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14. ABSTRACT
The DOE MHD Power Generation Program contained a broad range of scientific, engineering, and modeling activities including the study of plasma composition and structure, equilibrium and non-equilibrium ionization, plasma flow, arc formation and extinction, high temperature materials, and non-intrusive gas diagnostics. In this report, results from the DOE Program, and related international activities, were reviewed for their potential to complement research conducted under the AFOSR Theme "Plasma Dynamics for Aerospace Applications". Recommendations for the AFOSR Theme included: (1) Use of a two-temperature model for improved calculation of plasma properties and plasma modeling, (2) Operating conditions for potential improved stability and arc prevention in the boundary layer for plasma aerodynamic flow control, (3) Use of demonstrated non-intrusive diagnostics for plasma and boundary layer measurements, and (4) Testing of high-temperature materials for an MHD generator.

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Applying MHD Results

To A Scramjet Vehicle

Air Force Office of Scientific Research
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Nomenclature

B	Magnetic field
E_x	Hall field
E_y	Faraday field
J	Current density
K	Kelvins
M	Mach Number
Mw_e	Megawatt electrical
N	Number density
P	Pressure
S	Interaction parameter
T	Temperature
U	Velocity
V	Volts
W	Watt
β	Hall parameter
δ	Boundary layer thickness
λ	Wavelength
μ	Micro
σ	Conductivity

Subscripts

e	Electron
g	Gas
t	Total
w	Wall
x,y,z	Space coordinates

I. Introduction

The Department of Energy and its predecessor organizations, conducted a program of magnetohydrodynamic (MHD) power generation research, development, and demonstration (r,d&d) for over thirty years with a total investment of nearly $750,000,000 in r,d&d and facilities. For both closed-cycle (clean gas) and open-cycle (fossil-fueled) systems, scientific and engineering research was pursued until the mid-1970's. From that time until the early 1990's, the MHD Program was focused largely on open-cycle systems for base-load, stationary power generation facilities. Participants in the DOE Program included the Arnold Engineering Development Center, Argonne National Laboratory, AVCO, Babcock & Wilcox, General Electric, Massachusetts Institute of Technology, Mountain States Energy, Mississippi State University, Pacific National Laboratory, Stanford University, TRW, The University of Tennessee Space Institute, and Westinghouse Electric. International cooperative efforts were conducted on closed-cycle systems with researchers in Eindhoven, The Netherlands, and open-cycle systems with personnel at the High Temperature Institute, Moscow, Russia. DOE personnel also maintained contact with the MHD programs in Australia, France, Great Britain, India, Italy, Japan, and The Peoples Republic of China.

The DOE MHD Program contained a broad range of scientific, engineering, and modeling activities, including study of plasma composition and structure, equilibrium and non-equilibrium ionization, plasma flow, arc formation and extinction, high temperature materials, and non-intrusive gas diagnostics. Engineering research and development included electrode materials and fabrication, insulator development, generator design, current consolidation and control, magnet research, and seeding systems. Modeling efforts included overall systems analysis for efficiency calculations, generator operation, and stability analysis. Many results from these efforts have application to the research being pursued under the AFOSR Theme, Plasma Dynamics for Aerospace Applications and have the potential of reducing the cost of research, development, or demonstration by avoiding the reinvention of existing technology or reducing the time to systems development by building upon an existing database. Application of results from the DOE MHD Program to aerospace systems may be grouped into four general technical areas:

- Plasma Assisted Ignition and Combustion – Plasma composition and structure, ionization, plasma flow, electrode and insulator development, high temperature materials, and non-intrusive gas diagnostics.

- Plasma Flow Aerodynamics and Control – High temperature materials, plasma flow, electrode and insulator development, current control, gas seeding techniques, gas conductivity measurement techniques, and non-intrusive gas diagnostics

- Physics of MHD Plasma Flow – Plasma structure, ionization, stability, and non-intrusive gas diagnostics.

- MHD Power Generation – Many research elements, particularly materials for the long duration operation of MHD power generation in a scramjet (Ajax type) system.

Each topical area will be addressed separately in this report utilizing information from several sources. Results of DOE contractual research projects are contained in contractor's final technical reports and a wide variety of technical papers from university, industry, and academic sources that are available in the proceedings from the annual SEAM (MHD technical society) Conferences. International activities are covered more completely in proceedings of the International Liaison Group (ILG) conferences.

II. MHD Plasma Assisted Ignition and Combustion

Introduction and Background Projects

Efficient ignition, mixing, combustion and flame stabilization processes operating in a high-velocity, hydrocarbon-air system are of critical importance to the successful development of the supersonic combustion ramjet (scramjet). Even in the highly turbulent scramjet flow environment, the flame speed of most practical fuels is much slower than the combustor flow velocity. Residence time of the fuel-air mixture in a scramjet combustor is likely to be very short. Fuel injection from either a scramjet combustor wall or through a centerline injector strut will provide only a minimum volume for a wake-stabilized flame. (1)

Production of a non-thermal, non-equilibrium plasma by an electrical discharge has shown promise in improving the ignition and combustion process and efficiency for a scramjet engine. Several analytical and experimental projects have been conducted using a weakly ionized gas to study the magnetohydrodynamic (MHD) effects of plasma-assisted combustion (PAC). These projects have modeled and verified the effects of an arc-generated or radio frequency (RF) generated plasma on ignition and combustion of hydrogen/air and hydrocarbon/air mixtures.

A model for an arc generated plasma system (4) is assumed to begin with a streamer discharge between electrodes, forming a weakly ionized, highly non-uniform plasma. The streamer is assumed to exist in a region of cold, weakly ionized gas with excited internal vibrational and electronic states. Next, the streamer is assumed to transition to a fully developed, hot arc. The fully developed arc is modeled using equations for the conservation of mass, momentum and energy in a plasma containing neutral particles, molecules, positive ions, and electrons. Equations for transport of electron energy, vibrational energy, electrical conduction, and chemical kinetics complete the arc-generated plasma model. MHD effects were considered in the electromotive force generated by assuming magnetic field strengths of one and two Tesla together with a total arc current of 10A, initial arc diameter of 2 mm, and arc temperature of 6000 K. (2)

Several experiments involving PAC have been conducted with propane and methane in flowing combustible mixtures to investigate arc discharge or RF discharge plasma assisted ignition and combustion and validate the assumptions used to model discharge and plasma properties. (3,5,6,8) The experiments typically utilized an RF or high frequency (HF) discharge to initiate and sustain ionization in the flow, a direct current electric field to produce an arc current, and a magnetic field to produce the MHD effect. Tests covered the following nominal range of conditions:

- $M = 0.4 - 2.5$
- $P = 8 - 20$ kPa
- $T_t = 300 - 100$ K
- $B = 1.5$ Tesla

Data were obtained using various techniques, including optical pyrometry and photography to obtain evidence of PAC effects. Measurements showed a significant increase in combustion efficiency with the PAC system at lean fuel-air ratios but not at a fuel-air stoichiometry greater than one. Several measurements were made to determine the electrical power input to the arc and plasma. While no attempt was made to establish a minimum power requirement for PAC, a reasonable power budget must be maintained for practical application of PAC.

Measurements of the plasma and arc showed a general agreement with model predictions; however, improvements in both modeling and measurements were felt to be necessary in order to improve the agreement between theory and experiment. [9] Several areas for potential improvement have been identified as a result of these studies, including modeling of the arc formation and structure, measurement of the arc temperature, measurement of the electron concentration, and a need to apply non-interference absorption spectroscopy to the system.

Application of Results from MHD Power Generation Research

Arc formation in MHD power generation is regarded as a serious problem potentially detrimental to both the integrity and lifetime of the generator. Consequently, a significant analytical and experimental effort has been pursued in the DOE MHD Program to understand the plasma conditions and channel design that could lead to an arc formation. Modeling and evaluation of the properties of an arc after formation also were studied. In the following section, analytical and experimental MHD studies applicable to both plasma and arc will be reviewed. MHD results will be presented in a sequence of applications for pre-ionization, arc formation, plasma formation, and arc/plasma diagnostics. The application of these data to PAC research also will be discussed and project recommendations developed.

Initial RF or Pre-ionization

A critical prerequisite in the ability of any gas phase element to become an electrical conductor is that it be partially ionized. [10] Some of the atoms or molecules in the gas must be stripped of one or more of their electrons. This ionization may occur through processes such as electron impact, positive ion impact, absorption of a quantity of radiant energy, or the gas becoming hot enough to produce thermal ionization by collision with neutral atoms. [11] Even at hypersonic velocities, the static temperature of the gas at the entrance to a scramjet combustor is not high enough to produce a thermal ionization level sufficient for conductivity to support an arc for PAC; therefore, the use of an RF discharge has been investigated [5,6,12,13] as a pre-ionizer to initiate and maintain the gas conductivity necessary to support a plasma arc discharge. An RF discharge capable of producing an electron number density of $3x10^{11}cm^{-3}$ is considered to be necessary to ionization. Experiments have shown that an RF discharge will produce an electron temperature of $10^4 - 10^5$ K and a gas temperature of nominally 1000 K. A low gas temperature increase thus shows that energy from the RF discharge goes into electron excitation and molecular dissociation rather than a translational mode, resulting in an electrically conductive plasma.

Development and Formation of an Electrical Arc

An electrical arc may be defined as a self-sustaining discharge between electrodes that has a voltage drop at both the anode and cathode. [11] A general discussion of the theoretical and analytical aspects of the electrical arc is beyond the scope of this report and may be found in reference 11.

In the DOE MHD power generation program, it was required to maintain an efficient and long-duration generator wall design. [14] This design requirement necessitated a good understanding of the mechanisms of current transport and the capability to predict conditions under which electrical arcing would occur. These studies of arc prevention in an MHD generator will provide guidance for determining the requirements for an arc formation to be used in PAC and complement the arc modeling efforts described in references 2 and 4.

