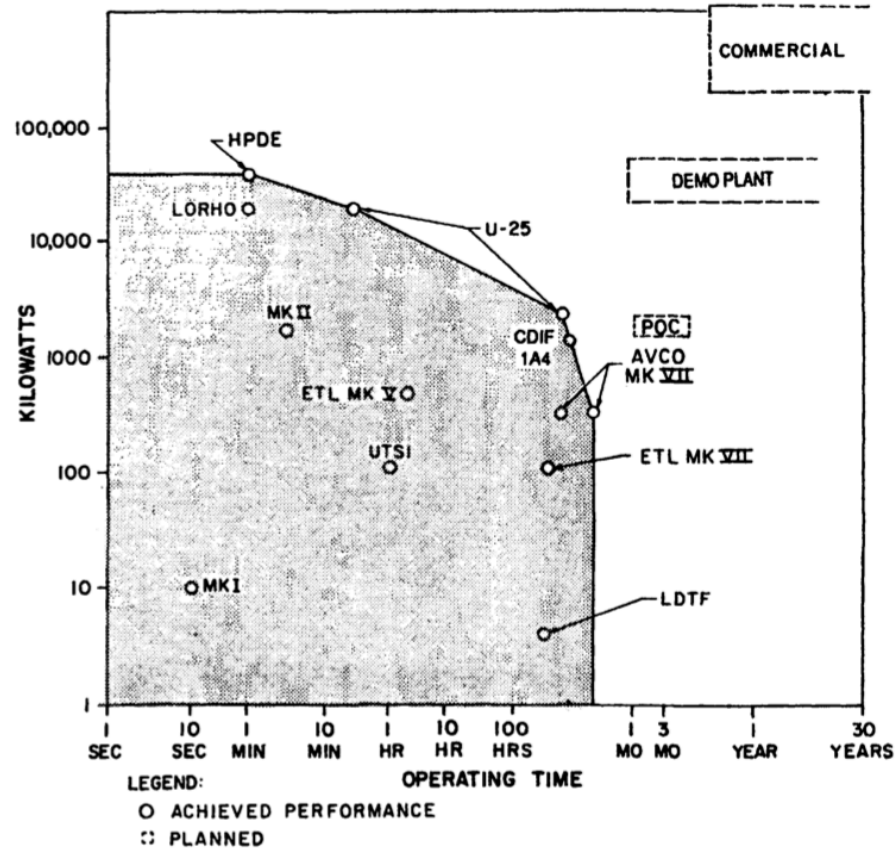


Figure 12. The research opportunities in MHD generators regarding scale and long-duration time.<sup>23</sup>

The latest technical research of MHD concentrated on problematic technical issues and a description of future aspects of magnetohydrodynamic power extraction. For instance, Pian and Schmitt<sup>76</sup> continued research on the wall surface leakage effects in MHD generators. Pian et al.<sup>77</sup> studied various MHD generator designs for a combined-cycle demonstration. Several reviews were written from very different perspectives. Pian and Kessler<sup>23</sup> contributed to the field with a review of open-cycle magnetohydrodynamic power generators, wherein they focused on describing MHD channel designs and performance in coal combustion flows only. In Pian and

Kessler's review, the operating time and MHD generator design scales are documented. Figure 12 shows the research opportunities in MHD systems regarding scale and long-duration time.

In 2004, many works following the discontinued research into MHD power extraction focused on the needs and roles of MHD generators in power generation. For instance, Kayukawa discussed carbon-dioxide restrictive, fossil-based power generation and described how MHD generators could be a key component in these types of systems.<sup>8</sup> In two other papers, Kayukawa and co-workers presented the concept of an MHD power cycle for power generation, which in contrast is different from earlier studies that considered MHD generators as purely a topping cycle.<sup>78,79</sup> Following this work, the idea of combined open-cycle and closed-cycle MHD generators was a design consideration in future systems.<sup>80</sup> Although these new ideas and concepts were proposed, no other experimental, numerical, or analytical research in combustion gas MHD generators were evident in the literature. The final paper in the field of magnetohydrodynamic power extraction from seeded combustion gases was that of Kayukawa, a review paper that focused on the technical limitations and possible future directions in this research area.<sup>10</sup> A research opportunity is the idea of scaling of magnetohydrodynamic combustors and generators.

Pian

It is noteworthy to mention that a new field of MHD research has been evident following the last review paper by Kayukawa.<sup>10</sup> This field is referred to as MHD interactions for cold-air hypersonics. However, as Hypersonic MHD is not within the scope of this dissertation, a collection is cited here for completeness.<sup>12,81-116</sup> This collection is not within the scope because magnetohydrodynamic interactions are focused on ionized cold air for aircraft enhancements. This field has not been reviewed in the literature of MHD and could result in cross-functional ideas from the knowledge of this field for combustion magnetohydrodynamics in the future.

## **Chapter 3: Methodology**

### **3.1 PRODUCT DEVELOPMENT METHODOLOGY**

The objective of this work is to design multiple oxy-fuel combustion systems for magnetohydrodynamic applications based on computational fluid dynamics (CFD) design tools. Physical architectures of oxy-fuel combustion systems for magnetohydrodynamic power extraction require high-velocity, high-temperature axial flows. Therefore, the design methodology of rocket engines can be used to understand oxy-fuel combustion characteristics.

Fluid dynamics in rocket engines can provide these design requirements, and substantial literature is available on rocket engine designs. Rocket engine literature is a highly empirical science with a collection of numerical simulations. Therefore, oxy-fuel combustion systems in this current work were designed based on rocket engine technologies. In the design methodology, rocket engine design texts, nozzle gas dynamics equations, injection schemes, and heat transfer semi-empirical and empirical data were considered.

The design criteria that drove the architecture aimed to provide gas flow velocities at Mach numbers near 2 and gas temperatures near 2800 K at the end of the nozzle expansion. The novelty of the current MHD combustor design and that of others lie in the combustion process itself and the flow regime. For instance, in previous architectures used in MHD combustors coal preheated air combustion was the focus. In this design methane-oxygen combustion was the combustion criterion. Russian MHD combustion devices used a similarly combusted natural gas and preheated air, but they did not study natural gas and oxygen combustion in their MHD research. Therefore, methane, a major constituent of natural gas, was considered as the fuel in these oxy-fuel combustion systems. Methane oxygen theoretically attains a maximum temperature in a slightly-rich configuration. Since the temperature is of vital importance to MHD applications, a slightly-

rich equivalence ratio or O/F ratio was selected for this system. Another design criterion was to design a combustor that is characterized with a thermal rating of near 100 kW for initial conceptualization, design, and testing. This combustor architecture is referred to as the small-scale MHD design in the dissertation. Following the small-scale combustor design, larger-scaled combustion devices were of interest. The rationale behind this consideration, of other combustors with larger ratings, is to answer questions regarding scaling effects in combustion. The thermal rating criterion is a characteristic of combustion burners and devices, which relates the mass flow rate and the higher heating values of the fuel. The second large-scale combustion device design will be described in a later section, and the focus now is on the design of the smaller-scale oxy-combustion device.

A system design that has influenced the architecture of this small-scale oxy-combustion technology for MHD applications is that of Roy and Wu.<sup>117</sup> The two-dimensional schematic from the research work of Roy and Wu is shown for comparison and identification of past MHD specifications and hardware.<sup>117</sup>

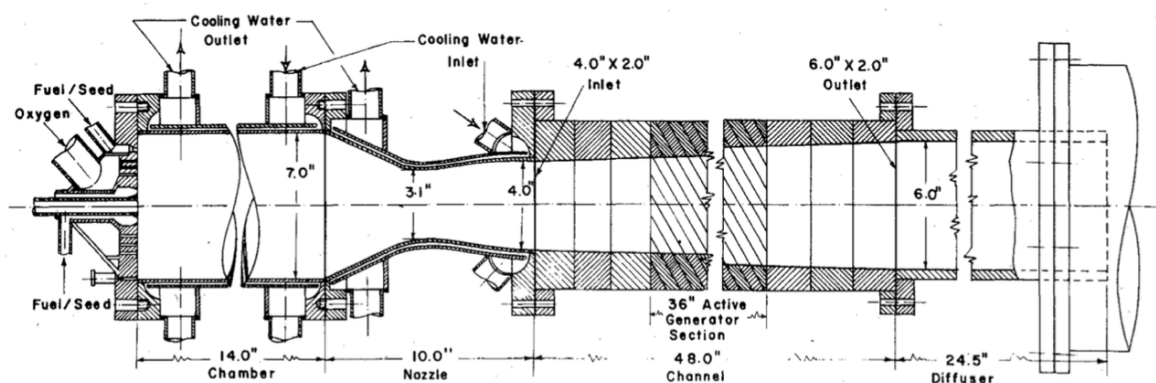


Figure 13. Seeded coal-air MHD combustor and generator from the work of Roy and Wu.<sup>117</sup>

The design methodology can be characterized as an analytical and coupled numerical approach. The analyses were performed in one-dimension, two-dimension, and three-dimensions for enhanced understanding of the physics in the combustor. A systems engineering design methodology involved design reviews, collaborative discussions with the U.S. Department of Energy researchers provided guidance and expertise on the MHD interface and MHD extraction physics.

A review of the literature of magnetohydrodynamic power extraction provided a strong background for the interface, subsystem, and system analyses. In addition to an extensive volume of literature on the subject of MHD systems in the past, elements from rocket propulsion, mechanics of propulsion, and design of liquid rocket engine texts were consulted extensively during this process.

The starting point in the design method was the design of the nozzle. The nozzle subsystem profile governs the compressible flow behavior of the combustion gases during expansion, the mass flow rate in the system, and the heat transfer. Based on previous cryogenic combustion designs for igniters, a small throat diameter was selected. This small size was used to compute the thermal rating, which is constrained to less than 100 kW. The throat diameter of the nozzle, in the oxy-combustor design, was 5 mm. This cross-sectional area constrains the total mass flow rate of the gases, and hence the thermal rating of the system. For an O/F ratio of 3.5, and this cross-sectional area, the mass flow rate of the fuel is 1 g/s. These conditions lead to a thermal rating of near 60 kW.

The NASA CEA code provided the combustion gas properties for the converging-diverging nozzle.

The nozzle definition was designed by assuming an isentropic process. The contraction ratio, expansion ratio, and half-angles were defined using isentropic flow relations and the constraints at the end of the nozzle. Conical nozzles were considered instead of a parabolic profile.

The combustion envelope, which is referred to as the length from the injection plane to the throat plane, was determined based on liquid propulsion empirical data for the given throat diameter. The  $L^*$  parameter selected for this design was approximately 100 mm. Liquid propulsion empirical data was used as an estimate of the combustion chamber length or characteristic length scale. Since spray atomization and evaporation process time is not necessary, this approach could be used to approximate the length scale of gaseous combustion, which renders a conservative approximation of the combustor length. The characteristic length used in the design could in theory be significantly less in length, since the empirical data is for cryogenic propulsion engines. This reduction in length could offset trade-offs in using a low-thermal conductivity material, such as Inconel 718 super alloys.

An investigation of various super alloy (low conductivity materials) and their material property variations with respect to higher temperature were examined. Several aerospace graded materials were considered in the design, however, the high-strength, high corrosion resistance characteristics of a particular material led to the use of Inconel 718. The particular materials under consideration, which received attention, included nickel-based alloys, such as Inconel 625 and 718, and cobalt-based alloys. In previous MHD architectures, copper alloys were selected for its high thermal conductivity. In addition to low or high conductivity metal materials, Yttria-stabilized Zirconia thermal barrier coatings (YSZ-TBC) were considered for the small-thermal-scale Oxy-Combustor. However, TBC coatings have shown difficulties in manufacturing at small scales and they led to expensive design costs. Therefore, after these considerations,



Inconel 718 was selected for its low-thermal-conductivity properties and its high-strength at temperatures between 500-650 C. The proposed idea is that a low conductivity material may be beneficial in MHD power generation systems. Therefore, a conclusion from this study was that many trade-offs existed. The tradeoffs concerned heat transfer design methods, material selection (i.e. manufacturability, availability, cost), and material survivability at high temperatures for oxy-combustion. This idea may be of increasing importance as the thermal power rating of Oxy-Combustors for MHD applications is increased.

A regenerative-water cooling channel strategy was established for an Inconel 718 cooling jacket structure.

During the design of the regenerative-cooled jacket, interface definition was required in the architecture. A spark ignition system was selected to provide activation energy (12 kV) to the gas mixture. This system was placed at a specific position on the wall. Other interfaces included sensors to quantify combustor performance. For instance, two sensors and their conduits were designed in the combustor architecture. A sensor was used to measure the static temperature at a point in the wall structure. Also, a static pressure transducer was positioned to measure the combustion chamber pressure during experiments.

The injector design was based on a previous swirl-coaxial methane-oxygen rocket engine. The most vital system of a combustor is the injector. The injection method can affect the mixing, momentum flux ratio between the reactants, mixing lengths, ignition, and the combustion dynamics of the flame front. A swirl-coaxial methane-oxygen injector was selected to provide partially premixed flames, which have received extensive attention by the combustion science field for its promising advantages over premixed and non-premixed flames. Although the flame front is not visible due to an absence of optical windows, the high-temperature flame at the exit is the main

area of observation that indicates injector performance. Several iterations and analyses, both analytical and numerical in nature, were conducted to define final swirl-coaxial injector architecture. These analyses enabled a detailed understanding of the geometric effects on the flow path of methane through four tangential ports. Previous tangential-port-injection schemes had been used in previous MHD combustor systems.

Reactant and water feed systems were analyzed based on the nominal operating design conditions of the oxy-fuel engine. The feed system included reactant and water tanks, tank regulators, stainless steel piping, solenoid and ball valves, flowmeters, thermocouples, and pressure transducers for each flow path. In addition to the main flows, nitrogen and carbon dioxide flow paths were included for purging and safety prevention during experiments. For automatic observations, feed system components were connected to a data acquisition device for controlled data management.

The findings of the design of an Oxy-Combustion experimental system for MHD applications illustrates the final architecture, which was based on iterative numerical CFD analysis. The designed electrical system configuration in the experimental facility can be seen in the Results and Discussion chapter. The final blueprints, three-dimensional solid models, fluid models, and photographs of the small-scale MHD combustor will be presented in the Results and Discussion Chapter. In general, several uncoupled numerical analyses were performed to understand the methane gas in the injector, non-premixed, turbulent combustion modeling of the combustion gas flows into the combustion chamber and through the nozzle, and to model the turbulent cold flow of water through the jacket structure in the MHD combustor.

In summary, this systems engineering methodology in its entirety was used to generate two oxy-fuel combustion systems for magnetohydrodynamic power extraction devices, which are seen as a promising transformative technology to enable high-efficiency electrical power generation.

### 3.1.1 Analytical Combustor and Nozzle Design Equations

The nozzle subsystem design was carried out from a quasi-one-dimensional approach. This is a conventional method, which is used extensively in the design of inlets, exhausts, turbine, turbojets, and rocket engine. The basic equations for this analysis are described in the following set of equations.

$$\text{Equation of state:} \quad p = \rho RT \quad (6)$$

$$\text{Continuity:} \quad \rho u A = \text{constant}, \quad d(\rho u A) = 0, \quad \text{or} \quad \frac{d\rho}{\rho} + \frac{du}{u} + \frac{dA}{A} = 0 \quad (7)$$

$$\text{Momentum:} \quad dp = -\rho u du \quad (8)$$

$$\text{Energy:} \quad dh + u du = dq - dw \quad \text{or} \quad dh + u du = 0 \quad (9)$$

$$\text{Speed of sound :} \quad \frac{dp}{d\rho} = \left( \frac{\partial p}{\partial \rho} \right)_s = a^2 \quad (10)$$

$$\text{Combined momentum and continuity:} \quad -\frac{M^2 du}{u} + \frac{du}{u} + \frac{dA}{A} = 0 \quad \text{or} \quad \frac{dA}{A} = \frac{du}{u} (M^2 - 1) \quad (11)$$

From theory, found in many gas dynamics or aerodynamics texts, nozzle flows can be evaluated as an isentropic ideal gas behavior. Therefore, the isentropic relations can be invoked in the analysis:

$$\frac{T_o}{T} = 1 + \frac{u^2}{2c_p T} = 1 + \frac{\gamma - 1}{2} M^2 \quad (12)$$

$$\frac{p_o}{p} = \left( \frac{T_o}{T} \right)^{\frac{\gamma}{\gamma - 1}} \quad (13)$$

$$\frac{\rho_o}{\rho} = \left( \frac{T_o}{T} \right)^{\frac{1}{\gamma - 1}} \quad (14)$$

Equations 6-14 can be used to find the mass flow rate per unit area as

$$\frac{\dot{m}}{A} = \rho u = \rho M \sqrt{\frac{(\gamma R T_o)}{1 + \frac{\gamma-1}{2} M^2}} = \frac{p_o \sqrt{\gamma}}{\sqrt{R T_o}} M \left( \frac{1}{1 + \frac{\gamma-1}{2} M^2} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (15)$$

For the choked or sonic condition, seen at the throat section of nozzles, this equation simplifies to the following:

$$\frac{\dot{m}}{A^*} = \frac{p_o \sqrt{\gamma}}{\sqrt{R T_o}} \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (16)$$

The area ratio, in reference to this choked condition, denoted with an asterisk, can be found from the previous two equations, which yields,

$$\frac{A}{A^*} = 1/M \left( \left( \frac{2}{\gamma+1} \right) \left( 1 + \frac{\gamma-1}{2} M^2 \right) \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (17)$$

The above set of equations is a complete description of an isentropic flow of ideal gas in nozzles for any given fluid. A particular fluid may be described by a constant specific heat ratio, gas constant  $R$ , stagnation pressure  $p_o$  and temperature  $T_o$ , and constant mass flow rate.

A schematic of the MHD combustor and its subsystems is shown in Figure 14. This figure outlines the reactants, nozzle inlet, throat, and exit planes, and an interface section for a secondary device for MHD extraction.

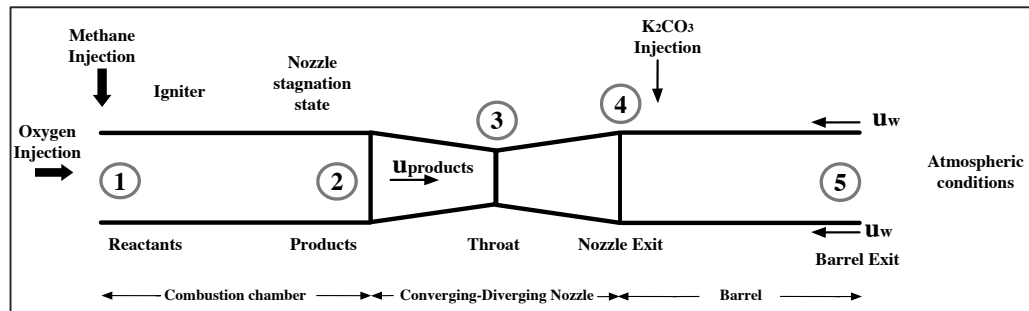


Figure 14. Design schematic for the oxy-fuel combustor for Magnetohydrodynamic Power Extraction.

