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DR-2822
DOE/ET/10780-T1

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A HIGH MAGNETIC FIELD MHD GENERATOR PROGRAM

Final Report for the Period July 1, 1976—December 31, 1979

By
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April 1980
Date Published

Work Performed Under Contract No. AC01-76ET10780

Stanford University
Stanford, California

U. S. DEPARTMENT OF ENERGY

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A HIGH MAGNETIC FIELD MHD GENERATOR PROGRAM

FINAL REPORT

for the period

July 1, 1976 - December 31, 1979

Submitted by

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Date Published - April 1980

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Prepared for

THE UNITED STATES DEPARTMENT OF ENERGY

Under Contract No. EX 76-C-01-2341

FOREWORD

This final report for Contract No. EX 76-C-01-2341 has involved the efforts of many members of the High Temperature Gasdynamics Laboratory staff and the Principal Investigators are pleased to acknowledge the contributions of the following staff members:

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ABSTRACT

A theoretical and experimental program was undertaken to investigate MHD channel phenomena which are important at high magnetic fields. The areas studied were inhomogeneity effects, boundary layers, Hall field breakdown and electrode configuration and current concentrations. In addition, a program was undertaken to study steady-state combustion disk and linear channels in an existing 6 Tesla magnet of small dimensions.

The structure of the inhomogeneities in the Stanford M-2 was characterized and compared with theoretical results from a linearized perturbation analysis. General agreement was obtained and the analysis was used to compute stability regions for large size generators. The Faraday electrical connection was found to be more stable than the Hall or diagonal wall connections.

Boundary layer profile measurements were compared with theoretical calculations with good agreement. Extrapolation of the calculations to pilot scale MHD channels indicates that Hartmann effects are important in the analysis of the sidewall, and Joule heating is important in calculating heat transfer and voltage drops for the electrode wall.

Hall field breakdown was shown to occur both in the plasma and through the interelectrode insulator with the insulator breakdown threshold voltage lower than the plasma value. The threshold voltage was shown to depend on the interelectrode gap but was relatively independent of plasma conditions.

Experiments were performed at 5.5 Tesla with both disk and linear MHD channels.

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1.0 INTRODUCTION

Practical MHD generators in central station power plants are expected to operate with magnetic fields of 5 or 6 Tesla. The interaction parameter (ratio of MHD force to working fluid inertia force) for such a generator will normally exceed 10 and experimental facilities available today provide an interaction parameter of about one. A number of important effects in MHD channels are greatly influenced by the magnetic field and by the interaction parameter. For this reason a program was undertaken at the Stanford University High Temperature Gas-dynamics Laboratory to investigate these phenomena in existing facilities and to develop analytical procedures so that MHD designers could predict performance of large practical systems at high magnetic fields. It was planned that a 7 Tesla magnet would be supplied Stanford as government-furnished equipment during the third year of the contract so that extrapolation of laboratory results could be reduced from that necessary with existing facilities.

A program was designed to undertake investigations in the following areas of research:

- inhomogeneity phenomena
- boundary layer phenomena
- Hall field breakdown phenomena
- electrode configuration and current concentration
- 6 Tesla magnet investigations

Earlier theoretical work has shown that the deleterious effect of inhomogeneities in the working fluid in an MHD channel increases with increasing magnetic field. It is not unreasonable to expect a 30 per cent decrease in effective conductivity and power output for a given size channel from that of a uniform plasma. However, no experimental characteristics of the uniformity of the working fluid was available and this program was directed at developing suitable diagnostics and measuring the conditions in the Stanford M-2 MHD channel. Inhomogeneities may be caused by acoustic and other waves in the MHD channel so an analytic and experimental effort was carried out to predict and measure waves and this growth rate as a function of generator conditions and magnetic field.

Boundary layers have an important influence on the layers in MHD generators. They affect electrode voltage drops, heat transfer, wall friction, and the core flow through interactions such as separation. Because of the influence of magnetic field on current distribution and the $\bar{j} \times \bar{B}$ force it is essential to understand the influence of high magnetic fields on boundary layer profiles and surface parameters such as Stanton number and Pictin coefficient. Measurements were made of the insulator wall velocity profile and the electrode wall temperature and electron concentration profiles. Comparisons of measurements with advanced two-dimensional boundary layer computer codes including MHD effects showed the importance of the boundary layers on computing channel pressure drop and electrode voltage lines.

The Hall field which can be substantial in an MHD generator is definitely related to the power output per unit length but there is a limit to the practical Hall field even though expected magnetic fields make values possible. Hall field breakdown phenomena were investigated with attention directed to both plasma breakdown and insulator breakdown.

Electrode voltage drops, electrode life, and Hall field are influenced by current distribution and concentration. Measurements were made of current distributions and 3-dimensional calculations were made of current patterns for electrodes designed to reduce current concentration.

The High Temperature Gasdynamics Laboratory has a 6 tesla superconducting magnet suitable for small scale tests with both disk and linear MHD channels. Steady state, combustion gas experiments were conducted with both configurations.

This report describes in summary form each of the areas mentioned above. Great detail is given in the quarterly reports and in a number of papers and topical reports listed in section 7.0. Where appropriate the sections which follow include a discussion of the application of the research results obtained in the present program to large scale MHD generators. The most important conclusions are summarized in section 8.0.

2.0 INHOMOGENEITY PHENOMENA

It is well known that inhomogeneities of the properties of the plasma working fluid, in particular of its electrical conductivity, can significantly degrade the performance of MHD generators, compared to that predicted for a uniform plasma. The steady inhomogeneities associated with boundary layers or current concentrations due to the electrode configuration can be calculated by time-independent codes. However the effects of fluctuating inhomogeneities of the core plasma, which is the subject investigated here, are more difficult to predict.

In general, such fluctuating nonuniformities arise from two sources. First the plasma entering the generator is not uniform, but will have a spatio-temporal structure which is characteristic of the source and upstream components, i.e., the combustor, seed injector system, nozzle, etc. Secondly, these inhomogeneities may be modified and enhanced by plasma instabilities in the generator, associated with current flow in the magnetic field.

Several idealized theories have described possible instabilities in MHD plasma systems but their experimental verification is tenuous. Only in the case of the ionization instability in non-equilibrium noble gas plasmas has the instability been clearly identified and its effects studied in some detail. For combustion plasmas the predicted instabilities have not been unequivocally observed, though this may be due to the relatively low Hall parameters to which experiments have been restricted.

The effect of plasma nonuniformities on generator performance has generally been described in terms of an effective conductivity which is a function of the spatial structure and amplitude of the inhomogeneities, and is less than the conductivity in the uniform case. Theoretical treatments characterize the plasma nonuniformities by statistical averages and then compute the effective conductivity from the appropriate averaged form of Ohm's law. Data required to test these theories are not available from experiments. In particular, measurements of local conductivity fluctuations and two-point correlations are required to evaluate the statistical averages. Some measurements of the spectra of light emission fluctuations have been reported [2.18], but these represent some unspecified spatial average values. From two-point correlations, the convective nature of

the fluctuations was indicated but no detailed information on the spatial structure was obtained and no connection with the effective conductivity was established.

An important component of the work reported here has been the development of diagnostic techniques by which the nonuniformities and fluctuations of plasma properties can be characterized. These are reported in Section 2.1 and include spatially resolved optical techniques which essentially measure the temperature or conductivity, as well as a high frequency microphone probe for measuring pressure fluctuations at the channel walls.

Sections 2.2 and 2.3 summarize the results of measurements using these two types of techniques on the Stanford M-2 system, and characterize the nonuniformities and fluctuations in terms of statistical quantities over a range of external system parameters.

In Section 2.4, a linear perturbation analysis is outlined, which describes fluctuating inhomogeneities of plasma properties in terms of two acoustic waves and a convected entropy wave. This facilitates the interpretation of experimental data and also indicates how nonuniformities propagate with decay or growth through the generator, depending on the external parameters. Finally, some projections are made concerning the implications of this theory for the effect of inhomogeneities on the performance of large-scale MHD generators.

2.1 Development of Diagnostic Techniques

Several new diagnostic techniques for acquiring data on plasma inhomogeneities were developed, as outlined in the following subsections.

2.1.1 Plasma Luminosity Technique

In this simple technique, the optical emission in a small solid angle about a line of sight normal to the flow axis is collected by an optical system and detected, i.e., converted to an electrical output signal. It is convenient to seed the flow with a small concentration of sodium and, by spectral filtering, detect emission from one of the resonance lines at $\lambda = 589.0, 589.6$ nm. The emitted intensity is given by

$$I \propto n_0^{\text{Na}} \exp(-E_{01}^{\text{Na}}/kT) \quad (2.1)$$

where n_0^{Na} is the concentration of sodium atoms in the ground state and $E_{01}^{\text{Na}} = 2.10 \text{ eV}$ is the energy difference between the 3s (ground) and 3p levels. The electrical conductivity on the other hand is given by

$$\sigma \propto n_e \propto (n_0^K)^{1/2} \exp(-E_{\text{ion}}^K/2kT) T^{3/4} \quad (2.2)$$

where n_0^K is the potassium ground state atom concentration and $E_{\text{ion}}^K = 4.34 \text{ eV}$ is the ionization energy.

For I and σ , the dependence on atom concentration is weak but the dependence on temperature is exponentially strong and almost equal, because $E_{01}^{\text{Na}} \approx E_{\text{ion}}^K$. By dissolving a small quantity of sodium, together with the potassium seed in ethanol fuel, the ratio n_0^{Na}/n_0^K is accurately known so that the luminosity signal I provides a good relative measure of the conductivity.

The emission signal I represents a line of sight average weighted by the effect of absorption. To obtain an effectively unweighted average of the core plasma condition, it is important that the plasma be optically thin for the detected radiation, i.e., the optical depth defined by Eq.(2.3) should be small.

$$\tau_\lambda \equiv \int_0^L \alpha(\lambda) dx \ll 1. \quad (2.3)$$

This can be ensured by using low sodium concentrations and/or spectrally detuning from line center. However, if the plasma is optically thin, thermal radiation from the far wall of the channel will also be detected, and in the case of hot walls will add a steady background signal to the fluctuating plasma signal. This can either be corrected for or circumvented by using a cooled wall or optical port on the opposite wall.

In practice this diagnostic technique has been realized very simply by using a small lens to focus the emission onto an optical fiber which transmits to a remotely mounted narrow band (0.5 nm) interference filter followed by a silicon photodiode. A flat frequency response to at least 10 kHz can be obtained with good signal/noise and adequate spatial resolution. On account of its simplicity and cheapness, it is practical to mount several such probes at different positions in the channel walls

to obtain information on the spatial structure of the conductivity non-uniformities via two-point correlations of their outputs.

2.1.2 Extended Line-Reversal Technique

The line reversal technique is well known and has been extensively used at Stanford for time-averaged temperature measurements with high spatial resolution in MHD channels [2.1, 2.2]. It is essentially similar to the luminosity technique with the addition of a transilluminating beam from a standard tungsten ribbon lamp which allows the emission and absorption to be measured and related via Kirchhoff's law to give the temperature to an accuracy of $\leq 1\%$. The conditions to be satisfied to obtain accurate measurements of the line-of-sight averaged core temperature viewed through the proximal boundary layer have been detailed by Daily and Kruger [2.3]. The basic requirement is that the optical depth be of order 0.5 or less, and this is most readily ensured by using a monochromator which can be set to a narrower bandwidth, and is more easily tuned than an interference filter. Also, because a fixed optical train is used rather than an optical fiber, line reversal measurements involve more elaborate and less flexible setups than the luminosity technique.

Under this contract, the line-reversal technique has been extended to extract measurements of three statistical quantities related to temperature and seed concentration fluctuations in combustion plasmas. This work is reported in detail in references [2.4 and 2.5] and is briefly outlined below.

The fluctuations in temperature and sodium atom concentration are written in the form

$$\exp(-E_{01}^{\text{Na}}/kT) \equiv \langle \exp(-E_{01}^{\text{Na}}/kT) \rangle (1 + \xi_1(t)) \quad (2.4)$$

$$\alpha L \equiv \langle \alpha L \rangle (1 + \xi_2(t)) \propto n_0^{\text{Na}} \quad (2.5)$$

where the angle brackets indicate time averages, and ξ_1 , ξ_2 represent fluctuation amplitudes. By making measurements of the time average and mean square detected intensities at two or more lamp temperatures, it is

possible to extract values for the statistical quantities $\langle \xi_1^2 \rangle$ $\langle \xi_2^2 \rangle$ and $\langle \xi_1 \xi_2 \rangle$. These can be used to infer the magnitude and source of luminosity (or conductivity) fluctuations. If $\langle \xi_1^2 \rangle \gg \langle \xi_2^2 \rangle$, luminosity fluctuations are due principally to temperature fluctuations which probably originate in the mixing and combustion of fuel and oxidizer. Conversely, if $\langle \xi_2^2 \rangle \gg \langle \xi_1^2 \rangle$, the fluctuations are due primarily to those of the seed atom concentration, which probably originate in the seed injection and mixing process.

It should be noted that because this extended line-reversal technique yields time-average statistical data, it cannot be used for correlations with other techniques which yield signals which are a continuous function of time. Also, of course, the plasma under study must be statistically stationary over the measurement duration.

2.1.3 Laser-Induced Fluorescence (LIF) Technique

This technique, first suggested by Self and Kruger [2.6] represented a major development effort with the specific aim of obtaining local (3-D resolved) measurements of temperature (or conductivity) with good time resolution.

With reference to Fig. 2.1, the basic idea is to use a tunable laser to optically pump atoms of a suitable seed material from a thermally populated middle level to an upper level which is populated to a negligible degree in the absence of the pump. The pumped upper level atoms rapidly decay both by fluorescence back to the middle level, with isotropic emission at the transition wavelength, and by collisional quenching. By focusing the laser beam to a waist of small diameter, and collecting the fluorescence radiation along an orthogonal direction, the measurement volume may be restricted to small dimensions, typically a cylinder ~ 0.1 mm diameter and a few mm long.

The fluorescence signal is proportional to the laser power and to the population in the middle level, which is related to that of the ground level via the usual $\exp(-E_{01}/kT)$ term; thus the LIF technique can provide a localized relative measure of the temperature. The frequency response (bandwidth) for temperature fluctuations depends on the signal/noise ratio, as discussed below.

Figure 2.1 Atomic energy level diagram.

It is very convenient to employ the 3p (middle) and 4d (upper) levels of sodium for several reasons. First, the fluorescence signal is proportional to the 3p population, which is the upper level for the resonance (3p-3s) lines utilized in the luminosity and line-reversal techniques, and which corresponds closely to the electron concentration and hence the conductivity. Second, the pumped transition (3p-4d) lies in the yellow, some 20 nm shorter in wavelength than the resonance lines, and is well suited for pumping by a dye laser using an argon ion laser as pump. Third, it happens that the 3p (middle) and 4d (upper) levels are doublets and give rise to two closely spaced optical transitions at 568.26 and 568.82 nm. This complication is actually very advantageous. Pumping on either line produces fluorescence on both lines, because the upper levels rapidly equilibrate, so that by pumping on one line and detecting the fluorescence on the other eliminates background interference due to elastic scattering of the pump radiation due to Rayleigh molecular scattering or Mie scattering from particulates, e.g., soot or ash. Thus, in practice, the waist of the laser beam is imaged by the collection optics onto the entrance slit of a monochromator to provide the necessary spectral isolation. The entrance slit also acts as a field stop, or spatial filter, to minimize the collection of background plasma radiation.