The arc process begins in a generator when the diffuse (uniform) current density in the core of the gas is transported through a velocity and temperature boundary layer, and, due to a decrease in electrical conductivity, it constricts to form an arc. [15] On a cold electrode wall the changes proceed from the diffuse mode to a micro-arc mode (about 1A/arc) to a big-arc mode (about 100A/arc), with an increase in current density. [16] The critical current density for a transition from diffuse to micro-arc was determined to increase directly with electrode temperature and wall temperature. While the bulk-plasma temperature affects the critical micro-arc current for the transition to the big-arc mode, the wall temperature has little effect. Critical current density here is defined as the minimum current between cathode and anode that must be established in order for an arc to occur. Also, the establishment of a current density (and applied voltage) must account for both the cathode and anode voltage drops.

Data from references 15 and 16, including efforts from AVCO, MIT, Stanford and TRW, indicate that increasing the current density in the core of the gas and decreasing the wall temperature both contribute to a destabilization of uniform current flow and a transition to an arcing mode. Arcing also will decrease the boundary layer voltage drop, since a hot, constricted transport process replaces the diffuse current transport across a relatively cold boundary layer.

Experimental data on arcing characteristics were obtained in references 16 and 17. Variables in these studies included bulk plasma temperature, electrode temperatures, and boundary layer thickness. In reference 16, type 304 stainless steel electrodes were tested in a potassium seeded, combustion gas plasma with bulk plasma temperatures of 2400, 2700 and 2800 K; cathode wall temperatures of 650, 800 and 1200 K, and anode wall temperatures of 650 and 750 K. Data from experiments of cathode and anode voltage drop versus time-averaged current density show the transition points between diffuse current, micro-arcs, and big-arcs. These data show the critical current density from micro-arc mode to big arc mode increases with bulk plasma temperature, while the critical voltage drop decreases. The lowest critical current density measured at a wall temperature of 650 K and bulk plasma temperature of 2600 K was 2.5 A/m^2 and 3 A/m^2 at a wall temperature of 1200 K and bulk plasma temperature of 2400 K.

In reference 17, experimental data on critical current density for transition from diffuse to micro-arc to big-arc modes for copper electrodes were obtained as functions of electrode temperature and boundary layer thickness with and without the presence of a magnetic field. Wall temperatures varied from 1000 to 2300 K and boundary layer thickness from 1 to 10 mm. Gas temperature in these experiments was nominally 2500 K for all experiments. Critical current density for the transition to big-arcs was found to increase with wall temperature and decrease with boundary layer thickness and Hall parameter. A general expression was derived for the critical current density as a function of these variables. In these experiments the most significant variable controlling the transition to big arcs was the wall temperature.

Modeling of the Arc Structure and Temperature

Modeling studies of the structure of an arc discharge are reported in references 18 and 19, while measurements of arc current are reported in reference 20 and related to gas core properties and wall temperature. It is predicted that current concentrations on an electrode will grow to discharge structures transverse to the core gas flow in microseconds. The electron temperature within the arc discharge is estimated to be in the range of 4000 – 6000 K, and outside the electron number density is estimated to be $10^{19}cm^{-3}$ and electron temperature about 2500 K. The discharges are predicted to grow and saturate after 10 microseconds.

In reference 20, data from experiments at several facilities including Avco, MIT and Stanford are used to predict arc characteristics. Wall temperatures range from 300 to 1800 K and boundary layer thickness from 1.2 to 4.8 cm. At a nominal gas core current density of $1A/cm^2$ and electrode wall temperature of 1700 K, the arc current is estimated to be 1A and voltage about 100 v.

Modeling of the Plasma Formed by the Arc

It is assumed in this system that air entering the scramjet inlet has experience some degree of pre-ionization or seeding to make it electrically conductive. The air or air/fuel mixture then passes through an arc, resulting in ionization and dissociation. A plasma now exists that contains heavy particles at the average gas temperature, T_g, and electrons at a higher temperature, T_e, nominally 2500 K. It also is assumed that the ions and electrons are in equilibrium at the electron temperature, T_e, [21] and the electron number density is on the order of $10^{19}\ cm^{-3}$. These conditions are generally consistent with the concept of a two-temperature plasma [22] with non-equilibrium ionization that has been used widely to calculate plasma properties over a range of conditions encountered in a non-equilibrium MHD generator [23] of the Faraday type.

Modeling and experimental studies for PAC are reported in references 2 and 4 on the plasma arc discharge and the plasma evolution and combustion reaction downstream of the discharge. Results of the two-temperature model for a plasma used in an MHD non-equilibrium generator and related studies may complement this PAC model.

Two of the questions pertinent to any model of the PAC based on non-equilibrium ionization are: (1) is the plasma evolution rapid enough to maintain a high level of electron number density and (2) does the energy transfer rate between the electron gas and vibrational modes of the diatomic species support a level of active radicals to drive the combustion process. In a scramjet combustion process, both of these questions must be considered in light of the short residence time of species within the combustor. A model for the plasma evolution in a linear, non-equilibrium MHD generator is presented in reference 23. The electron number density is evaluated using the Saha equation at the electron temperature, T_e, to characterize the electron gas. This model predicts an exponential rise in electron number density after a short induction period and a distance of a few centimeters) at an electron temperature of 2600 K. Reference 24 contains an analysis of the energy transfer rate between an electron gas and vibrational modes of diatomic gases. The electron vibrational energy transfer is characterized by δ_v, the electron energy vibrational loss factor, that is strongly dependent upon the electron velocity distribution function. A model is developed for the energy transfer rate from the translational motion of the electron to a diatomic gas, and it is shown that the vibrational energy transfer is the most active energy transfer mode at typical MHD conditions. Results of the analysis support the need for a high value of T_e due to the exponential increase in δ_v between 2000 and 4000 K for T_e.

Measurement Techniques

Reports from several analytical and experimental studies have cited the need for the development and application of measurement techniques to improve modeling assumptions and provide a better understanding of PAC. [3,4] Application of visible emission spectroscopy is reported in reference 6 to detect chemical species in the RF discharge region and in the flame downstream of an RF plasma.

Diagnostics developed for data measurements in MHD studies may find a good application in PAC studies. References 25 and 26 provide typical examples of MHD diagnostics. Reference 24 describes measurements of effective electrical conductivity, electron number density, and electron temperature from the analysis of probe signals and spectroscopic data. Reference 26 presents the results of non-coincident sampling on the measurements of atomic number density and temperature by multiwavelength emission-absorption.

In reference 25, measurements were made in an argon-potassium plasma under MHD conditions at a range of current densities (1 – 12 A/cm^2), magnetic field strengths (0 – 3.55 Tesla) and pressures (2.1 – 8.2 bar). Gas core temperature in all experiments was nominally 1800 K. The effective electrical conductivity was calculated from probe data and the electron temperature was measured in one of the lines of the potassium resonance doublet (766.5 nm). Relative variations in electron number density were calculated from spectroscopic data. Electron temperatures were measured in the range of 2500 – 3500 K and effective conductivity in the range of 0.2 – 1.1 A/v-cm. Data were compared to the theory [27] and were found to agree within anticipated experimental accuracy.

The work reported in reference 26 is a totally non-intrusive, optical approach and emphasizes the accuracy of the measurement techniques in spite of fluctuations in temperature and optical depth for the subject. The technique described is a generalized method of the classical line reversal technique of temperature measurement but is adapted for a harsh, high-temperature environment with fluctuations. This potassium emission-absorption system (PEAS) uses a multiwavelength spectroscopic approach for direct measurement of average temperature and seed atom density. Both the electron number density and electron conductivity are calculated by assuming ionization equilibrium and an electron collision frequency model. [28] The potassium resonance line is used in these measurements.

Both of these demonstrated techniques may find application in PAC research by providing data from a turbulent flow environment of a scramjet combustor that will improve modeling efforts for PAC technology.

Conclusions and Program Recommendations

In the previous discussion it has been shown that a good synergy exists between PAC studies and MHD power generation efforts in modeling and experimental arc and plasma studies. Experimental data from arc and plasma measurements required for PAC modeling and analysis may be obtained by the use of established MHD project non-intrusive techniques.

The conditions produced by a pre-ioinzer (n_e=3x10^{11} cm^{-3}, T_e=10^4 – 10^5 K and T_g=1000 K)[13] are good starting input conditions for an arc discharge model and are generally consistent with those used in the PAC project models.[2,6,12] However, the arc current of 10 A/arc used in the PAC project model[2] should be re-examined in light of the data in reference 16 showing the micro-arc current to be 1 A/arc and big-arc current to be 100 A/arc.

MHD data on critical current density required to initiate an arc will be helpful in the area of managing the power budget for PAC application in a scramjet. It was demonstrated in several MHD experiments[15,16,17] that a low electrode wall temperature and thin boundary layer both result in a lower critical current density requirement for initiation of an arc discharge; however, a low electrode wall temperature will result in a higher voltage drop in the system at both the anode and cathode for the establishment of an arc discharge. Cold wall operation for PAC application will require the use of metal electrodes rather than a ceramic or cermet. MHD experience has shown that platinum caps on metal electrodes, particularly in areas of current concentration, will increase the lifetime of the metal electrodes significantly. An experimental effort is recommended to study the trade off between critical current density, wall temperature, and voltage drop in PAC application. Data from such experiments will assist in the establishment of minimum power requirements for PAC application at representative scramjet inlet, exit, and combustor entrance conditions.

MHD experience strongly supports the use of a two-temperature model as an approach to plasma modeling.[22,23] It has been verified in the successful modeling of the MHD non-equilibrium generator. Plasma modeling efforts in PAC application should examine the model for the induction period (reference 22) in any modeling of the plasma involving T_g, T_w, T_e, and arc current in studies to minimize the power budget for PAC. Consideration of this induction period is particularly important due to the exponential increase in electron vibrational energy transfer between T_e of 2000 and 4000 K, as discussed in this reference. Models may require modification to incorporate an induction period in the chemical kinetic model for plasma produced by an arc discharge in PAC at anticipated scramjet conditions.