### 3.1.2. Heat Transfer Analysis of Combustion Chambers and Nozzles

The most important parameter in the small MHD combustion system is related to the heat transfer, which may cause devastating thermal stress effects and lead to failure. Therefore, considerable time was spent on analyzing the survivability of the combustor, cooling requirements, and the material resistance to failure at high-temperatures. A simplified one-dimensional resistance model was analyzed to investigate heat transfer in the entire system. The basic equations used in the analysis is presented.

$$q = h_g(T_{aw} - T_{wg}) = \frac{k}{t}(T_{wg} - T_{wc}) = h_c(T_{wc} - T_{co}) \quad (18)$$

The Bartz semi-empirical relation, which was used to compute the local heat transfer coefficient  $h_g$ , is expressed as<sup>92</sup>

$$h_g = \left[ \frac{0.026}{D_t} \left( \frac{\mu c_p}{Pr^{0.6}} \right)_{ns} \left( \frac{p c_{ns} g}{c^*} \right)^{0.8} \left( \frac{D_t}{R} \right)^{0.1} \right] \left( \frac{A_t}{A} \right)^{0.9} \sigma \quad (19)$$

Where the turbulent boundary layer correction factor is expressed as<sup>92</sup>

$$\sigma = \frac{1}{\left[ \left( 0.5 \left( \frac{T_{wg}}{T_{c_{ns}}} \right) \left( 1 + \frac{\gamma-1}{2} M^2 \right) + \frac{1}{2} \right)^{0.68} \left( 1 + \frac{\gamma-1}{2} M^2 \right)^{0.12} \right]} \quad (20)$$

The heat transfer by conduction through the wall was evaluated. The temperature gradients in the system cause thermal stress. Therefore, the stress states for a wall thickness of 1 mm was investigated for the Inconel 718 structure.

The cooling requirements were computed using the Sieder-Tate Equation in accordance with conventions in the design of rocket engine walls.

The heat transfer analysis was an iterative process. The aim was to maintain a static temperature of 525 C in the Inconel combustor structure exposed to gases near 3300 K and cold coolant at 300 K.

### 3.2 COMPUTATIONAL FLUID DYNAMICS (CFD) MODELING OF COMBUSTION

#### 3.2.1 Basic equations, sub-models, and mesh generation

To understand the combustion gas properties throughout the combustion section and nozzle, a three-dimensional global model of the combustor was pre-processed and executed in ANSYS Fluent.<sup>118,119</sup> The species were modeled by the non-premixed combustion sub-model, which is a probability density function method commonly in industry. Also, in ANSYS, a standard k-e turbulent model, and a radiation model were included in the global model to resolve the flow field. The governing equations are listed as the following:

$$\text{Continuity:} \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (21)$$

$$\text{Momentum:} \quad \frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g} + \vec{F} \quad (22)$$

$$\text{Mixture fraction:} \quad f = \frac{Z_i - Z_{i,ox}}{Z_{i,f} - Z_{i,ox}}, \text{ where } \sum f = 1$$

$$\text{Equivalence ratio relation to mixture fraction: } f = \frac{\phi}{\phi + r} \quad (23)$$

$$\text{Favre mean mixture fraction: } \frac{\partial}{\partial t} (\rho \bar{f}) + \nabla \cdot (\rho \vec{v} \bar{f}) = \nabla \cdot \left( \frac{\mu_t + \mu_t}{\sigma_t} \nabla \bar{f} \right) \quad (24)$$

Standard k-e model turbulent transport:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (25)$$

$$\frac{\partial}{\partial t} (\rho \epsilon) + \frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} - S_\epsilon \quad (26)$$

The modeling parameters and setup for this CFD combustion model are shown in more detail in Table 1. The sub models that make up the global fluid model included the following:

Standard k-epsilon viscous model, radiation, species were modeled using the non-premixed combustion model, and compressibility effects were accounted for in the setup.

Table 1: Sub-models and implemented conditions in the 3D non-premixed combustion model.

<b>Modeling Characteristics</b>	Non-premixed modeling inputs
<b>Models</b>	Energy – On Viscous – Standard k-epsilon Radiation – P1 Species – Non-premixed combustion Inlet diffusion – On Compressibility effects – On Fuel stream reach flammability limit - 0.23 Mass fraction of CH <sub>4</sub> – 1 Mass fraction of O <sub>2</sub> - 1
<b>Material</b>	PDF mixture Absorption coefficient – wsggm-domain-based
<b>Boundary conditions</b>	<b>Fuel inlet:</b> Mass flow rate - 0.000264114 kg/s per orifice Hydraulic diameter - 0.0006096 m Mean mixture fraction – 1 <b>Oxidizer inlet:</b> Mass flow rate - 0.003697591 kg/s Hydraulic diameter – 0.004699 m <b>Outlet:</b> Hydraulic diameter – 0.004572 m

A structured computational mesh for the fluid domain was generated in ANSYS Fluent, which is shown in Figure 15.

Certain data sets were of interest, such as the mas fraction contours, pressure contours, static and total temperature contours, velocity vectors, and the temperature profile along the wall to estimate heat flux and the heat rejected-input fractions for each combustion condition.

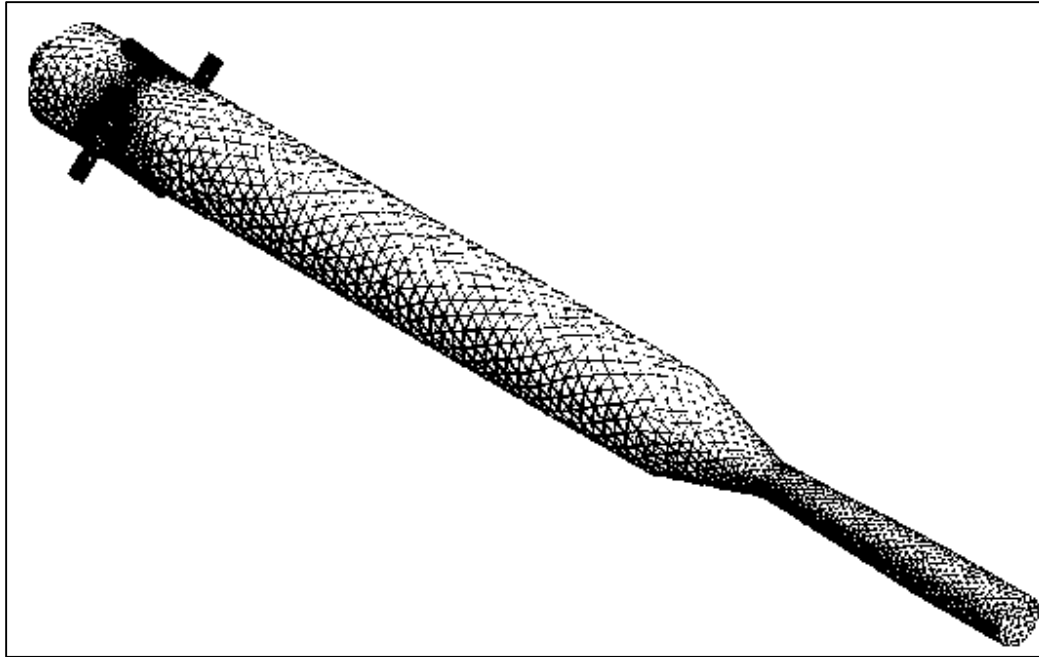


Figure 15. The discretized mesh for the PDF-based, non-premixed combustion model.

### 3.3 COMPUTATIONAL FLUID DYNAMICS (CFD) MODELING OF COOLING DESIGN

An uncoupled three-dimensional analysis was investigated to understand turbulent water flow fields through the jacket structure. The computational mesh incorporated the exact dimensions of the Inconel jacket structure. The developed fluid domain, and its discretized elements in the mesh, from the combustor architecture, which can be seen in Figure 16. The fluid domain was discretized into a course, medium, and fine mesh for variation in mesh quality on the results. The final mesh consisted of 150, 000 elements. Sensitive areas in the flow field, such as flows around the igniter probe and thermocouple required mesh refinement to capture details near these sections in the counter-flow jacket. In this analysis, the data of interest included pressure, temperature, and velocity contours throughout the jacket structure. The heat transfer, originating from the combustion section through the nozzle, was a major concern that motivated this numerical



analyses. The jacket structure consisted of six equivalent nearly-square channels to ensure high-velocity coolant flows. The channels are approximately 2 mm in width and height. The rib structures separating the channels were designed to act as fins to redistribute the heat from the interior surface of the combustor, the gas-side face of the structure. The design was based on regenerative-cooled rocket engines that use liquid methane to pass in channels before injection and combustion.

The basic equations that govern the water flow in a jacket are described. A simplified energy equation, one which assumes viscous dissipation to be small, was used to model incompressible water. The following equations were used in ANSYS Fluent for CFD modeling:

$$\text{Continuity:} \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (27)$$

$$\text{Momentum:} \quad \frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g} + \vec{F} \quad (28)$$

$$\text{Energy:} \quad \frac{\partial(\rho E)}{\partial t} + \nabla \cdot [\vec{V}(\rho E + p)] = \nabla \cdot [k_{eff} \nabla T - \sum_j h_j J_j + (\bar{\tau}_{eff} \cdot \vec{V})] + S_h \quad (29)$$

$$\text{Simplified Energy Equation:} \quad \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\lambda}{\rho C_p} \frac{\partial^2 T}{\partial x^2} + \frac{\lambda}{\rho C_p} \frac{\partial^2 T}{\partial y^2} \quad (30)$$

The sub-models and the boundary conditions imposed on the jacket structure for modeling the flow in three-dimensions are shown in Table 2. Also, Figure 16 demonstrates the water cooling jacket architecture, computational geometry and discretized mesh used in the ANSYS numerical solver.

Table 2. The sub-models and boundary conditions for the coolant jacket fluid domain.

Modeling Characteristics	CFD Solver Conditions
<b>Models</b>	Energy – On Viscous – Standard k-epsilon
<b>Boundary conditions</b>	<b>Inlet:</b> Gauge Total Pressure- 862.09 kPa Initial Gauge Pressure- 620.53 kPa Hydraulic diameter - 0.00256 m  <b>Outlet:</b> Gauge Pressure: 101.3 kPa Target mass flow rate: 0.668 kg/s Hydraulic diameter: 0.00258 m

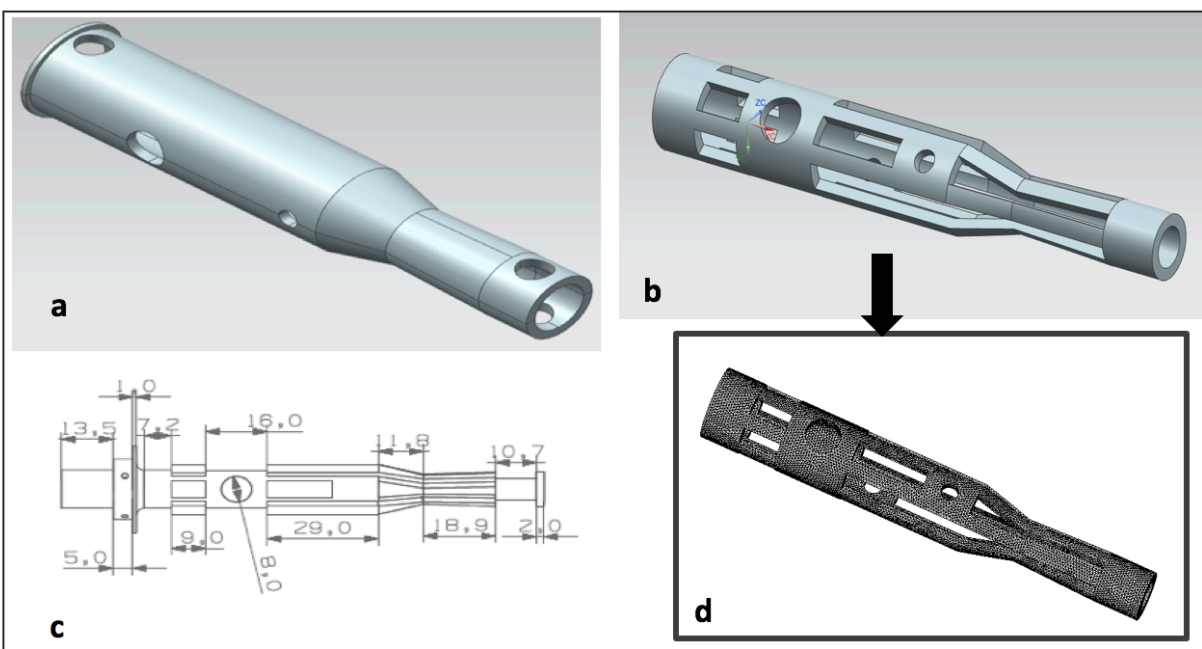


Figure 16. The small-scale MHD Combustor cooling jacket and a two-dimensional schematic are shown in mm units above, specifically, in Windows A and C. The MHD cooling jacket flow domain and mesh are shown in windows b and d.

### **3.4 MAGNETOHYDRODYNAMIC GENERATOR ANALYSIS**

#### **3.4.1 MHD Theoretical Analysis and Considerations**

The problem that we are interested in this work is the evaluation of output electrical power from various constant-pressure combustion flows in a constant-velocity MHD generator. This work was presented in a conference proceeding. The work examined a conceptual, analytical study of oxy-methane in MHD generators.<sup>120</sup> The simplified analysis followed similar assumptions and processes in the application of a quasi-one-dimensional approximation for MHD flows.<sup>16</sup> A simplified description of the system is required to present the system configuration in question. The MHD system consists of a subsonic or supersonic chamber (and nozzle), similar to a conventional rocket propulsion system. The combustor unit then interfaces with an MHD generator. The working fluid then passes through the MHD generator, or accelerator in the case that the Lorentz force promotes an increase in velocity. The MHD duct or channel is characterized with segmented electrodes and insulators in a square geometric configuration. Following this generating section, the fluid enters a quiescent-air atmosphere or may be passed to a secondary cycle since the temperature remains above 2000 K. In the open cycle MHD system we are characterizing in this study, hydrocarbon combustion is considered to occur in an oxygen environment.

The adiabatic flame temperatures in this type of environment, in addition to an alkaline seed material of low fractions, is assumed to obtain a sufficiently conductive state, at lower temperatures. It is assumed that potassium carbonate or cesium seed material is introduced to the combustion gas products. Therefore, inside the combustion chamber, the combined mixture (hydrocarbon oxygen and seed materials) then interact with flame front before proceeding to the MHD generator section. The flows entering and exiting a constant-velocity MHD generator is of interest.

To analyze compressible flows, subjected to the conditions in a linear Faraday magnetohydrodynamic generator, the governing set of equations are described in this section. The basic reference frame and the process of MHD power extraction used in this local analysis can be seen in Figure 17. The objective of this analysis is to understand a qualitative assessment of the physical interactions of a one-dimensional combustion gas flow in the course of generating electric power from an electrically conducting partially premixed flame. The analysis may provide design constraints for the experimental design of an MHD generator. The flame characteristics, such as the flame length, luminosity, and gas conditions have been shown in the past to affect the electrical power generation and performance of an MHD generator. In this conceptual study, the magnetohydrodynamic interactions occurring in the MHD generator device were simplified to a one-dimensional flow of an electrically conducting gas moving with a constant-velocity. Previous design work on open-cycle MHD generators have extensively followed a similar one-dimensional approach, termed the “quasi-one-dimensional MHD approximation.”<sup>16</sup> This method permits basic insight into the complex physics of an electrically conducting gas interacting with electrodes and subjected to a constant magnetic field. A one-dimensional approach is extensively utilized in the industrial practices and research of rocket engines, turbo machinery, and other aerospace devices.

The basic formulation is described for a simplified understanding of the basic physical interactions of a combustion gas with an external magnetic field. In Figure 17, the reference frame and schematic used in this simplified analysis of an MHD generator with continuous electrodes.

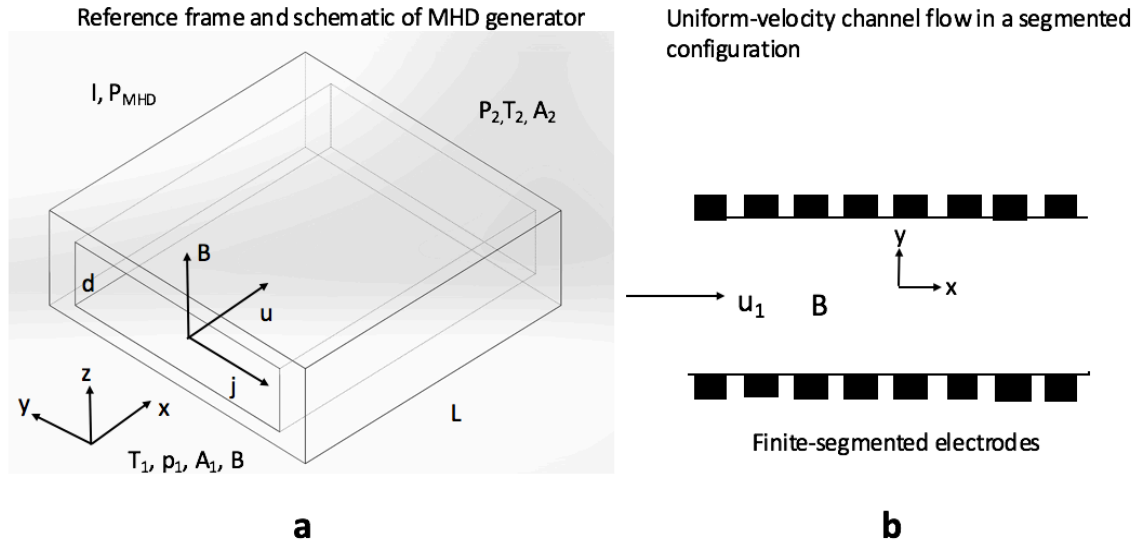


Figure 17. Reference frame and schematic used in this simplified analysis of a constant-velocity MHD generator.

Certain assumptions were made in this analysis which follows that of classical works on engineering magnetohydrodynamics.<sup>16</sup> These assumptions are listed for brevity and clarity. The MHD generator configuration was assumed to be linear and of the variable cross-section with continuous electrodes for first order approximations. The MHD is designed as a square channel, as seen in Figure 17(a). The effects of friction and heat transfer to the generator walls were neglected, which permits isentropic relations. The flow into the open-cycle MHD generator was considered as the combustion products in chemical equilibrium. The combustion products were considered as an ideal gas with constant specific heats and constant and uniform flow properties. Therefore, the electrical conductivity, flow velocity, pressure and temperatures were assumed to behave as a constant. The magnetic field is assumed to be a constant value, which can vary from 2-6 Tesla. The flow was assumed to eject into the quiescent air at atmospheric pressure. The electrical conductivity was assumed to be a constant when considering a stoichiometric one-step

reaction of methane-oxygen, which is a strong function of the seed mass fraction and pressure. The gas state was assumed to be characterized as a gas of low degree of ionization, i.e. a weakly ionized gas state.