Despite the spatial filtering, the "signal" level due to the background radiation is typically very much larger than the fluorescence signal, due to the fact that the former originates from a much larger volume than the latter. This problem is overcome by amplitude modulating the laser (and hence the fluorescence signal) and using narrow band phase-sensitive detection to discriminate against the unmodulated background. The modulation frequency is chosen to be much higher than the bandwidth for fluctuation measurements, where the spectral content of the background fluctuations is small. The limiting noise level is then set by the component or irreducible shot noise due to the steady level of the background which lies in the measurement bandwidth about the modulation (carrier) frequency.

Preliminary experiments to establish the technique were made on a bench-scale burner whose temperature could be modulated sinusoidally by modulating the air supply. These are reported in reference [2.7].

Further details of the final system and its optimization with respect to optical configuration, seed level, detection electronics, etc. are given in Kowalik's thesis [2.5]. In measurements in the M-2 combustion MHD plasma channel, using a laser power of 200 mW, a collection aperture of $\sim F/1$, and a bandwidth of 400 Hz at a modulation frequency of 100 kHz (provided by an acousto-optic modulator), a usable signal/noise ratio of ~ 2 was obtained. This relatively low S/N performance results primarily from the high background emission within the spectral bandwidth detected, which is due to both continuum radiation and to line radiation from the far wings of the sodium resonance lines (589.0, 589.6 nm) which are known to decrease much more slowly than $(\Delta\lambda)^{-2}$ as would be expected from simple collision broadening concepts [2.8]. The signal/noise could, of course, be increased by increasing the pump laser power.

2.1.4 Pressure Probes

Wall-mounted pressure taps connected to remotely located pressure transducers are widely used to measure the static pressure in MHD channels. However, to measure pressure fluctuations with high sensitivity and with a flat response to high frequencies is more difficult. The natural choice of detector or transducer is a condenser microphone but it is impractical to mount this directly in the channel wall because of heat transfer and seed condensation problems. Consequently, a probe-tube microphone instrument has been developed, shown schematically in Fig. 2.2. The probe tube is typically 1/8 in diameter and 6 in long and connects to a water-cooled probe tip which mounts in the channel wall. The other end of the probe tube, which has provision for purge gas connects to the condenser microphone and preamplifier (Brüel and Kjaer, Model 4136).

The use of a probe tube introduces resonances into the system response, which were eliminated by two means. First, by using helium as the purge gas the frequencies of the lowest resonances are raised. Secondly, an acoustic damping section is introduced into the tube between the tip and the purge supply point. Figure 2.3 shows the response without and with the damping, and indicates a perfectly flat response to ~ 2 kHz which falls slowly by ~ 2 db up to 8 kHz. The sensitivity range is from 0.0001 psi to 3 psi and the response is linear over this range. Full details of the probe design are given in reference [2.9].

Figure 2.2 Schematic of probe tube microphone assembly.

Figure 2.3 Frequency response of .6 inch length, 1/8 inch diameter microphone probe.
Upper trace with no damping. Lower trace with center position damping.

2.1.5 Electrical Diagnostics

For most of the studies of plasma fluctuations and nonuniformities the MHD test channels were equipped with electrodes in a Faraday configuration and internal voltage pins mounted in the insulating sidewalls. Current fluctuations from the electrodes and voltage fluctuations from the pins were recorded.

The voltage pins were of 0.76 mm diameter iridium wire extending 2 mm into the plasma. They were mounted in rows of four or five pins in the sidewall between electrode pairs with spacings of 1-3 cm, and were used in two modes. In the absence of magnetic field, and with a regulated current driven between electrodes from an external supply, the voltage signals between pins give a measure of the local conductivity. With magnetic field and the electrodes open-circuited, the voltages between pins principally reflect fluctuations in plasma velocity.

In measuring both electrode currents and pin voltages, there may be high common-mode voltages which are isolated using isolation buffer amplifiers.

2.1.6 Diagnostic Data Handling

An important part of any diagnostic technique is the processing and interpretation of its output, which is invariably an analog voltage signal. In the experiments reported below the various signals were conditioned and recorded on multitrack analog tape recorders and analyzed subsequently. In the analysis, the signals were digitized and stored in an HP 2100 computer which computed six basic statistical functions, as follows: rms fluctuation intensity, probability density function, frequency spectrum, auto-correlation function, cross-correlation function and cross-spectral density function.

2.2 Measurements of Conductivity Fluctuations and Nonuniformities in the Stanford M-2 Channel

Four basic series of experiments were made which can be broken down according to the principal type of optical diagnostic technique used and by the type of channel hardware used. Accordingly, the experiments are divided according to whether only line-of-sight (LOS) optical diagnostics

were used, or whether point measurements by laser-induced fluorescence were made. In each case a test series was run first in a special diagnostic channel with no magnetic field, and secondly in an MHD generator channel in the magnet.

The reasons for this form of test program were twofold. First, it is much easier to obtain diagnostic access outside the magnet, so that it is best to prove out a new technique under the simpler conditions. Second, experiments with the diagnostic test section, immediately downstream of the combustor and nozzle, were aimed at characterizing plasma inhomogeneities resulting from the combustor, and which are also, of course, those entering the generator. Experiments with the generator channel in the magnet were made to investigate how the inhomogeneities were modified by generator action.

All the experiments employed the Stanford M-2 combustor system [2.10], shown in Fig. 2.4, which is a swirl-stabilized, liquid fuel spray combustor having opposed swirl O_2 and N_2 injection. It attaches to a brick-lined plenum fitted with a subsonic nozzle feeding channel hardware of internal dimensions 3 cm wide (B-field direction) x 10 cm high. It was used with ethanol fuel having appropriate amounts of dissolved KOH and NaOH seed.

Only a brief summary of the experiments and the salient results are given here. Full details are given in Kowalik's thesis [2.5]

2.2.1 Experiments with LOS Techniques in the Diagnostic Channel

The objectives of these experiments were

- a) to demonstrate the extended line-reversal technique in the M-2 system
- b) to compare optical and voltage probe measurements of conductivity
- c) to obtain an initial characterization of inhomogeneities in the M-2 system
- d) to investigate the effect of a combustor modification on the inhomogeneities.

The diagnostic test section, with the locations of the various measurement stations, is shown in Fig. 2.5, where the upper and lower diode windows refer to luminosity measurements. Additionally a pressure

Figure 2.4 Schematic diagram of the Stanford M-2 combustor.

Figure 2.5 Schematic diagram of the diagnostics channel.

probe was fitted in the combustor plenum. Following a shakedown test, two series of experiments were made for a range of flow conditions. The first used the M-2 combustor system in its standard configuration; for the second the combustor was modified by reducing the plenum chamber length to approximately one third.

For all test conditions, satisfactory agreement was obtained for the mean temperatures calculated from the metered combustor inputs, and measured by line reversal, and also for the conductivity, calculated for the measured temperature, and measured by the voltage pins with a current supplied via the electrodes.

Measurements of the statistical quantities $\langle \xi_1^2 \rangle^{1/2}$, $\langle \xi_2^2 \rangle^{1/2}$ and $\langle \xi_1 \xi_2 \rangle^{1/2}$ by the extended line reversal technique are shown in Table 2.1. This shows that conductivity fluctuations are determined more by temperature fluctuations than by seed concentration fluctuations, and that the correlation between temperature and seed fluctuations is negligible, as one would expect.

The percentage rms fluctuation intensities of signals from the various diagnostics are shown in Table 2.2. The column labelled emission refers to signals from the line-reversal apparatus with the lamp off, and indicate fluctuation amplitudes of order 10%. The diode signals indicate rather lower levels which are attributed to the inclusion of the steady radiation from the far channel wall. The fluctuations in conductivity from the voltage pins are generally somewhat larger, but it is believed that these are less reliable than the optical ones. The pressure probe fluctuations are very much smaller ~ 0.1%. No significant difference in the fluctuation intensities was observed between the standard plenum configuration (runs A,B) and the shortened version (runs C).

Table 2.3 lists the maximum (positive) or minimum (negative) cross-correlation coefficients for various signal pairs, where zero correlation is entered for magnitudes < 0.2. The time delays for maximum (or minimum) correlations between different axial stations were of the order of 0.2-0.6 msec, and corresponded to the delay expected from the flow velocity in each case. No correlation was observed between the pressure and any other diagnostic signal.

Cross-correlations between diagnostics located at different heights in the channel such as line-reversal emission, upper diode or middle pins,

Table 2.1
Results of fluctuating line-reversal measurements.

Run Series	$\langle \epsilon_1^2 \rangle^{1/2}$	$\langle \epsilon_2^2 \rangle^{1/2}$	$\langle \epsilon_1 \epsilon_2 \rangle$
B1	0.111	0.031	-0.001
B2	0.098	0.040	-0.001
B3	0.096	0.055	-0.002
B4	0.072	0.062	-0.002

Table 2.2

Signal fluctuation intensities from line-of-sight experiments in diagnostics channel.

Run Series	Fluctuation Intensity (% rms)						
	Emission	Upper Diode	Lower Diode	Upper Pins	Middle Pins	Lower Pins	Pressure Probe
A1	10.8	3.6	3.8	10.9	--	20.0	0.10
A2	8.4	4.4	3.6	9.4	--	14.1	0.12
B1	10.5	9.0	5.1	--	--	--	0.07
B2	9.2	4.5	3.3	--	--	--	0.08
B3	9.2	4.6	3.4	--	--	--	0.10
B4	6.8	2.5	2.0	--	--	--	0.11
C1	10.0	5.2	5.7	17.2	14.9	28.7	0.16
C2	16.8	5.5	5.0	16.5	10.5	14.7	0.22
C3	7.8	3.0	3.4	20.1	7.3	13.1	0.21

Table 2.3

Maximum (or minimum) cross-correlation coefficients between signals from line-of-sight experiments in the diagnostics channel.

Run Series	N ₂ /O ₂ (mass)	Maximum (or minimum) cross-correlation coefficient between signals*										
		2,4	2,5	3,5	3,4	4,5	2,3	1,2	1,3	1,7	3,7	5,7
A1	1.0	-.32	0	-.33	0	+.47	0	-.23	0	--	--	--
A2	0.5	-.34	0	-.33	0	+.21	0	0	0	--	--	--
B1	1.0	--	--	--	--	--	0	-.50	-.23	--	--	--
B2	0.5	--	--	--	--	--	0	0	0	--	--	--
B3	1.0	--	--	--	--	--	0	-.41	-.23	--	--	--
B4	0.5	--	--	--	--	--	0	0	0	--	--	--
C2	1.0	-.59	0	0	+.44	0	-.44	0	-.31	-.53	-.38	+.30
C3	0.5	-.30	0	0	0	-.22	0	0	-.22	-.32	0	0

*

1 = Line-reversal emission

5 = Lower pins

2 = Upper diode

6 = Pressure probe

3 = Lower diode

7 = Middle pins

4 = Upper pins

lower pins exhibited a strong dependence on the N_2/O_2 mass ratio. When cases of equal total mass flow were compared, correlations observed at a N_2/O_2 ratio of 1.0 were considerably larger than those observed at a N_2/O_2 ratio of 0.5. The dependence in N_2/O_2 ratio is believed to result from changes in the gas flow pattern due to changes in the swirl and mixing. The stronger correlations at $N_2/O_2 = 1$ may have been the result of larger plasma nonuniformities which crossed two or more diagnostic measurement volumes. The polarities of the transverse correlations from the first two experiments (A and B run series) were consistent with this hypothesis. The upper and lower voltage pins had positive correlations as would be expected for equivalent diagnostics. The diode and emission signals had negative correlations which matched the opposite detector polarities of the two diagnostics. The shapes and time delays of the two types of transverse correlations, however, were noticeably different. The voltage pins correlations had zero time delays and narrow widths (high frequency). The diode-emission correlations had nonzero time delays and broader widths (low frequency). Typical examples of frequency spectra from the various diagnostics are displayed in Fig. 2.6.

Signals from the line-reversal, plasma luminosity and internal voltage pin diagnostics had relatively smooth spectra with most of their fluctuation energies in the lower frequencies; however, apparent resonances were present at higher frequencies. Occasional spikes were also observed in emission, diode and voltage pin spectra. These generally occurred at frequencies of the order of 100 Hz. The predominantly low frequency spectra of all of the diagnostics suggested that nonuniformities were relatively long in the axial flow direction. Frequencies of a few hundred Hz combined with velocities of a few hundred m/s produced characteristic length scales of the order of 1 meter. No definitive explanations of the occasional spikes or periodicities in the fluctuation spectra were found; however, spectra of the line-reversal signal exhibited more prominent spikes at the larger mass flowrates. These resonances may have been related to auxiliary flows associated with the two open windows.

Frequency spectrum of line-reversal emission signal.

Frequency spectrum of upper diode signal.

Frequency spectrum of upper pins signal.

Frequency spectrum of pressure signal.

Figure 2.6 Run Series A1, low-pass filter set to 1 kHz.

2.2.2 Experiments with LOS Techniques in the M-2 Generator

The generator channel, of internal dimensions 3 x 10 cm and 100 cm long, was fitted with thirteen stainless steel electrode pairs in a segmented Faraday configuration. The magnet gap was increased to allow better access for diagnostics, which resulted in a maximum operating field of ~ 2.0 T. The diagnostics used included a pressure probe at electrode pair #2, and a luminosity probe internal voltage, pins, and electrode current instrumentation at electrode pair #7.

The combustor was run at constant conditions, $\dot{m} = 0.068$ kg/s, burning ethanol, seeded with potassium and sodium, stoichiometrically in oxygen (no added nitrogen) to give a high temperature (~ 2800 K) and conductivity (~ 14 mho/m). Measurements of fluctuations were then made as a function of the electromagnetic parameters, i.e., magnetic field and current, to determine their effect on conductivity fluctuations. Currents to each electrode pair were controlled and augmented through the use of external load resistors and batteries.

Table 2.4 shows the magnetic field and average current densities for the six run conditions tested, together with the rms fluctuation intensities measured. The latter, together with the cross-correlations, frequency spectra and cross-spectral densities were generally similar to those observed in the diagnostic channel with certain exceptions and dependencies on Band J as noted below.

The luminosity fluctuation percentage was independent of B field but decreased with increasing current. It is believed that this is due not to a decrease in fluctuation amplitude but to an increase in the mean luminosity due to Joule heating.

The electrode current fluctuation percentage increased with average current. This is believed to be due to the fact that the higher currents were achieved with lower load resistances, which made the current more sensitive to conductivity fluctuations; a simple analysis shows that

$$\frac{\Delta I}{I} = \left(\frac{\Delta \sigma}{\sigma} \right) \cdot \left(\frac{1}{1 + \frac{R_p}{R_L}} \right) \quad (2.6)$$

where R_p is the average plasma resistance and R_L is the load resistance.

Table 2.4

Current densities and magnetic field strengths
for the M-2 generator experiment.

Run Series	Average Current Density (A/cm ²)	Magnetic Field Strength (T)
D1	0	0
D2	0	2
D3	0.64	2
D4	1.34	2
D5	0.54	0
D6	1.24	0

Signal fluctuation intensities from the
M-2 generator experiment.

Run Series	Fluctuation Intensity (% rms)			
	Luminosity	Current	Internal Voltage	Pressure
D1	3.2	--	--	0.13
D2	3.4	--	2.5	0.12
D3	3.4	2.3	15.5	0.13
D4	2.5	3.6	6.6	0.25
D5	3.3	2.6	5.6	0.12
D6	2.7	3.4	5.3	0.12

Luminosity-current and luminosity-voltage correlations were distinctly different. The former were stronger and concentrated at low frequencies, while the latter had the opposite polarity and were more uniform in the range 0-2 kHz. These differences may be related to the relative sizes of the measurement volumes. The current responds to conductivity fluctuations averaged over the whole channel cross-section, whereas the voltage pin signal responds to local fluctuations. The measurement volume of the luminosity signal is intermediate in size.