Diagnostic techniques developed and utilized in previous MHD research [24 - 28] may find application in PAC studies to provide data useful in modeling and understanding PAC. Data obtained by these techniques include effective electrical conductivity, electron number density, plasma temperature, and atom number density under conditions similar to the turbulent environment anticipated in a scramjet combustor.

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III. Plasma Aerodynamic Flow Control

Introduction and Background Projects

Analytical and experimental studies of both electrohydrodynamic (EHD) and magnetohydrodynamic (MHD) application to aerodynamic flow control have been pursued with promising results. Potential application of these technologies for a hypersonic vehicle includes drag minimization,[6] control of the transition[6] and separation points[5,7] in a boundary layer, effects on shockwave/boundary layer interaction,[6] flow around a blunt body,[1] and inlet flow control.[4] EHD and MHD may find application in different flow regimes depending on whether or not a magnetic field is present. Boundary layer control is an MHD attractive application due to the presence of a low velocity, low gas volume region.[6] EHD has been investigated over a Mach number range of 0.2 – 2.0 without an applied B-field.[8] MHD has been tested for effectiveness of boundary layer control under nominal conditions of Mach 4 and a B-field of 0.4 Tesla.[2] Modeling studies have suggested that MHD boundary layer flow control may be effective under conditions with an electrical conductivity of 0.3 – 3.0 mho/m and a B-field of 1.0 – 1.5 Tesla, with gas flow over a flush, single pair of electrodes.[2]

Although the effect of MHD boundary layer flow control has been modeled and demonstrated, investigators have identified the need for several improvements. Modeling and study of the processes involved in MHD boundary layer flow control may be improved by examining the results of flows over multiple electrodes and direct measurements of pressure and/or velocity within the boundary layer.[2] Additional benefits to boundary layer flow control may be obtained from studying effects of both electrode design and operating temperature. Operating conditions also must be established to prevent arcing within the boundary layer in order to achieve effective MHD boundary layer flow control.[3]

Application of Results from MHD Power Generation Research

Extensive theoretical modeling and experimental data in the technical area of boundary layer plasma flow over electrodes are available from existing MHD research and may be applied to plasma assisted aerodynamic flow control studies. Conditions investigated in MHD power generation were for electrodes within flows having a nominal conductivity of 1.0 mho/m and magnetic field of 1.0 Tesla, which are within the range suitable for MHD flow control, as identified in the previously-mentioned modeling study. These data to be evaluated from MHD power generation research include:

- Modeling of the MHD boundary layer over multiple electrodes,
- Application of non-intrusive measurements of gas temperature, velocity, electron density, and conductivity in an MHD boundary layer,
- Establishing conditions under which electrical breakdown between electrodes may occur within a boundary layer.

Formulation of MHD Boundary Layer Problem

In any application of MHD technology, including power generation and aerodynamic flow control, where plasma passes between electrodes, the process of either adding energy or removing energy from the flow must involve a boundary layer. Many modeling and experimental projects have been conducted in MHD power generation programs to study the role of a boundary layer in MHD. These results are applicable to plasma assisted aerodynamic flow control, as well as MHD power generation. Understanding the physical characteristics of the gasdynamic boundary layer and their modification by electromagnetic effects is important in any MHD application. Both the velocity and temperature profiles in a boundary layer will be modified from their classical aerodynamic form via electromagnetic body force and turbulent damping processes. [(17)] A quantitative measurement of the turbulent boundary layer structure is necessary to accurately predict the wall friction, heat transfer and electrode performance for efficient transfer of energy in the electrically conducting fluid for any plasma assisted aerodynamic flow control process application. [(11)]

On the electrode wall, MHD effects will modify the energy equation for boundary layer enthalpy or temperature profiles as a result of Joule heating. As a result of Joule heating, the electrode wall temperature may exceed the core flow temperature under certain situations. On a sidewall or insulator wall, MHD effects are accounted for through modification of the momentum equation. This modification primarily affects the boundary layer velocity profile that will be modified from the conventional $1/7^{th}$ power law for turbulent shear stress. [(10)]

Modeling of the MHD Boundary Layer

The aerodynamic modeling effort for the boundary layer in an MHD flow has focused on two primary objectives: (1) development of the equations for describing the boundary layer in plasma flow and methods of their solution; and (2) development of the theory for inter-electrode electrical breakdown in the plasma boundary layer flow and approaches to prevention of this breakdown.

Three references, 9, 14 and 15, highlight the development of boundary layer equations for MHD plasma flow in simplified models that will allow a reasonably accurate, rapid, and inexpensive boundary layer analysis in repetitive calculations. Emphasis in the analysis is on boundary layer growth, aerodynamic and chemical property profiles, and prediction of flow separation point. Each model begins with the assumption that the turbulent boundary layer in an MHD flow closely resembles that encountered in classical aerodynamic flow. On an electrode wall, the flow may be subjected to a retarding magnetic body force similar to an adverse pressure gradient in classical flow.

Two different solution techniques are illustrated in references 9 and 15. The former uses a modified Patankar-Spalding approach that includes MHD effects in the momentum and energy equations, while the latter uses an adaptation of the Karman momentum integral method for analysis. The Karman momentum integral method uses a classical approach of assuming that free stream or core flow values of velocity, density, and pressure are boundary conditions for the calculations. The boundary layer is treated as the flow over a flat plate, with velocity gradients imposed by both the static pressure gradient and the MHD forces. If the Hall parameter in the flow is high, current will concentrate as it approaches the electrode, producing a non-equilibrium body force acting through the boundary layer. Another deviation from classical theory is a greatly increased roughness and high skin friction coefficient due to segmentation of the electrode wall.

Electrical Breakdown and Arcing in the Boundary Layer

Due to the serious nature of electrical breakdown and arcing between electrodes in an MHD application, a significant amount of study has been devoted to this subject. References 20 to 24 discuss representative results of these studies.

In references 20 and 21, a model is developed to predict inter-electrode electrical breakdown and arc formation. A solution technique is developed for simultaneous solution of unsteady boundary layer equations for the fluid state and Maxwell equations for the electrical state. The model assumes the presence of a spatially uniform magnetic field and turbulent, compressible boundary layer with Lorentz force and Joule heating present. Breakdown is predicted in an atmospheric pressure MHD flow when the Hall voltage between adjacent electrode segments exceeds a critical value in the range of 30 – 100 v. It also is predicted that the gas temperature deep in the boundary layer may exceed the core flow due to Joule heating. This may make this region more conductive than the core flow and may lead to axial current flow between electrodes through this path. For a core flow temperature of 2500 K, a wall temperature of 1800 K, and boundary layer thickness of 5 mm, breakdown is predicted at a Hall voltage of about 40 v, and a near wall gas ($y/\delta = 0.1$) temperature of 3200 K is predicted. Further development and elaboration of this model [21] is presented to show the different effects predicted for an anode and a cathode wall. The Lorentz force acting on an arc is shown to drive the arc into an anode wall (leading to high heating rates and possible damage) and drive an arc off a cathode wall.

Results of several studies involving the electrical breakdown in an electrode boundary layer are presented in references 22, 23 and 24. These studies focus on the thermal (Joule heating) and electrostatic (field effect) causes of breakdown in the electrode boundary layer and include both theory and experimental data. Electrical breakdown in a boundary layer represents the transformation of current from the distributed flow across a surface to a concentrated arc mode on an electrode. Joule heating occurs in the boundary layer, particularly at the cathode, due to electron-neutral and ion-neutral collisions. Thermal breakdown thus will depend on both the thickness of the thermal boundary layer and the temperature profile within the boundary layer.[22]

When a potential is applied between a cathode and anode, the voltage gradient will be large in the boundary layer. The electric field at the electrode surface will depend directly on the cathode voltage drop, and, as the potential between electrodes increases, both the cathode voltage drop and electric field gradient will increase. A high field gradient will be responsible for an electrostatic breakdown in the boundary layer. The critical electric field for air is approximately 30×10^3 v/cm; however, this must be determined for each specific working fluid, electrode surface, and electric field property combination. Cooled graphite and steel electrodes were tested in a plasma stream of 2350 to 2950 K. No breakdown was observed at an electrode wall temperature of 1500 K but breakdown occurred at a wall temperature of 1700 K. [23] Electrostatic breakdown has been determined to be the dominant mode of breakdown in the boundary layer of an MHD plasma flow but thermal breakdown may be experienced in a boundary layer with thickness greater than 0.10 mm. [22]

An extensive collection and correlation of experimental data on arcing in the boundary layer of MHD flow is contained in references 25 and 26. Graphs are presented showing critical core (Faraday) current density for boundary layer arc formation as a function of electrode surface temperature and boundary layer thickness. Experimental data on arc current are plotted versus boundary layer thickness, core flow velocity, and Hall parameter. Critical core current density is shown to decrease with increasing boundary layer thickness. Arc current is shown to increase with boundary layer thickness but decrease with core flow velocity. An arc model is proposed that shows a good correlation with experimental data for an effective wall roughness height of 1 mm. There is a very strong indication from this collection of data that boundary layer thickness has a significant effect on arc current, and it is virtually certain that arc current will increase with increasing boundary layer thickness. [25] To maximize core current density while preventing arcs, a high electrode wall temperature and thin boundary layer are recommended. If an arc does form, however, a lower arc current (with less potential for damage) may be expected with a thin boundary layer flow and high core flow velocity. Experiments show that, at a Faraday current density of 1 A/cm^2, arc current is approximately 1 A at a boundary layer thickness of 1 mm but 6 A at 10 mm. [26]

Boundary Layer Property Experimental Measurements

As MHD modeling efforts become more sophisticated, it is increasingly important to provide experimental measurements for validation of code details and refinement. A knowledge of temperature, velocity, and seed atom profiles in the thermal boundary layer of an MHD flow is vitally important to the development of accurate heat transfer, skin friction, and conductivity models. Both body forces and Joule heating will alter the boundary layer structure, as compared to conventional aerodynamic flow. Several good examples of research in this area are contained in references 16 to 19 and 27 to 29. These emphasize the development and demonstration of non-intrusive data acquisition techniques.