### 3.4.2 Basic Equations for One-Dimensional MHD flows

The governing equations are described for the quasi-one-dimensional magnetohydrodynamic approximation. The conservation of mass in differential form in the x-direction, therefore v and w velocity components are equal to zero and assuming steady flow (d/dt=0), is expressed as

$$\frac{d}{dx}(\rho u A) = 0 \quad (31)$$

The conservation of momentum can be expressed regarding the current density j as

$$\rho u \frac{du}{dx} = -\frac{dp}{dx} + j_y B_z \quad (32)$$

Alternatively, it may be expressed regarding the scalar electrical conductivity, the loading parameter K, velocity in the x-direction (u) and the constant magnetic field B:

$$\rho u \frac{du}{dx} + \frac{dp}{dx} = -\sigma(1 - K)uB^2 \quad (33)$$

The loading parameter K is defined as the ratio of the electric field to the product of the velocity and magnetic field (E/uB). The conservation of energy equation can be expressed as

$$\rho u \frac{dH}{dx} = j_y E_y + j_x E_x \quad (34)$$

From Ohm's law, the current density relations in the x and y-direction are the following (which may include the effects of ion slip if certain modifications were made)

$$j_x = \frac{\sigma}{1+(\omega\tau)^2} [E_x - \omega\tau(E_y - uB_z)] \quad (35)$$

$$j_y = \frac{\sigma}{1+(\omega\tau)^2} (E_y - uB_z + \omega\tau E_x) \quad (36)$$

Hall currents are not considered in linear Faraday generators. Therefore, when considering a continuous-electrode, linear Faraday MHD generator, and only accounting for the transverse current, the conservation of energy equation can be expressed as

$$\rho u \frac{d}{dx} (c_p T + \frac{1}{2} u^2) + \frac{dp}{dx} = -\sigma(1 - K)Ku^2B^2 \quad (37)$$

The gas state properties can be related using the equation of state for an ideal gas.

$$p = \rho RT \quad (38)$$

The unknown variables in the above set of equations include gas variables ( $\rho$ ,  $p$ ,  $h$ , and  $u$ ) and the current densities (in two dimensions). Also, the electric fields in the x-direction ( $E_x$ ) and y-direction ( $E_y$ ), the MHD generator cross-sectional area  $A$ , and scalar electrical conductivity  $\sigma$  are unknown parameters. The final prescribed variable is the magnetic field  $B$ . As mentioned above, the problem of interest is a first-order approximation of electrical output for various flows in a constant-velocity MHD generator. Therefore, the above equations can be reduced for flow between two states, the inlet of the MHD generator and the outlet of the MHD generator. The relationship between the stagnation conditions of flames at the inlet interface is a controlling set of parameters that govern output power in these devices. The oxy-methane system is considered. The combined governing relations of momentum and energy can form another expression in a simpler form:

$$puc_p \frac{dT}{dp} = \frac{E}{B} \quad (39)$$

Alternatively, regarding the loading parameter, which is assumed to be independent of the spatial coordinate variable  $x$

$$\rho c_p \frac{dT}{dp} = K \quad (40)$$

Since the gas is assumed to be ideal, the equation of state can be simplified,

$$\frac{K dp}{p} = \frac{c_p}{R} \frac{dT}{T} = \left( \frac{\gamma}{\gamma-1} \right) \frac{dT}{T} \quad (41)$$

This relationship can then be integrated between the two points (specified in Figure 17) to relate the pressure ratio to the temperature ratio regarding  $K$  in an MHD generator.

$$\frac{p_2}{p_1} = \left( \frac{T_2}{T_1} \right)^{\gamma/K(\gamma-1)} \quad (42)$$

The cross-sectional area ratio between states 1 and 2 can then be formulated from this relation, considering an area variation in the  $x$ -direction. However, the electrode distance  $d$  and the electrode spacing  $s$  must be specified. The area ratio expression is

$$\frac{A_2}{A_1} = \frac{\rho_1}{\rho_2} = \frac{p_1}{p_2} \frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\left[ \frac{K(\gamma-1)}{\gamma} \right] - 1} \quad (43)$$

From Maxwell's equations and the generalized Ohm's law, the current density relationship to the electrical conductivity per electrode cross-sectional area can be written. This expression neglects the Hall parameter effects and assumes the electrical conductivity as a scalar quantity.



$$j_y = \frac{I}{A} = \sigma u B (1 - K) \quad (44)$$

The total current,  $I$ , induced through the electrically conducting gas and flowing in the external load can be approximated by:

$$I = \sigma u B (1 - K) A \quad (45)$$

Then, the output power per unit volume (power density) and the total output power can be approximated with the following equations:

$$JE = \sigma u^2 B^2 K (1 - K) \quad (46)$$

$$P_{MHD} = \sigma u^2 B^2 K (1 - K) L d \left( \frac{s_1 + s_2}{2} \right) \quad (47)$$

The above formulation summarizes the methodology of this simplified MHD generator analysis. In the next section, we examine the design characteristics of a constant-velocity MHD generator for alkaline-laden oxy-fuel combustion flows. Since the maximum power output was of interest, the load factor  $K$  was defined for this case. Therefore, the loading parameter was defined as 0.5. However, the load parameter may vary (i.e.  $0 < K < 1$ ) in real gas flows. The MHD channel configuration is analyzed for MHD direct power extraction when considering a given perfect gas in chemical equilibrium. The motivation is the determination of operating characteristics for various MHD design configurations. The critical parameters are analyzed in the next section, specifically for a given fluid state entering the MHD design parameters are evaluated. The variation of the area, MHD duct length with pressure, power density, and maximum power output for given initial inlet parameters was investigated.

### 3.5 EXPERIMENTAL METHODOLOGY

The MHD combustor hardware was tested for realistic operating conditions for MHD systems, to study the feasibility of using oxy-fuel flames in MHD systems. Many tests were

devised to investigate the combustion performance in the 60 kW MHD combustor. Figure 18 illustrates the experimental system used for studying oxy-fuel flames. A brief description of the experimental system is given. The experimental system consisted of reactant and coolant delivery systems, the 60 kW; spark-plug ignited, MHD combustor with both a static pressure and temperature measurement system, exhaust system, and an intensified ICCD camera for high-speed imaging. The reactant delivery system is a pressure-fed system of methane and oxygen, where the volumetric flow rates are recorded by flowmeters. Static pressure and volumetric flow rates monitored the flow properties for each test. In the MHD combustor system, a spark-plug provided 12 kV ignition energy to initiate the flame propagation in the chamber. A pressure sensor recorded static pressure in the chamber.

To characterize the combustor technology, three variables were considered important to for MHD systems: burn time, O/F ratio, and theoretical chamber pressure. The burn time or combustion residence time in combustors may range from transient to long-duration performances. This parameter is crucial to simulate or demonstrate flames for realistic MHD systems. Short transient performance tests were defined as experiments conducted for less than 10 seconds. While long-duration performance tests investigated burn times above 10 seconds, but less than 120 seconds. The O/F ratio is the ratio of oxidizer mass to fuel mass in the combustion system. This ratio has been seen to be critical to MHD systems because of the static temperature in the flow impact ionization state, and hence electrical conductivity.

Two sets of experiments were established to study fuel-rich oxy-fuel flames, specifically, oxy-flames with an O/F of 2 and 3.5. The first set of experiments corresponded to the O/F of 2, which analyzed combustion performance for chamber pressures of 50-110 psi and burn times of 2-120 seconds. Twenty-seven fuel-rich oxy-fuel experiments were completed for an O/F ratio of

2. While the second set of experiments, those that approximate realistic MHD system operation conditions, tested flames at an O/F of 3.5, chamber pressures of 90-110 psi, and long burns from 10, 30, 60, and 120 seconds. The number of experiments tested at an O/F ratio of 3.5 totaled 31. Table X illustrates the organization of the experiments. Table X. Tabulated data of oxy-fuel experiments organized by O/F ratio and short and long duration.

Recorded temperature data was taken at the inlet and exit of the cooling channel structure in the MHD combustor, to compute the heat flux rejected to the MHD combustor structure. Furthermore, the heat flux data permits an analysis of the heat loss fraction in the system. The heat loss fraction in MHD systems is critical since it is an indirect measure of the system's efficiency.

Intensified ICCD imagery from select experiments is discussed in Chapter 4, to demonstrate the observed oxy-fuel flame behavior.

## **Chapter 4: Results and Discussion**

### **4.1 INTRODUCTION**

Chapter 4 discusses the results and discussion. Subsection 4.1 describes the design criteria and specifications of the injector, combustion chamber, nozzle, and cooling jacket for the nominal design point. The nominal design point and characteristics of the system are described in a table. In addition, this section describes the experimental setup for the demonstration of fuel-rich and slightly-fuel rich oxy-fuel flames for a variety of burn times. Subsection 4.2 discusses the computational model results and discussion, specifically the non-premixed port-injection and combustion gas flow path through the nozzle. Subsection 4.3 describes the computational modeling of the cooling jacket, which is subjected to empirical boundary conditions for the local gas-side heat-transfer coefficient and a uniform local coolant heat-transfer coefficient. Subsection 4.4 addresses the conceptual design of an MHD generator for various combustor scales or sizes.<sup>120</sup> Subsection 4.5 addresses the experimental results of only the slightly-fuel-rich oxy-fuel flames, corresponding to an O/F ratio of 3.5, for long-duration experiments. Long-duration oxy-fuel flame data was selected for discussion since these are characteristic of realistic MHD conditions, if seeded flames were injected. The experimental data described in this section includes the static temperatures of the combustor at a point on the exterior surface and high-speed ICCD photography of the flames for 10, 30, 60, 120, and 300 seconds. The heat loss fraction, based on the uniform heat flux and the higher heating value (HHV) of methane, is plotted with long-duration burn time.

### **4.2 PRODUCT DESIGN AND EXPERIMENTAL HARDWARE TESTING FACILITY**

The MHD combustor has been designed based on rocket engine technologies and empiricism for a thermal input of less than 100 kW. The purpose of this design point was to contribute to the MHD literature at this scale, which has not been studied in the previous MHD

generator research. This claim is substantiated by the work of Pian and Kessler in a recent review article on MHD generators. The objective of this system design was to demonstrate oxy-fuel combustion to understand the flame structure at various burning times. The MHD combustor was designed for a total mass flow rate of 4.5 g/s. Oxy-methane was the selected fuel and oxidizer combination. However, in future work, other designs could incorporate oxy-coal. In order to provide the highest flame temperature in the system, as is required for magnetohydrodynamic extraction, slightly-fuel rich flames were selected. This classification of combustion corresponded to an O/F ratio of 3.5. Considering this particular design point, the actual thermal input of the system is approximately 60 kW, assuming an HHV of methane. The HHV is considered convention in MHD generator designs. To be used as an MHD combustor, the sensitivity of the system required specific gas conditions, namely an under expanded gas state, gas velocities near 2000 m/s for supersonic flows, and temperatures above the threshold for enhanced electrical conductivity. Table 3 describes in detail the MHD combustor design criteria, subsystem characteristics, and results of heat transfer analyses.

The oxy-combustion system was constructed of an Inconel nickel alloy structure and manufactured using electric discharge machining (EDM). To aid in visualization and interface definition in the design workflow, multiple designs were manufactured by additive manufacturing for prototyping. The part interfaces, which include the fuel injector manifold and exterior shells of the jacket, were welded in the manufacturing phase of the work.

The nozzle design was of the conical shape with a throat size of approximately 3.7 mm. The convergence and divergence half-angles were 15 and 2 degrees respectively. The nozzle system was designed with a low divergence half-angle to provide a gradual expansion. In past MHD generator designs, gradual expansions and low-half angles are seen. For instance, the MHD

combustor and nozzle of a noteworthy MHD generator confirms this design methodology.<sup>117</sup> The nozzle characteristics are shown in Table 3. The nozzle diameter was selected to provide an under expanded nozzle state and meet the design criteria on the basis of isentropic expansion.

The combustor cylindrical length was defined to be 83 mm, and was based on an empirical dataset, on characteristic length, for the design of liquid rocket engines of various sizes.<sup>121</sup> The combustor and nozzle inlet had the same diameter.

The injector was defined as a coaxial swirl injector. The fuel manifold was in a ring configuration with four tangential ports to permit passage of fuel into the injection plane. Each individual fuel port size was defined as 1.588 mm. This diameter was defined to achieve fuel injection velocities close to 25 m/s in each port. The oxygen entered in a coaxial arrangement and contacted the four fuel streams approximately 12.5 from the oxygen inlet plane. The oxygen injection velocity was determined from another design criterion, the momentum flux ratio. The oxygen injection velocity in the coaxial swirl injector was defined as 5 m/s.

Figure 19 presents a detailed drawing of the exact dimensions in the combustor, nozzle, and instrumentation ports in the oxy-combustion system.

Table 3. Oxy-combustion system and subsystem design characteristics for MHD applications

Oxy-Combustion System and Subsystem Design Characteristics		
<b>Design Criteria:</b>	Thermal Rating: less than 100 kW Oxy-combustion at 8 bar and O/F 3.5 Oxy-combustion product gas characteristics: Gas velocities of 2000 m/s and temperatures of 2800-2000 K	
<b>System characteristics</b>	Inconel nickel-alloy structure Overall oxy-combustor length of 126 mm	
<b>Subsystems</b>		
<b>Coaxial Swirl Injector</b>	Number of tangential ports Fuel port diameter Fuel injector port L/D Fuel injection velocity Fuel pressure drop Oxygen port inlet diameter Oxygen injection velocity Momentum Flux ratio (MFR)	4 1.59 mm 3.98 25 m/s 20 psi 10 mm 5 m/s 16
<b>Combustion Chamber</b>	Combustor diameter Cylindrical length L/D Spark Igniter location from injection plane Empirical Characteristic Length	10 mm 83 mm 8.3 29.2 mm 50 mm
<b>Nozzle</b>	Inlet diameter Throat diameter Throat heat flux Surface heat transfer coefficient at the throat Outlet diameter Convergence/divergence angles Choked mass flow rate	10 mm 3.68 mm 7.6 MW/m <sup>2</sup> 3039 W/m <sup>2</sup> -K 5 mm 15 degrees; 2 degrees 4.5 g/s
<b>Combustor-Cooling Channel Structure</b>	Wall thickness Number of cooling channels Square shape characteristics Number of obstructions in coolant flow path Coolant volumetric flow rate Coolant flow velocity Convective cooling heat transfer coefficient Coolant	1 mm 6 2 mm x 2 mm 3 17.8 LPM 14.7 m/s 69500 W/m <sup>2</sup> -K Pressurized liquid water at 13 bar
<b>General Heat Transfer Characteristics</b>	CFD prediction of heat loss fraction Experimental heat loss fraction Analytical heat loss fraction	7 percent 5 percent 20 percent

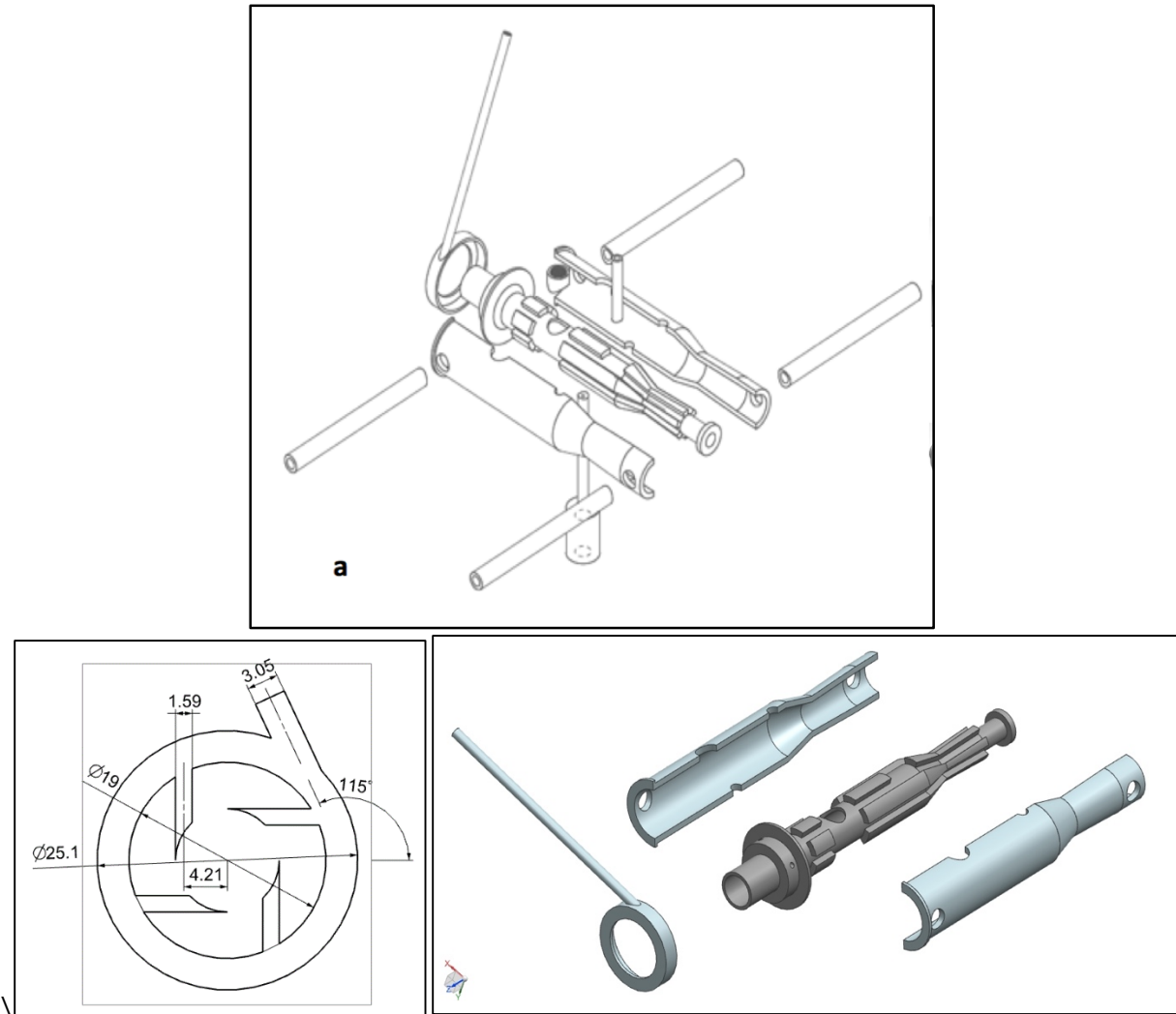


Figure 19. Assembly of the MHD Combustor (Top). Coaxial swirl injector cross-section (bottom left) and an exploded view of the fuel ring manifold and individual ports in the fuel injector (bottom right).