The rms pressure fluctuation intensities were generally small (~ 0.1%), but a significant enhancement was observed in run D4 at the highest current with magnetic field. A significant luminosity-pressure correlation was observed only for this run, and it was concentrated at low frequencies.

The general picture that emerges from these tests is that fluctuations in the generator output are due primarily to current fluctuations resulting from the low frequency, large (axial) scale, convected inhomogeneities of plasma conductivity generated in the combustor. There is evidence of smaller scale transverse inhomogeneities which are "averaged" by each electrode pair. In addition, at moderate current densities and magnetic fields there is a coupling between the conductivity fluctuations and pressure fluctuations, through the $\mathbf{J} \times \mathbf{B}$ interaction term. As a result, there is an increase in the pressure fluctuation level, which is concentrated at low frequencies (because the pressure fluctuations are driven by the low-frequency conductivity fluctuations). (See Section 2.3 below.)

2.2.3 Experiments with the LIF Technique in the Diagnostic Channel

One result from the experiments using LOS techniques was that the nature of conductivity-related fluctuations appeared to depend on the measurement volumes of the various diagnostics. This suggests that local (3D resolved) measurements may be necessary to fully characterize the inhomogeneities. The LIF technique was investigated as the most promising method of acquiring such data. Following exploratory tests [2.7] on a bench scale using a small Perkin-Elmer burner, experiments were made using the diagnostics channel section attached to the M-2 combustor, to investigate the feasibility of the LIF technique under

combustion MHD conditions, and to compare measurements with those obtained by LOS techniques.

The diagnostic channel was modified by addition of a tail section as shown in Fig. 2.7. This had an enlarged cross-section with water-cooled walls, so that the plasma was essentially a confined jet at the station where fluorescence radiation was collected. Open ports were used to circumvent window fouling, and the exhaust system was operated under suction to prevent plasma exiting the ports. Luminosity measurements were made at the locations labelled upper and lower diode windows in the main test section.

A schematic of the LIF diagnostic system is shown in Fig. 2.8. The exciting laser beam, modulated by the AOM, passed vertically through the centerline of the tail section where it was focused to a waist $\sim 300 \mu\text{m}$ diameter opposite the collection window which was centered 18 cm downstream of the lower diode window. The fluorescence signal was collected by a pair of F/1, 10 cm diameter plastic Fresnel lenses which were protected from channel radiation by an intervening shield of heat-absorbing glass. The fluorescence radiation was spatially filtered by a field stop aperture 8 mm x 1 mm, collimated, spectrally filtered by a narrow band interference filter and detected by a photomultiplier. A filter was employed rather than a monochromator to make a compact system. Coherent (phase-sensitive) detection was employed using a lock-in amplifier.

To tune the laser to the required pump transition wavelength, the output beam could be directed by a subsidiary mirror to a $3/4 \text{ m}$ grating monochromator. However this procedure did not allow the tuning to be continuously monitored during the experiment.

To help understand and isolate the various sources of background noise, the signal output from the lock-in amplifier was recorded for three conditions of excitation for each test condition, namely with the laser tuned, with the laser blocked, and with the laser detuned. With the laser blocked the noise is due to background plasma (and wall) radiation; with it detuned one has additional noise due to elastically scattered laser light from plasma and walls, while with the laser tuned one has the fluorescence signal superimposed on the noise. Additionally the laser power was monitored for fluctuations.

Figure 2.7 Schematic diagram of the diagnostics channel and tail section.

Figure 2.8 Optical configuration of LIF diagnostic for diagnostics channel experiments.

Test runs were made with seeded ethanol burned stoichiometrically at a mass flowrate of 0.114 kg/s and at N_2/O_2 ratios of 1.0 or 0.5. The sodium seed concentration (0.5% NaOH by weight in the fuel) was ten times that used in the LOS measurements. Tests were made without and with potassium seed (7% KOH by weight in fuel) to determine what fraction of the background radiation was due to potassium.

Three test series were run on separate days. The first two were checkout experiments in which the signal/noise performance was investigated and improved. In these experiments a modulation (carrier) frequency of 25 kHz was used, and it was found that a principal source of noise was due to the fluctuations in the background emission which persisted up to at least 80 kHz. Consequently, for the third series the modulation frequency was increased to 100 kHz (the maximum of the lock-in). The final detection bandwidth was 400 Hz.

A summary of the LIF data on the third test is shown in Table 2.5. The rms fluctuation intensity with the laser tuned is larger than with it detuned, which is in turn larger than with it blocked. This is as expected, but comparing the tuned-detuned values, whose difference represents the fluorescence signal, it is seen that the S/N ratio is relatively low, and is rather worse in the presence of potassium. The fluctuation intensities from the diode signals are probably low due to the presence of thermal radiation from the far channel brick liner. The background emission measurement is made with the laser beam blocked and without the lock-in amplifier, and is effectively a line-of-sight averaged measure of the plasma luminosity in the spectral bandpass of the interference filter.

The last three lines in the table show the percentage of the laser power absorbed, the percentage scatter, i.e., the increase of the mean fluorescence signal between the laser detuned and the tuned conditions, and the background to fluorescence ratio. The latter is the ratio of the mean background signal (laser blocked) to the mean fluorescence signal (laser tuned - laser blocked), which lies in the range 100-400. It is the shot noise associated with the mean level of the background emission which is the principal noise limitation of the measurement technique.

Table 2.5

Summary of data from LIF demonstration experiments.

Run Series		E1	E2	E3	E4	E5
N_2/O_2 (mass)		1.0	1.0	1.0	1.0	0.5
Seed		Na	Na	Na	Na+K	Na+K
Excitation Wavelength (nm)		568.26	568.26	568.82	568.26	568.26
Obscuration Disk		no	yes	no	no	no
Fluctuation Intensities (%rms)	Tuned	18.2	20.7	20.9	31.7	19.7
	Blocked	9.9	13.8	5.9	13.7	14.1
	Detuned	10.1	17.2	6.7	27.0	17.8
	Background Emission	16.8	13.0	17.1	17.1	12.2
	Upper Diode	9.7	8.8	9.6	8.4	3.6
	Lower Diode	7.6	5.9	6.6	5.2	2.3
Absorption (%)		4	5	10	5	5
Scatter (%)		5	13	7	22	18
Background-to-Fluorescence		180	190	100	250	400

Despite the relatively low signal to noise, significant cross-correlations were obtained between the fluorescence signals and those from the lower diode signals, and it was demonstrated that the LIF technique is feasible under combustion MHD conditions. Additionally, a number of factors related to the performance of the LIF technique were evaluated, which indicated modifications to give improved performance and which were incorporated in the later experiments in the M-2 generator channel described below.

2.2.4 Experiments with the LIF Technique in the M-2 Generator

For these measurements the LIF apparatus was modified as shown in Fig. 2.9. A monochromator was added to allow continuous monitoring and exact tuning of the laser frequency. Also, the narrow band interference filter was replaced by a second monochromator whose passband could be set much narrower than the filter. This accomplished two things. First it gave better rejection of elastically scattered light at the laser wavelength; second it narrowed the spectral bandwidth of the background radiation accepted into the detector, and hence lowered the associated shot noise level.

A plan section of the M-2 generator set up is shown in Fig. 2.10. The LIF diagnostic was set up to measure near the exit of the generator section, with the laser beam passing vertically through the channel centerline. Open ports were used with suction on the exhaust. Additional diagnostics included sidewall voltage pins at the seventh electrode pair, electrode current monitoring and a microphone pressure probe in the plenum.

Three test series (FGH) were run in the M-2 generator. The generator operating conditions are summarized in Table 2.6, where p_n is the nozzle pressure and p_u and p_d are the pressures upstream and downstream of the open ports at the LIF measurement station.

In the measurements, the laser beam had a power of ~ 100 mW, was modulated at 100 kHz, and was tuned to the 568.82 nm transition, fluorescence being observed in a monochromator bandwidth of 0.06 nm on the 568.26 nm transition. The final detector bandwidth was 400 Hz for the fluorescence apparatus and 10 kHz for the other diagnostics.

Figure 2.9 Optical configuration of the LIF diagnostic for M-2 generator experiments.

Figure 2.10 Fluorescence optics in the M-2 generator configuration.

Table 2.6

Basic conditions for LIF experiments in the M-2 generator.

Date	Run Series	$\dot{m}$ (kg/s)	N ₂ /O ₂ (mass)	NaOH (wt.%)	KOH (wt.%)	P _n (Pax10 ⁻⁵)	P _u (Pax10 ⁻³)	P _d (Pax10 ⁻³)	B (T)	j (A/cm ²)
5/ 7/79	F1	0.11	1.00	4.5	0	2.8	1.8	4.8	0	0
5/ 7/79	F2	0.11	1.00	1.5	0	2.8	1.8	5.1	0	0
5/ 7/79	F3	0.11	1.00	1.5	0	2.8	1.8	5.4	1.8	0
5/10/79	G1	0.09	0.75	2.9	0	2.4	3.9	6.9	0	0
5/10/79	G2	0.16	0.75	2.9	0	6.9	2.0	8.2	0	0
5/10/79	G3	0.09	0.50	2.9	0	3.1	3.2	6.1	0	0
5/10/79	G4	0.09	0.75	2.9	0	2.4	3.1	5.7	0	0
5/10/79	G5	0.09	1.00	2.9	0	2.1	2.8	5.4	0	0
5/15/79	H1	0.09	1.00	5.0	0	4.1	3.7	7.8	0	0
5/15/79	H2	0.09	1.00	5.0	0	4.1	2.8	3.7	0	0
5/15/79	H3	0.09	1.00	5.0	0	4.1	1.8	3.2	0	0
3/15/79	H4	0.09	1.00	5.0	0	4.1	2.0	3.0	0	0
5/15/79	H5	0.09	0.75	5.0	6.0	4.8	1.4	3.9	1.8	0
5/15/79	H6	0.09	0.75	5.0	6.0	4.8	1.4	3.9	1.8	0
5/15/79	H7	0.09	0.75	5.0	6.0	4.8	1.5	3.9	1.8	1.6
5/15/79	H8	0.09	0.75	5.0	6.0	4.8	1.4	3.9	0	0
5/15/79	H9	0.09	0.75	5.0	6.0	4.8	1.4	3.9	0	2.0
5/15/79	H10	0.09	0.75	5.0	0	4.8	1.4	3.9	0	0
5/15/79	H11	0.09	0.75	5.0	0	4.8	1.4	4.2	0	0
5/15/79	H12	0.09	1.00	5.0	0	4.1	1.9	3.5	0	0
5/15/79	H13	0.09	1.00	5.0	0	4.1	1.9	3.5	0.7	0
5/15/79	H14	0.09	1.00	5.0	0	4.1	1.9	3.5	1.8	0

Table 2.7

Summary of LIF results from the M-2 generator experiments.

Run Series	F _{rms} (%)	S/N	E _{rms} 568.26 nm (%)	E _{rms} 567.2 nm (%)	τ _F (ms)	τ _E (ms)	-ρ _{FE}	B/F	τ _{opt}
F1	10.1	1.9	13.9	---	0.7	0.6	0.70	66	1.37
F2	11.1	1.5	10.0	---	0.6	0.6	0.66	69	0.51
F3	12.2	1.6	11.8	---	0.7	0.7	0.67	60	0.43
G1	12.9	2.6	13.9	---	---	1.4	0.39	107	1.29
G2	8.9	1.2	8.7	---	0.7	1.5	0.42	52	1.26
G3	10.7	2.6	11.8	---	1.7	4.7	0.68	70	1.54
G4	11.3	1.6	13.1	---	2.9	3.6	0.52	57	0.70
G5	8.1	2.1	11.1	---	2.0	1.7	0.71	32	0.53
H1	11.4	2.4	15.2	---	0.9	1.7	0.66	40	---
H2	10.5	2.0	---	---	1.8	1.9	0.69	54	---
H3	9.2	1.9	13.3	---	1.4	4.0	0.65	47	---
H4	10.4	2.3	15.1	11.9	0.8	0.6	0.78	43	0.98
H5	10.3	2.0	14.4	---	0.7	0.7	0.66	63	1.12
H6	8.6	1.6	9.7	8.8	0.8	1.4	0.61	58	1.03
H7	7.8	1.4	7.7	---	1.5	2.6	0.37	74	1.47
H8	9.7	1.8	11.9	8.2	1.2	2.3	0.70	65	1.31
H9	7.7	1.4	9.2	---	0.6	1.8	0.39	76	---
H10	7.6	1.5	10.0	8.5	0.8	2.5	0.49	62	1.51
H11	8.0	1.6	10.7	---	2.5	3.1	0.49	57	1.51

In the third series (H), a fourth signal was recorded in addition to those with the laser beam tuned, blocked and detuned. This fourth signal was taken with the laser tuned but with the monochromator detuned to 567.2 nm, so as to isolate the noise due to continuum plasma emission from that on the 3p-4d line. Also, in the third series, experiments were made to investigate the effect of Zeeman splitting of the spectral lines, due to the magnetic field, on the technique.

Results from the LIF diagnostic in the M-2 channel are summarized in Table 2.7. Included in the table are fluorescence fluctuation intensities (F_{rms}), their signal-to-noise ratios (S/N), background emission fluctuation intensities (E_{rms}), fluorescence and background emission integral time scales (τ_F and τ_E), maximum cross-correlation coefficients between the fluorescence and background emission signals (ρ_{FE}), background-to-fluorescence ratios (B/F) and average optical depths (τ_{opt}). The B/F ratio was noticeably improved over the earlier measurements in the diagnostic channel. The fluorescence fluctuation intensities were obtained at tuned laser conditions. The S/N ratio was the ratio of these fluctuation intensities to those from corresponding blocked (or detuned) laser conditions. For some run series, both total background emission (568.26 nm) and continuum component background emission (567.2 nm) fluctuation intensities were measured. The average optical depth τ_{opt} was a parameter calculated from the absorption of laser power by the plasma at 568.82 nm (path length ~ 10 cm). A reduction of optical depth (and of the fluorescence signal) with increasing magnetic field was observed, as expected on the grounds of Zeeman splitting of the pumped line.

Mean value measurements of the components of the background emission signal in the third experiment found the signal to be approximately 65% continuum emission and 35% line emission. Background measurements taken with no seed in the plasma also suggested that approximately 15% of the continuum or 10% of the total radiation came from the opposite sidewalls.

Noise levels obtained from the LIF diagnostic were consistent with those expected from shot noise in the detection bandwidth (400 Hz) due to background emission in the spectral bandwidth accepted by the monochromator.

The background emission signal was found to be primarily "continuum" radiation which appeared to be radiation from the far wings of the sodium resonance 3s-3p lines (589.0, 589.6 nm). These are only ~ 20 nm from

the 3p-4d transitions used for the LIF diagnostic and are quite broad for the sodium concentrations and path length involved [2.8]. Noise from this source appears to be the basic limitation of the LIF diagnostic in the form utilized here.