Many of the measurement techniques used in MHD boundary layer flow studies have their origin in those used for conventional aerodynamic and combustion studies. Research in measurement of velocity, temperature, and electron number density profiles and electrode voltage drop within the boundary layer are presented in references 16 to 19. These measurements were made without the presence of a magnetic field. A laser Doppler velocimeter (LDV) system was used to measure the profiles of average flow velocity and turbulence intensity in the boundary layer. The system was capable of measuring velocity up to 2000 m/s with a special resolution of approximately 0.1 mm. An argon ion laser was used as the light source and 0.4 – 1.0 μm diameter zirconium powder was used as the light scattering target in these experiments.[17] Spectroscopic diagnostics were used in the temperature measurement system (line reversal) and electron number density measurements (absolute intensity of energy states in the potassium atom). Electron number density diagnostic measurements relied on the Saha equation.[19]

A boundary layer model was constructed using continuity, momentum, energy and electron-ion continuity expressions. Core flow temperature in the experiments was approximately 2200 K and wall temperature was estimated to be 2000 K. A wall roughness (sand grain roughness) of 2 mm was used to fit the model to the experimental results. Data show that the electron temperature (T_e) was close to the T^*_e (equilibrium) profile while n_e (electron number density) varied from n^*_e in the boundary layer.[18] Effects of Joule heating on the boundary layer temperature profile were predicted well by the model. Calculation of the Stanton number for the electrode wall shows an increase of about 15% with current present as compared to conditions with no current present.[16]

A technique is described in references 29 and 30 in which available potassium D-line spectra are used to determine a temperature profile and bulk atomic density data in a boundary layer. The spectra were obtained in several tests at the two major DOE MHD test facilities located in Tullahoma, TN and Butte, MT. Data were recorded by a potassium emission-absorption system that was developed as a non-intrusive measurement diagnostic for temperature and average number density of neutral seed atoms. This system is suitable for either a clean gas or particle-laden flow and is insensitive to misalignment and/or window fouling.

The potassium D-line spectra in an MHD flow are deeply self-reversed due to relatively cool boundary layer flow surrounding a hot core flow. Actual line shape is a complicated path integral of temperature and potassium number density with influences of pressure and flow composition in collision broadening of the line. Boundary layer profile data are obtained by solving the inverse problem by fitting the spectral line shape to an eight-parameter model involving wall and core flow temperatures, boundary layer thickness, and seed properties. In applying this technique over the range of T_{wall} = 1750 – 1925 K, T_{core}= 2450 – 2675 K and δ = 1.4 – 3.8 cm, recovery of a temperature profile and bulk atomic number density may be determined in high temperature turbulent boundary layer flows. This technique for obtaining the spectra is robust and requires only limited optical access.

Another technique for determining the temperature profile and kinetics of boundary layer reactions by measurement of hydroxyl concentration is described in reference 28. The concentration of the hydroxyl molecule is a significant indication of chemical reactions occurring in a boundary layer of a flow containing products of hydrocarbon combustion. Data were obtained using a resonance laser induced fluorescence technique. Several measurements of hydroxyl concentrations were made in the boundary layer from 0.25 – 3.25 mm above a 600 K electrode wall. Data have shown the hydroxyl concentration to be between the frozen and equilibrium flow values in this region and were used to estimate a temperature profile.

A laboratory demonstration for the measurement of electron density and conductivity by a non-intrusive, far infrared Faraday rotation technique is described in reference 27. This was applied to the combustion products of a hydrocarbon fuel. Electron number density was measured from $2x10^{19}$ to $9x10^{19}$ cm^{-3} with good agreement to equilibrium (Saha) calculations based on emission-absorption flame temperature and neutral atom number density. Electron collision frequency data measured by far infrared transmission were used to calculate electron conductivity of 4 to 12 mho/m. This technique is anticipated to provide more sophisticated spatial resolution measurements than the conventional line reversal; however, it must rely on optical windows that are far infrared transparent.

Conclusions and Program Recommendations

It has been shown in references 2, 3, 5 and 8 that MHD effects can alter the separation point, skin friction, and heat transfer on a hypersonic scramjet vehicle's surfaces significantly. This can be of great significance to the vehicle's overall performance but must be balanced against the power budget required to achieve this improvement. Research results related to boundary layer modeling and measurements from MHD power generation research are applicable to the plasma assisted aerodynamic flow control research efforts.

Modeling studies[9,14,15] in MHD power generation have shown that boundary layer analysis may begin with a classical aerodynamic formulation with modifications due to the effects of Joule heating and the Lorentz force. Models should include the effects of roughness of 1 – 2 mm (sand particle diameter equivalent) in skin friction calculations[25,26] to account for the effects of multiple electrodes.

Results from MHD projects can provide guidance for limitations of plasma aerodynamic flow control to minimize the probability of arcing in the boundary layer with the subsequent potential for damage. In the boundary layer, electrical breakdown between electrodes may be expected if the Hall voltage exceeds 40 volts. A high Faraday current density, with significant MHD effects, is achievable without arcing if a thin boundary layer is maintained. In this MHD application, boundary layer thickness is the primary variable, but electrode wall temperature is also important. It is recommended that the electrode wall temperature be maintained below 1700 K. While these conditions provide good guidance on operating limitations, experiments similar to those described in references 20, 22 and 24 should be conducted with the anticipated flow conditions and thermo-chemistry for plasma aerodynamic flow control applications.

Non-intrusive boundary layer measurement techniques[16 - 19, 27 - 29] have been developed and successfully applied in MHD power generation research. These have provided data on velocity, temperature, and electron number density profiles, with a boundary layer that significantly assists the validation and refinement of analytical efforts. The LDV and line-reversal techniques most frequently were used for non-intrusive data acquisition, but infrared Faraday rotation shows promise for improved spatial resolution. Application of any of these techniques is recommended in plasma aerodynamic flow control studies to acquire data for use in modeling and analyses.

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IV. Physics of MHD Plasma Flow

Introduction and Background

The background research efforts in this topic area include papers covering a broad range of efforts including studies of plasma effects on internal[3] and external[6] aerodynamics, and combustion[7] for a hypersonic vehicle; modeling of plasma flow either with or without the presence of a magnetic field;[1,2,5] and measurements of plasma properties by non-intrusive optical techniques.[3,4]

Experiments reported in reference 3 investigated plasma control of oblique shocks, induced separation, and mixing enhancement in a duct. A 2-dimensional model for gas temperature and power input was developed, assuming the gas is weakly ionized, in equilibrium and ideal. Plasma temperatures were measured by optical spectroscopy. A plasma glow and afterglow visualization technique is reported in reference 6 for the study of a plasma flow around a truncated cone-cylinder at Mach 2.5. Plasma effects on the flow aerodynamics around the model were observed for shock waves, boundary layer, and expansion waves.

Research reported in reference 7 concerned the measurement of high-speed ethylene-air combustion gas parameters under the combined effects of electrical discharge and chemical reactions. Passive molecular and atomic spectroscopy was used for plasma diagnostics. Plasma-assisted combustion gas temperature measurements were obtained to an accuracy of 200 – 400 K by fitting calculated spectra to experimental ones. Experiments reported in reference 4 utilized both microwave transmission and optical emissions diagnostics to measure plasma parameters and molecular gas temperature.

Significant modeling efforts have been pursued to define the plasma flow fields and their application in combustion assistance and aerodynamic flow control for hypersonic vehicles. These efforts have identified several challenges in both development and solution of equations including electromagnetic effects. First, the accurate prediction of plasma properties in any model that may apply to a range of conditions is difficult.[7] Modeling requires several assumptions and accurate measurement of plasma properties to validate any aerodynamic and/or combustion model[5] in the presence of both electric and magnetic fields. Second, the solution of three-dimensional equations describing the plasma flow in the presence of these fields is an extremely complex and time-consuming process.[1,2] Finally, the development and application of non-intrusive optical techniques for plasma flow measurements require a significant effort to produce accurate and reproducible data for model verification.[3,4]

Application of Results from MHD Power Generation Research

Determination of accurate plasma property values for use in modeling studies has been an important element of MHD power generation research. Experimental measurements have been used successfully to validate and refine theoretical predictions of plasma properties. Power generation research also has required the investigation of non-uniformity and stability issues associated with plasma properties for extended MHD generator operating times. Uniformity and stability will also be important issues associated with successful MHD applications in a hypersonic vehicle. The subject of this section will be, therefore, to review, summarize and apply analytical and experimental MHD power generation studies of plasma transport properties and characterization of a plasma flow through a magnetic field to hypersonic vehicle MHD applications. Both development of plasma flow models and approximations that simplify the solution process for the plasma flow equation will be addressed. Aspects of plasma flow instability, non-uniformity, and secondary flow are included, together with techniques for plasma measurements and diagnostics.

Transport Properties

Early in the MHD power generation program it was determined that no single, complete, and exact theory existed for modeling a partially ionized plasma of arbitrary composition that included both electron and heavy-particle transport properties in the presence of a magnetic field. A wide discrepancy of complexity was found to exist between exact theory calculations of plasma transport properties and the approximate formulas likely to be used in practical design and analysis calculations. Classical theory also was based on the assumption of small departures from thermodynamic equilibrium and thus was not well suited to describe a two-temperature plasma.

Reference 8 contains results of a study applying kinetic theory of partially ionized plasma to the calculation of transport properties for conditions representative of an MHD generator. Emphasis is placed on developing approximate formulas for both electron and heavy-particle properties. Results of the study include expressions for electrical and thermal conductivity, thermal diffusion, and viscosity in a two-temperature plasma. Expressions are simplified by applying the assumptions of small electron mass and small collision energy exchange in a collision-dominated plasma. Electron transport properties may be calculated accurately by Sonine polynomial expressions, and heavy-particle transport properties are calculated by classical methods. Mixture rules are developed for plasma components, and results of the approximate expressions are compared with classical theory.