The spark ignition system was positioned in the combustor, based on previous LO<sub>2</sub>/LCH<sub>4</sub> igniter heritage designs and combustion experience. A spark plug was used to provide the activation energy to initiate flame propagation.

A cooling jacket structure was designed to adequately cool the oxy-combustion system. For a nominal operating temperature condition in the wall, within the yield strength constraints of the material, the combustor wall structure was designed to be 1 mm in thickness. The temperature



was constrained to 525 Celsius. Although, adiabatic flame temperatures can exceed 3000 C. The analytical heat transfer was estimated to be 7.6 MW/m<sup>2</sup>. To remove this heat flux, a high convective cooling mechanism was implemented in the design. The wall structure was modified to include additional thickness for the incorporation of cooling channel passageways. Six cooling channels were designed in the combustor structure. In the cooling channel design, several obstructions were required for instrumentation. These obstructions to the coolant flow field included the spark ignition port, a thermocouple port and a pressure transducer port. These cylindrical obstructions were analyzed using CFD for optimal placement. The cooling channel structure was designed to be of approximately square in shape. The cross-section of each individual cooling channel was 2 mm x 2 mm cross-sections. The detailed characteristics of the cooling channels are outlined in Table 3. A detailed two-dimensional engineering drawing is presented in Figure 21, in order to illustrate the combustor main body, cooling channels and jacket design. The dimensions are in millimeter units.

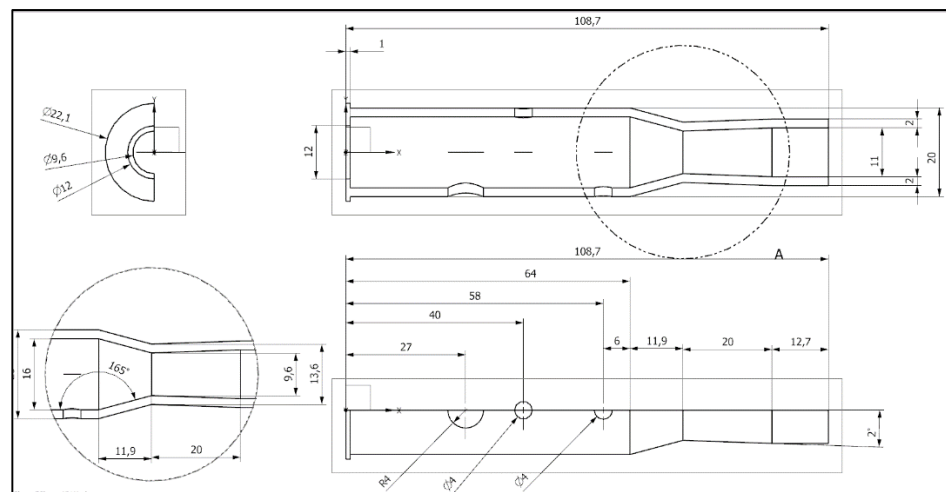


Figure 20. Two-dimensional drawing of the exterior shell components of the cooling jacket structure.

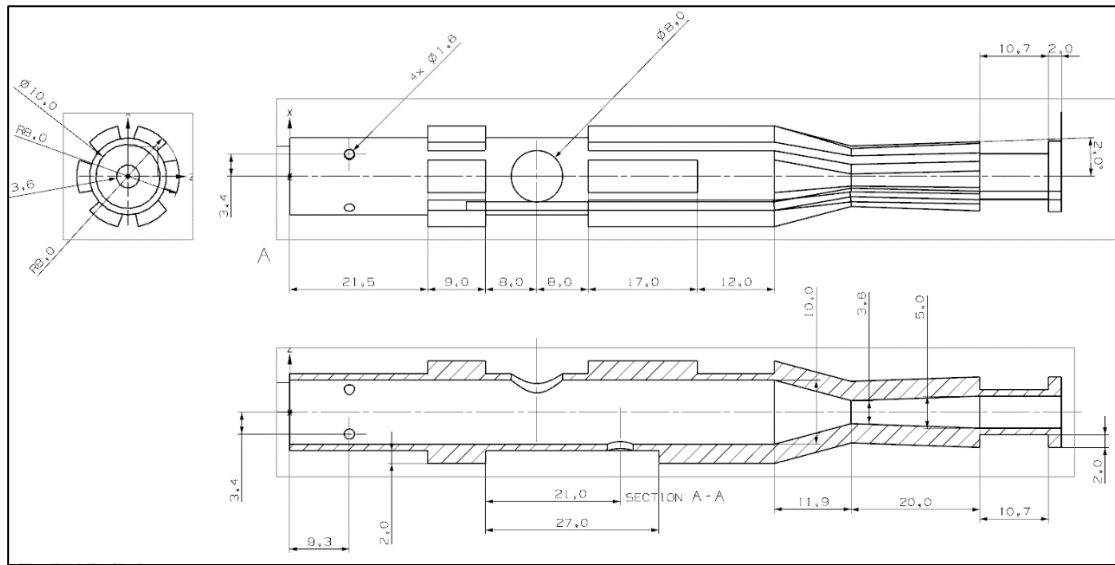


Figure 21. Two-dimensional drawing of the main combustor body, profile, and cooling jacket component systems.

The experimental setup of the MHD combustor was designed to test in a safe and remotely accessed location at the University of Texas at El Paso's NASA Center for Space Exploration and Technology Research. The MHD combustor facility and hardware is shown in Figure 22. The system was installed and wired in an altitude simulator chamber, which is capable of vacuum conditions. The oxy-combustion system was connected to a reactant delivery system for pressure-fed methane and oxygen. In addition, the cooling channel inlets interfaced with a regenerative water delivery system. The regenerative water cooling system pumped the water to a highly pressurized state before injection into the cooling channels. The pressurized state was required to increase the boiling temperature of the coolant and prevent nucleate boiling behaviors. Figure 22 depicts photographs of the MHD combustor facility, reactant lines, and water delivery systems for the regenerative cooling system. The MHD combustor placement and the experimental configuration is also seen in Figure 22. The setup design is shown in a piping and instrumentation

diagram (PID). The PID is shown in Figure 23. The specific reactant lines and instrumentation, such as flow meter, pressure transducers, thermocouples, and valve systems, are shown in detail.

Figure 24 shows photographs of the experimental system and oxy-fuel combustion demonstration hardware for MHD applications.

Figure 25 shows close-up images of the MHD combustor prior to welding. These photographs show the detail and surface finishing of the EDM manufactured parts.

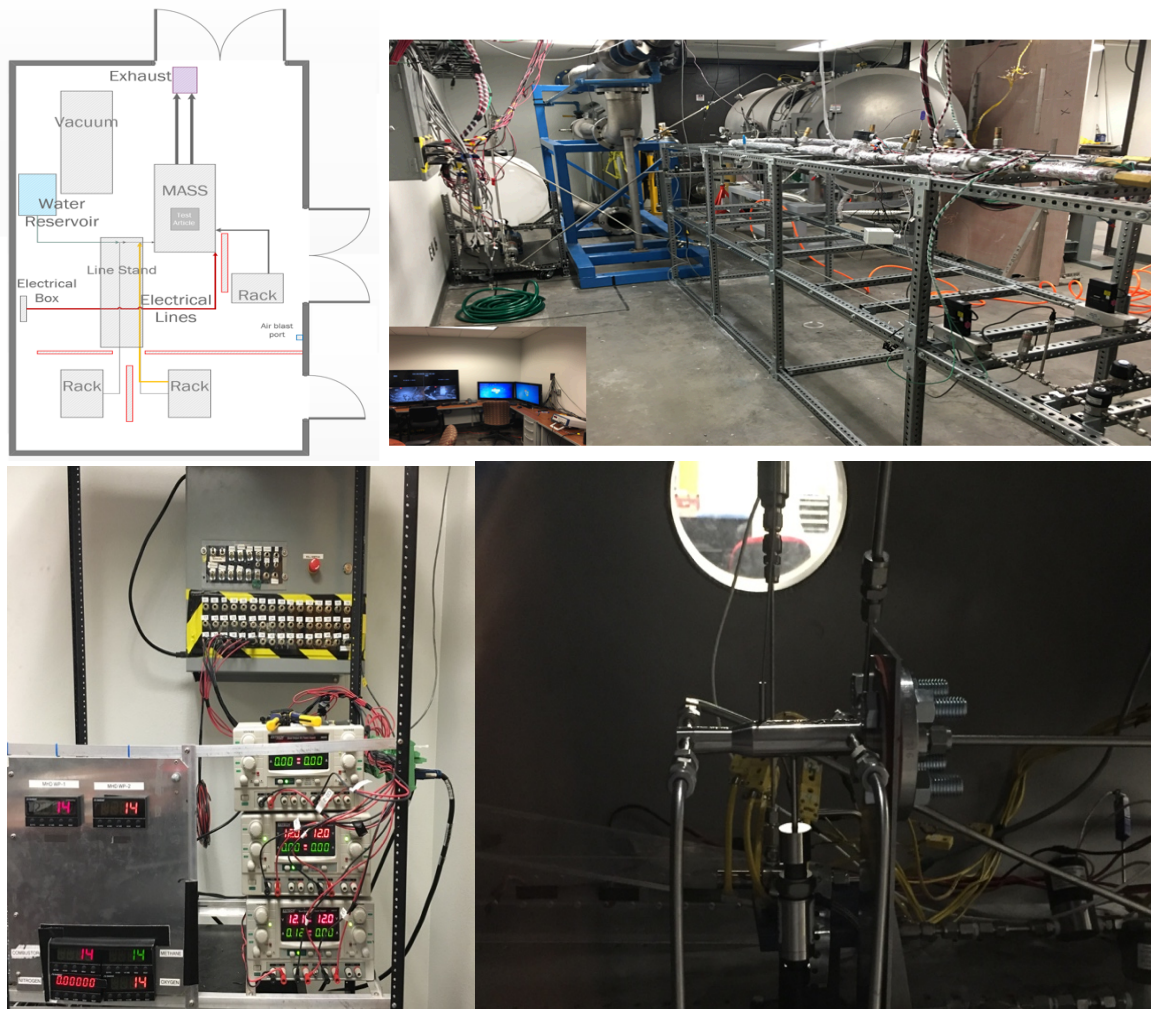


Figure 22. MHD combustor experimental facility at the University of Texas at El Paso.

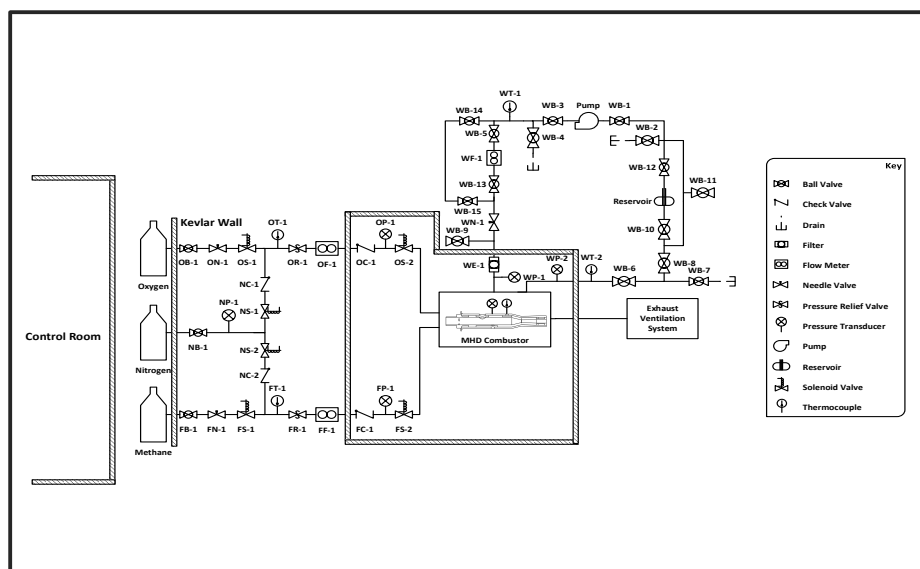


Figure 23. MHD Combustor experimental setup: reactant and water cooling systems and other instrumentation.

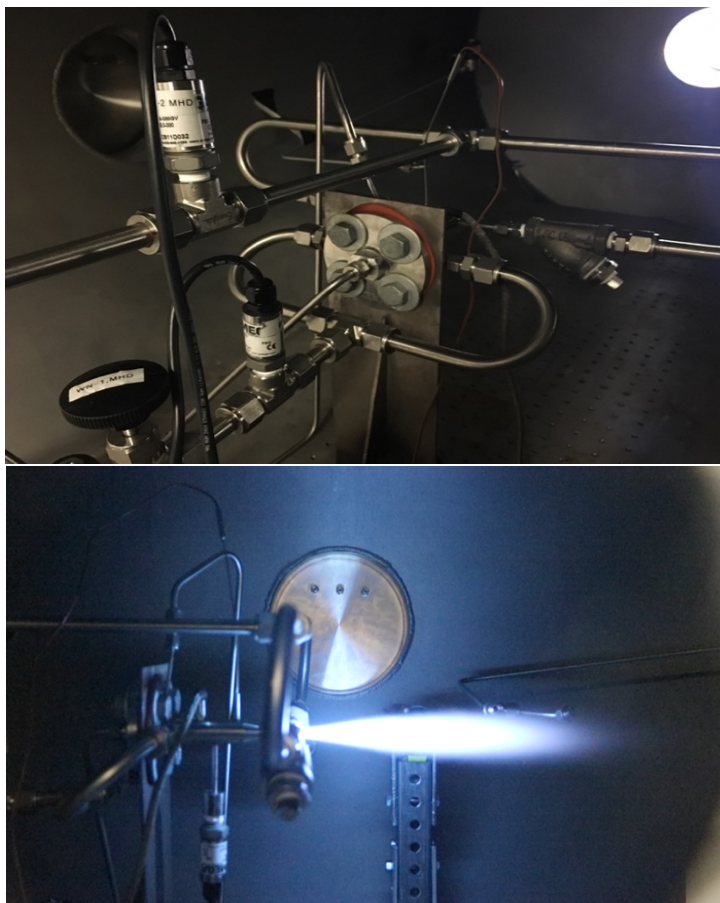


Figure 24. Photographs of the experimental setup (left) and a demonstration test with the following combustion conditions: O/F 3.5, theoretical chamber pressure of 110 psi, and 30 seconds of operating time.

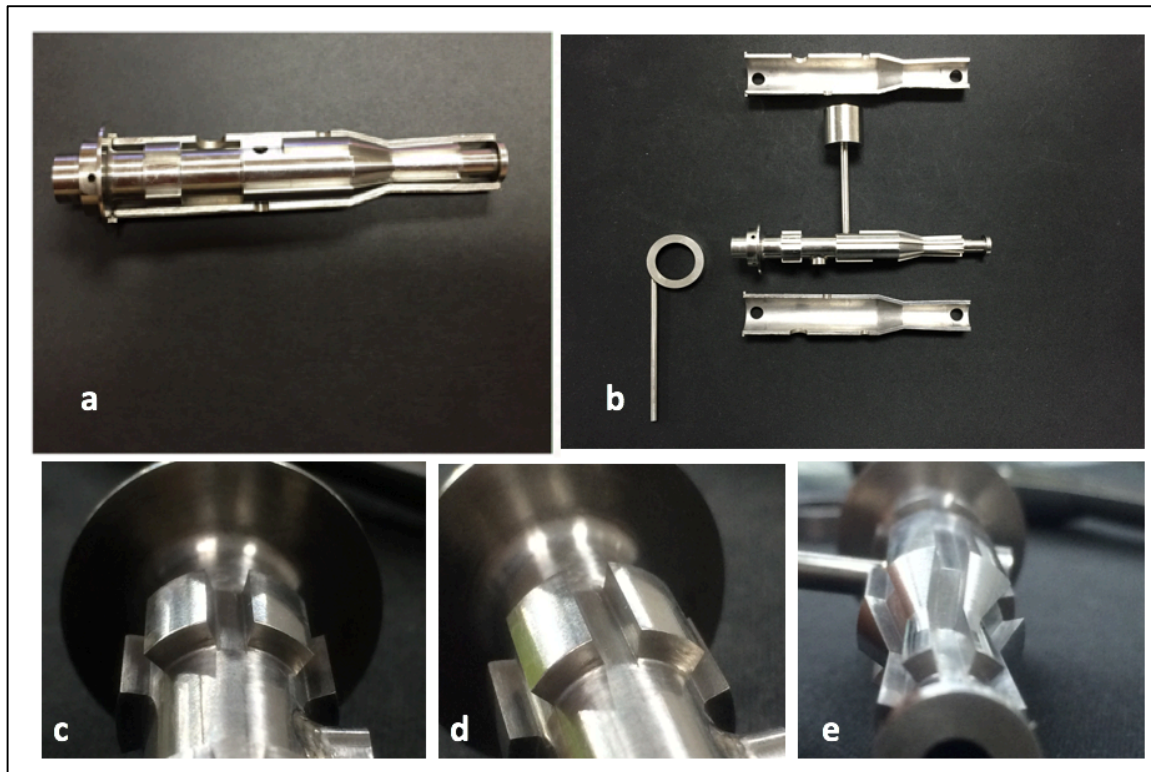


Figure 25. The MHD combustor prior to welding. These photographs show the detail and surface finishing of the EDM manufactured parts for the MHD oxy-combustion system.

#### 4.3 OXY-FUEL COMBUSTION MODELING RESULTS

Oxy-fuel combustion modeling was performed to understand the injection flow paths of methane and oxygen and predict the flow properties in each section of the system. Several models were developed in two-dimensions and in three-dimensions. In both models, the temperature contours and profiles were of interest in select locations. Computational fluid dynamics models



were also used to analyze the pressure and velocity magnitudes in the MHD combustor design. The area of interest was the nozzle exit plane, where the flame ejects from the system. This region of the flow is where the flame would hypothetically interface with an MHD generator section.

A comparison has been made between analytical and numerical analyses of the gas properties at the nozzle exit plane. Both methods yielded similar results. For instance, considering an isentropic process from the inlet of the nozzle to the outlet, the gas pressure, temperature, and velocity are reasonably similar to the CFD data. From the isentropic analytical analysis, for this specific nozzle geometry, the velocity at the nozzle outlet is approximately 2000 m/s and the temperature is nearly 2800 K. In contrast, the CFD generated data from a two-dimensional model varied by a small percentage.