Typical frequency spectra of the fluorescence signal and of the shot noise due to the background emission are shown in Fig. 2.11. Significant cross-correlations were observed between the current signal from electrode pair #7 and both the fluorescence and background emission signals. Correlations between current and background emission signals were significantly stronger than correlations between current and fluorescence signals in cases both with and without magnetic fields. No significant correlations were observed between the plenum pressure probe signal and either the fluorescence or the background emission signal. Comparing the results of the local measurements from the fluorescence signals and the LOS-averaged measurements obtained from the background emission signals, there were many similarities. Both were predominantly low frequency fluctuations which had approximately Gaussian probability density distributions and generally strong correlations were obtained between the two signals. RMS fluctuation intensities of the two signals were of comparable magnitudes, and trends involving the effects of window pressure drop and current density on fluctuation levels were similar. The different degree of correlation obtained between each of the two signals and the electrode current signal, however, suggested that some characteristics of the fluctuations may have depended upon the size of the measurement volumes. In particular, the local fluorescence fluctuations appeared to be less related to the global current fluctuations than were the intermediate volume background emission fluctuations. This result suggested that there may also have been significant differences between local and LOS conductivity fluctuations in the M-2 generator.

Results from the LIF experiments identified three factors which significantly affected conductivity fluctuations in the M-2 generator. These included the degree of suction at the window, the current density in the channel and the N_2/O_2 ratio in the combustor.

Increasing pressure drops across the channel windows appeared to increase fluorescence fluctuation levels. With sufficiently large pressure drops, beam wander also became a problem. The trends were consistent with

Figure 2.11 Frequency spectra of the fluorescence and background emission shot noise signals from the LIF diagnostic during run series H1. Low-pass filters were set to 1 kHz.

the general notion that larger suction inflows through the windows would create more disturbances in the plasma.

The decrease in fluorescence fluctuation levels observed with moderate current densities appeared to be related to Joule heating in the plasma. The decreases in the fluctuation intensities were primarily the result of increased mean fluorescence signals when the current was applied. Absolute fluctuation levels remained relatively constant; thus, the currents may have heated the plasma without altering its non-uniformities. Temperature increases in the plasma core estimated from the mean fluorescence signals were of the order of 30 K.

No discernible trends related to the N_2/O_2 ratio were found in the absolute fluorescence and background emission fluctuation intensities; however, integral time scale ratios of the two signals appeared to show a pattern. At constant mass flowrate and window pressure drop, decreasing N_2/O_2 ratios produced smaller integral time scale ratios (τ_F/τ_E). This trend is probably the result of changes in the nonuniformity length scales as the N_2/O_2 ratio was varied. It is consistent with the conclusions drawn from the LOS experiments, regarding the dependence of transverse length scales on combustor flow patterns, as determined by input swirl.

2.2.5 Nature of Conductivity Inhomogeneities in the Stanford M-2 System

The results of the work reported in this section allow one to characterize the conductivity inhomogeneities in the Stanford M-2 Combustion MHD system briefly as follows.

Conductivity fluctuations inferred from optical measurements in the M-2 combustion system were predominantly low frequency (< 1 kHz) fluctuations without periodicities. Such fluctuations were indicative of conductivity nonuniformities with relatively long axial length scales (0.1 to 1.0 m). Transverse length scales, inferred from cross-correlation coefficients of signals from line-of-sight optical diagnostics, were also relatively large (0.01 to 0.10 m), and these length scales appeared to depend upon the N_2/O_2 ratio in the M-2 combustor. Smaller scale non-uniformities, such as those associated with the dissipative length scales of turbulence, did not appear to be significant.

Magnitudes of conductivity nonuniformities corresponded to conductivity fluctuation intensities of the order of 10% rms. These fluctuation intensities were only weakly dependent upon combustor and generator conditions, and they were similar for local and line-of-sight averaged measurements. The conductivity fluctuations appeared to be principally related to temperature nonuniformities which were convected with the mean plasma flow, and probability density functions of the fluctuations had approximately Gaussian distributions.

An impression of the shape of conductivity nonuniformities is shown in Fig. 2.12. The nonuniformities appear to resemble the "streamers" defined by Shamma, et al. [2.11]; long axial length scales were distinguishing features. Aspect ratios (ratios of two transverse length scales) of the nonuniformities could not be determined from the present data; however, correlations obtained between various conductivity related fluctuations suggested that the nonuniformities had broad distributions of length scales.

The most prominent trend in the data from the nonuniformity experiments was the dependence of transverse length scales on the N_2/O_2 ratio. These data prompted a subsequent experiment by Craig Wynn in which the flow conditions and diagnostics were chosen to investigate the N_2/O_2 ratio effects on conductivity nonuniformities. The results confirmed and extended those reported above on the effect of N_2/O_2 ratio on transverse length scales. One new trend from the data was that at constant mass flowrate, the strength of transverse correlations (or the magnitude of transverse length scales) peaked near a N_2/O_2 ratio of 1.25 with sharp declines at higher and lower N_2/O_2 ratios. Data with fixed fuel and oxygen flowrates exhibited similar trends, but the declines in correlation coefficients at lower N_2/O_2 ratios were less pronounced. The combined results suggested a strong influence of the N_2/O_2 ratio on transverse length scales with weaker effects associated with the individual combustor flowrates.

The dependence on N_2/O_2 ratio is most probably related to the changing swirl, atomization and mixing mechanisms in the M-2 combustor and plenum. The longer transverse scales (higher transverse correlations) at $N_2/O_2 \approx 1$ corresponding to zero net swirl suggest that larger nonuniformities occur with no net swirl, and that the increased swirl at

AXIAL LENGTH SCALES

$$0.1\text{m} < l_a < 1.0\text{m}$$

TRANSVERSE LENGTH SCALES

$$0.01\text{m} < l_t < 0.10\text{m}$$

Figure 2.12 Generalized appearance of conductivity nonuniformities in the M-2 combustion system. The distinct boundaries of the nonuniformities are drawn to depict the various length scales; experimental data suggest that these boundaries are actually gradual transitions.

lower or higher N_2/O_2 ratios produced smaller scale inhomogeneities. These results are consistent with observations by Owen, et al. [2.12] and by Kerr [2.13]. However the specific details of the nonuniformities in swirl-stabilized spray combustors is probably very dependent on the particular configuration and operating conditions.

2.3 Measurements of Fluctuations in the Stanford M-2 Channel

Experimental Arrangement and Procedure

The experiments, which were conducted utilizing Stanford's M-2 MHD facility consisted essentially of the simultaneous measurement of steady-state and fluctuating quantities within the MHD system as a function of generator electrical configuration and flow conditions [2.14,2.15,2.16]. Measurements were made of the inherent oscillations in plasma pressure, electrode current, and transverse electric field, at three axial locations within the generator channel. The fluctuations in the combustor plenum pressure and in the total core Hall voltage were also obtained. The position and orientation of these measurements are presented in Fig. 2.13.

The fluctuations in electrode current were measured from current shunts located in the electrode pair load line. The electric field measurements were taken from iridium voltage pins placed in the insulator wall of the channel. Pressure fluctuations were measured with the special probe tube microphone previously described. All signals were simultaneously recorded on a multitrack analog tape recorder for post-test statistical analyses.

The majority of the experimental conditions were run with the generator operating in the normal segmented electrode Faraday configuration and experimental results that follow apply for this case. Measurements were made for various values of applied magnetic field strengths and current densities. External battery supplies were used both to augment generator current during normal applied magnetic field operation and also to permit the study of fluctuating quantities under purely applied current (no magnetic field) operation. Two major series of experiments were performed -- one in December 1976, and the other in July 1978. Some flow conditions were duplicated in order to check the reproducibility of earlier results. A summary of the basic parameters of the more recent series of experiments is presented in Table 2.8.

Post-test analyses of the fluctuation signals were performed by digitizing the analog data stored on the magnetic tape unit through the analog/digital converter unit and then applying various statistical computations on a computer. Statistical calculations included the rms

Figure 2.13 Position of fluctuation measurements. Inherent fluctuations in electrode current (I), transverse electric field (V) and pressure (P) were measured at three electrode locations. Generator channel dimensions: channel height $h = 10$ cm, channel width $w = 3$ cm, distance between measurement locations $l = 19$ cm.

Table 2.8

Parameters of the July 1978 magnetoacoustic tests.

EXPERIMENT	$\dot{m}$ [lbm/s]	N ₂ /O ₂	u_c [m/s]	M	T _c [K]	σ_c [mhos/m]	J [A/cm ²]	B [T]
IV,V	.15	0	200	.19	~ 2800	10	0 - 1.1	0,2.,2.4
II	.20	0	270	.25	~ 2850	15	0 - 1.5	0 - 2.4
III	.30	.25	410	.39	~ 2800	15	0 - 1.4	0 - 2.4
II	.40	.50	540	.52	~ 2750	12	0 - 1.5	0,2.4
V	.60	.50	710	.69	~ 2750	-	0 - 1.1	0,2.4

Terminology:

$\dot{m}$ - total mass flowrate
 N₂/O₂ - ratio of injected nitrogen to oxygen (by mass)
 u_c - experimentally derived core velocity
 M - computed Mach number
 T_c - analytically derived core temperature
 σ_c - experimentally derived core conductivity
 J - range of average current density
 B - range of applied magnetic field

Additional Parameters:

reactants - ethanol and stoichiometric oxygen, injected nitrogen, and 1% potassium seed by weight
 13 segmented electrode pairs
 generator cross sectional area - 3 cm x 10 cm
 generator length - 50 cm
 pressure ~ 1 atm
 density ~ .12 kg/m³
 electrode length to pitch ratio - .5
 electrode surface temperature ~ 1200 K

value, the probability distribution, the autocorrelation function, the spectral density function, the coherency and relative phase functions, and the cross-correlation coefficient. The fast Fourier transform (FFT) was employed where applicable. Generator steady-state performance values were measured in a time-averaged manner by a VIDAR scanning unit and were reduced on the computer. Steady-state values were used to provide relative fluctuation levels.

Experimental Results

The range in values of the relative fluctuation levels, normalized by the background steady-state (time-averaged) values, were as follows:

- Pressure $P'/P_0 \sim .1\% - .7\%$. Larger at high $\vec{J} \times \vec{B}$ and at higher mass flow rates.
- Electrode current $I'/I_0 \sim 1\% - 6\%$. Larger near short circuit.
- Transverse voltage $V'/V_0 \sim 2\% - 10\%$. Larger at high $\vec{J} \times \vec{B}$.
- Total Hall voltage $V'_H/V_{H_0} \sim 3\% - 5\%$. Larger at high $\vec{J} \times \vec{B}$.

Results of extensive analyses of the data are summarized below for four basic modes of operation.

Noninteraction, background measurements ($J=0$), $B=0$). With the generator maintained at open circuit with no applied magnetic field the normal background fluctuations may be studied:

- The pressure fluctuations were found to be predominantly acoustic, and acoustic standing wave resonances were exhibited. A typical frequency spectrum of pressure for this case is shown in Fig. 2.14. Characteristic frequencies are observed. The pressure signals correlated strongly from one axial position to another with maximum correlation near zero delay time indicating that the pressure signals are predominately acoustic. ("Hydrodynamic" noise would be expected to correlate poorly in the axial direction and, if correlated, to show a convective nature.) The relative phase between the coherent (correlated) axial pressure measurements indicated an in-phase then out-of-phase behavior that is characteristic of acoustic standing waves.

Figure 2.14 Frequency spectrum of upstream pressure during operation at open circuit with no applied magnetic field. Mass flow conditions $\dot{m} = .15 \text{ lbm/s}$, $N_2/O_2 = 0$.

- The characteristic frequencies in pressure can be associated with system acoustic resonances. The natural frequencies of the M-2 MHD facility including combustor, plenum, MHD channel, diffuser, and exhaust ducts were calculated assuming plane wave acoustics. (Effects of fluid motion and steady state property gradients were neglected.) The first calculated system resonances (49 Hz, 94 Hz) and the first calculated channel resonances (530 Hz, 905 Hz) compare with the experimentally observed low frequency (~10 Hz, ~40 Hz, ~75 Hz) and high frequency (~600 Hz, ~1000 Hz) peaks resp. in the pressure spectra. The very low frequency mode experimentally observed at ~10 Hz may be due to a low grade combustor instability or to resonances in the exhaust scrubber system not included in the theoretical calculation.
- The voltage pins registered small fluctuations in plasma potential.

Open circuit generator measurements ($J=0$, $B \neq 0$). With the generator operated at open circuit with applied magnetic field, the voltage measurements (through the velocity induced electric field) provide an indication of the inherent velocity fluctuations.

- The applied magnetic field was observed to have a negligible effect on the character of the background pressure fluctuations.
- Transverse voltage fluctuations were induced by the velocity oscillations associated with the acoustic waves. For this case the transverse voltage measurements exhibited characteristic frequencies similar to those observed in the pressure. (See Fig. 2.15.) The transverse voltage signals correlated strongly in the axial direction and showed acoustic standing wave behavior similar to that of the pressure measurements. The pressure and transverse voltage at the same location showed a strong coherence (correlation as a function of frequency) and an approximate ± 90 degree phase relationship as would be expected between pressure and velocity fluctuations with normal acoustic standing waves. Velocity amplitudes calculated from the measured induced voltages compared reasonably with the velocity amplitudes expected to be associated with the measured level of acoustic pressure.
- The induced voltage measurements showed that the acoustic waves were axial. The voltage signals correlated strongly in magnitude and phase in

Figure 2.15 Frequency spectrum of middle voltage measured from top to bottom voltage pins during operation at open circuit with applied magnetic field. Mass flow conditions $\dot{m} = .15 \text{ lbm/s}$, $N_2/O_2 = 0$.

the transverse direction indicating the acoustic waves were one-dimensional. The voltage readings became more acoustic-like with increasing separation between transverse voltage pins indicating the existence of local small-scale voltage disturbances (perhaps due to turbulence) which average out over space.

No magnetic field, externally powered generator measurements ($J \neq 0$, $B=0$).

With the generator subjected to an applied electric field and with no applied magnetic field (thus no induced voltages), voltage and electrode currents respond primarily to the plasma conductivity.

- Applied current had a negligible effect on the character of the background pressure fluctuations.
- Electrode current measurements demonstrated the presence of convected conductivity nonuniformities. Frequency spectra of electrode current for this case are smooth, exhibiting no characteristic peaks. The energy is contained primarily in low frequencies ($\lesssim 200$ Hz) and decreases with increasing frequency. A typical electrode current spectrum is shown in Fig. 2.16. As shown in Fig. 2.17, the current fluctuations are strongly correlated in the axial direction with maximum correlation lag times corresponding approximately to the flow time. Electrode arc noise would be independent from one electrode pair to another and would be expected to correlate poorly.)
- Transverse voltage measurements demonstrated the presence of convected conductivity nonuniformities. For this case, the voltage signals showed features similar to those exhibited by the electrode current. The voltage measurements were somewhat less low-frequency dominated than the electrode current.
- The convected conductivity nonuniformities were three dimensional. The electrode current, which represents an integrated response to the spatial conductivity distribution, correlated poorly with the internal voltage pin measurements. Voltage fluctuations correlated weakly in the transverse direction. The conductivity nonuniformities were concluded to have transverse length scales of the order of or less than the voltage pin separation ~ 1 inch. Autocorrelation analyses of the voltage data indicated the axial length scale of the conductivity nonuniformities to

Figure 2.16 Frequency spectrum of upstream electrode current during operation with applied current and no applied magnetic field. Mass flow conditions $\dot{m} = .15 \text{ lbm/s}$, $\text{N}_2/\text{O}_2 = 0$.