Plasma Flow Non-uniformity and Instability

Non-uniformity or instability in the transport properties or flow of plasma may degrade the performance of any MHD application. Formulas relating conductivity (σ) and Hall parameter (β) to the severity and structure of plasma non-uniformity are required in order to perform reliable feasibility studies and design calculations for MHD applications. Expressions may be derived to predict degradation of MHD performance on the basis of a generalized isotropic turbulence assumption. Effective values of σ and β may be calculated for a plasma exhibiting arbitrarily large, random, three-dimensional inhomogenities in electron density, if the statistical characteristic of the non-uniformities can be estimated. [9]

Results of a study [10] were reported for the growth of a perturbation in a two-temperature MHD plasma that was initiated by a highly ionized spark, and a model was developed to describe the effect on a linear MHD generator. Growth of the non-uniformity created by the spark is shown to effect current distribution over a distance comparable to that between electrodes. Existence of a high-conductivity spot in a generator is shown to cause a localized concentration of Faraday current and a shorting of the local Hall field, resulting in formation of two eddy current cells with counter-rotating currents. The model predicts a Hall current density in the region of the spark to be 15 times larger than in the initial plasma after 0.33 μs. A spark and hot spot will cause a negative power output spike in an MHD generator, with current density entering a load reduced by 18% in the center region and 3% in the area away from the spot. After 0.33 μs the model predicts that the electron temperature in the hot spot has changed from 2550 to 9220 K and current density from 2.33 A/cm^2 to 34 A/cm^2. The Hall parameter was predicted to decrease from 7.59 to 0.59.

Three-dimensional effects on fluid and electrical properties have been modeled [(11)] for two cases of a rectangular cross-section MHD generator. The first case is for a diagonally conducting sidewall generator, and the second is for a generator with insulating sidewalls. Results of the models show that secondary flows may be initiated in an MHD generator, are driven by the non-circularity of the generator, and may be influenced by the Lorentz forces. Secondary flows are shown to have a significant impact on both viscous losses and heat transfer in a generator.

In the case of an insulating sidewall, the model's results are similar to those obtained from models that assume a very large wall surface roughness of 5 mm. A significant overshoot of the velocity profile in the boundary layer near the sidewall also is predicted that is attributed to a larger pressure gradient ($dp/dx - J_yB$) near the surface than in the core flow. The model was applied to the design and proposed operating conditions of a Faraday generator with insulating sidewalls sponsored by DOE for testing at AEDC. Results of the model are presented for predicted current density, electrical conductivity and overall power output of the generator. These results closely agree with predictions that neglect secondary flows but assume a significant average wall roughness.

The effects of non-uniformities on performance of a non-equilibrium generator are examined in reference 12. It is concluded that for any generator there exists a critical Hall parameter below which the plasma is uniform. It also is proposed that full ionization stabilizes the plasma, and, for a given magnetic field strength, the seed fraction should be chosen so that it is fully ionized at the desired current density and power output. A detailed experimental study of plasma stability in a regime of fully ionized seed is presented in reference 13. Seed fractions of 0.5×10^{-5}, 1.0×10^{-5} and 2.3×10^{-5} were studied and desired current density and conductivity achieved by controlling the seed fraction. Using this stabilizing method is shown to increase the power density of a non-equilibrium Faraday generator significantly. A stable plasma state was achieved by matching the characteristics of the external circuit to the plasma characteristics which is not difficult if a high value of UxB is maintained through the generator by a high value of the plasma velocity, U.

In reference 14, effects of thermal and velocity non-uniformity were investigated experimentally for an equilibrium MHD generator over a range of Hall parameters from 2 to 7. Strong variation of plasma properties in the direction normal to the magnetic field and flow confirm the prediction of strong degradation of Hall parameter in this type of generator.

Wave-like fluctuations (electrochemical waves) of electron temperature and density may be expected to propagate and grow in a two-temperature plasma. [(15)] A very high fluctuation observed at Hall parameter (β) above 2 and n_e greater than 2×10^{13} cm^{-3} correlates well with electrochemical wave theory. Low amplitude fluctuations at lower Hall parameters and electron density values are predicted by both electrochemical and magnetoacoustic wave theories. Either type of disturbance is capable of causing a large reduction in plasma conductivity and power output from a generator. Large effects are most likely to occur in a non-equilibrium generator. Electrical fluctuations were measured in a non-equilibrium generator and compared with theories for electrochemical and magnetoacoustic waves to confirm these predictions of performance degradation and operating limits.

An analytical study of current and voltage non-uniformities occurring in a linear, combustion driven MHD generator was reported in reference 16. These non-uniformities can be associated with current transport from the plasma to a wall element (electrode) or with current leakage along the generator wall. A model is proposed in this study to define the stability boundaries for development of electrical non-uniformities and methods of control are discussed.

A Z-transform has been used to analyze the electrical behavior of an infinite length (no end effects) Faraday generator with discrete electrodes. (17) Decreasing the electrode pitch to channel height ratio favors long wavelengths, as predicted by theory, with the instability having a wavelength close to twice the electrode pitch.

A modeling and experimental study was conducted to investigate ionization instability in a non-equilibrium generator, with emphasis on the influence of electrode separation upon the instability.(18) A linear perturbation analysis of the governing equations was conducted to predict dependence of the critical Hall parameter for growth of the instability on electrode spacing, current density, and magnetic field. Experiments were conducted in a generator with a nominal core plasma temperature of 2100 K, current density of 0.4 – 3.0 A/cm^2 and magnetic field of 1.65 – 4.05 Tesla. Once the instability occurs, the effective Hall parameter remains constant no longer but increases with increased B-field. Large-scale fluctuations of the electric field and electron number density also occurred. Effective scalar conductivity decreases far below the expected value. The critical Hall parameter (β_c) was related to generator geometry and wavelength (λ_w) of the instability. Results showed that λ_w decreased with increasing B-field, increasing current density, and decreasing electrode (anode-cathode) separation. Although β_c decreases as electrode separation increases, it reaches an asymptotic limit that depends on current density. Wavelength of an instability was found to increase with increasing electrode separation. For a given separation, however, wavelength decreased with increasing B-field or increasing current density. Effective core plasma conductivity did not show any experimentally significant dependence on electrode separation.

In an open-cycle MHD generator the flow of plasma through a magnetic field is influenced by the Hall effect, causing non-uniform Lorentz forces. The non-uniform Lorentz forces may cause secondary flows to develop in the generator, which are predicted to affect plasma momentum, heat transfer, and electrical behavior significantly. An experimental project (19, 20) was conducted to measure the effects of secondary flow in potassium-seeded hydrocarbon combustion plasma. The magnetic field strength was approximately 2.4 Tesla, and electrode and sidewall temperatures were approximately 1000 and 1900 K, respectively, during the experiment. Measurements of velocity and temperature were conducted at MHD interaction parameter, S, (ratio of transverse

Lorentz force to axial inertia of the flow) values of 0.0, 0.4, 0.85, 1.1, and 1.74. Velocity measurements of the X and Y components were made separately by laser-Doppler anemometry, and temperatures were measured by thermocouples. Secondary flows have been predicted to be of substantial magnitude, with transverse velocities greater than 10% of bulk velocity, depending on conditions. Measured profiles of the axial velocity and turbulence intensity were skewed strongly by secondary flows. At low values of S, the magnitude of secondary flow increased significantly with interaction, but at higher values of S, less sensitivity was observed. Peak secondary flow velocities were higher for S = 1.74 than for S = 0.85, but the differences were small considering S varied by nearly a factor of 2. It is theorized that viscous forces may cause the secondary flow to become less variable with interaction as this parameter increases. The effect of sidewall temperature variation on MHD secondary flow also was investigated. Since the non-uniform Lorentz force drives the secondary flow, it was anticipated that it would be a sensitive function of the difference between the sidewall and bulk plasma temperature. This effect was observed to occur for as little as a 100 K difference. Secondary flow increased the heat transfer to the electrode wall, causing as much as a 60% increase in the measured electrode wall temperature. The region near the electrode wall towards which secondary flow convected the hot core flow was nearly twice as conductive as the region adjacent to the opposing electrode wall.

Plasma Measurements and Diagnostics

Experimental measurement techniques used to determine properties of a flowing plasma have included spectroscopic line-reversal, measurement of spectral line absolute intensities, microwave diagnostics, voltage-current measurements, and probes. Fundamental properties measured included temperature, velocity, and electron density. Among the various plasma properties affecting MHD generator performance, the single most important one is the electrical conductivity (σ) of the plasma.

Examples of the techniques used to measure electron concentration in a potassium seeded, hydrocarbon combustion MHD plasma are presented in references 21 and 22. Both techniques are non-intrusive with reference 21 utilizing a sub-millimeter wavelength interferometer method, and reference 22 using the absolute intensity of visible emissions from higher (non-resonant) electronic states of potassium. Plasma temperature measurements in both sets of experiments were made by using line reversal of the resonant potassium (KI) lines. Theoretical values of electron concentrations were calculated by assuming thermal ionization of the potassium atoms in an equilibrium combustion gas composition. Plasma temperatures measured in reference 22 covered the range of 2400 – 3100 K, and experimental electron densities were measured to be from 1×10^{20} to $8\times10^{20}\,m^{-3}$. In experiments reported in reference 21, temperature measurements varied from 2548 – 2575 K, and electron densities were determined to be from 0.38×10^{20} to $0.74\times10^{20}\,m^{-3}$. The scatter between independent measurements in reference 21 was approximately 1% in temperature and 10% in electron density. It also is stated in reference 21 that the sub-millimeter laser interferometer technique offers a higher degree of accuracy than either an inductive (RF) probe or spectroscopic line reversal measurements for the determination of electrical conductivity.

The use of a combination of probe and spectroscopic techniques for the measurement of charged particle concentration in an MHD plasma was demonstrated in reference 23. As in previous examples, the plasma consisted of alkaline seeded products of hydrocarbon combustion. Local concentration of positive ions was determined through use of electrical probes, and beam-averaged electron concentration was determined using a sub-millimeter (0.337 mm) wavelength laser interferometer. Plasma temperature measured by line reversal was approximately 2050 K, and seed atom concentrations ranged from $3x10^{18}$ to $5x10^{19} m^{-3}$ in these experiments.