Figure 26 shows the results of a three-dimensional non-premixed combustion modeling effort in ANSYS Fluent. Additional details of this work can be found in Vidana et al. (2016).<sup>118,119</sup>

Figure 27 depicts a two-dimensional modeling effort to understand oxy-combustion flow properties for design purposes. The model is based on a standard k-epsilon viscous model. The boundary conditions for this analysis are described in Table 4. The two-dimensional modeling effort predicted combustion product gases traveling at 2070 m/s, static temperatures near 3220 K, and an absolute pressure of 16.4 psi (or 1.1 bar).

Both analytical and numerical results present evidence that the MHD combustor system was designed to meet magnetohydrodynamic requirements in accordance with design criteria.

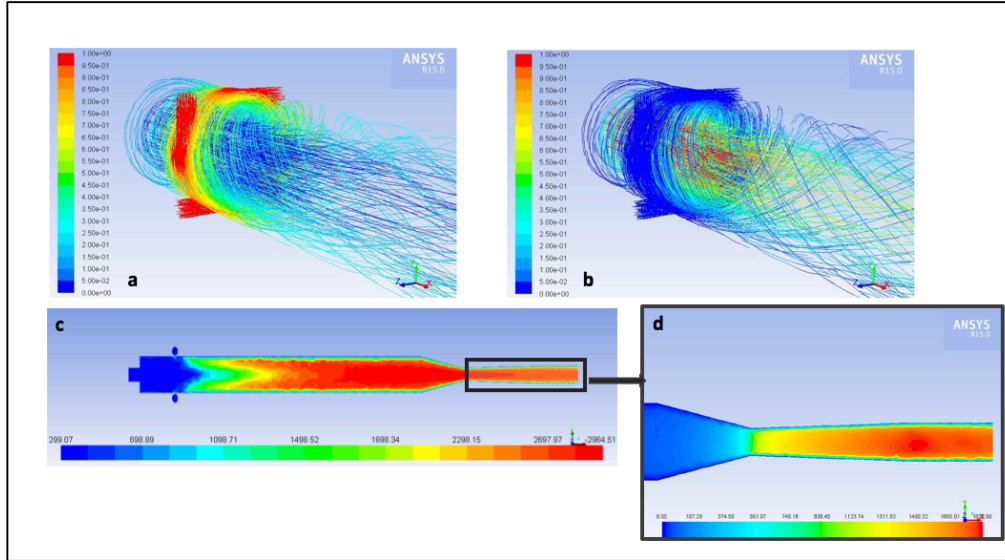
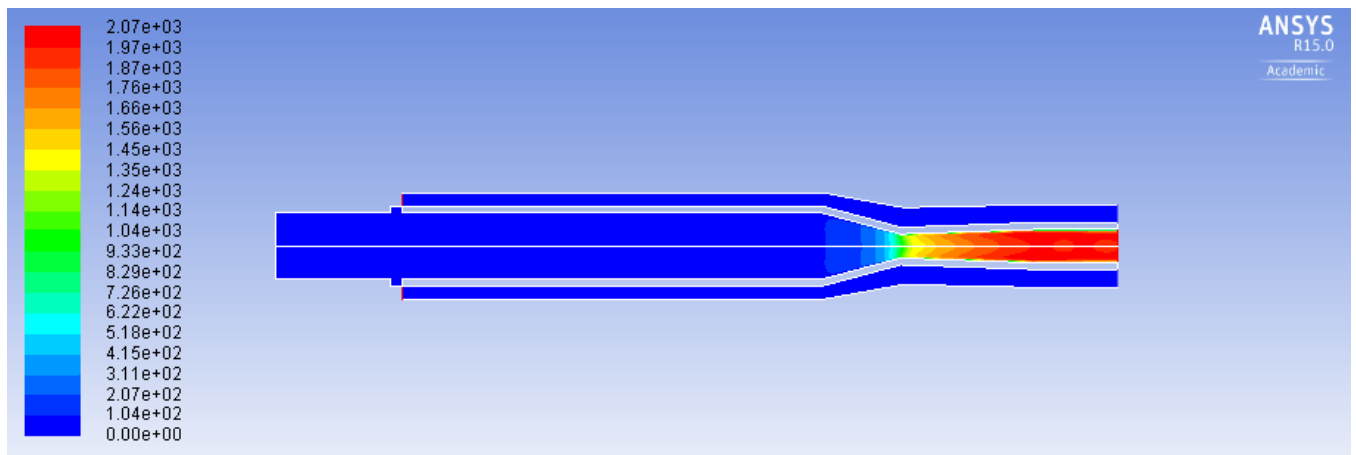


Figure 26. A standard k-epsilon viscous model was investigated to understand the non-premixed combustion and flow field in three-dimensions. The figure is separated by zone to describe the following: (a) mass fraction path lines for methane; (b) mass fraction path lines for coaxial oxygen injection; (c) static temperature contours in Kelvin; and (d) flow velocity contours.

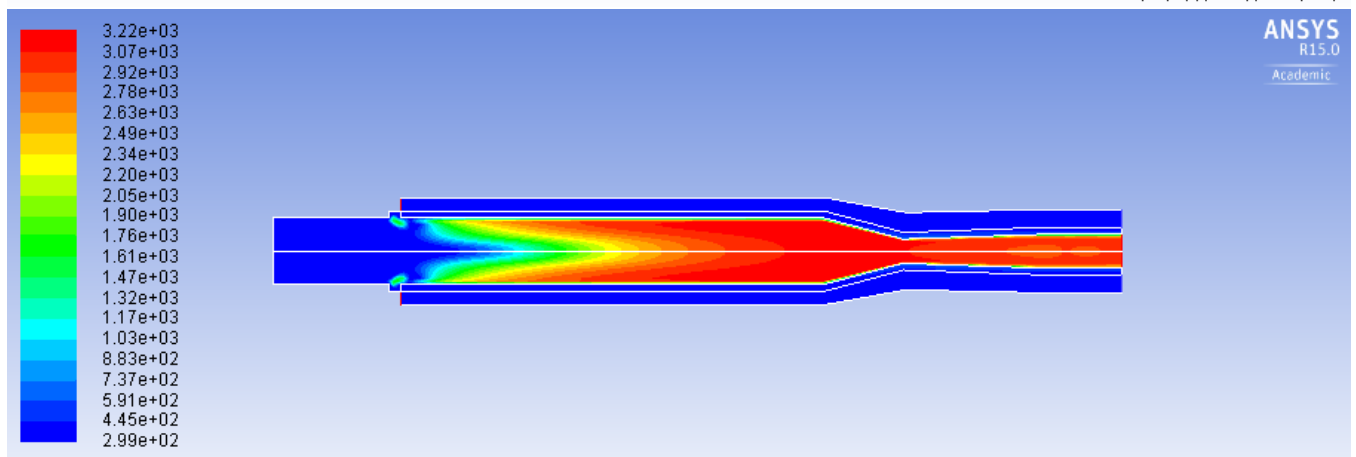
Table 4. Boundary conditions and model setup for the 2D/3D modeling of oxy-combustion.

Section	Input
<b>Models</b>	Energy-ON Viscous-Standard k-epsilon Species-non premixed combustion <ul style="list-style-type: none"> <li>• Inlet diffusion-ON</li> <li>• Compressibility effects-ON</li> <li>• Fuel stream rich flammability limit- .23</li> <li>• Mass fraction of CH4-1</li> <li>• Mass fraction of O2-1</li> </ul>
<b>Materials</b>	PDF Mixture Inconel 718 <ul style="list-style-type: none"> <li>• Custom density</li> <li>• Custom cp</li> <li>• Thermal conductivity function</li> </ul>
<b>Boundary Conditions</b>	Water Fuel inlet: <ul style="list-style-type: none"> <li>• Mass flow rate</li> <li>• Hydraulic diameter- 1.8 mm</li> <li>• Mean mixture fraction -1</li> </ul> Oxidizer inlet: <ul style="list-style-type: none"> <li>• Mass flow rate</li> <li>• Hydraulic diameter- 10 mm</li> </ul> Gas outlet: <ul style="list-style-type: none"> <li>• Atmospheric pressure (initial)</li> </ul> Water inlet: <ul style="list-style-type: none"> <li>• Velocity-17.6 m/s</li> <li>• Gauge Pressure</li> </ul> Water outlet: <ul style="list-style-type: none"> <li>• Atmospheric pressure (initial)</li> </ul>
<b>Solution Initialization</b>	Standard



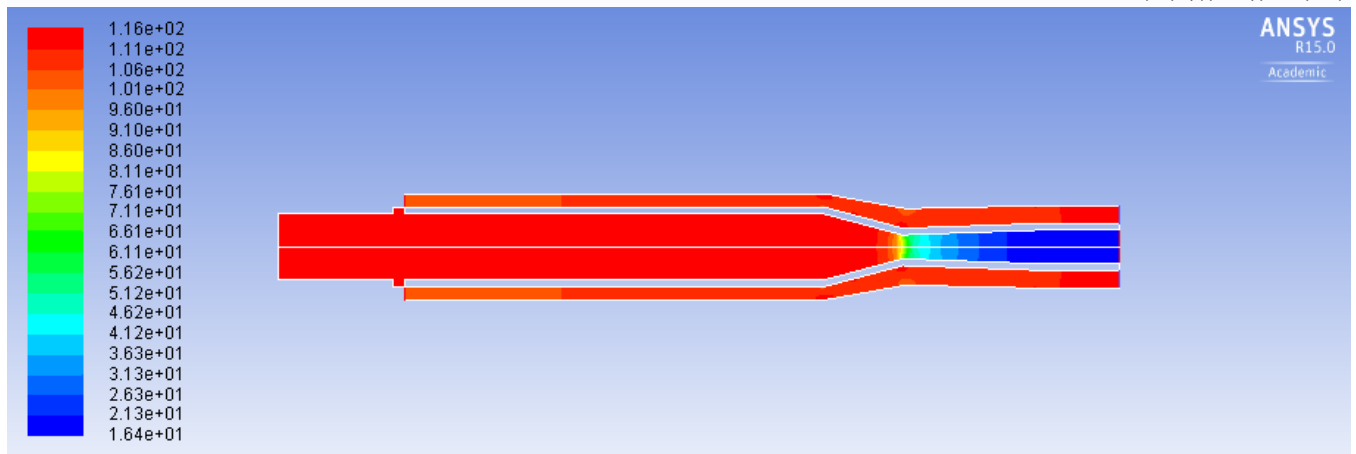
Contours of Velocity Magnitude (m/s)

Nov 14, 2016  
ANSYS Fluent 15.0 (axi, dp, pbns, pdf19, rke)



Contours of Static Temperature (K)

Nov 14, 2016  
ANSYS Fluent 15.0 (axi, dp, pbns, pdf19, rke)



Contours of Absolute Pressure (psi)

Nov 14, 2016  
ANSYS Fluent 15.0 (axi, dp, pbns, pdf19, rke)



Figure 27. Two-dimensional k-epsilon model with non-premixed oxy-combustion. The results of interest are the contours of velocity magnitude, static temperature, and absolute pressure.

#### **4.4 COOLANT CHANNEL FLOW MODELING RESULTS**

The coolant flow field in the cooling jacket structure, inclusive of the instrumentation obstructions, was analyzed using ANSYS Fluent. The computational flow domain was presented in the methodology, in addition to the boundary conditions. The flow domain was constructed to represent liquid water flowing in a counter-flow direction in a cooling jacket. Viscosity effects, i.e. the Standard k-epsilon turbulent sub-model, were incorporated into the cooling system model. The modeling characteristics, sub models, and boundary conditions used in this analysis can be seen in Table 2. A pressure inlet boundary condition of 130 psi (862 kPa). A pressure outlet was defined as 101.3 kPa. Empirical surface heat transfer coefficients were computed for three locations in the nozzle, which is based on Bartz empirical correlation. Bartz correlation was implemented as a first-order estimate for this analysis. In addition, the purpose of Bartz is to establish heat transfer convection boundary conditions CFD processing and to predict with reasonable accuracy. Figure 28 presents the static temperature contours from this CFD modeling effort. The hot sections are the converging nozzle sections near the throat and the entrance preceding coolant channel entry. Temperatures in the cooling jacket structure are higher since the velocity is significantly lower due to larger diameter in this section. Another hot section in the cooling jacket flow field is the The static temperatures in the cooling jacket are maximum in the nozzle throat area, since this is the section of maximum surface heat transfer coefficient and heat flux, as is expected from rocket engine texts, such as Huzel and Huang (1992) and Hill's text entitled, "Mechanics and Thermodynamics of Propulsion" (1992).<sup>121</sup> The maximum temperature in the flow field, based on empirical formulation coupled with CFD, is 440 K (167 C). Based on

experimental data, the water temperatures did not reach these temperatures. Therefore, a more detailed cooling jacket flow field may be necessary. The difference could be rectified by applying a heat transfer profile along the cooling jacket interior surface. This approach would provide a heat flux value at each individual location in the nozzle, in contrast to three major values based on empirical data. Based on semi-empirical approximations the nozzle is estimated to exhibit a heat flux of  $7.76 \text{ MW/m}^2$  at the nozzle throat area and  $4.41 \text{ MW/m}^2$  at the nozzle exit.<sup>118</sup>

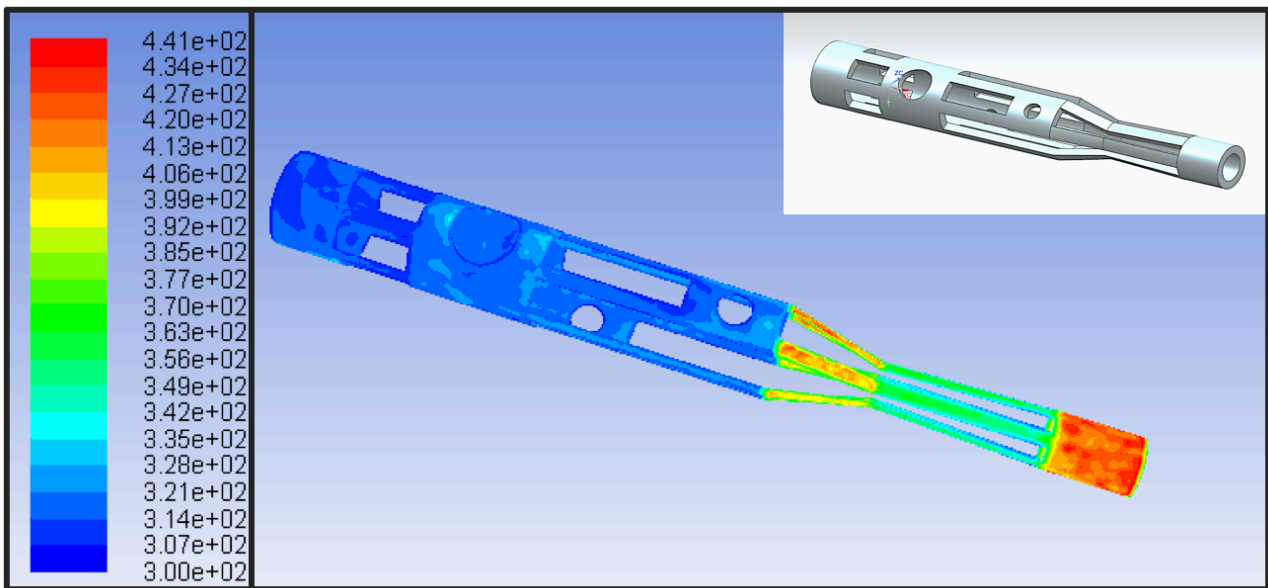


Figure 28. Static temperature contours of the MHD Cooling Jacket in Kelvin.<sup>118,119</sup>

#### 4.5 MAGNETOHYDRODYNAMIC GENERATOR ANALYSIS

The design analysis of a constant-velocity MHD generator is presented for various combustor sizes. Two cases were investigated. The first case was that of a small-scale combustor for proof of concept with a characteristic MHD inlet diameter of 5 mm. This geometry is the equivalent of a previously designed 13.5 N thruster (60 kW combustor). The second case study investigated an MHD generator inlet size of 50 mm. This exit length scale is associated with the

possible size of the next larger-scale MHD combustor. Therefore, a basic generator analysis was conducted to understand two questions:

- What is a possible shape, entrance and exit, of an MHD generator for a 1-MW MHD combustor?
- For various uniform conductivity values, what would be an expected output estimation in the MHD generator for two design cases?

In both design cases, the power output density was approximated for stoichiometric oxy-methane combustion at 9 bar with an area ratio expansion to 1.8 in the nozzle.

Considering the first case. The diverging exit diameter of the nozzle is 5 mm. The MHD generator inlet size was equivalent to the combustion chamber and nozzle system geometry at the MHD inlet-nozzle interface. The  $\text{CH}_4\text{-O}_2$  flame properties were computed based on chemical equilibrium. The methane oxygen properties in chemical equilibrium were computed by the NASA Chemical Equilibrium Application code. The combustion property details, i.e. stagnation properties at the inlet, nozzle flow properties at the nozzle-MHD inlet interface can be found in Table 5. The characteristics of interest were the input parameters entering the MHD inlet. For simplicity, the combustion gases are assumed to have a constant scalar electrical conductivity through the MHD channel. The electrically conducting gas flow enters the linear Faraday MHD generator at State 1 at a constant Mach number, static temperature of 2900 K and static pressure of 1.5 bar. The static pressure of the MHD generator exit is constrained to atmospheric conditions or 100 kPa. The electrical conductivity property was assumed to be 20-40 S/m, which is a strong function of the ration of potassium mass flow to methane mass flow. The external magnetic field was assumed to a constant of 3 Tesla.

Table 5. Design constraints on combustor, nozzle, and MHD Generator characteristics for a conceptual MHD generator analysis.

Design study constraints on combustor and MHD generator	Design Case 1	Design Case 2
Combustor stagnation pressure, 9 bar	MHD inlet height, 5 mm	MHD inlet height, 50 mm
Combustor stagnation temperature, 3338 K	MHD inlet Area, 1/40000 cubic meters	MHD inlet Area, 1/400 cubic meters
Nozzle expansion ratio, 1.8	Methane-oxygen electrical conductivity, 20 S/m	Methane-oxygen electrical conductivity, 20 S/m
MHD inlet static pressure p1, 1.5 bar	MHD generator area ratio , 1.45	MHD generator area ratio , 1.45
MHD inlet static temperature T1, 2907 K	Channel length, 0.27 m	Channel length, 0.27 m
MHD inlet speed of sound a1, 1074 m/s	Channel volume, 8.507 x10-6 cubic meters	Channel volume, 8.507 x10-4 cubic meters
Methane-oxygen electrical conductivity, 20-50 S/m	Maximum power output (K=0.5), 1531 W	Maximum power output (K=0.5), 153,135 W
MHD inlet Mach number, 1.8	Transverse current density (jy), 60,000 Amperes per meter	Transverse current density (jy), 60,000 Amperes per meter
MHD inlet specic heat ratio, 1.2	Continuous electrode area, 0.0017 square meters	Continuous electrode area, 0.017 square meters
MHD inlet flow velocity, 2000 m/s	Transverse Faraday current ,102 Amps	Transverse Faraday current ,1020 Amps
MHD exit static pressure p2, 100 kPa	MHD exit static temperature, 2431 K	MHD exit static temperature, 2431 K
External applied magnetic field, 3 T	Electrode distance 5 mm	Electrode distance 5 mm

The design space for an MHD generator geometry for various pressure ratios in a constant-velocity MHD generator determine is shown in Figure 29. This area ratio variation is seen to decay with increasing pressure ratio between states 2 (outlet of MHD generator) and 1 (inlet of MHD generator), which is a function of the load factor  $K$  ( $E/uB$ ). In addition, as expected, a linear variation of Transverse Faraday current density is a strong function flow velocity when considering a magnetic field of 3 T and a load factor of 0.5. The electrical conductivity value was varied from 20-50 S/m. Two analysis were carried to answer the questions posed in this study.