Figure 2.17 Cross-correlation coefficient between upstream and downstream electrode currents for applied current ($J = .75 \text{ A/cm}^2$) and no applied magnetic field ($B = 0.0\text{T}$). Mass flow conditions $\dot{m} = .3 \text{ lbm/s}$, $N_2/O_2 = .25$. Time scale 0.5 ms/div .

be ~.1 to 1. meter. The disturbances are thus elongated in the axial direction.

- The convected conductivity nonuniformities were found to have no associated pressure component. Pressure and electrode current measurements taken at the same location showed a very weak correlation. The same weak correlation existed between pressure and transverse voltage. The conductivity fluctuation amplitudes that would accompany the background acoustic oscillations were much too small to account for the observed electrical fluctuations for this case.

Interaction generator measurements ($J \neq 0$, $B \neq 0$). For the generator operated in the normal applied magnetic field and current configuration, the following observations were made.

- At high external loading (near open circuit) the electrode current and voltage measurements demonstrated the influence of the acoustic oscillations (characteristic frequencies in the frequency spectra; high correlation between measurements at these frequencies).
- At high current densities (near short circuit) the electrode current and voltage measurements demonstrated the influence of the convected conductivity nonuniformities (smooth frequency spectra; convected axial correlation).
- An interaction exists between fluctuations in electrode current and pressure fluctuations during operation at high current densities (near short circuit) and applied magnetic field. As shown in Fig. 2.18, the upstream rms pressure fluctuation levels increased with increasing current density, up to a factor of approximately 4. The increase is greater upstream than downstream within the channel. As shown in Fig. 2.19 frequency spectra of the pressure measurements indicate that at high current density the low frequencies (≤ 100 Hz) increase in amplitude while the higher frequencies are relatively unaffected. At high current densities the spectra of the current fluctuations begin to show characteristic peaks in the low frequencies corresponding to those observed in the pressure spectra. Pressure and electrode current measured at the same location exhibit an increasing coherence (correlation) with increasing current density. At low frequencies the pressure and electrode current oscillations occur in phase but quickly go out of phase with

Figure 2.18 RMS pressure level measured at upstream generator location as a function of average current density for mass flow conditions $\dot{m} = .15 \text{ lbm/s}$, $N_2/O_2 = 0$.
 □ -12/76 exp, $B = 0$, ■ -12/76 exp, $B = 2.4T$
 ○ -7/78 exp, $B = 0$, ● - 7/78 exp, $B = 2.4T$.

Figure 2.19 Comparative frequency spectra of upstream pressure fluctuations show low frequency growth. Mass flow conditions $\dot{m} = .15 \text{ lbm/s}$, $\text{N}_2/\text{O}_2 = 0$.

increasing frequency. The correlation is strongest below ~ 400 Hz. A typical coherence between pressure and electrode current at high current density operation is shown in Fig. 2.20.

Conclusions

Based upon the preceeding experimental observations, the inherent background disturbances within the Stanford M-2 MHD system may be characterized as a combination of acoustic standing waves (as evidenced by the nature of the pressure and open circuit voltage measurements) and convected, three dimensional conductivity inhomogeneities (as evidenced by the nature of the voltage and current measurements during applied current operation). The appearance of the background disturbances is illustrated schematically in Fig. 2.21. The increase in rms pressure level that occurs with increasing current density during normal applied magnetic field generator operation appears to be caused by fluctuations in the $\vec{J} \times \vec{B}$ current-magnetic field interaction force that result from current fluctuations induced by the convected inhomogeneities in conductivity.

2.4 Application of Theory to Large-scale MHD Generators

The usual quasi one-dimensional time-dependent MHD fluid conservation equations were employed as a starting point to develop a theory with which to compare the experimental results reported above. A closed set of equations for both the fluid and electrical variables was obtained by including the circuit equations for an ideal MHD generator. These equations describe as special cases, the Faraday, Hall, and diagonal-wall electrical connections.

To proceed further, it was assumed that each variable could be written as the sum of a time-independent (or unperturbed) term and a time-dependent (or fluctuating) term, and that the second term was small. With this latter assumption, a closed coupled set of first order linearized differential equations was obtained that described the fluctuations. Assuming, further, that axial gradients in the unperturbed variables were

P#7 vs. I#7

Figure 2.20 The coherency function and relative phase function between middle pressure and middle electrode current during operation with current ($J = 1.1 \text{ A/cm}^2$) and with applied magnetic field ($B = 2.4\text{T}$). Mass flow conditions $\dot{m} = .15 \text{ lbm/s}$, $N_2/O_2 = 0$.

Figure 2.21 Representation of background inhomogeneities in the Stanford M-2 MHD facility channel. The disturbances consist of a combination of one dimensional, axial acoustic standing waves and three dimensional, convected conductivity nonuniformities.

sufficiently small, solutions of these equations of the form $\exp [i(kx + \omega t)]$ exist, provided the wave number k and angular frequency ω satisfy a dispersion relation $D(\omega, k) = 0$.

The cubic dispersion relation gives three complex wave numbers, k_j , for a given frequency ω . The real part of the wave number gives the propagation velocity of the wave while the imaginary part indicates the growth or damping of the wave with distance. The controlling equations, for a given wave number k_j , provide a dependent set of relationships between the perturbations in all thermodynamic and electrical quantities. For example, selecting the wave temperature amplitude, T_j , as the independent variable then a set of constants, α_{ij} , may be computed which relate the various associated thermodynamic and electrical oscillations, ξ_{ij} , to the temperature. (Note the α_{ij} may be complex.) A sum of the effects of the three waves permits all fluctuating quantities to be expressed in terms of the three wave temperature amplitudes in the form

$$\xi_i(x, t) = \sum_{j=1}^3 \alpha_{ij} T_j e^{i(k_j x + \omega t)}.$$

To apply this theory to the Stanford M-2 channel, it was assumed that the observed fluctuations were excited by time-dependent disturbances originating at the boundaries of the MHD channel — either upstream at the combustor-plenum, or downstream at the diffuser. Specification (as a function of frequency) of three boundary conditions serves to determine the values of the three temperature amplitudes T_j , and thereby, values for all the fluctuating quantities. A present lack of precise knowledge of the boundary conditions hinders a complete quantitative comparison between theory and experiment, but as shown elsewhere [2.15, 2.16, 2.17] many of the features of the experimental results can be explained on the basis of reasonable assumptions about the boundary conditions. As pointed out in the previous section, the conditions for the M-2 channel experiments corresponded to a relatively weak magnetic interaction, and the new phenomena observed could be explained without the need to consider strong interaction effects. The discussion that follows will be directed toward the more general question of the propagation characteristics of traveling waves in MHD generators operating at high magnetic interaction typical of proposed full-scale MHD power systems.

The wave numbers, k_j , and the relative property constants, α_{ij} , are functions of the generator operating conditions. For the case of no interaction (no current or magnetic field) the three traveling waves correspond to normal forward and backward acoustic waves and a convected entropy (temperature) wave. In general the three waves are referred to as the forward and backward "magnetoentropic" wave. At high magnetic interaction the three traveling waves may have propagation and property characteristics quite distinct from normal acoustic and entropy waves. An example of this behavior is presented in Fig. 2.22, where the real part of the nondimensionalized wave number for the down-stream propagating wave is shown plotted against frequency for various values of the magnetic interaction parameter. The magnetoacoustic and acoustic wave numbers are seen to differ primarily at low frequencies, and the frequency range of significant difference is seen to increase with increasing interaction parameter.

Calculations were made of the propagation characteristics for the three traveling waves in an ideal subsonic, full-scale MHD generator for the three fundamental electrode connections - Faraday, Hall, and 45° diagonal wall. The working fluid was taken to be the products of stoichiometric combustion of a "typical" coal seeded with one percent (by weight) of potassium, added in the form of potassium carbonate. Parameter and property values midway along the duct were as follows:

L (generator length)	= 20 m
M_o (Mach No.)	= 0.8
P_o (static pressure)	= 202.6 k Pa (2 atm)
T_o (static temperature)	= 2500° K
ρ_o (gas density)	= 0.29 kg m ⁻³
γ_o (ratio of specific heat)	= 1.160
α_o (electrical conductivity)	= 6.6 mhos m ⁻¹
μ_o (electrical mobility)	= .42 T ⁻¹
$\hat{M}_o$ (mixture molecular weight)	= 29.6 kg/kg-mole
a_o (sound speed)	= 903 m s ⁻²
S (interaction parameter — B_o in teslas)	= .64 B_o^2
Ω_o (Hall parameter — B_o in teslas)	= .42 B_o

Figure 2.22 The nondimensional downstream wavenumber $\hat{k} \equiv kL$ normalized on the pure acoustic nondimensional downstream wavenumber $\hat{\omega}/(1+M)$, for a near sonic ideal Faraday generator with load factor $K_F = .5$ as a function of interaction parameter ($S \equiv L/L_1 = \sigma_0 B_0^2 L / \rho_0 u_0$) and angular frequency ($\hat{\omega} \equiv \omega L / a_0$).

Typical values for the axial gradients were also selected, as shown below.

$$\frac{L}{A} \frac{dA}{dx} \text{ (cross-sectional area gradient)} = +1.0$$

$$\frac{L}{P_o} \frac{dP_o}{dx} \text{ (static pressure-gradient)} = -1.0$$

$$\frac{L}{T_o} \frac{dT_o}{dx} \text{ (static temperature gradient)} = -.02$$

$$\frac{L}{a_o} \frac{du_o}{dx} \text{ (velocity gradient)} = 0.0$$

Employing these conditions, the dispersion relation was solved for the complex wave number, for the three values of the nondimensional frequencies $\hat{\omega} = .139, 1.39, \text{ and } 13.9$, which correspond with cycle frequencies of 1 Hz, 10 Hz, and 100 Hz, respectively. These frequencies cover the range of the approximate first ordinary acoustic resonance frequencies of the MHD channel ($a_o/2 L \approx 25 \text{ Hz}$). For each frequency, solutions were obtained for values of the load factor in the range $0 \leq K \leq 1$ and values of the interaction parameters in the range $0 \leq S \leq 30$. (The upper limit for S corresponds to $B_o = 6.8T$).

In general, for values of the magnetic interaction, larger than about 5, the propagation characteristics of the three traveling-waves were quite distinct from the propagation characteristics of ordinary acoustic and entropy waves. The traveling-waves at higher magnetic interaction were such that they were not easily recognizable as being "magnetoacoustic" or "magnetoentropic" waves and could be referred to only as being three unique traveling-waves.

To obtain an indication as to what MHD generator operating conditions could lead to large inherent fluctuations as a result of traveling-wave amplification, plots were made of the load factor and magnetic interaction parameter combinations that resulted in "significant" amplification of at least one of the three traveling-wave types for one of the three frequencies investigated. Here, "significant" amplification was arbitrarily chosen as those instances where traveling-wave amplitude

increases by a factor of 100 or greater per one transit of the MHD generator length. Results for the Faraday, Hall and 45° diagonal wall configuration MHD generators are shown, respectively, in Figs. 2.23, 2.24, and 2.25.

The theoretical calculations indicate that significant traveling-wave amplification would be expected to occur in the Hall and diagonal wall MHD generators for values of the magnetic interaction parameters greater than about 5 regardless of the load factor. As shown in Fig. 2.23, however, significant amplification does not occur in the Faraday MHD generator operating at higher value of the load factors (high load resistance) even for large values of the magnetic interaction parameter. Since full-scale Faraday MHD generators are expected to operate with load factors of the order of about .7 for maximum efficiency, it appears from these theoretical calculations that full-scale Faraday MHD generators may be less susceptible to significant traveling-wave amplification.

Conclusions

Even though electromagnetic effects on the propagation of hydrodynamic traveling-waves may be weak in laboratory-scale MHD facilities ($S \leq 1$), the theoretical calculations show that these effects may be quite strong in proposed full-scale MHD facilities ($S \approx 5 - 30$). Qualitatively, the potential for significant traveling-wave amplification is greater for two-terminal MHD generator configurations (Hall and diagonal wall) than for the Faraday configuration. Physically, this behavior results from the fact that with the former connections, a large transverse current is always present, independent of the load. Also, in the Hall and diagonal wall configurations the Hall parameter plays a role in affecting the traveling-wave propagation characteristics in a manner that does not occur in the Faraday MHD generator configuration. Stability for the Faraday configuration is aided by the fact that energy from the axially-propagating traveling-waves is externally dissipated by the corresponding current fluctuations through the parallel load resistances.

Figure 2.23 Region of "significant" traveling-wave amplification for at least one of the three traveling-waves. Ideal Faraday MHD generator as a function of load factor and magnetic interaction parameter.

Figure 2.24 Region of "significant" traveling-wave amplification for at least one of the three traveling-waves. Ideal Hall MHD generator as a function of load factor and magnetic interaction parameter.

Figure 2.25 Region of "significant" traveling-wave amplification for at least one of the three traveling waves. Ideal diagonal-wall ($\phi = 45^\circ$) MHD generator as a function of load factor and magnetic interaction parameter.

3.0 BOUNDARY LAYER PHENOMENA

3.1 Development of Diagnostic Techniques for Boundary Layer Measurements

To obtain experimental data on the important parameters in the boundary layers of MHD generator channels, several diagnostic techniques were developed having high spatial resolution in a direction normal to the wall. For the investigation of the electrode wall boundary layer spectroscopic techniques were developed to measure the time-average profiles of plasma temperature and of electron concentration. For the study of the side-wall boundary layer, a laser anemometer was developed to measure the profile of the flow-directed velocity component, from which the time-average value and the turbulence intensity were obtained.

3.1.1 Temperature Measuring Technique

A widely-used method for measuring the temperature of high temperature flowing gases is the optical emission/absorption or spectroscopic line-reversal technique [3.1 - 3.3]. It has been used previously for temperature profile measurements in combustion MHD channels by Daily [3.4] and by Kirillov et al [3.5].

The basis of the method relies on Kirchoff's law which for a gas in local thermodynamic equilibrium states that the volumetric spectral radiance e_λ (watts/m³/steradian/m) is related to the spectral absorption coefficient α_λ (m⁻¹) by

$$e_\lambda = \alpha_\lambda I_\lambda^0(T_p) \quad , \quad (3.1)$$

where $I_\lambda^0(T_p)$ is the spectral radiance of black-body radiation at the plasma temperature T_p , given by the Planck function

$$I_\lambda^0(T) = \frac{C_1}{\lambda^5 (\exp(C_2/\lambda T) - 1)} \quad (3.2)$$

where $C_1 = 1.1909 \times 10^{-16}$ watt m² steradian⁻¹

$C_2 = 1.4380 \times 10^{-2}$ m.K.

are the first and second radiation constants

Experimentally, the plasma, suitably seeded with an alkali metal, is transilluminated by radiation from a calibrated tungsten lamp of known brightness temperature T_L and the radiant power $P = I_\lambda \delta A \cdot \delta \Omega \cdot \delta \lambda$ received from an area δA in a solid angle $\delta \Omega$ and in a spectral range $\delta \lambda$ is measured.

For a plasma slab extending from $x = 0$ to $x = \ell$, the spectral radiance of the exiting radiation $I_\lambda(\ell)$ is given in terms of that incident from the lamp, $I_\lambda(T_L)$ by the radiation transfer equation, which, neglecting scattering from macroscopic particles, and utilizing eq. (3.1) may be written

$$I_\lambda(\ell) = \exp - \tau_\lambda(\ell) \int_0^\ell \alpha_\lambda(x) I_\lambda^0(x) \exp \tau_\lambda(x) dx. \quad (3.3)$$

$$+ I_\lambda(T_L) \exp - \tau_\lambda(\ell)$$

where the optical depth is defined by

$$\tau_\lambda(x) \equiv \int_0^x \alpha_\lambda(x) dx. \quad (3.4)$$

In general, in an inhomogeneous plasma, α_λ is a function of x through the variation of gas composition and temperature, while $I_\lambda^0(T_p)$ is a function of x through the variation of $T_p(x)$. Also α_λ and I_λ^0 are functions of λ , with α_λ being a rapidly varying function in the vicinity of a spectral line.