Design and application of electrical probes for direct property measurements in an MHD plasma are discussed in references 24, 25 and 26. Application of a probe may include direct measurement of electrical fields, ion and electron fluid velocity, ion current, and ion density. An experimental program to measure the ion density and level of electric charge non-uniformity in a supersonic MHD plasma using a Langmuir probe is described in reference 25. The calculated electron density was $7.7x10^{19} m^{-3}$ and agreed well with the experimental measurements. Another experiment to demonstrate the use of a three-coil, magnetic induction probe for measurement of electrical conductivity profile is described in reference 26. Results compared favorably with those obtained using a Langmuir probe.

Temperature measurements of a flowing MHD plasma using non-intrusive techniques are described in references 27, 28 and 29. A spectroscopic approach to MHD plasma temperature measurement is presented in reference 27. The study includes a model for correction to measurements required in a light-scattering, particle-laden medium. Laboratory demonstration of the capability of coherent anti-Stokes Raman spectroscopy (CARS) to provide both temperature and species concentration measurements with spatial and temporal resolution is reported in reference 28. CARS spectral shape depends on the characteristics of the probe volume. Thus temperature and species concentration may be determined by fitting the measured shape to computer-generated CARS spectra. Experimental fitting was performed using a nine-parameter Marquardt algorithm program. The Marquardt algorithm provides a numerical solution to a mathematical problem of minimizing a sum of squares, generally non-linear functions, that depend on a common set of parameters that arises especially in least squares curve fitting. In these experiments, temperature accuracy was estimated to be within 1% and species concentration within 2% using the spectral data. A high-speed, light polarization line-reversal method of temperature measurement in a plasma is presented in reference 29. This technique allows for the acquisition of several hundred temperature measurements on a time scale of 100 μs to 100 ms in an area where the conditions are rapidly changing, such as in a boundary layer arc.

Conclusions and Program Recommendations

Results from several MHD power generation research reports have shown ways to simplify and improve the plasma modeling efforts for hypersonic vehicle applications of MHD technology. Modeling simplifications can include calculating transport properties of a two-temperature plasma,[8] effects of instability or non-uniformity on plasma properties,[9,10] and determination of stable operating limits and operations for an MHD generator that will maximize performance.[11,12] Review of these approaches may provide guidance for methods to reduce the time and expense of modeling and analyses in evaluating MHD applications such as contained in references 1, 2, 4 and 5, particularly when applied to repetitive engineering design studies.

Operating conditions and geometric designs both have been shown to define boundaries for MHD generator instability, non-uniformity, and the onset of secondary flows.[16,17,18,19,20] The MHD interaction parameter, S, has been shown to be a good indicator for conditions leading to stability and performance of an MHD generator, a low value being generally recommended. A low value of S is achievable with a low value of B and high value of U in the generator,[13] conditions that are broadly consistent with scramjet operations and should avoid performance degradation in an MHD application. It is recommended that hardware oriented studies such as described in reference 3, include an examination of operating and geometric boundaries that may affect instability, non-uniformity and secondary flow in long-duration MHD applications.

Applications of both intrusive (probe)[24,25,26] and non-intrusive (optical and spectroscopic)[21,22,27,28,29] methods of measurement in MHD flows have been well documented and their limitations discussed. It is recommended that in any aerospace application of MHD technology that these diagnostic methods be reviewed, and possibly applied, to supplement those described in references 6 and 7. A combination of these existing, successfully demonstrated techniques therefore may be utilized to obtain accurate (and redundant) data to either develop or refine MHD plasma models or determine system performance.

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V. MHD Power Generation

Introduction and Background Projects

Projects in this topic area have included studies of on-board power generation utilizing either an equilibrium or a non-equilibrium MHD generator, MHD acceleration of combustion product gases, and inlet flow control. (1,2,4,5,7) In general, modeling studies have shown an equilibrium generator located aft of the combustor in a hypersonic vehicle to be the preferable choice for a flight Mach number equal to or greater than 10. If the Mach number is equal to or less than 9, a non-equilibrium generator located ahead of a combustor is preferable.(8) The processes of inlet flow control and MHD power generation were studied using a one-dimensional model of a system producing power from an equilibrium, potassium seeded, Faraday generator.(7) Systems modeled in references 1 and 6 included power production by a non-equilibrium ionization MHD generator. Both of these references stressed the importance of minimizing the energy requirements for the non-equilibrium ionization in the flow preceding the MHD generator. A modeling study also was conducted for the MHD acceleration of combustion product gases aft of a scramjet combustor. Experiments were conducted on a diagonally loaded peg wall design Faraday equilibrium MHD generator using K_2CO_3 seed. Two materials, zirconium oxide and lanthanum chromate, were utilized as electrode materials, and magnesia and alumina were utilized as insulator materials.(3) While these tests successfully generated power, they were of short duration and did not address options for electrode design, generator materials, long duration operation, or generator lifetime.

Application of Results from MHD Power Generation Research

It has been demonstrated clearly that an MHD process will generate electrical power, given the proper combination of plasma conductivity, and electric and magnetic field strength. The questions that need to be addressed for hypersonic vehicle on-board power generation include finding the proper combination of these parameters within the weight and volume limitations of the vehicle. Numerous results from classical MHD power generation research are applicable directly to the resolution of these questions for either the non-equilibrium or equilibrium MHD generator options. These data include:

- Modeling of generator operation and stability,
- Electrode, insulator and sidewall material selection,
- Generator mechanical and thermal design, and
- Long-duration operability and lifetime.

Analytical and experimental results from MHD generator research, development and demonstration will complement the previously cited background studies to assist in the development of either an equilibrium or non-equilibrium MHD generator for hypersonic vehicle application further. Data on generator mechanical design and electrode, insulator, and sidewall materials will be of assistance in developing a system capable of meeting mission weight, volume, durability, and lifetime requirements.

Electrode and Sidewall Lifetime

One of the most difficult technical issues associated with MHD generator lifetime is the development of electrodes, particularly anodes, that have adequate reliability and durability. Severe anode corrosion may occur as a result of electrochemical attack of anode surfaces by negatively changed oxygen ions that are driven to the anode surface by the electric field.[9] Electrical integrity of the MHD electrode requires a uniform current transfer to the electrode surface in the magnetic field direction and good current spread in the plasma flow direction. Thermal stability of the current transfer process through the gas boundary layer to the electrode surface (to avoid arcing) favors the use of high temperature electrodes with a surface temperature in excess of 1970 K.[10] Sidewall lifetime is also a problem in the MHD generator because the sidewall supports the highest electrical fields; the transverse Faraday field, E_y, plus the axial Hall field, E_x. Electrochemical corrosion of the sidewall elements may also occur, particularly in regions adjacent to the cathode wall.[11]

DOE Prototypical Generator

The goal of the DOE MHD Program was to develop a prototypical MHD generator capable of continuous operation for 2000 hours; therefore, the design of the prototypical generator pursued a traditional and conservative approach in both materials selection and fabrication techniques based on previous experience. Neither weight nor volume was a limiting factor in selection of either materials or construction methods for the generator design. An engineering development project was pursued to meet the DOE prototypical MHD generator's objectives. The project's results are reported in references 11, 12 and 13. Following testing of the prototypical generator for over 500 hours, a summary of final results evaluating the design selections and lessons learned was reported in reference 14.

The engineering development effort included evaluation of peg versus bar sidewall designs and electrode materials. Materials were chosen based on their availability, workability, and cost and included copper, tungsten, and molybdenum. Selection criteria also included erosion resistance for the sidewall elements. Designs using a water-cooled base with a tungsten or molybdenum cap (gas side) provided good thermal diffusivity and surface melting temperature. Metallic materials studied were also good candidates for substrates on ceramic pegs and cathodes. Substrates must act as a buffer between a high thermal expansion copper base and a low thermal expansion ceramic cap. Substrates also may provide a backup protection in the event of a cap failure. Ceramic caps with a metal base give great confidence for generator lifetime requirements. Ceramics have a high thermal conductivity, good thermal shock resistance, low electrical conductivity, and good corrosion resistance. Durable materials are required for a buffer between a ceramic cap and copper base. Tungsten-copper ($W_{.75}C_{.25}$) was selected and successfully brazed to a water-cooled, copper base.

Sidewall design choices were peg wall, which provides fine segmentation in E_x and E_y, and segmented bar wall with bars oriented to the equipotential lines. A segmented bar wall is a more reliable design if the equipotential lines are known, but peg wall provides reduced segmentation when voltage gradients are unknown a-priori in the generator. The best features of these two options were combined by using peg segmentation elements on a water-cooled bar. Ceramic caps also may be brazed to the metal element base, and a thermally conductive metal substrate also may be used. A metal cap may be advantageous since the metal-to-ceramic braze joint is exposed to lower, more uniform temperatures. Ceramic material is not exposed to arc impingement, and ceramic elements may be thin. Good results were obtained in sidewall tests using SiC pegs with a grooved copper base. Stainless steel and aluminum pegs also were used on the anode side of the sidewall, while tungsten-copper was used on the cathode side of the wall for edge protection. Tungsten, tungsten-copper, and molybdenum performed well on the leading edge of copper cathodes. Copper grooving, alloy foils and pastes were used successfully in reducing stress between a ceramic cap and metal braze.(11)

Anode design was based on the results of a 1000-hour test program described in reference 9. Successful anode design had a platinum cap (0.05 cm) and an upstream corner reinforced with a 0.25 cm square platinum block. This reinforcement was necessary because the Hall field (axial) produces current contraction along this edge. The remainder of the anode was a water-cooled copper block. Insulators between anodes were 0.19 cm boron nitride. Stainless steel capped electrodes also were tested, but they demonstrated a material loss rate two to three times that of the platinum capped electrodes. During these tests, the anode heat flux was approximately 250 to 140 W/cm^2 along the generator. Flow was supersonic throughout the generator, the peak magnetic field was 2.1 Tesla, and the generator was Faraday loaded. (9)