Figure 29 presents the variation of area ratio with the entrance and exit pressure states in an MHD generator. The area ratio and pressure relations were investigated for various load factors, i.e.  $E/uB$  and considering a variation of electrical conductivities.

Figure 30 presents the estimated current density of the Transverse Faraday current as a function of combustion product gas velocities for various uniform conductivities.

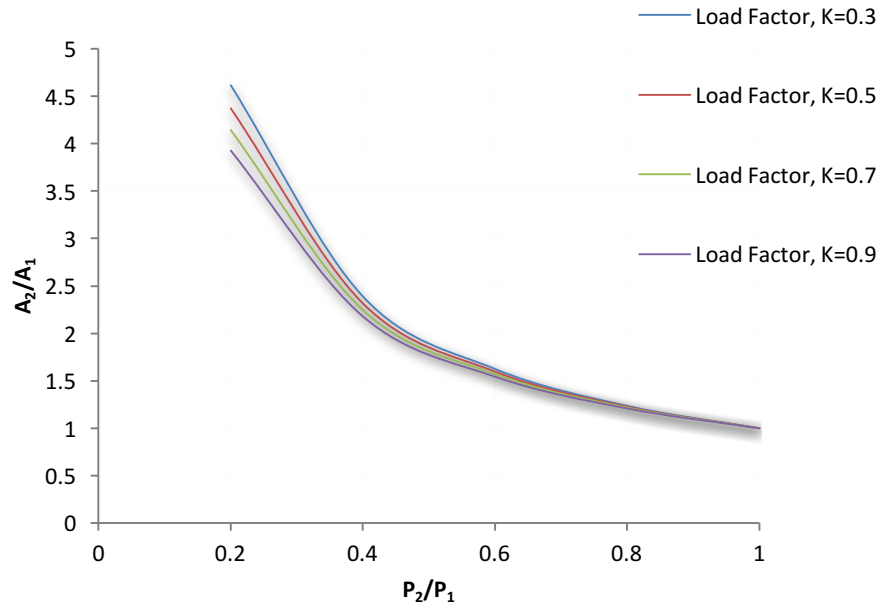


Figure 29. Area ratios for various outlet-inlet pressure ratios in a constant-velocity MHD generator.

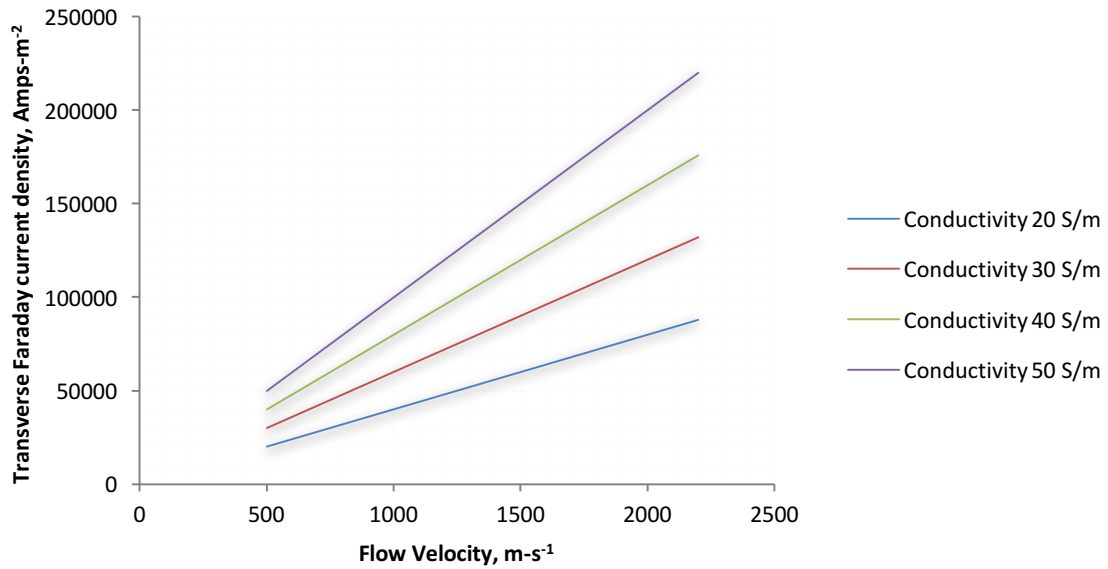


Figure 30. Transverse Faraday current densities for various gas flow velocities at the inlet of a constant-velocity MHD generator.

These results can be used to begin the design phase of an MHD generator. From these results, the design space of an MHD generator should be the large values of area ratio for a Linear Faraday MHD configuration. Although this is a conceptual analysis for the design of generators from first principles, the information can be utilized in the next phase of research. The design analysis has been revisited because of previous experiences in the literature of MHD, where the generator designs were effected by slagging effects, non-uniformities near electrode boundary layers, and electrical conductivities. These technical issues occurred as a consequence of pulverized coal combustion. In this case, a relatively clean burning fuel, methane, and oxygen was considered for new advanced MHD generator systems.

In general, a constant-velocity linear Faraday MHD generator analysis was investigated for two geometric configurations considering a supersonic inlet flow field into the generator. The larger scale MHD inlet configuration was estimated to exhibit 153 kW of power output with a constant electrical conductivity of 20 S/m. From this simplified inviscid analysis with constant properties the output power density increased by a factor of 100 when the inlet was increased to 55 mm. This analysis is summarized as a first-order approximation. Real gas flows are highly non-uniform in flow properties and in electrical conductivity due to non-equilibrium effects in MHD generators. However, this analysis may be used to confine the design space of experimental MHD generator geometries, which interface with supersonic nozzles.

The next phase of the work describes the experimental demonstrations and successful performance of an oxy-fuel combustion system.

#### **4.6 EXPERIMENTAL RESULTS OF SLIGHTLY FUEL RICH OXY-METHANE FLAMES**

The MHD combustor hardware underwent extensive testing for slightly-fuel rich oxy-combustion flames. The experiments focused on observations that represented operating

conditions for MHD power extraction applications. The aim of this work was to investigate the flame structure, as a function of operating or burn time, in order to study the feasibility of using oxy-fuel flames in MHD systems. A number of tests were devised to investigate oxy- combustion, specifically for various long-duration burn times.

Three variables were considered important for MHD systems: burn time, O/F ratio, and theoretical chamber pressure. Therefore, proof-of-concept experiments or demonstrations focused on characterization flames as function of burn time, O/F, and theoretical chamber pressure. The burn time, or combustion residence time in combustors may range from transient to long-duration performances. This parameter is crucial to simulate or demonstrate flames for realistic MHD systems. Short transient performance tests were defined as experiments conducted for less than 10 seconds. While long-duration performance tests investigated burn times above 10 seconds, but less than 120 seconds. The O/F ratio is the ratio of oxidizer mass to fuel mass in the combustion system. This ratio has been seen to be critical to MHD systems because the static temperature in the flow impact ionization state, and hence electrical conductivity.

Two sets of experiments were conducted in this experimental investigation of oxy-combustion systems. Fuel-rich flames were studied, which corresponds to an O/F of 2. Twenty-seven fuel-rich oxy-fuel experiments were successfully completed for an O/F ratio of 2. However, the focus of the dissertation is limited to the demonstration of oxy-methane flames at a slightly-fuel rich state for MHD conditions. These experiments of interest were carried out for O/F of 3.5, chamber pressures of 90-110 psi, and long burns from 10, 30, 60, and 120 seconds. A total number of 31 slightly-fuel-rich oxy combustion experiments were investigated and documented. In these experiments, several datasets were recorded, such as flow rates, surface temperature in the combustor wall, differential temperatures in the cooling jacket for heat flux, and the chamber

pressure in the combustor. Recorded temperature data was taken at the inlet and exit of the cooling channel structure in the MHD combustor, in an effort to compute the heat flux rejected to the MHD combustor structure. Furthermore, the heat flux data and heat loss fraction in the experimental system was computed. The heat loss fraction in MHD systems is critical parameter since it is an indirect measure of the system's efficiency and it calculates the heat rejected to the thermal input from the fuel. The results of the short and long-duration experiments at O/F of 3.5 are presented by Intensified ICCD images from high-speed video.

The scientific contribution to the field of magnetohydrodynamic literature is clearly shown in an updated plot of MHD operating time and MHD combustor thermal rating. This plot was first introduced by Pian and Kessler, which is shown in Figure 31.<sup>23</sup>. This plot is shown for clarity and its value to the field. The most recent compilation of MHD generator time and thermal rating was compiled in 1999.

However, this plot has been updated, which can be seen in Figure 32. Figure 32 includes the experiments of oxy-methane combustion at 7.58 bar, 60 kW thermal rating, and various operating times, which were conducted at the University of Texas at El Paso. The updated plot demonstrates the areas of technical and scientific contribution to the field. Furthermore, an additional contribution lies in the fact that this is an advanced oxy-combustion system for MHD power extraction applications. This small-scale, 60 kW, MHD Combustor was tested at the University of Texas at El Paso. Experimental data was acquired for “small” and “long-duration” operating times. The area in yellow indicates future research opportunities in the field of MHD generators in terms of scale and operating time. Future work may include designing MHD combustors for thermal ratings within the 100 kW-5000 kW for experimental analysis at the “small” operating time. Other combustor design efforts may be focused oxy-combustion hardware



that extend into advancing “long-duration” experiments for power generation. Select data from slightly-fuel-rich (O/F of 3.50 oxy-methane combustion experiments are presented.

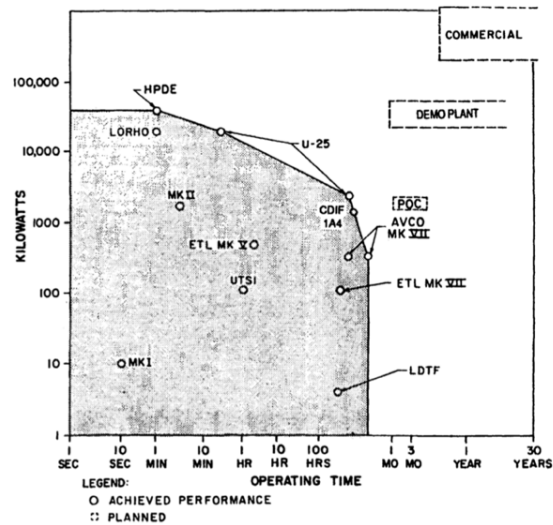


Figure 31. The field of small and large-scale MHD generator experiments are shown as of 1999.<sup>23</sup>

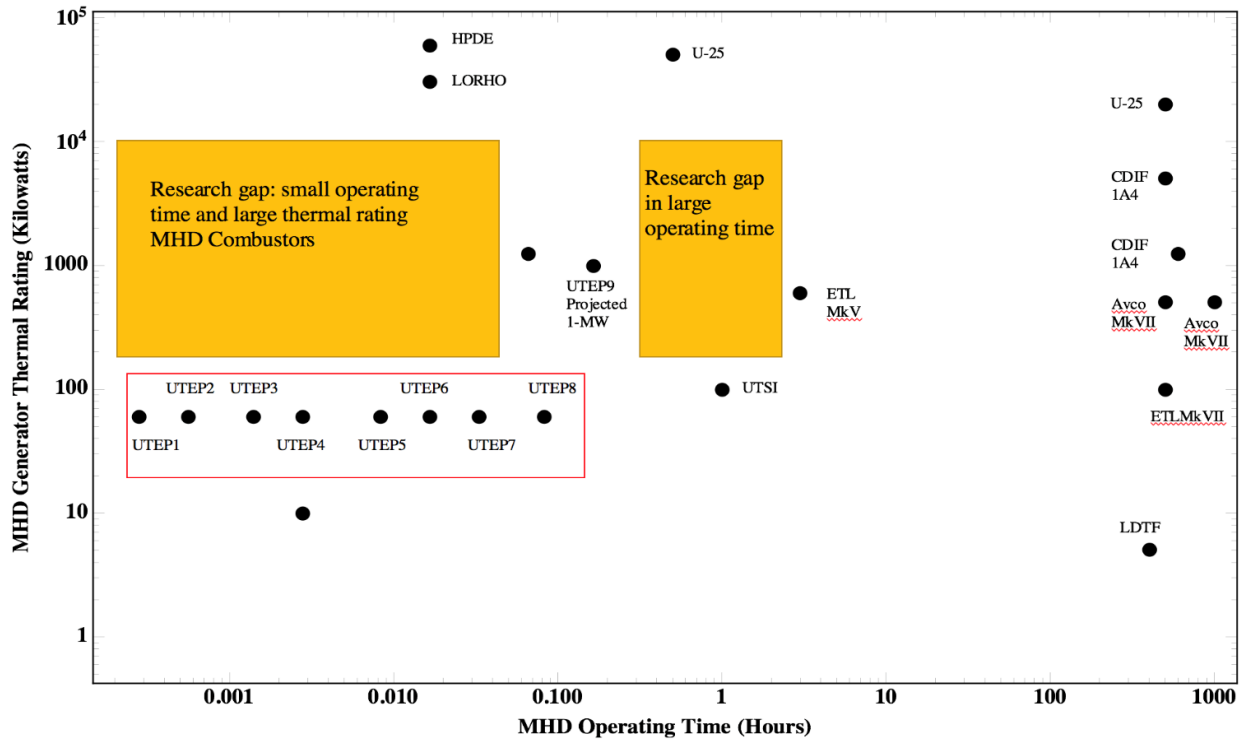


Figure 32. Updated plot of the field of MHD experiments. The plot describes the research areas and opportunities for expanded research. The plot represents MHD generator experimental data by MHD operating time in hours and MHD generator thermal rating.

Figure 33 shows an image from a perpendicular perspective through optical windows. The MHD combustor was operated for constant pressure oxy-combustion at 7.58 bar, O/F of 3.5, and for an operating time of 10 seconds. The data represents the flame structure midway into the test. Figure 34 shows the results of a flame at the same conditions, however, for a longer operating time of 30 seconds.



Figure 33. Oxy-combustion flame structure for constant pressure combustion at 7.58 bar, O/F 3.5, and an operating time of 10 seconds.



Figure 34. Oxy-combustion flame structure for constant pressure combustion at 7.58 bar, O/F 3.5, and an operating time of 30 seconds.

Figure 35 shows an image of a long-duration experiment test, from the top field of the MHD combustor. These results correspond to several oxy-combustion experiments under the same conditions at 7.58 bar and O/F of 3.5 for 2 minutes. The data represents the flame structure midway into the test.

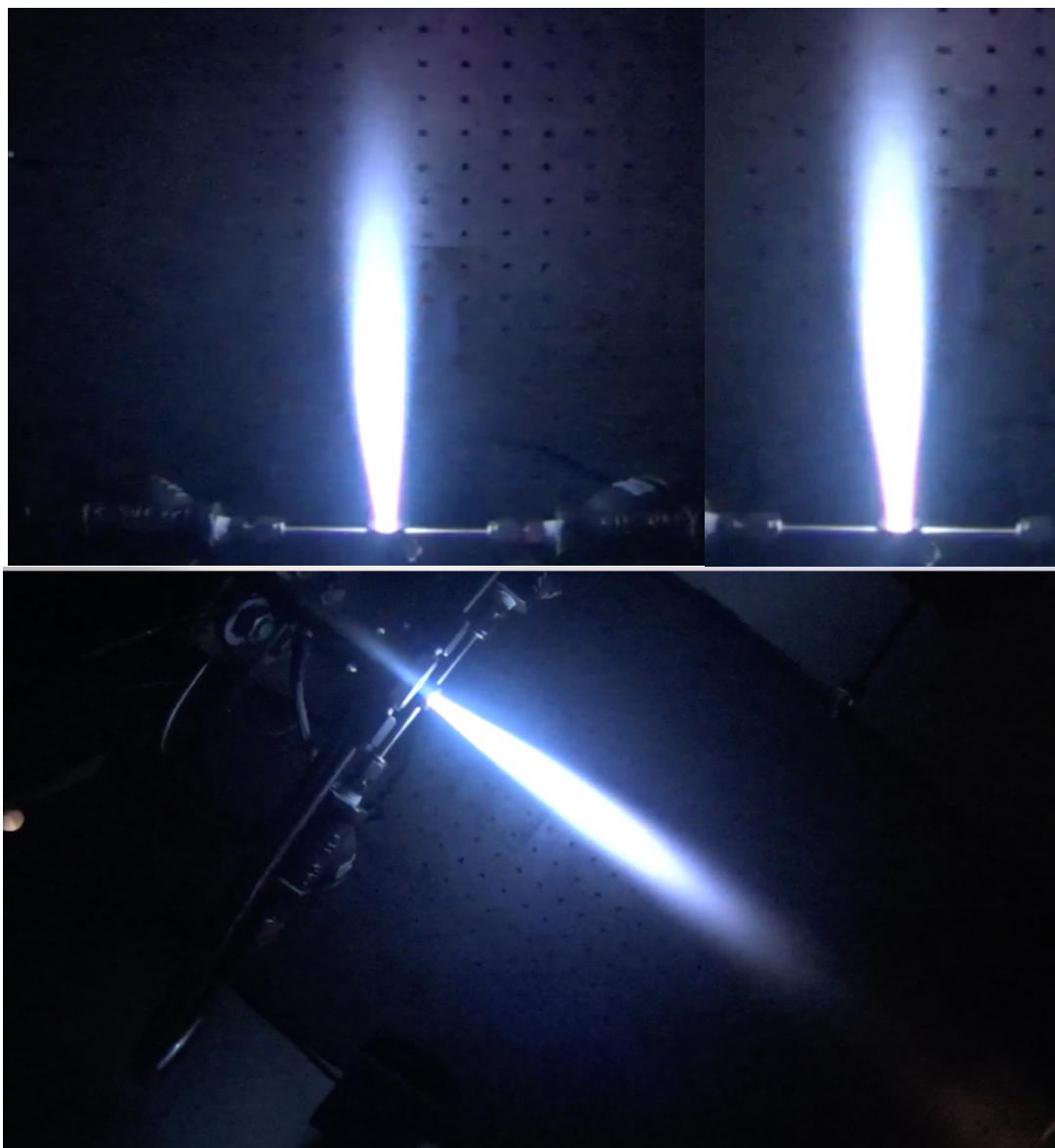


Figure 35. Oxy-combustion flame structure for constant pressure combustion at 7.58 bar, O/F 3.5, and an operating time of 120 seconds.