For a plasma of uniform composition and temperature, eq. (3.4) can be written explicitly as

$$I_\lambda(\ell) = [1 - \exp - \tau_\lambda(\ell)] I_\lambda^0(T_p) + [\exp - \tau_\lambda(\ell)] I_\lambda^0(T_L) \quad (3.5)$$

Note that when the plasma is optically thick, $\tau_\lambda(\ell) \gg 1$, e. g. with heavy seeding or near the center of a strong spectral line, $I_\lambda(\ell)$ is due primarily to plasma radiation (first term) and originates mainly from the region near $x = \ell$; very little of the incident radiation (second term) penetrates to $x = \ell$. On the other hand when the plasma is optically thin, $\tau_\lambda(\ell) \ll 1$, e. g. with light seeding or remote from spectral lines, the plasma contributes little to $I_\lambda(\ell)$, and the incident radiation is transmitted with little attenuation.

There are various ways of using eq. (3.3) to implement the measurement of plasma temperature. For a uniform plasma, then when $T_L = T_p$ we have

$$I_\lambda(\ell) = I_\lambda^0(T_p) = I_\lambda^0(T_L) \quad , \quad (3.6)$$

independent of wavelength. This is called the reversal condition and experimentally, as the wavelength is changed by tuning a monochromator in the collection optics, the spectral line is "invisible" against the continuum background from the lamp, when the lamp is adjusted to $T_L = T_p$.

In MHD plasmas, where T_p is typically higher than the maximum temperature T_L (~ 2500 K) for stable lamp operation, an extrapolation scheme is used [3.4, 3.6]. By measuring the received powers P_L from the lamp alone (without the plasma), P_p from the plasma alone (with the lamp blocked) and P_{L+p} from the lamp and plasma, the plasma temperature can be shown from eq. (3.5) to be given by

$$T_p = T_L \left\{ 1 - \left(\frac{\lambda T_L}{C_2} \right) \ln \left[\frac{P_p}{P_p + P_L - P_{L+p}} \right] \right\}^{-1} \quad , \quad (3.7)$$

where the Wien approximation, $\exp(C_2/\lambda T) \gg 1$, has been used.

A disadvantage of this scheme is that the signal P_L must be obtained from a pre or post test calibration with the plasma absent, and it is difficult to maintain the system steady to the required accuracy over long periods.

An alternative scheme was devised to circumvent this problem, by tuning the monochromator to take measurements of P_p and P_{L+p} sequentially and continuously at two wavelengths i.e. at two optical depths. If the second wavelength is completely off the line ($\tau_\lambda = 0$), then $P_p = P_{L+p} = P_L$ and one could effectively use eq. (3.7). However it can be shown in general for any two wavelengths (or optical depths), the plasma temperature can be calculated from the four signals $P_p^{(1)}$, $P_{L+p}^{(1)}$, $P_p^{(2)}$, $P_{L+p}^{(2)}$ together with a relative calibration of the transmission of the optics and the sensitivity of the detector versus wavelength. For the case when the two wavelengths are close together, so that this calibration factor is effectively invariant, the temperature can be calculated from

$$T_p = T_L \left\{ 1 + \frac{\lambda T_L}{C_2} \ln \left[1 - \frac{P_{L+p}^{(1)} - P_{L+p}^{(2)}}{P_p^{(1)} - P_p^{(2)}} \right] \right\}^{-1} \quad (3.8)$$

Further details are given in the paper by James and Kruger [3.7].

For measurements in an MHD channel, where the walls have necessarily to be maintained below the core plasma temperature, the plasma is non-uniform along the line of sight. In particular, measurements of the electrode wall boundary layer profile are made using radiation passing through the sidewall boundary layers. When the optical depth is large, i.e. near line center or for heavy seeding, the collected emission is heavily weighted to the region near $x = \ell$, i.e., to the proximal boundary layer which is cooler than the core plasma. Under these conditions the spectral profile of the line has a central minimum flanked by maxima (at $\pm \Delta\lambda_{\max}$ from line center) on either side. The line is said to be self-reversed.

The implications of plasma non-uniformity on temperature measurements in MHD channel flows was investigated in some detail by Daily and Kruger [3.8]. Their basic result is that to obtain reliable measurements of the core temperature, the monochromator should be detuned into the line wing ($\Delta\lambda > \Delta\lambda_{\max}$) where the optical depth $\tau_\lambda(\ell) \approx 0.5$. Moreover they calculate the correction ΔT that must be added to the apparent, measured temperature as a function of optical depth, to obtain the core temperature. This correction is constant for $\tau_\lambda(\ell) \leq 0.5$ but increases rapidly for larger optical depths.

The actual correction to be applied depends on the particular circumstances, e. g. the core and wall temperatures, the core and boundary layer thicknesses, the seed (emitter) concentration, the boundary layer temperature profile shape and the emission line shape assumed, and must be calculated for the particular case. For instance for core and wall temperatures of 2600 K and 2000 K, core and boundary layer widths of 5 and 2 cm respectively, a sodium mass fraction of 0.01%, a (1/10)th power temperature profile and assuming a Voigt profile, the temperature correction is ~ 40 K (1.5%) provided $\tau_\lambda(\ell) \leq 0.5$. For the sodium resonance

(D) line at $\lambda = 5890 \text{ \AA}$, under these conditions $\Delta\lambda_{\text{max}} \approx 1 \text{ \AA}$ and the monochromator must be detuned $\Delta\lambda \approx 2.5 \text{ \AA}$ to $\lambda \sim 5887.5 \text{ \AA}$ to obtain an optical depth of 0.5. If the potassium resonance line ($\lambda = 7665 \text{ \AA}$) is used for the measurement, then because of the heavy seed concentration ($\sim 1\%$ by mass of K) the line is very broad and the monochromator must be detuned to a significantly greater amount to obtain an optical depth of 0.5.

A critical requirement set by the measurements of the electrode wall boundary layer was to achieve the highest practical spatial resolution and to make measurements as close to the electrode surface as possible. In the optical set up (Fig. 3.1) the tungsten ribbon lamp is imaged to the centerline of the channel, and this image is viewed by the collection optics. The spatial resolution is controlled by the area δA of the image that is viewed, and by the solid angle $\delta\Omega$ in which it is viewed. The former is determined by the field stop, which in practice is the entrance slit of the monochromator. The latter is controlled by the aperture stop which can be placed at any convenient point in the collection optics. Because monochromators are normally designed with vertical slits, and the electrode surface is horizontal, two mirrors were used to rotate the virtual image of the slit by 90° , as well as to facilitate access to the channel in the magnet.

The spatial resolution is set by the height of the bundle of collected rays at the proximal wall of the channel, and an analysis shows that for a given $\delta A \delta\Omega$ product (or étendue), which controls the collected power, the best resolution is obtained when this height is $\sqrt{2}$ times the height of the virtual image of the slit on the channel centerline. As δA and $\delta\Omega$ are reduced together (subject to the foregoing condition), the spatial resolution improves until one reaches a fundamental limit set by diffraction. At this limit, the spatial resolution for the width of the M-2 generator channel can be calculated to be $\sim 300 \text{ }\mu\text{m}$ (0.3 mm), and spatial resolution of this order was obtained in practice.

A consequence of designing for the highest spatial resolution is that the collected power is low and time resolution must be sacrificed to obtain adequate signal/(shot) noise for accurate measurements. Hence only time-average measurements were made.

Figure 3.1 Optical design for the ABL experiments.

Figure 3.2 Optical design for the IBL experiments.

The measurement of boundary layer profiles required an optical system having a variable object location, so that measurements could be made at different distances from the electrode surface. The optical scanning system should not only vary the position of the object location, but should do so such that the optical path moves parallel to the surface from which the boundary layer is developing, and such that the collection solid angle stays constant.

The first requirement will be met if a scanning mirror is placed at the focal point of the lens closest to the plasma. The second requirement will be met if an aperture stop is placed on the scanning mirror, or anywhere in the optical system on the detector side of the scanning mirror.

The scanning system described above was used in all the experiments to scan the measurement point perpendicular to the electrode surface.

In the apparatus used for temperature measurements with induced generator currents, additional components were used to obtain spatial distribution information in the axial (flow) direction. The axial distribution was obtained by using a linear detector array rather than a single detector. Since the slits of the monochromator have a virtual image in the boundary layer, with its long dimension lying along the flow direction, information from separate points along this line can be obtained simultaneously by using multiple detectors at the monochromator exit slit.

A schematic of the 2-D scanning system is shown in Fig. 3.2. A linear detector array was constructed for the 2-D scanning system by mounting 12 small fiber optics bundles in a line as close together as possible. The exit slit of the monochromator was imaged onto the linear detector array. The fiber optics had a 0.61 mm diameter, and each of the fiber optics bundles was routed to a separate photodiode detector.

The optical diagnostic system used repetitive scanning techniques to reject the effects of low-frequency system variations on the data. This was especially important when data were being taken with generator current, as it was difficult to maintain a steady current level over the several minutes required to measure a boundary layer profile. The repetitive variations due to the position scan, spectral scan, and chopper modulation were performed simultaneously. The N_e measurement (see below) required simultaneous variation of the

position scan mirror and the chopper. In the experiments with induced currents, the temperature measurement required simultaneous variation of the position scan mirror, the spectral scan mirror, and the chopper.

The effect of the simultaneous variation of two or three devices that affect the signal from the optical-system detector is that the signal is modulated at two or three frequencies. To recover the desired information the signal must be demodulated and time-averaged. This process was accomplished off-line by computer. The raw data were digitized and stored on magnetic tape for use with the demodulation software. The details of this procedure are given in James' thesis [3.9].

3.1.2 Electron Concentration Measurement Technique

In connection with the study of the electrode wall boundary layer, it is a matter of some interest to determine to what extent the plasma is not in local thermodynamic equilibrium. In particular the electron concentration may be elevated above the equilibrium value for the local temperature in the near-electrode region due to finite rate recombination kinetics. To study this question experimentally requires a technique capable of measuring the electron concentration with high spatial resolution.

The method selected employs a technique used by McGregor [3.10] and Daily [3.4] utilizing the high-lying lines of the potassium atom. It relies on the fact that the high-lying states, due to their close energy spacing to other nearby states and to the continuum, will be in equilibrium with the free electrons, even when the free electrons are not in equilibrium with the ground state potassium atoms. For the states in equilibrium with the free electrons, the number density of atoms with excited state N_j^+ can be related to the electron number density N_e and potassium ion number density N_K^+ by the Saha equation.

$$N_e N_K^+ = N_j \frac{g_i^+}{g_j} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} \exp(-\epsilon_{j\lambda}/kT) \quad (3.9)$$

where g_i^+ and g_j are the ion and excited state degeneracies and $\epsilon_{j\lambda}$ is the energy difference between the excited state and the ionization limit.

The number densities of these excited states are measured by performing an

absolute intensity measurement on radiation emitted from upper to lower state transitions, $N_j \rightarrow N_l$. The lower state is chosen to be a nonground state in order to minimize reabsorption of the emitted radiation. The upper state is chosen to be as close to the ionization limit of the potassium atom as is practical. In the present experiments, 6D-4P ($5360 \text{ \AA}$), 7D-4P ($5112 \text{ \AA}$), and 8D-4P ($4965 \text{ \AA}$) transitions were used. The following equation relates the population of the upper state to the measured absolute intensity S in the plasma:

$$N_j = \frac{4\pi S}{h\nu L A_{jl}} \quad (3.10)$$

where L is the path length of the plasma. This equation relies on the Einstein coefficient A_{jl} , a fundamental constant of the potassium atom which is only known to $\pm 50\%$ for the desired transitions. This limits the absolute accuracy of the diagnostic to $\pm 25\%$. The values of A_{jl} used were taken from Ref. 3.10.

The concentration of potassium ions N_K^+ is not exactly equal to the concentration of electrons due to the existence in combustion flows of negative ions, particularly OH^- . For this reason, N_K^+ is typically greater than N_e by about 10%. This effect is taken into account in the N_e data reduction by allowing that $N_K^+ = FN_e$, where F is obtained from an equilibrium computer calculation and is assumed independent of temperature over the range of interest.

The basic optical setup for the N_e measurement is identical to that used in the temperature measurement. The signal from a calibrated lamp is passed through the plasma, using a chopper to modulate the lamp radiation. The known intensity of the calibration lamp is used to determine a calibration factor K for the optical system, such that

$$I = KP$$

where I is the radiation intensity and P the photomultiplier output. The line strength S is determined from

$$S = \int_{\nu_0 - \Delta\nu}^{\nu_0 + \Delta\nu} I \, d\nu = \int KP \, d\nu = KS \quad (3.11)$$

where S is signal with the lamp blocked.

Combining eqs. 3.9 - 3.11, and the electron attachment correction $N_k = FN_e$, an expression is derived for N_e in terms of fundamental constants and the experimental quantities, K , s , T , and L .

$$N_e = \left[\frac{4\pi Ks}{Fh\sqrt{LA}} \frac{g_i^+}{g_j} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} \exp\left(\frac{-\epsilon_{j\lambda}}{kT}\right) \right]^{1/2} \quad (3.12)$$

Note that a temperature measurement is required as part of the electron number density measurement. The temperature measurement was performed using the technique described above.

As in the temperature measurement, the N_e measurement is also affected by the existence of cool sidewall boundary layers, causing the measured N_e value to be lower than the centerline N_e value. A boundary layer correction procedure was applied that is similar to that used in the temperature measurement described above.

3.1.3. Velocity Measuring Technique

Laser anemometry affords a powerful non-intrusive technique for measuring flow velocity in high temperature gases with high spatial resolution [3.11, 3.12]. However its application to MHD channel flows poses a number of challenging problems related to the high temperature, high velocity and the difficulty of access.

In previous work [3.13] at Stanford, a laser anemometer in a single beam backscatter configuration was used to make measurements in the electrode wall boundary layer of an MHD generator [3.4]. For measurements in the insulating side wall boundary layer a crossed-beam, forward scatter instrument was developed which capitalized on the possibility of optical access through the electrode walls.

In the crossed-beam configuration, shown in Fig. 3.3, two beams of equal intensity derived from the same laser are caused to intersect at their common focus at a small angle ψ . In the measurement volume common to both beams, a pattern of standing waves or fringes are found with fringe spacing

$$\begin{aligned} \lambda_F &= \lambda_0 / 2 \sin (\psi/2) \\ &\sim \lambda_0 / \psi \quad (\text{when } \psi \ll 1) , \end{aligned} \quad (3.13)$$

Figure 3.3 Differential scatter geometry.

where λ_0 is the free space wavelength of the laser. The normal to the plane of the fringes is perpendicular to the common axis of the incident laser beams.

A small particle passing through the fringe volume scatters a pulse of light which is amplitude modulated at a (Doppler) frequency

$$f_D = u/\lambda_F \quad (3.14)$$

where u is the velocity component normal to the fringes. Thus the velocity sensitive direction is perpendicular to the bisector of the incident-beams and lies in their plane.