Gas-side materials performance and manufacturability of the anode and sidewall designs were evaluated in tests reported in reference 12. Anodes were designed with platinum cap and 0.95 cm tungsten between the cap and copper base. Sidewall tests compared straight and Z-bar shaped sidebars. Anode insulator gaps were 0.019 cm to eliminate aggressive attack of anodes leading edge arcs. AlN insulators were used at the anode-to-sidewall joint. Sidewalls utilized tungsten caps on tungsten-copper, molybdenum, or copper bases. Tungsten caps on a tungsten-copper base demonstrated better projected lifetime (over 2000 hours) than a tungsten cap on a molybdenum base. Addition of an oxide grain-stabilized phase such as zirconium (ZGS) into platinum produces a much finer grain structure, making platinum more resistant to arc track corrosion and grain boundary attack. High purity platinum is also more resistant to chemical and thermal attack.(12) Performance of the Z-bar shape sidewall elements was evaluated in a 40-hour confirmation test. Measurements showed reduced interbar voltages and circulating currents and reduced potential for arc breakdown at the anode-sidewall corner joint for the Z-bar as compared to straight bar sidewall design.(13)

The success of all previous materials and design selections was confirmed in the testing of the prototypical MHD generator in the DOE facility at Butte, Montana. Over 500 hours of testing were accumulated with approximately 300 hours at nominal (1.5 Mwe) power conditions. The Z-bar sidewall design operated successfully, giving trouble-free service throughout the test program. Sidebars consisted of tungsten cap/copper base, tungsten-copper cap/ copper base and tungsten-copper cap/tungsten-copper base elements. The tungsten-copper base worked well as a waterside material for sidebars. Cathodes designed with a copper base and tungsten cap performed successfully. Tungsten showed very good performance in resisting both arc and electrochemical corrosion. Aluminum nitride (AlN) insulator caps were used in corner regions as reinforcement against electrical breakdown between the cathode elements and sidewalls. Anode elements were water-cooled copper base with brazed platinum-on-tungsten caps and upstream corners reinforced by thick strips of platinum. Aluminum nitride corner tiles were used for electrical insulation in anode/sidewall corner joints. The anode wall design worked well in the testing. There were no fundamental design problems in the choices made for the generator. A more coarse tile segmentation could have been used, however, which would have simplified fabrication. Further development of ceramic material for electrode and sidewall elements also was recommended.(14)

Electrode Design Studies

The effects of coatings or ceramic caps on metal MHD electrodes was investigated theoretically and experimentally, with results reported in reference 15. Both the model and experiments show that the use of refractory material will potentially increase electrode life by distributing current more evenly on the electrode surface. The high surface temperature of an electrode designed to utilize a refractory cap reduces the thermal gradient in the gasdynamic boundary layer over the electrode and heat loss to the electrode wall.(15)

Effects of electrode size on MHD generator performance were investigated in experiments with the electrode width-to-pitch ratio set at 0.23 and 0.79. Since the typical width-to-pitch (electrode and insulator) ratio is approximately 0.50, this study examined two extremes representing narrow and wide electrodes. Electrode surface temperatures were maintained at 530 and 1600 K representing a cold wall and hot wall operation. Insulators between electrodes were uncooled in all cases, and boundary layer temperature was controlled at either 2200 or 750 K. Results showed that a coupling between the electrode temperature and boundary temperature occurred with large electrodes but not with small electrodes. A more diffuse current transfer to the electrode was observed in the case of large electrodes and hot boundary layer. The observation of a diffuse current transfer supports the desirability of hot electrode wall operation with large width-to-pitch electrodes.(16)

Hot Ceramic Electrode Studies

The design and materials choices made for the DOE MHD prototypical generator were based on extensive previous experience with these choices and ease of fabrication, but they may not be suitable for an aerospace application where both weight and volume are critical constraints on the design. Use of electrically conductive ceramic materials will allow hot electrode operation, resulting in lower heat losses and higher efficiency in an MHD generator than in the case of a cold wall operation. The potential for arcing is reduced greatly due to a reduction of cooler plasma layers along the electrode surface. Ceramic oxide electrodes also offer greater resistance than refractory metals to degradation in oxidizing conditions found at the anode.(17)

Use of hot wall electrodes requires knowledge of the thermal, mechanical, chemical, and electrical performance of materials at temperatures above 1970 K and under a variety of electrical loadings. An important requirement for a ceramic or semi-conducting electrode material is that its electrical conductivity closely matches that of the plasma at the electrode surface. Conductivity of the ceramic should be in the range of 0.1 – 1.0 mho/m at 1870 – 2070 K.[19] Analytical and experimental results from the study of ceramic oxide materials for hot wall MHD electrodes and brazing of ceramic caps to metal substrates are presented in references 18 – 26.

Results from investigations at MIT of ceramic electrodes operating at temperatures greater than 1970 K with heat transfer rates exceeding150 W/cm^2 in a seeded plasma of approximately 2495 K and conductivity of approximately 1.5 A/cm^2 are reported in references 19 and 20. Data are obtained for the conductivity of a system of compounds having the composition $(La_{0.75}Sr_{0.25}FeO_3)_{0.5}(SrZrO_3)_{0.5}$ and the composition $(La_{0.75}Sr_{0.25}FeO_3)_{0.25}(SrZrO_3)_{0.75}$. A high melting temperature in excess of 2570 K and a high conductivity make these compounds promising candidates for electrode use. Conductivity was not enhanced in these experiments by the substitution of Cr for Fe. Electrochemical corrosion was related to electronic conductivity, current density, electrode thickness, and phase stability.[18, 19]

Tests of hot pressed electrodes based on $LaCrO_3$ and sintered insulators of MgO and $MgAlO_2$ were conducted at the Westinghouse facility. Two general classes of materials may be considered for hot (T >1970 K) electrodes: (1) refractory oxides based on either ZrO_2 or HfO_2, or (2) somewhat less refractory, but electrically conducting, oxides of either perovskite or spinel structures. While more sophisticated electrode chemistries and structures may provide improved refractory properties, attention to microstructure and ceramic processing becomes more critical to insure adequate resistance to seed attack of the electrode.

The $La_{0.95}Mg_{0.05}CrO_3$, $La_{0.95}Mg_{0.05}CrO_3/ZrO_2$ composite and $LaCrO_3$-$LaAlO_3$ were most resistant and showed little erosion, reaction, or fracturing during testing. A reduction of porosity from 7% to 2% in the composites was achieved by hot pressing at higher temperature and pressure for a longer time than in the initial fabrications. Sintered MgO insulators showed less reaction with electrodes near the plasma, while $MgAlO_2$ was subject to less thermal stress and reaction with liquid potassium seed. It was concluded that: (1) the major source of electrode degradation was reaction with potassium seed and it was more pronounced at the cathode wall; (2) the presence of porosity, impurities, second phases and cracks in the material were more critical to seed attack than material composition differences; and (3) $LaCrO_3$ based electrodes were more resistant to attack than the Mg-Al-Fe oxide electrode compositions.[20]

In MHD power generation, electrodes are wanted that have the capability of operating at about 2000 K with an electrical resistivity of about 1 ohm/cm and good resistance to thermal shock, chemical attack, and erosion. Rare earth chromites doped with strontium, by virtue of their high refractory and good electrical properties, have been investigated for use as MHD electrode materials. Perovskite-type oxide solutions based on mixed oxides of rare earth and first row transition metals offer diverse electrical, magnetic, and catalytic properties.

Research on $LaCrO_3$ doped with alkaline earths has shown that Cr evaporates at high temperatures, leaving an excess of La_2O_3 that is both porous and hygroscopic. Yttria-based perovskites, however, are slightly less refractory but possess better corrosion resistance and mechanical properties than La composites. The conductivity of Yttria-doped chromites is lower than La but shows less variation of conductivity with oxygen partial pressure and thus is a good candidate material for MHD electrode application.(21)

Spinel Electrode Material Development at the U.S. National Institute of Standards and Technology (NIST) (formerly NBS) and MIT

Another approach to the development of hot MHD electrodes was pursued at NIST and MIT with the study of combinations involving Mg-chromate and Mg-aluminate spinels and magnetite (Fe_3O_4) and hercynite ($FeAl_2O_4$). The general formulation for a spinel is $A_8B_{16}O_{32}$. The attractiveness of a spinel for an MHD electrode material comes from its high electronic conductivity and a minimum variation of conductivity with temperature above 1970 K.

The work at NIST focused on the $MgCr_2O_4$ (melting point of 2670 K) and the $MgAl_2O_4$ (melting point of 22370 K) spinels with addition of up to 30 mole percent Fe_3O_4 to produce compositions with sufficient electrical conductivity while maintaining the high temperature stability of the spinel. Conductivities of above 0.1 mho/cm were measured at temperatures above 1470 K. The $MgAl_2O_4$ combination was recommended for use with a clean fuel due to its lack of reactivity with any potential seed material in the plasma. A 70% Fe_3O_4 – 30% Co_3O_4 spinel was recommended as a good alternative to the more conventional Pt as a "lead-out" material due to its high electrical conductivity. Its operating temperature range is approximately 1870 – 870 K where at the 870 K temperature it may be brazed to a metal-alloy wire such as stainless steel.(22)

Research at MIT took a different approach by developing an electrode of 70% $FeAl_2O_4$ – 30% Fe_3O_4 spinel while using $MgAl_2O_4$ without any additive as an insulator. The electrical conductivity of the $FeAl_2O_4$ is totally electronic and is1 mho/cm at 1870 K. The operating temperature of the electrode is limited to the 2050 K melting point of $FeAl_2O_4$. While the work at NIST focused on electrode material formulation and conductivity measurements, the MIT effort proceeded to testing of their electrodes at 75 – 300 W/cm^2, plasma temperature of 2495 K, surface temperatures of 1570 – 1970 K, and current densities of 2.5 – 5 A/cm^2 for 2 – 5 hours of operation.(23)

These research efforts have shown that spinel materials are suitable for application in hot electrode operation. In the designs tested, the Mg-aluminate composition had an operating temperature advantage, while the $FeAl_2O_4$ – Fe_3O_4 composition had an electrical conductivity advantage.