From these experimental demonstrations of oxy-combustion flames, at various conditions, oxy-combustor systems show promise for the development of advanced combustor and MHD application hardware. Quantitative experimental findings may provide additional datasets.

## **Chapter 5: Conclusions and Future Work**

In general, oxy-combustion for magnetohydrodynamic power extraction has generated significant interest. Therefore, extensive research efforts are underway to develop the next generation of energy systems. Broad impacts of this work targets oxy-combustion technologies for advanced power generation.

The proposed idea is to use oxy-combustion flames to provide enhanced energetic environments that may lead to more-stable electrical conductivity profile in magnetohydrodynamic systems. Oxy-combustion technologies were proposed in a number of studies as a means of providing high enthalpy, electrically conductive flows for direct conversion of electricity.

A detailed review of the previous works in the magnetohydrodynamic power extraction literature led to many conclusions. A conclusion is that the boundary layer is a critical region that governs the electrical conductivity, in addition to the heat transfer. Trade-offs exist when considering subsonic or supersonic combustion products for magnetohydrodynamics. Limited data is available on supersonic combustion gases for MHD applications. Conceptual and system studies from the early works to the most recent findings have been documented in this dissertation document. In the past, scaling effects and processes have not been documented in the field of magnetohydrodynamic literature. Therefore, a first-iteration of oxy-combustion for MHD application was defined and designed for a small-scale thermal rating criterion. In this case, a small scale criterion was set for less than 100 kW. For this scale, the design criteria, combustor subsystem design, and cooling channel design of an oxy-combustion system was presented. Analytical and numerical computations led the design process and methodology. Both analytical and numerical analysis were performed to understand the combustion heat transfer and cooling

flow fields. These design and development efforts were aimed at resolving two research questions in the dissertation. The research questions of this work include the following:

- What are the current research opportunities in the field of combustion magnetohydrodynamics?
- Considering small-scale thermal rating devices, could methane-oxygen combustion flames and their structure provide an adequate high-temperature flow-field, if seeded with potassium, for Lorentz forces to act on charged particles?

A thorough review was documented in this work to answer the first research question. Previous works in the field have been indicated to define the current research opportunities in the field. The review emphasized a particular emphasis on the theory, ions in flames, system powertrain studies of previous MHD power extraction, and slag-seed interactions in the most recent works. A number of future directions is apparent from this review.

With regards to the second research question, a design, development methodology, numerical modeling, and testing of a small-scale oxy-combustion combustor was documented. In this work, the combustor subsystems and cooling channel designs have been defined to meet magnetohydrodynamic power extraction specifications. Based on previous findings, temperatures in the range of 2800-3000 K may enable magnetohydrodynamic power extraction. The hardware design was aimed to contribute systems rated less than 100 kW for demonstration and produce gas velocities of 2000 m/s gas and temperatures of 2800-3000 K. From the experimental and numerical results of oxy-combustion in this combustor hardware, the oxy-combustion flames may be beneficial for magnetohydrodynamic power extraction. The experimental performance of oxy-combustion systems demonstrates promise for power generation technologies.

Computational fluid dynamics models were used as a design and optimization tool for advanced energy systems. A non-premixed combustion flow field was analyzed in a steady-state computational fluid dynamic model. This analysis was used to predict static temperatures, heat transfer coefficients, and heat transfer in oxy-combustion systems at 8 bar. Based on analytical computations the heat transfer coefficient, heat transfer, and heat loss fractions were computed. A comparison of analytical, computational, and experimental values of heat loss fractions in this oxy-fuel combustion system resulted in a reasonable accuracy.

However, certain areas remain unanswered. For instance, the seeding process was not included in the design or testing, since it was not within the scope of the dissertation work. Scaling investigations are required to answer the effectiveness of this approach at scales near 1-MW or above. These larger-scale demonstrations are required for a commercial-scale evaluation. Another research opportunity that requires more work is the analysis of the combustion dynamics, which is critical to the electrical conductivity profile and boundary layers in MHD systems. Combustion dynamics may be more problematic at the larger-scale in oxy-combustion systems.

Future work is needed to fine tune the design of oxy-combustion systems. Aspects that require additional analysis are the trade-offs of a smaller-combustion chamber made of nickel-based Inconel 718 structure. The impact of the characteristic length is directly tied to the heat loss in the system during combustion. Analysis of other copper super alloys or composite ceramic materials may be investigated for combustion MHD applications. Also, the product definition and development of a larger-thermal-rating Oxy-Combustion system for scaling studies is needed. A 1 MW Oxy-Combustor was designed for this study in the future. Figure 36 shows a comparison of the combustor scales for MHD applications by CAD models. Although, many areas remain unexplored, the concept of MHD may be a promising method for power generation in the future.

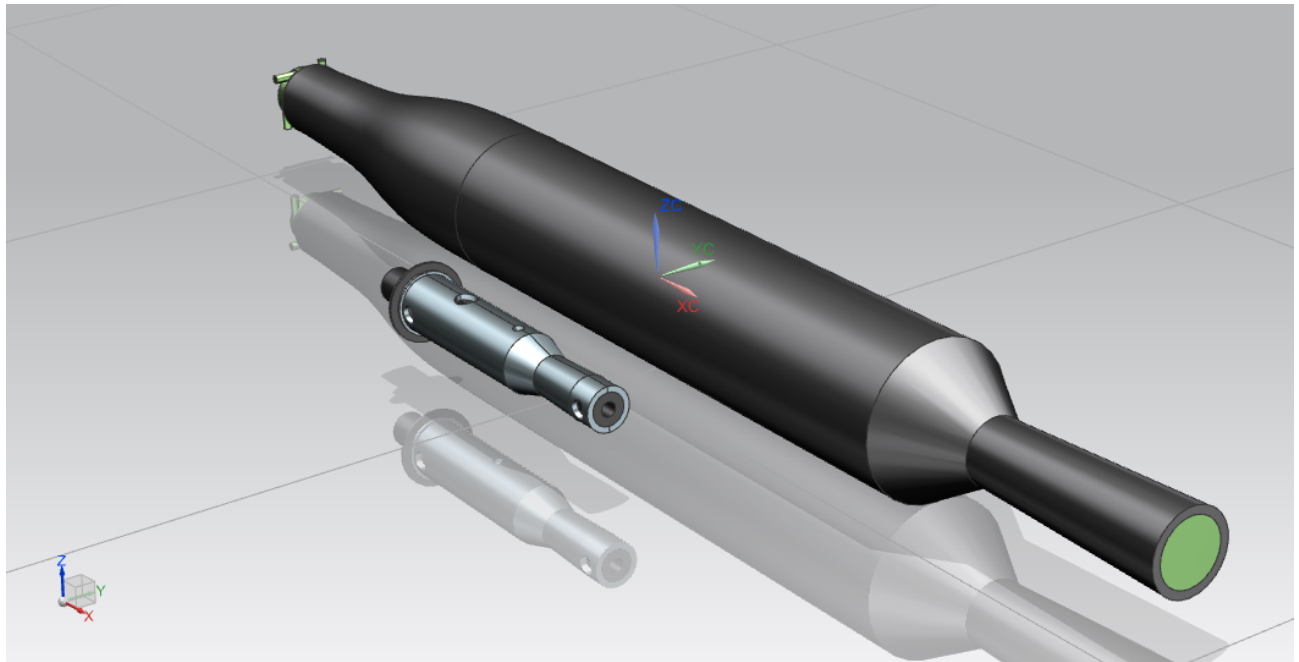


Figure 36. Rendering of both Oxy-Combustion Energy Systems (60 kW and 1 MW) for MHD applications.



## References

- <sup>1</sup> Bychkov, V., Modestov, M., and Law, C. K., “Combustion phenomena in modern physics: I. Inertial confinement fusion,” *Progress in Energy and Combustion Science*, vol. 47, Apr. 2015, pp. 32–59.
- <sup>2</sup> Ju, Y., and Sun, W., “Plasma assisted combustion: Dynamics and chemistry,” *Progress in Energy and Combustion Science*, vol. 48, Jun. 2015, pp. 21–83.
- <sup>3</sup> Brewster, B. S., Cannon, S. M., Farmer, J. R., and Meng, F., “Modeling of lean premixed combustion in stationary gas turbines,” *Progress in Energy and Combustion Science*, vol. 25, Aug. 1999, pp. 353–385.
- <sup>4</sup> Poinso, L. Y. M. G. G. S. T., Staffelbach, G., and Poinso, T., “Large Eddy Simulations of gaseous flames in gas turbine combustion chambers,” *Progress in Energy and Combustion Science*, vol. 38, Dec. 2012, pp. 782–817.
- <sup>5</sup> Kayukawa, N., “Open-cycle magnetohydrodynamic electrical power generation: a review and future perspectives,” *Progress in Energy and Combustion Science*, vol. 30, Jan. 2004, pp. 33–60.
- <sup>6</sup> P Pian, C. C., and Kessler, R., “Open-Cycle Magnetohydrodynamic Power Generators,” *Journal of Propulsion and Power*, vol. 15, Mar. 1999, pp. 195–203.
- <sup>7</sup> Kayukawa, N., and Wang, Y., “Advanced Coal Power Cycle with a Stand-Alone Magnetohydrodynamic Generator,” *Journal of Propulsion and Power*, vol. 20, May 2004, pp. 566–571.
- <sup>8</sup> Kayukawa, N., “New Fossil Power Systems and the Role of Open-Cycle Magnetohydrodynamics Generators,” *Journal of Propulsion and Power*, vol. 18, Jul. 2002, pp. 871–878.
- <sup>9</sup> Kayukawa, N., and Wang, Y., “Stand-Alone Scheme of Open-Cycle Magnetohydrodynamic Power Generation System,” *Journal of Propulsion and Power*, vol. 19, Sep. 2003, pp. 972–975.
- <sup>10</sup> Kayukawa, N., “Open-cycle magnetohydrodynamic electrical power generation: a review and future perspectives,” *Progress in Energy and Combustion Science*, vol. 30, Jan. 2004, pp. 33–60.
- <sup>11</sup> Macheret, S. O., Shneider, M. N., Miles, R. B., and Lipinski, R. J., “Electron-Beam-Generated Plasmas in Hypersonic Magnetohydrodynamic Channels,” *AIAA Journal*, vol. 39, Jun. 2001, pp. 1127–1138.
- <sup>12</sup> Shneider, M. N., and Macheret, S. O., “Hypersonic Aerodynamic Control and Thrust Vectoring by Nonequilibrium Cold-Air Magnetohydrodynamic Devices,” *Journal of Propulsion and Power*, vol. 22, May 2006, pp. 490–497.
- <sup>13</sup> Macheret, S. O., Shneider, M. N., and Miles, R. B., “Magnetohydrodynamic and Electrohydrodynamic Control of Hypersonic Flows of Weakly Ionized Plasmas,” *AIAA Journal*, vol. 42, Jul. 2004, pp. 1378–1387.
- <sup>14</sup> Macheret, S. O., Shneider, M. N., and Miles, R. B., “Magnetohydrodynamic Control of Hypersonic Flows and Scramjet Inlets Using Electron Beam Ionization,” *AIAA Journal*, vol. 40, Jan. 2002, pp. 74–81.
- <sup>15</sup> Macheret, S. O., Shneider, M. N., and Miles, R. B., “Magnetohydrodynamic Power Extraction from Cold Hypersonic Airflows with External Ionizers,” *Journal of Propulsion and Power*, vol. 18, Mar. 2002, pp. 424–431.
- <sup>16</sup> Sutton, G. W., and Sherman, A., *Engineering Magnetohydrodynamics*, New York:

- McGraw-Hill, Inc., 1965.
- 17 Rosa, R., *Magnetohydrodynamic energy conversion*, New York: 1968.
- 18 HARTMANN, J., *Hg-DYNAMICS I*, Levin & Munksgaard, 1937.
- 19 Fialkov, A., "Investigations on ions in flames," *Progress in Energy and Combustion Science*, vol. 23, 1997, pp. 399–528.
- 20 Tufts, F. L., "The Phenomena of Ionization in Flame Gases and Vapors," *Physical Review (Series I)*, vol. 22, Apr. 1906, pp. 193–220.
- 21 Van Tiggelen, A., Shuler, K. E., and Fenn, J. B., *Ionization in high temperature gases*, New York: Academic Press, 1963.
- 22 Fialkov, A., "Investigations on ions in flames," *Progress in Energy and Combustion Science*, vol. 23, 1997, pp. 399–528.
- 23 P Pian, C. C., and Kessler, R., "Open-Cycle Magnetohydrodynamic Power Generators," *Journal of Propulsion and Power*, vol. 15, Mar. 1999, pp. 195–203.
- 24 Faraday, M., "Experimental Researches in Electricity," *Philosophical Transactions of the Royal Society of London*, vol. 122, Jan. 1832, pp. 125–162.
- 25 Jackson, W. D., Petrick, M., and Klepeis, J. E., "A Critique of MHD Power Generation," *Journal of Engineering for Power*, vol. 92, 1970, pp. 217–14.
- 26 Thomson, J. J., and Thomson, G. P., *Conductivity of electricity through gases*, London: Cambridge University Press, 1928.
- 27 Mukherjee, N. R., Fueno, T., Eyring, H., and Ree, T., "Ions in flames," *Symposium (International) on Combustion*, vol. 8, Jan. 1961, pp. 1–22.
- 28 Calcote, H. F., "Electrical properties of flames," *Symposium on Combustion and Flame, and Explosion Phenomena*, vol. 3, 1948, pp. 245–253.
- 29 Calcote, H. F., "Ion and electron profiles in flames," *Symposium (International) on Combustion*, vol. 9, Jan. 1963, pp. 622–637.
- 30 Calcote, H. F., Kurzius, S. C., and Miller, W. J., "Negative and secondary ion formation in low-pressure flames," *Symposium (International) on Combustion*, vol. 10, Jan. 1965, pp. 605–619.
- 31 Calcote, H. F., and King, I. R., "Studies of ionization in flames by means of langmuir probes," *Symposium (International) on Combustion*, vol. 5, Jan. 1955, pp. 423–434.
- 32 Pergament, H. S., and Calcote, H. F., "Thermal and chemi-ionization processes in afterburning rocket exhausts," *Symposium (International) on Combustion*, vol. 11, Jan. 1967, pp. 597–611.
- 33 KERREBROCK, J. L., "Magnetohydrodynamic generators with nonequilibrium ionization," *AIAA Journal*, vol. 3, Apr. 1965, pp. 591–601.
- 34 Way, S., and Hundstad, R. L., "Direct generation of power from a combustion gas stream," *Symposium (International) on Combustion*, vol. 8, Jan. 1961, pp. 241–251.
- 35 Chu, C. K., "Magnetohydrodynamic Nozzle Flow with Three Transitions," *Physics of Fluids*, vol. 5, 1962, pp. 550–11.
- 36 Bohachevsky, I. O., "Simple Waves and Shocks in Magnetohydrodynamics," *Physics of Fluids*, vol. 5, 1962, pp. 1456–13.
- 37 Saric, W. S., "Incompressible Magnetohydrodynamic Entrance Flow in a Plane Channel," *Physics of Fluids*, vol. 12, 1969, pp. 1412–9.
- 38 Nichol, J., Siminski, V., and Wolfhard, H. G., "Ionization in rocket flames," *Symposium (International) on Combustion*, vol. 8, Jan. 1961, pp. 235–241.
- 39 Rosa, R. J., "Physical Principles of Magnetohydrodynamic Power Generation," *Physics of*

- Fluids*, vol. 4, 1961, pp. 182–14.
- 40 Way, S., DeCorso, S. M., Hundstad, R. L., Kemeny, G. A., Stewart, W., and Young, W. E., “Experiments With MHD Power Generation,” *Journal of Engineering for Power*, vol. 83, 1961, pp. 397–408.
- 41 Bünde, R., Muntenbruch, H., Raeder, J., Volk, R., and Zankl, G., *MHD Power Generation*, Berlin, Heidelberg: Springer Berlin Heidelberg, 1975.
- 42 Sutton, G. W., and Robben, F., “Preliminary experiments on MHD channel flow with slightly ionized gases,” Brooklyn: 1962, pp. 307–321.
- 43 Rosa, R. J., “Physical Principles of Magnetohydrodynamic Power Generation,” *Physics of Fluids*, vol. 4, 1961, pp. 182–14.
- 44 Sherman, A., “Viscous Magnetohydrodynamic Boundary Layer,” *Physics of Fluids*, vol. 4, 1961, pp. 552–7.
- 45 Lapp, M., and Rich, J. A., “Electrical Conductivities of Seeded Flame Plasmas in Strong Electric Fields,” *Physics of Fluids*, vol. 6, 1963, pp. 806–12.
- 46 Dimmock, T. H., and Kineyko, W. R., “The low pressure, combustion gas plasma,” *Combustion and Flame*, vol. 7 IS -, 1963, pp. 283–291.
- 47 GILLESPIE, J., and TURCOTTE, D. L., “ELECTRICAL RESISTANCE AND SHEATH POTENTIAL ASSOCIATED WITH A COLD ELECTRODE,” *AIAA Journal*, vol. 1, Oct. 1963, pp. 2293–2299.
- 48 Turcotte, D. L., and Friedman, W., “Electrode interactions in seeded combustion products,” *Symposium (International) on Combustion*, vol. 10, Jan. 1965, pp. 673–683.
- 49 CELINSKI, Z. N., and FISCHER, F. W., “Effect of electrode size in MHD generators with segmented electrodes,” *AIAA Journal*, vol. 4, Mar. 1966, pp. 421–428.
- 50 Eustis, R. H., and KESSLER, R., “Effects of electrode and boundary-layer temperatures on MHD-generator performance,” *AIAA Journal*, vol. 6, Sep. 1968, pp. 1640–1646.
- 51 Pian, C. C. P., and MERCK, W. F. H., “Boundary-layer separation from the electrode wall of an MHD generator,” *AIAA Journal*, vol. 14, Nov. 1976, pp. 1585–1588.
- 52 HIJIKATA, K. (Tokyo Institute of Technology, Tokyo, Japan); MORI, Y.; OHTAKE, K.; OKAZAKI, K., “Analysis of the seeded combustion gas boundary layer near a cold electrode,” *AIAA Journal*, vol. 15, Dec. 1977, pp. 1778–1784.
- 53 GUPTA, B., and Raju, G. V. R., “Analytical evaluation of electrode potential drops in MHD plasmas,” *Journal of Propulsion and Power*, vol. 2, Jul. 1986, pp. 383–384.
- 54 Blackman, V. H., Jones, M. S., and Demetriades, A., “MHD Power Generation Studies in Rectangular Channels,” New York: 1962, pp. 180–210.
- 55 Rao, K. R., and Erteza, A., “A cylindrical coaxial MHD generator,” *Applied Scientific Research*, vol. 21, 1969, pp. 427–441.
- 56 Mullaney, G. J., and Dibelius, N. R., “Small MHD Power generator using combustion gases as an energy source,” *American Rocket Society*, Oct. 1961, pp. 555–557.
- 57 Louis, J. F., Gal, G., and Blackburn, P. R., “Detailed theoretical and experimental study on a large MHD generator,” New York: 1964.
- 58 Blackburn, P. R., Gal, G., and Louis, J. F., “Detailed theoretical and experimental study on a large mhd generator,” *AIAA Journal*, vol. 3, Aug. 1965, pp. 1482–1490.
- 59 IKEDA, S., MASUDA, T., KUSAKA, Y., HONDA, T., and AIYAMA, Y., “Experiment on MHD generator with a large-scale superconducting magnet /ETL Mark V/,” *AIAA Journal*, vol. 14, Nov. 1976, pp. 1655–1656.
- 60 Simons, T. D., Mitchner, M., and Eustis, R. H., “Analysis and measurement of property