For the high velocities of interest for MHD flows, it is necessary to make the angle ψ small, so as to keep f_D in the range (≤ 50 MHz) set by the bandwidth of photomultiplier detectors. In the present work an Ar^+ laser ($\lambda = 514.5$ nm) was used with $\psi \sim 2^\circ$. Hence $\lambda_F \sim 15$ μm and $f_D \sim 30$ MHz for $u \sim 450$ m/s.

The scattered light pulses can be detected either in forward scatter or backscatter. For particles of size on the order of the wavelength, the forward scatter signal amplitude is typically 100 times larger than that in backscatter and for that reason forward scatter was chosen as shown in Fig. 3.4.

Two parallel beams from beamsplitter B-S, were focused by lens L_1 and deflected by mirrors M_1 and M_2 to pass through the channel vertically via open ports in the lower and upper electrode walls, where they crossed to form a fringe volume at the center line of the side wall to which they were parallel. The geometry of the incident beams and the collection optics inside the channel are shown in Fig. 3.5.

The dimensions of the measurement volume were approximately 0.3 mm diameter by 4 mm long, and measurements were made to within ~ 0.5 mm of the sidewall. The position of the measurement volume could be scanned through the sidewall boundary layer by translating together the mirrors and lenses $L_1 M_1$ in the transmitting optics and $L_2 M_4$ in the receiving optics.

The signals detected by the photomultiplier were processed by a digital counter (TSI model 1096), which incorporates several signal validation logic circuits. The counter outputs validated signals, in binary

Figure 3.4 Optical arrangement.

Figure 3.5 Beam geometry in channel.

form, corresponding to the number of cycles of a crystal-controlled clock (400 MHz) for individual particles to cross eight fringes. These signals were inputted to a minicomputer (HP 2100) where they were inverted to give the velocities, and accumulated in blocks of 16 K. From each block the average velocity and turbulence intensity was then calculated, together with the velocity probability density function which was printed out on-line as hard copy. Figure 3.6 is a schematic of the data acquisition system, while Fig. 3.7 shows a typical print out of the velocity data.

To provide scattering centers the flow was seeded with ZrO_2 powder (mean size $\sim 1 \mu m$) fed into the ethanol fuel line in the form of a paste in glycerin from a syringe pump. Validated signal data rates as high as 6,000/sec were obtained at a feed rate of less than 1 g/min of ZrO_2 . Thus the data to produce velocity data in a plot such as Fig. 3.7 at a single station was ~ 3 secs.

Once the laser anemometer and data reduction system was optimized, it produced very reliable data and allowed the velocity profile in the sidewall boundary layer to be determined with high accuracy and high spatial resolution. Complete details of the measurement system are given in the report by Rankin [3.14].

Figure 3.6 Data acquisition system for laser anemometer.

Figure 3.7 Velocity probability distribution function--higher velocity.

3.2 Measurement of Joule Heating Effects in the Electrode Boundary Layer

Theoretical and experimental investigations concerning Joule heating effects in MHD electrode-wall boundary layers were performed. A simple integral model of the boundary layer showed that Joule heating can have a major impact on heat transfer and voltage drop in a large MHD generator, with voltage drop affected more than heat transfer for a $1/7$ th power enthalpy profile. A near-wall Couette flow model of the boundary layer demonstrated that Joule heating very near the wall can lead to a substantial increase in the wall heat flux, and that this increase is largely independent of boundary layer length scales.

Experimental measurements were performed of temperature and electron number density profiles on a laboratory scale MHD generator. Comparisons between calculations from the two-dimensional theory and measurements for cases without current generally showed good agreement when the turbulence model properly accounted for effects of free stream turbulence, though small discrepancies were observed between theory and experiments for the overall profile shape. Measurements of electron number density profiles indicated that some degree of nonequilibrium existed near the wall, but the effect was small. The degree of nonequilibrium measured was higher than that predicted from the two-dimensional theory. Comparisons of experimental temperature profiles without current to profiles with current showed a marked temperature increase in the boundary layer due to Joule heating. The magnitude of the increase was well predicted by the two-dimensional boundary layer theory. Measured temperature profiles with current and magnetic field did not agree with predictions. The predicted profile in the inner region of the boundary layer for a case with current and magnetic field was above a similar case without current, whereas measurements for anode boundary layers were below control profiles without current. A cathode boundary layer behaved opposite to the anode boundary layers. It was shown that three-dimensional recirculation induced by nonuniformities in axial current could perhaps explain the discrepancies.

As mentioned earlier, a DOE topical report [3.9] has been written on Joule heating effects and a complete description of the theoretical and

experimental work is given there. In the sections which follow a review of the analytical models is presented followed by the experimental results.

3.2.1 Theoretical Models of the Electrode Boundary Layer

The coordinate system used in the theoretical analysis of the electrode wall boundary layer is shown in Fig. 3.8. The distance between opposing electrodes is $2l$, and the distance between walls perpendicular to the magnetic field (these are the insulating walls in a Faraday generator) is $2w$. Both of these quantities may vary with x . A sign convention is maintained for heat fluxes such that a positive heat flux denotes energy flowing in the positive coordinate direction. This implies that the heat flux to the wall is ordinarily negative, as the walls are typically cooler than the plasma.

In all of the theoretical analyses in the present work, various general assumptions are made. Some of these assumptions are made to restrict the class of problems considered. Others neglect certain phenomena for which currently available models are either excessively complex or insufficiently accurate to justify their use in the present work. These general assumptions are enumerated below.

1. Diffuse-mode current transport
2. Non-slagging generator
3. Faraday-mode generator
4. Equations averaged over an electrode-insulator cycle
5. Radiation only minimally modeled
6. Two-dimensional boundary layer approximations are made
7. Cathode effects ignored
8. Turbulence effects on source terms ignored
9. Unity Lewis number assumed

Four models were considered beginning with a simplified integral boundary layer model which was useful for making estimates of effects and in gaining an intuitive feel for a problem. For this model an integral energy balance is performed in which

1. Radiation heat transfer is ignored.

Figure 3.8 MHD generator coordinate system and geometric definitions.

2. Magnetic field effects are ignored.
3. Free stream conditions are constant.
4. A core region exists in the generator in which all variables are constant in y . This implies that the heat flux is zero in the core. With these assumptions, an energy balance yields the following equation:

$$0 = q_w + \frac{d}{dx} \int_0^l \rho u h dy + \int_0^l \frac{J^2}{\sigma}$$

The enthalpy h is the stagnation enthalpy. The integration is performed from the wall ($y = 0$) to the channel centerline ($y = l$).

The solution of this equation is simplified by two further assumptions: (1) h equals h_∞ past a finite enthalpy boundary layer thickness Δ , and (2) Joule heating may be neglected for $y > \Delta$. (The second assumption will result in the model overpredicting the effect of Joule heating.) Calculations using this model showed qualitatively that Joule heating effects can be important in large scale generators.

Because the previous model used $1/7$ power temperature and velocity profiles the Joule heating was not properly accounted for near the electrode. A simple model which corrects this deficiency is the Near-electrode Couette Flow Model in which the energy differential equation near the wall

$$0 = \gamma \frac{d^2 h}{dy^2} + \frac{J^2}{\sigma} ; \quad \gamma = \frac{\mu}{\rho r}$$

is solved in closed form. This model was found to give good agreement with more sophisticated models for electrode heat flux.

A full integral boundary layer model was developed for its potential value to engineering designers. However for the present investigation it is desired to compare measured profiles with calculated profiles to search for any discrepancies between theory and experiment. Therefore the differential equations for the two-dimensional boundary layer were formulated and solved by numerical techniques. The equations used are summarized below.

Conservation equations

Continuity:
$$\frac{\partial \rho \bar{u}}{\partial x} + \frac{\partial \rho \bar{v}}{\partial y} + \frac{\partial \rho \bar{w}}{\partial z} = 0$$

Momentum:
$$\rho \bar{u} \frac{\partial \bar{u}}{\partial x} + \rho \bar{v} \frac{\partial \bar{u}}{\partial y} = \frac{\partial}{\partial y} \left[(\mu + \rho \epsilon_m) \frac{\partial \bar{u}}{\partial y} \right] - \frac{\partial p}{\partial x} + J_y B_z$$

Energy:

$$\begin{aligned} \rho \bar{u} \frac{\partial \bar{h}}{\partial x} + \rho \bar{v} \frac{\partial \bar{h}}{\partial y} = & \frac{\partial}{\partial y} \left[\left(\frac{\mu}{Pr} + \rho \epsilon_D \right) \frac{\partial \bar{h}}{\partial y} \right] + \frac{1}{2} \frac{\partial}{\partial y} \left[(\mu + \rho \epsilon_m) \left(1 - \frac{1}{Pr} \right) \frac{\partial \bar{u}^2}{\partial y} \right] \\ & + \frac{J^2}{\sigma} + J_y u B_z - \dot{Q}_r \end{aligned}$$

Electron-Ion Continuity:

$$\rho \bar{u} \frac{\partial \bar{C}_e}{\partial x} + \rho \bar{v} \frac{\partial \bar{C}_e}{\partial y} = \frac{\partial}{\partial y} \left[\rho (D_a + \epsilon_D) \frac{\partial \bar{C}_e}{\partial y} \right] + \dot{R}_e$$

where the electron and ion continuity equations have been combined to eliminate the electric field. Here D_a is the ambipolar diffusion coefficient, ϵ_m and ϵ_D are eddy diffusivities for momentum and diffusion equations, respectively, h is the stagnation enthalpy, and C_e is the electron mass fraction.

Boundary Conditions

$$\begin{aligned} y = 0; \quad u &= 0 \\ v &= 0 \\ C_e &= C_e^*(T_w) \\ q_c &= \frac{\mu}{Pr} \frac{\partial h}{\partial y} \end{aligned}$$

$$q_w = H(T_o - T_w) = q_c + q_R$$

Here H is a heat transfer conductance to a coolant at temperature T_o , q_R is the radiation heat flux to the wall, and q_c is the convective heat flux.

A complete description of the several sub-models used in this differential method is given in Reference 3.9.

3.2.2 Experimental Work

The experimental work undertaken was designed to provide fundamental data on plasma phenomena as affected by Joule heating, and to examine effects of interest for MHD channels that are influenced by Joule heating. The fundamental data consist of spectroscopic measurements of temperature and electron number density profiles under varying conditions in the electrode wall boundary layer of the Stanford M-2 MHD generator. Effects that were examined include boundary layer voltage drops, heat flux changes due to Joule heating, and Hall field breakdown.

The data were taken in two major experimental series, denoted ABL (Applied Field Boundary Layer) and IBL (Induced Field Boundary Layer). The ABL series was conducted with an applied electric field from battery banks and no magnetic field. Measurements were made of temperature profiles and N_e profiles. The IBL series was conducted in a magnetic field, with batteries used to augment the Faraday current. Temperature profile measurements were performed, and in addition voltage drops, electrode temperature, and Hall field breakdowns were observed as affected by Joule heating. The experimental hardware has been described elsewhere [3.9], and the diagnostics are described in Section 3.1.2.

Comparison of data and theory is shown for four different sets of data in Fig. 3.9. The data displayed were chosen to span a variety of run conditions and experimental days (with $J = 0$, $B = 0$). Complete descriptions of the runs may be found in Reference 3.9. The theoretical calculation uses standard values of the turbulence constants, i.e., $\kappa = 0.41$, $A_0^+ = 25.0$, $\lambda = 0.085$, and $A_c = 0.005$. As mentioned earlier, the initial plasma temperature in the theoretical calculations is set such that the data and theory agree in the channel core at the measurement point.

Electron number density (N_e) profiles were measured in the ABL series of experiments in an attempt to observe N_e nonequilibrium. The measurements were performed under conditions without current. In addition to the N_e profiles, temperature profiles were measured, thus allowing the equilibrium N_e to be calculated using an equilibrium computer program. The equilibrium N_e profiles are compared to the measured N_e profiles.

Figure 3.9 Comparison of temperature profile data to calculations for various run conditions.

The agreement of the experimental profiles with theoretical profiles in the bulk of the boundary layer is shown in Figs. 3.10 and 3.11. The plots show measured N_e values, equilibrium N_e based on the measured temperature, and theoretical calculations of N_e . The measurements were performed on separate days, with identical run conditions of $N_2/O_2 = 1.0$, and a mass flow rate of 0.182 kg/sec, resulting in a nominal free stream temperature of 2550°K. The plots demonstrate that the electron number density was essentially at equilibrium over the bulk of the flow. As the electron number density is at equilibrium, the agreement between the data and theory reflects the degree of success in modeling the temperature profile. Although the agreement between the data and the calculations is generally very good, the measured N_e profiles seem to have a slightly greater slope than the theoretical profiles in the region 5 mm to 15 mm from the wall. The source of this discrepancy is not known. (This discrepancy is also observed in the temperature profiles.) It should be noted that the N_e values were multiplied by a factor such that the N_e and N_e^* values would agree in the outer part of the boundary layer. This is necessary because of the uncertainties in the Einstein coefficients (~25%) and random errors (~10%).

The effect of Joule heating on temperature is demonstrated in Fig. 3.12. The steepening of the temperature profile near the wall is evident and it is clear that Joule heating would affect the electrical conductivity and voltage drop. More details and data for a number of test conditions are displayed in Reference 3.9.

3.2.3 Conclusions

Experimental measurements were performed of temperature and electron number density profiles on a laboratory scale MHD generator. Comparisons between calculations from the two-dimensional theory and measurements for cases without current generally showed good agreement when the turbulence model properly accounted for effects of free stream turbulence, though small discrepancies were observed between theory and experiments for the overall profile shape. Measurements of electron

Figure 3.10 Experimental N_e data, equilibrium N_e based on the measured temperature, and theoretical N_e . The N_e data is normalized to match the equilibrium data in the core.

Figure 3.11 Experimental N_e data, equilibrium N_e based on the measured temperature, and theoretical N_e . The N_e data is normalized to match the equilibrium data in the core.

Figure 3.12 Theory and data for temperature profiles with and without applied current (anode boundary layer).

number density profiles indicated that some degree of nonequilibrium existed near the wall, but the effect was small. The degree of nonequilibrium measured was higher than that predicted from the two-dimensional theory. Comparisons of experimental temperature profiles without current to profiles with current showed a marked temperature increase in the boundary layer due to Joule heating. The magnitude of the increase was well predicted by the two-dimensional boundary layer theory. Measured temperature profiles with current and magnetic field did not agree with predictions. The predicted profile in the inner region of the boundary layer for a case with current and magnetic field was above a similar case without current, whereas measurements for anode boundary layers were below control profiles without current. A cathode boundary layer behaved opposite to the anode boundary layers. It was shown that three-dimensional recirculation induced by nonuniformities in axial current could perhaps explain the discrepancies.

3.3 Measurement of Velocity Profile and Turbulence Intensity in the Sidewall Boundary Layer

In contrast to conventional duct flow, for MHD generators the boundary layers on adjacent walls experience different body forces and joule heating with associated variations in friction and heat transfer. This is because of the electric current which must pass through the electrode boundary layer where it is generally considered uniform except near the corners but which may vary greatly through the insulator wall boundary layer according to the conductivity and velocity profiles. Electrode voltage drops have been a major interest in MHD generator development and consequently the electrode boundary layer has been studied by several investigators [3.4,3.15]. The pioneering work of Hartmann and Lazarus [3.16] showed that the insulator wall velocity profile in a liquid metal flow could be modified by electromagnetic effects with a concomitant effect on wall friction. Other investigators extended this work [3.17] and Sonju [3.18] showed the significance of the Hartmann phenomenon in a combustion-driven MHD channel with no net current flow.