Research at the Battelle Pacific Northwest National Laboratory (PNNL)

The DOE MHD Program sponsored research and development of ceramic electrode materials for several years at the Battelle Pacific Northwest National Laboratory (PNNL). Results of this work involving yttrium chromites and hafnium oxide composites for hot MHD electrodes and lead out materials are reported in references 24 – 26.

Studies of doped yttrium chromites for high temperature MHD electrodes have shown them to have a high electrical conductivity over a wide range of temperature without the formation of hygroscopic decomposition that may produce structural degradation. These materials have better resistance to electrochemical attack than lanthanum chromites. Properties measured included electrical conductivity, thermal diffusivity/conductivity, melting point, thermal expansion, and electrochemical resistance. Most chromites studies for MHD applications are either Mg or Sr doped lanthanum chromites. These chromites exhibit excellent conductivity with a small temperature dependence of conductivity, but loss of Cr at high temperature leads to catastrophic mechanical degradation. Doped yttrium chromite exhibits similar electrical and mechanical properties without formation of hygroscopic compounds. Melting point of the yttrium chromite compounds studies covered the temperature range of 2300 – 2600 K and demonstrated resistance to electrochemical attack by potassium seed.[(24)]

Research at PNNL continued with the development and testing of hafnium oxide/rare earth oxides/ indium oxide composite hot electrodes and leadouts. Electrical potential for current transfer to these hot electrodes was determined to be approximately 1/3 that required for a cold, metal electrode. Current transfer to the hot electrode was diffuse, with no evidence of arcing and ohmic heating through the electrode. The concept investigated was stabilized $HfO_2 - Re_xO_y$ (Re = Pr, Ce, Tb, Yb, Er or Y) refractory caps, with $HfO_2 - Re_xO_y - In_2O_3$ lower temperature, electrically conducting ceramic leadout material between the ceramic cap, and the cooled, copper support block.

Hafnium oxide based refractory caps used rare earth oxides to stabilize the cubic hafnium oxide crystal structure and increase the electrical conductivity to greater than 1 mho/m above 1100 K. Current leadouts used similar materials to increase electrical conductivity further to between 10 and 100 mho/m above 300 K. Indium oxide containing materials in the leadout were only used in the 300 – 1500 K temperature range and not in the refractory caps exposed to the plasma. The composition tested for the refractory cap was $0.66HfO_2{:}0.29PrO_{1.83}{:}0.05Yb_2O_3$, and the leadout was $0.47HfO_2{:}0.20PrO_{1.83}{:}0.03 Yb_2O_3{:}0.30In_2O_3$.

Test conditions for evaluating these electrodes were plasma temperature, 2600 – 2700 K; heat flux, 45 W/cm^2; current density, 0.75 – 1.0 A/cm^2; and electrode refractory cap temperature, 1670 – 2050 K. Liquid potassium seed was used in all tests. Thermal stress resistance of the ceramic in initial tests was low but was improved in later testing through the addition of 5 weight% of ZrO_2 particles to the electrode mix and increasing controlled, closed porosity in the ceramic during fabrication.

Leadout and Brazing Studies

One problem in fabricating hot ceramic electrodes is the method of attachment of the electrode to the metal (copper) base material used for cooling and/or structural support. The attachment must be electrically conductive and mechanically compliant to accommodate the differences in thermal expansion between ceramic and metal. Both a high temperature (braze or pressure bond) and a low temperature (RTV silicone rubber and polyamide) method were developed for attachment of the ceramic to the metal base. Both methods used a metal mesh as a conducting, compliant layer between ceramic and metal.(25) Work to improve the leadout conductivity by addition of small amounts of tin oxide (SnO_2) to the indium oxide was reported in reference 17. A composition of 95-mole % In_2O_3 and 5-mole % SnO_2 was determined to have a conductivity of about an order of magnitude higher than pure In_2O_3.(17)

Results of the development and testing the brazed ceramic-to-metal samples for electrode insulators and insulating sidewalls are reported in reference 26. Ceramics such as SiC, Si_3N_4, and AlN have a unique property combination of high thermal conductivity and low electrical conductivity, making them good choices for insulator materials. Aluminum nitride (AlN) was selected as the primary ceramic for this study based on both material cost and previous use in MHD generators. Five materials were selected for brazing to the AlN:copper, tungsten copper ($W_{0.75}C_{0.25}$), tungsten, molybdenum, and steel (ASME A36). A compliant layer of copper was placed between the base metal and AlN ceramic since the greatest thermal stress on the brazed element occurs in the cool down from the brazing operation rather than in MHD testing. Samples were tested successfully in a small generator at the DOE facility at the University of Tennessee Space Institute. Testing lasted for 52 hours, with 47 hours continuous operation. Nominal heat flux in the generator, measured at the anode wall, was $160 W/cm^2$.(26)

Conclusions and Program Recommendations

Several studies have been conducted for MHD applications in a hypersonic vehicle using either a non-equilibrium or an equilibrium generator.[2,6,7,8] Nominal operating conditions used for these studies were a non-equilibrium generator entrance temperature of 1600–2000 K; equilibrium generator entrance temperature of 2500 – 3000 K; magnetic field strength of 0.5 – 1.5 Tesla, and current density of 2 – 5 A/cm^2. These conditions, covering a wide range of possible generator operations, are broadly consistent with existing data and experimental conditions from classical MHD power generation research, development, and demonstration efforts.

As previously discussed, there are two separate and distinctly different general approaches to the mechanical design and operation for an MHD generator that may be suitable for hypersonic vehicle application. One approach is a highly cooled design using copper base electrode materials with tungsten, molybdenum, or platinum caps and platinum reinforcement blocks on anode corners, as used for the prototypical generator in the DOE MHD Program.[11 - 14] Insulator materials BN and AlN and Z-bar sidewalls were also part of this generator design.

A second general approach to generator design and operation utilizes hot, electrically conductive ceramic or semi-conducting materials for electrodes.[17 - 26] Ceramic microstructure and processing, rather than caps, are utilized in this approach to protect the electrodes. This concept requires less cooling, resulting in a potentially higher efficiency and more compact generator than in the cold electrode wall approach. These features make it an attractive option for a weight- and volume-limited hypersonic vehicle system.

Either generator design approach may find potential application in electrical power generation required to support the operation of an ionizer, plasma assistance in ignition and combustion, and/or inlet/plasma aerodynamic control for a hypersonic vehicle. An extensive base of materials research, hardware design, and long-duration demonstration test data exists for the cold wall approach.[9, 11 - 13] However, the hot wall approach has an existing materials research and electrode design database, but limited generator testing. The ceramic electrode database also includes development of leadout materials for use between a hot ceramic electrode and a base metal, as well as the development of brazing techniques for ceramic-to-metal attachment.[17,26] Experimental data have been obtained for hot ceramic electrodes operating at a nominal plasma temperature of 2600 K, heat flux of 50 W/cm^2, current density of 1.0 A/cm^2, and surface temperature of 2100 K. At these nominal operating conditions with a hot boundary layer and a large width-to-pitch electrode design, current transfer to the electrode was observed to be diffuse with less potential for arcing than with a cold wall design.

In conclusion, there are three program recommendations in this topic area that focus on classical MHD power generation for a hypersonic vehicle. First, the existing MHD data from both the hot electrode wall[17 - 20] and cold electrode wall[12,13,16] generator operation should be utilized in hypersonic vehicle MHD system studies, such as contained in references 7 and 8. Studies using MHD generator experimental data will result in a refinement of generator weight, volume, and cooling requirements and power production estimates and integration approaches for long-duration hypersonic vehicle MHD systems. These studies also may assist in the matching of generator design and operation with mission scenarios and identify additional critical technology research needs.

Second, existing data for hot ceramic electrode materials and fabrication techniques, including leadouts,[17 - 26] should be utilized to fabricate and test a complete hot electrode wall generator at a scale capable of producing the power required for MHD applications in a hypersonic vehicle. The generator should be operated continuously with the magnetic field strength, current density, plasma conditions, and duration times consistent with anticipated mission requirements to validate performance, operability, and durability of the system.

It is stated in references 6 and 8 that the static temperature at the exit of a typical hypersonic airbreathing vehicle inlet does not generally exceed 2000 K, therefore, an ionizer is required for MHD power generation. Operating data for hot ceramic electrodes have been obtained at a nominal electrode surface temperature of 2100 K.[18 - 20] If the recovery temperature at an electrode wall of a generator located just aft of a hypersonic vehicle inlet was, therefore, nominally 2400 K without cooling, then a surface temperature of nominally 2100 K could be achieved with minimal active cooling. The operating temperatures for a hot ceramic electrode wall generator are, therefore, nominally consistent with temperatures anticipated aft of the inlet. The third program recommendation is, therefore, using existing performance data on hot ceramic electrodes to conduct an analysis to determine whether or not it is practical to utilize a hot wall, non-equilibrium generator immediately aft of the inlet of a hypersonic vehicle operating below Mach 9. This study may include the generation of power required for both the operation of an ionizer and inlet aerodynamic control.

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VI. Contract Information Summary

Personnel, Publications, Significant Interactions, and Inventions

This final technical report was prepared by Harold F. Chambers, Jr of HFC Consulting who is solely responsible for the content. A technical paper and presentation titled "Aerospace Applications of the DOE MHD Program Results, Part I: Ignition, Combustion and Aerodynamics" was presented at the January 2007 AIAA Aerospace Sciences Meeting in Reno, Nevada. Both the paper and presentation were based on the work performed in Contract FA9550-05-C-0160. Significant interactions which occurred during the course of this contract were technical discussions with Dr. Joel Muehlhauser at The University of Tennessee Space Institute (UTSI), a visit to UTSI for the purpose of obtaining reference materials from their library, use of the DOE Technical Information web site to obtain technical reports and use of the AIAA web site to obtain papers used to describe the background work in the four technical topic areas of this report. No inventions or patents were produced as part of the work under this contract.