- disturbances in a combustion magnetohydrodynamic plasma,” *Physics of Fluids*, vol. 27, 1984, pp. 1880–8.
- 61 Pian, C. C. P., and HALS, F. A., “MHD generator performance analyses for the advanced power train study,” *Journal of Propulsion and Power*, vol. 1, Jan. 1985, pp. 89–96.
- 62 MCCLAINE, A. W., SWALLOM, D. W., and KESSLER, R., “Experimental investigation of subsonic combustion-driven MHD generator performance,” *Journal of Propulsion and Power*, vol. 1, Jul. 1985, pp. 263–269.
- 63 ROSA, R., FARRAR, L., and TRUDNOWSKI, D., “Electric arc behavior in a boundary layer,” *Journal of Propulsion and Power*, vol. 4, Sep. 1988, pp. 466–471.
- 64 Wilson, W. W., Srikantaiah, D. V., Shepard, W. S., Cook, R. L., Wilson, W. W., Srikantaiah, D. V., Shepard, W. S., and Cook, R. L., “Laser Velocimetry Measurements at the Diffuser Exit of a Coal-Fired MHD Channel,” *Journal of Propulsion and Power*, vol. 4, Nov. 1988, pp. 571–576.
- 65 Scott, J. D., and Simpson, S. W., “Electrical No uniformities in Commercial-Scale Slagging Magnetohydrodynamic Channels,” *Journal of Propulsion and Power*, vol. 5, Nov. 1989, pp. 738–743.
- 66 Pian, C. C. P., SADOVNIK, I., Petty, S. W., and MCCLAINE, A. W., “Voltage-current characteristics of the insulator gaps in a slagging magnetohydrodynamic generator,” *Journal of Propulsion and Power*, vol. 6, Jul. 1990, pp. 482–489.
- 67 Pian, C. C. P., Petty, S. W., and MCCLAINE, A. W., “Experimental investigation of factors affecting the cathode wall slag-layer resegmentation frequency,” *Journal of Propulsion and Power*, vol. 7, Nov. 1991, pp. 1036–1042.
- 68 Pian, C. C. P., and Schmitt, E. W., “Wall surface leakage effects on magnetohydrodynamic power generator performance,” *Journal of Propulsion and Power*, vol. 12, Jan. 1996, pp. 70–77.
- 69 LUONGO, C. A., and KRUGER, C. H., “Slag/seed interaction in coal-fired MHD generators,” *Journal of Propulsion and Power*, vol. 2, Nov. 1986, pp. 521–527.
- 70 Pian, C. C. P., “Data analysis of diagonally connected magnetohydrodynamic power generator experiments,” *Journal of Propulsion and Power*, vol. 3, Mar. 1987, pp. 128–135.
- 71 Pian, C. C. P., SADOVNIK, I., Petty, S. W., and MCCLAINE, A. W., “Voltage-current characteristics of the insulator gaps in a slagging magnetohydrodynamic generator,” *Journal of Propulsion and Power*, vol. 6, Jul. 1990, pp. 482–489.
- 72 Pian, C. C. P., Petty, S. W., and MCCLAINE, A. W., “Experimental investigation of factors affecting the cathode wall slag-layer resegmentation frequency,” *Journal of Propulsion and Power*, vol. 7, Nov. 1991, pp. 1036–1042.
- 73 ISHIKAWA, M., SUEMURA, T., FUJITA, M., and UMOTO, J., “Effects of external control circuit on coal-fired supersonic diagonal-type MHD generator,” *Journal of Propulsion and Power*, vol. 9, Sep. 1993, pp. 749–756.
- 74 Goforth, R. C., and Kruger, C. H., “Investigation of secondary flows in magnetohydrodynamic channels,” *Journal of Propulsion and Power*, vol. 9, Nov. 1993, pp. 889–897.
- 75 Pian, C. C. P., Petty, S. W., Schmitt, E. W., and Farrar, L. C., “Prototypic magnetohydrodynamic anode designs and test results,” *Journal of Propulsion and Power*, vol. 11, Nov. 1995, pp. 1330–1337.
- 76 Pian, C. C. P., and Schmitt, E. W., “Wall surface leakage effects on

- magnetohydrodynamic power generator performance,” *Journal of Propulsion and Power*, vol. 12, Jan. 1996, pp. 70–77.
- 77 Pian, C. C. P., Kessler, R., and Schmitt, E. W., “Magnetohydrodynamic generator design for a combined-cycle demonstration power plant,” *Journal of Propulsion and Power*, vol. 12, Mar. 1996, pp. 390–397.
- 78 Kayukawa, N., and Wang, Y., “Stand-Alone Scheme of Open-Cycle Magnetohydrodynamic Power Generation System,” *Journal of Propulsion and Power*, vol. 19, Sep. 2003, pp. 972–975.
- 79 Kayukawa, N., and Wang, Y., “Advanced Coal Power Cycle with a Stand-Alone Magnetohydrodynamic Generator,” *Journal of Propulsion and Power*, vol. 20, May 2004, pp. 566–571.
- 80 Okuno, Y., Okamura, T., Suekane, T., Yamasaki, H., Kabashima, S., and Shioda, S., “Magnetohydrodynamic Power Generation Experiments with Fuji-1 Blowdown Facility,” *Journal of Propulsion and Power*, vol. 19, Sep. 2003, pp. 894–900.
- 81 Nagamatsu, H. T., and Sheer, R. E., “Magnetohydrodynamic Results for Highly Dissociated and Ionized Air Plasma,” *Physics of Fluids*, vol. 4, 1961, pp. 1073–13.
- 82 Macheret, S. O., Shneider, M. N., Miles, R. B., and Lipinski, R. J., “Electron-Beam-Generated Plasmas in Hypersonic Magnetohydrodynamic Channels,” *AIAA Journal*, vol. 39, Jun. 2001, pp. 1127–1138.
- 83 Macheret, S., “Introduction: Weakly Ionized Plasmas for Propulsion Applications,” *Journal of Propulsion and Power*, vol. 24, Sep. 2008, pp. 898–899.
- 84 Macheret, S. O., Shneider, M. N., and Miles, R. B., “Magnetohydrodynamic and Electrohydrodynamic Control of Hypersonic Flows of Weakly Ionized Plasmas,” *AIAA Journal*, vol. 42, Jul. 2004, pp. 1378–1387.
- 85 Macheret, S. O., Shneider, M. N., and Miles, R. B., “Magnetohydrodynamic Control of Hypersonic Flows and Scramjet Inlets Using Electron Beam Ionization,” *AIAA Journal*, vol. 40, Jan. 2002, pp. 74–81.
- 86 Macheret, S. O., Shneider, M. N., and Miles, R. B., “Magnetohydrodynamic Power Extraction from Cold Hypersonic Airflows with External Ionizers,” *Journal of Propulsion and Power*, vol. 18, Mar. 2002, pp. 424–431.
- 87 Shneider, M. N., and Macheret, S. O., “Modeling of Plasma Virtual Shape Control of Ram/Scramjet Inlet and Isolator,” *Journal of Propulsion and Power*, vol. 22, Mar. 2006, pp. 447–454.
- 88 Burakhanov, B. M., Likhachev, A. P., Medin, S. A., Novikov, V. A., Okunev, V. I., Rickman, V. Y., and Zeigarnik, V. A., “Advancement of Scramjet Magnetohydrodynamic Concept,” *Journal of Propulsion and Power*, vol. 17, Nov. 2001, pp. 1247–1252.
- 89 Balasubramanian, R., Anandhanarayanan, K., Krishnamurthy, R., and Chakraborty, D., “Magnetohydrodynamic Flow Control of a Hypersonic Cruise Vehicle Based on AJAX Concept,” *Journal of Spacecraft and Rockets*, vol. 53, Jul. 2016, pp. 759–762.
- 90 Dietiker, J.-F., and Hoffmann, K. A., “Numerical Simulation of Magnetohydrodynamic Flows,” *Journal of Spacecraft and Rockets*, vol. 41, Jul. 2004, pp. 592–602.
- 91 Chul Park; David W. Bogdanoff; Unmeel B. Mehta, “Magnetohydrodynamics Energy Bypass Scramjet Performance with Real Gas Effects,” *Journal of Propulsion and Power*, vol. 17, Sep. 2001, pp. 1049–1057.
- 92 Park, C., Bogdanoff, D. W., and Mehta, U. B., “Theoretical Performance of a Magnetohydrodynamic-Bypass Scramjet Engine with Nonequilibrium Ionization,”

- Journal of Propulsion and Power*, vol. 19, Jul. 2003, pp. 529–537.
- 93 Fujino, T., Yoshino, T., and Ishikawa, M., “Aerodynamic Heating of Reentry Body Equipped with Onboard-Surface Hall Magnetohydrodynamic Generator,” *Journal of Propulsion and Power*, vol. 26, Jul. 2010, pp. 638–648.
- 94 Shneider, M. N., Macheret, S. O., Zaidi, S. H., Girgis, I., and Miles, R. B., “Virtual Shapes in Supersonic Flow Control with Energy Addition,” *Journal of Propulsion and Power*, vol. 24, Sep. 2008, pp. 900–915.
- 95 Riggins, D. W., “Analysis of the Magnetohydrodynamic Energy Bypass Engine for High-Speed Airbreathing Propulsion,” *Journal of Propulsion and Power*, vol. 20, Sep. 2004, pp. 779–792.
- 96 Bisek, N. J., Gosse, R., and Poggie, J., “Computational Study of Impregnated Ablator for Improved Magnetohydrodynamic Heat Shield,” *Journal of Spacecraft and Rockets*, vol. 50, Sep. 2013, pp. 927–936.
- 97 Gaitonde, D. V., “High-Speed Magnetohydrodynamic Flow Control Analyses with Three-Dimensional Simulations,” *Journal of Propulsion and Power*, vol. 24, Sep. 2008, pp. 946–961.
- 98 Borghi, C. A., Carraro, M., and Cristofolini, A., “Analysis of Magnetoplasmadynamic Interaction in the Boundary Layer of a Hypersonic Vehicle,” *Journal of Spacecraft and Rockets*, vol. 42, Jan. 2005, pp. 45–50.
- 99 Bobashev, S. V., Erofeev, A. V., Lapushkina, T. A., Poniaev, S. A., Vasil'eva, R. V., and Van Wie, D. M., “Effect of Magnetohydrodynamics Interaction in Various Parts of Diffuser on Inlet Shocks: Experiment,” *Journal of Propulsion and Power*, vol. 21, Sep. 2005, pp. 831–837.
- 100 Schneider, S. J., “Annular Magnetohydrodynamic Physics for Turbojet Energy Bypass,” *Journal of Propulsion and Power*, vol. 29, Jan. 2013, pp. 186–194.
- 101 Yang, P., Zhang, B., Li, Y., Wang, Y., Duan, C., Fan, H., and Gao, L., “Investigation of MHD power generation with supersonic non-equilibrium RF discharge,” *Chinese Journal of Aeronautics*, vol. 29, Aug. 2016, pp. 855–862.
- 102 Gaitonde, D. V., “Magnetohydrodynamic Energy-Bypass Procedure in a Three-Dimensional Scramjet,” *Journal of Propulsion and Power*, vol. 22, May 2006, pp. 498–510.
- 103 Kim, M., and Boyd, I. D., “Effectiveness of a Magnetohydrodynamics System for Mars Entry,” *Journal of Spacecraft and Rockets*, vol. 49, Nov. 2012, pp. 1141–1149.
- 104 Murray, R. C., Zaidi, S. H., Carraro, M. R., Vasilyak, L. M., Macheret, S. O., Shneider, M. N., and Miles, R. B., “Magnetohydrodynamic Power Generation Using Externally Ionized, Cold, Supersonic Air as Working Fluid,” *AIAA Journal*, vol. 44, Jan. 2006, pp. 119–127.
- 105 Adamovich, I. V., Rich, J. W., and Nelson, G. L., “Feasibility Study of Magnetohydrodynamics Acceleration of Unseeded and Seeded Airflows,” *AIAA Journal*, vol. 36, Apr. 1998, pp. 590–597.
- 106 Murakami, T., and Okuno, Y., “Radio-frequency power assistance on a compact magnetohydrodynamic electrical power generator under high-density magnetic flux,” *Applied Physics Letters*, vol. 93, 2008, pp. 051503–4.
- 107 Shang, J. S., and Surzhikov, S. T., “Magnetoaerodynamic Actuator for Hypersonic Flow Control,” *AIAA Journal*, vol. 43, Aug. 2005, pp. 1633–1652.
- 108 Shang, J. S., Kimmel, R. L., Menart, J. A., and Surzhikov, S. T., “Hypersonic Flow

- Control Using Surface Plasma Actuator,” *Journal of Propulsion and Power*, vol. 24, Sep. 2008, pp. 923–934.
- 109 Su, W.-Y., Chang, X.-Y., and Zhang, K.-Y., “Effects of Magnetohydrodynamic Interaction-Zone Position on Shock-Wave/Boundary-Layer Interaction,” *Journal of Propulsion and Power*, vol. 26, Sep. 2010, pp. 1053–1058.
- 110 Fujino, T., and Ishikawa, M., “Feasibility of an Onboard Surface Hall Magnetohydrodynamic Power Generator in Reentry Flight,” *Journal of Propulsion and Power*, vol. 25, Jan. 2009, pp. 83–93.
- 111 Fujino, T., Sugita, H., Mizuno, M., Funaki, I., and Ishikawa, M., “Influences of Electrical Conductivity of Wall on Magnetohydrodynamic Control of Aerodynamic Heating,” *Journal of Spacecraft and Rockets*, vol. 43, Jan. 2006, pp. 63–70.
- 112 Fujino, T., Matsumoto, Y., Kasahara, J., and Ishikawa, M., “Numerical Studies of Magnetohydrodynamic Flow Control Considering Real Wall Electrical Conductivity,” *Journal of Spacecraft and Rockets*, vol. 44, May 2007, pp. 625–632.
- 113 Ni, M.-J., “Recent advances in computational techniques for MHD flow and application to fusion,” *Fusion Engineering and Design*, vol. 87, Sep. 2012, pp. 1544–1549.
- 114 Gaitonde, D. V., “Effect of Hall Currents on Simulated Three-Dimensional Scramjet with Magnetohydrodynamic Bypass,” *Journal of Propulsion and Power*, vol. 22, May 2006, pp. 700–703.
- 115 Li, D., Keefer, D., Rhodes, R., Merkle, C., Kolokolnikov, K., and Thibodeaux, R., “Analysis of Magnetohydrodynamic Generator Power Generation,” *Journal of Propulsion and Power*, vol. 21, May 2005, pp. 424–432.
- 116 Li, C.-H., Tan, H.-J., and Wang, D.-P., “Influence of Secondary Flow Injection Angle on a Fluidic Shock Control Technique,” *Journal of Propulsion and Power*, vol. 31, Mar. 2015, pp. 674–684.
- 117 Roy, G. D., and L Wu, Y. C., “Study of Pressure Distribution Along Supersonic Magnetohydrodynamic Generator Channel,” *AIAA Journal*, vol. 13, Sep. 1975, pp. 1149–1153.
- 118 Vidana, O., Chaidez, M., Lovich, B., Aboud, J., Hernandez, M. J., Cabrera, L. A., and Love, N. D., “Component and System Modeling of a Direct Power Extraction System,” Reston, Virginia: American Institute of Aeronautics and Astronautics, 2016, pp. 1–13.
- 119 Hernandez, M. J., Cabrera, L. A., Vidana, O., Chaidez, M., and Love, N. D., “Design of a Supersonic Oxy-Methane Combustor for Direct Power Extraction,” Reston, Virginia: American Institute of Aeronautics and Astronautics, 2016, pp. 1–10.
- 120 Hernandez, M. J., Cabrera, L. A., Choudhuri, A. R., and Love, N. D., “Conceptual Study of Oxy-Methane Flows in a Constant-Velocity Faraday Magnetohydrodynamic Generator,” Reston, Virginia: American Institute of Aeronautics and Astronautics, 2016, pp. 1–9.
- 121 Huzel, D. K., and Huang, D. H., *Modern Engineering for Design of Liquid Propellant Rocket Engines*, tur: The American Institute of Aeronautics and Astronautics, 1992.

## **Vita**

Manuel Johannes Hernandez earned his Bachelor of Science and Master of Science in Mechanical Engineering from the University of Texas at El Paso (UTEP). In 2013 he joined the doctoral program in Mechanical Engineering. His research interests are in areas related to design of power generation technologies, hot gas path (HGP) components, and numerical modeling.

Dr. Hernandez was the recipient of numerous honors and awards. In 2013, he was the recipient of the U.S. Department of Education's GAANN Fellowship and the NASA MIRO Scholarship for his doctoral studies. In 2016 he was selected for the NASA Graduate Internship. In addition, Dr. Hernandez's research was selected for the American Institute of Aeronautics and Astronautics (AIAA) Best Paper Award. Dr. Hernandez presented his research at several international conference meetings.

While pursuing his degree, Dr. Hernandez worked as a research associate for the Department of Mechanical Engineering. He interned at the National Energy Technology Laboratory and NASA Glenn Research Center for his work on power systems. He also was selected to attend the Princeton Combustion Summer School Program at Princeton University in 2015 and 2016.

Dr. Hernandez's dissertation entitled, "Design and Experimental Investigation of an Oxy-Fuel Combustion System for Magnetohydrodynamic Power Extraction," was supervised by Dr. Norman Love. Dr. Hernandez is pursuing an R&D position in the power generation industry.

Permanent address: 5001 N. Mesa St. Apt 2408  
El Paso, TX 79912

This thesis/dissertation was typed by Manuel Johannes Hernandez.