In constant property MHD flows the current density varies across the insulating wall boundary layer due to a decrease in velocity toward the wall. The current interacts with the external magnetic field to produce a varying body force across the boundary layer which modifies the velocity profile from that existing in the absence of MHD interaction. This phenomenon is known as Hartmann flow. In a gaseous plasma the variation of temperature, and hence electrical conductivity, across the boundary layer has a further effect on the current density. The inclusion of variable properties thus can result in additional alteration of the current and of the fluid flow. Hartmann flow with the inclusion of variable properties has been called, in this work, "extended Hartmann flow" and is the primary concern of this study.

The investigation reported here includes a numerical solution of the insulating wall boundary layer equations which include electromagnetic effects in their formulation. Predictions are made of both the temperature and velocity profiles and the associated Stanton number and friction coefficient. An experimental determination of the velocity

profile in an operating MHD generator was made using a laser anemometer developed in the Stanford High Temperature Gasdynamics Laboratory. Comparison of the numerical and experimental results was satisfactory and showed clearly the major importance of the extended Hartmann effect in influencing the insulating wall boundary layer.

3.3.1 Model and Computational Procedure

A schematic diagram of a segmented Faraday-type MHD generator is shown in Fig. 3.13. The working fluid of the generator, which in the present work was the products of combustion of ethanol with a small fraction of potassium added to form a partially ionized gas or plasma, flows in the positive x direction. A magnetic field is externally imposed in the positive z direction. The interaction between the flowing ionized gas and the magnetic field generates a current and/or an electric field. In the case of a segmented Faraday generator, the current flows in the negative y direction. This current is transmitted to external loads by electrodes on the top and the bottom of the channel. The insulating walls of the generator are the walls which are normal to the magnetic field. It is the boundary layers on these walls which are the subject of this work.

The basic equations for extended Hartmann flow consist of the two-dimensional boundary layer equations including MHD effects, where momentum terms in the y -direction and three-dimensional effects have been neglected as being small. The equations for the core of the channel are the special case of the boundary layer equations without gradient terms. The assumption that three-dimensional effects can be neglected will become more accurate as the aspect ratio of the channel increases. To minimize the corner effects on the present model and measurements, only the center of the insulating wall was investigated. Ohm's law in two dimensions including Hall effect is used. The basic time-averaged equations are as follows:

Continuity

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (3.15)$$

Figure 3.13 Schematic of MHD generator.

Momentum

$$\rho u \frac{\partial u}{\partial x} + \rho w \frac{\partial u}{\partial z} = J_y B - \frac{dP}{dx} + \frac{\partial}{\partial z} (\mu_{\text{eff}} \frac{\partial u}{\partial z}) \quad (3.16)$$

Energy

$$\begin{aligned} \rho u \frac{\partial H}{\partial x} + \rho w \frac{\partial H}{\partial z} = \frac{1}{Pr} \frac{\partial}{\partial z} (\mu_{\text{eff}} \frac{\partial H}{\partial z}) + (1 - \frac{1}{Pr}) \frac{\partial}{\partial z} [\mu_{\text{eff}} \frac{\partial}{\partial z} (\frac{u^2}{2})] \\ + \vec{J} \cdot \vec{E} + \dot{q}_{\text{rad}} \end{aligned} \quad (3.17)$$

Ohm's Law

$$J_x = \frac{\sigma}{1 + \beta^2} [E_x - \beta(E_y - uB)] \quad (3.18a)$$

$$J_y = \frac{\sigma}{1 + \beta^2} [E_y - uB + \beta E_x] \quad (3.18b)$$

The boundary conditions at the wall are that the enthalpy is specified and the velocity is zero. At the outer edge of the boundary layer either the enthalpy and velocity are specified or a symmetry condition is invoked as discussed in the section on numerical methods. The basic equations do not represent a closed set of equations. To close the set, equations of state, a turbulence model, and an electrical model are needed.

The equations of state used for the plasma properties were curve fits to thermochemical equilibrium calculations for the products of combustion of alcohol burned in oxygen with nitrogen added and seeded with potassium hydroxide. These curve fits and equilibrium computations are discussed in References [3.14] and [3.19].

An eddy viscosity model as described by Kays [3.20] was used. The expression for the eddy viscosity μ_t is defined through Prandtl's mixing length ℓ as

$$\mu_t = \rho \ell^2 \left| \frac{du}{dz} \right| \quad (3.19)$$

The actual modeling of the mixing length is divided into three different regions. In the near wall region ℓ grows linearly with distance from the wall through the relationship

$$\ell = \kappa z \quad (3.20)$$

where the proportionality constant κ is usually set to 0.41. In the viscous sublayer, the Van Driest damping function, D , multiplies the above equation so that $\ell = \kappa z D$. The damping function is

$$D = 1.0 - \exp(-z^+/A^+) \quad (3.21)$$

where

$$z^+ = z \left(\sqrt{\frac{\tau_w}{\mu}} \right)_{\text{wall}}$$

In this expression z^+ is the distance from the wall expressed in "wall coordinates", where the wall shear stress τ is used for normalization, and A^+ is an effective sublayer thickness in the same coordinates. A^+ is a function of the pressure gradient, wall roughness, and blowing. In the outer wake region of the boundary layer the mixing length is modeled as being a constant proportional to the boundary layer thickness; thus if $z > \lambda \delta_{99}/\kappa$

$$\ell = \lambda \delta_{99} \quad (3.22)$$

Thus for the modeling of the mixing length three constants are involved, κ , λ , and A^+ . Details of this model are given in Reference [3.14].

The current distribution and electric fields were found for an assigned average current in the y-direction by solution of Maxwell's equations with the assumption of infinite segmentation so that the average current in the x-direction was zero. The variable properties and velocity as a function of z were obtained from the last step of the boundary layer solver and the calculated current densities and electric fields were then used in the boundary layer code.

Numerical Techniques

The boundary layer equations above were solved using a finite difference scheme based on a boundary layer code developed at Stanford and known as STAN5 [3.21]. It was necessary to modify STAN5 to include the $J_y B'$ term in the momentum equation and the $\vec{J} \cdot \vec{E}$ term in the energy equation. A second modification to STAN5 was made to provide a stable scheme for the computation of internal flows. This involved using a separate core solver to calculate the pressure gradient and the outer boundary layer conditions. Details are given in Reference [3.14].

3.3.2 Experimental Procedure and Results

The laser anemometer system used in this work has been reported in detail elsewhere [3.13,3.14] and only its essential features will be discussed here.

A dual beam, real-fringe system was used in (near) forward scatter with access obtained via mirrors through open ports in the top and bottom electrode walls as shown in Fig. 3.4. The measurement volume was ~ 0.25 mm diameter and ~ 4 mm long (y-direction) and could be scanned in the z-direction by translating the transmitting and receiving optics together. The fringe spacing was $15.2 \mu\text{m}$, yielding a Doppler frequency of ~ 16 MHz for $U \sim 240$ m/s. Particles of ZrO_2 ($\sim 1 \mu\text{m}$ size) were supplied by injecting a paste of powder, glycerin and ethanol into the fuel line by a mechanically driven piston, at a rate of ~ 1 g/min to obtain a data rate of $\sim 5,000/\text{sec}$.

The detected signals were processed by a counter-type processor (TSI 1096) having an effective clock frequency of 500 MHz, which yields a velocity resolution of $\sim 0.2\%$. The digital data output from the counter were fed to a minicomputer which processed sets of 8 data blocks each of 2048 signals at each measurement station. The computer processed the $\sim 16\text{K}$ individual velocity measurements to output, on-line, the mean velocity, the turbulence intensity and a histogram of the velocity probability density.

The generator configuration used in the experiments is shown schematically in Fig. 3.14. The dimensions of the channel are given in

Figure 3.14 Generator configuration for measurement of insulating wall boundary layer.

Table 3.1. The measurement point, at the center of the insulating wall, was located 24 channel widths downstream from the nozzle. The channel, 10 cm high by 5 cm wide, was operated at a total mass flowrate of 0.11 Kg/sec with a nitrogen to oxygen (N_2/O_2) ratio of 0.5 by weight. Adjacent electrodes were paired and augmented with 240 volts to produce an average current density of 0.74 amp/cm^2 based on total current and electrode wall area. This current density resulted in a Hartmann number based on current density of 26. The Reynolds number was 8200, based on the channel half width. Table 3.2 summarizes the flow conditions.

Velocity profiles were measured for three different generator conditions. The first profile was a control case measured with zero magnetic field and current. This profile was used as a basis of comparison for the other two profiles and for the adjustment of parameters in the numerical calculations to account for hydrodynamic effects in the channel not included in the present model. The second profile was measured with a magnetic field of 2.4 Tesla, but with the generator open circuited, so that there was no net current. The third profile was measured with a magnetic field of 2.4 Tesla and with the generator operated in an augmented short-circuit mode. The second and third profiles were obtained at nearly the same time by making velocity measurements with and without current at each point in the boundary layer.

The velocity profile and the turbulence intensity (normalized on the core average velocity) measured for the control case are shown in Figs. 3.15 and 3.16. Figure 3.15 shows a calculated profile as a solid line. One of the primary purposes of the control profile was to provide a case against which the calculations could be compared without MHD effects. The control profile was fuller than would be expected from a standard boundary layer. Daily [3.4] in measurements of the electrode wall boundary layer, also found the velocity profile to be fuller than was predicted by calculations. In the present profiles, however, this effect is even more pronounced than in those measured by Daily.

With cold air flowing over smooth plates, investigators have used values of $K = 0.41$, $\lambda = 0.084$ and $A^+ = 26$ to obtain good agreement

Table 3.1

Channel Configuration

Construction

Mgo lined water-cooled metal shell

Channel Dimensions

Height: 0.10 m (between electrode walls)
Width: 0.05 m (between insulating walls)
Channel inlet to,
 First electrode: 0.60 m
 Last electrode: 1.06 m
 Measurement point: 1.10 m

Electrodes

Number: 13
Size: 5.00 cm by 1.85 cm
Pitch: 3.8 cm
Material: Type 310 stainless steel
Cooling: Water cooled copper back plate
Operating Temperature: 1000 K to 1350 K

Magnetic Field

2.4 Tesla, uniform over electrode area

Table 3.2
Flow Conditions

Fuel: Ethanol
Oxidizer: Stoichiometric amount of oxygen
Diluent: Nitrogen, N_2/O_2 0.5 by weight
Seed Material: KOH dissolved in fuel
Amount Seed: 1% Potassium in flow by weight
Anemometry Particles: Zirconia 0.5-2 μm diameter
Flux of Particles: 0.65 g/min
Total Flowrate: 0.11 Kg/sec
Plenum Heat loss: 130 Kw
Flame Temperature: 2760 K
Electrode Temperature: 1075-1200 K
Insulating Wall Temperature: 2000 K
Mean Core Velocity: 200 m/sec
Fluid Properties at Channel Inlet:
 Density: 0.13 Kg/m³
 Viscosity: 8.2×10^{-5} Kg/m-sec
 Thermal Conductivity: 0.19 J/m-sec-K
 Electrical Conductivity: 11.5 mho/m
Non-dimensional Parameters based on channel half width:
 Reynolds number: 8200
 Classical Hartmann number: 23
 Current Hartmann number: 26
Length Reynolds number: 3.6×10^5

Figure 3.15 Sidewall velocity profiles.

Figure 3.16 Sidewall turbulence intensity profiles.

between theory and experiment. The insulator wall channel construction for the present experiments used MgO ceramic pieces about 2 inches long in the flow direction and loosely fitted to permit thermal expansion during high temperature operation. Temperature gradients in the ceramic pieces caused bowing toward the channel center so the wall surface condition was not well defined. Inspection after cooldown suggested that steps at 2-inch intervals as much as 2 mm high could be expected. Because of this unavoidable uncertainty in the condition of the wall, it was decided to select boundary layer parameters that gave a good fit to the data for the $J = B = 0$ case and not change them for the other cases. In this way the uncertain wall conditions could be accounted for and the effects of magnetic field and current could be observed. Work is continuing at Stanford to improve the understanding of the turbulence parameters so that a less ad hoc selection can be made. For the solid curves in Fig. 3.15, the following parameters were used: $K = 0.6$, $\lambda = 0.6$ and $A^+ = 43$. Good agreement with the experimental data was obtained.

The calculated and measured velocity profiles for a magnetic field of 2.4 Tesla and with the generator in open-circuit operation are also shown in Fig. 3.15. The associated measured turbulence intensity profile is given in Fig. 3.16. The open-circuit profile would be expected to be fuller than the control case due to the effect of recirculating currents in the channel. However, the profiles with and without magnetic field actually show no significant difference. There are two reasons for this. The first is that the control profile is already sufficiently full that the small effect does not show up. The second reason is that turbulence damping (Sonju [3.18]) acts to reduce the fullness of the profile, thus working against the Hartmann effect. A single solid curve is shown for the control case ($B = J = 0$) and the $B = 2.4$, $J = 0$ case.

At each measurement position, augmented short-circuit data were obtained alternately with the open-circuit data. The velocity profile for the augmented short-circuit case is again presented in Fig. 3.15 and the turbulence intensity is shown in Fig. 3.16. The velocity profile clearly shows that the maximum velocity occurs not at the center of the channel, but near the wall. This phenomenon is unique to extended Hartmann flow. The effect is a result of the rapid decrease of the

current density toward the wall, and hence of the MHD body force, due to the decrease in electrical conductivity near the cool wall. This reduction of MHD body force causes an increase of velocity near the wall relative to the $B = 0$ case. The alteration in velocity profile increases the skin friction and, through convection effects, also increases the heat transfer. Although the velocity overshoot phenomenon is clear evidence of extended Hartmann flow, a simple steepening of the boundary layer can occur without the overshoot under some conditions. The Hartmann number of 26 in the present experiments is about the value to be expected in a commercial MHD power plant in which both the velocity and magnetic field would be higher than for the present measurements.

In order to make the numerical calculations for comparison with the experimental data, it was necessary to have an estimate of the wall temperature. The wall temperature was not measured in the present tests but was based on numerous past measurements which showed values of about 2000 K. This figure, corresponding to a wall to core temperature ratio of 0.74, was used to fit the data. As can be seen in Fig. 3.15, the agreement between theory and experiment is very good. To indicate the effect the wall temperature has on the profile, Fig. 3.17 shows the calculated profiles with several different wall temperatures, but with the other conditions held constant. With a core to wall temperature ratio of unity, the calculated profile is not modified by extended Hartmann flow. As the core to wall temperature ratio is decreased an overshoot occurs. A further decrease in the temperature ratio increases the amount of overshoot.

Figure 3.17 Effect of wall temperature on extended Hartmann flow velocity profiles.

3.4 Application of Theory to Large-Scale MHD Generators

For both the electrode and sidewall boundary layers, extensions of the theory were made to "pilot plant size" channels. The main thrust in each case was to show the difference in predictions based on approximate theories and those based on the more detailed calculations developed in the present research program.

3.4.1 Electrode Boundary Layers

To demonstrate the importance of current and magnetic field interactions in the electrode wall boundary layer, calculations were performed using the two-dimensional boundary layer model described above for a pilot plant scale generator. The conditions for the calculations are summarized in Table 3.3,

Table 3.3

MHD Generator Calculation Conditions

Inlet Temperature	2750 K
Inlet Area	0.16 m ²
Magnetic Field	6.0 tesla
Inlet Pressure	5.5 atm
Load Factor	0.75
Aspect Ratio	1.0
Electrode Temperature	1800 K
Velocity	800 m/s

A Faraday generator with a magnetic field of 6 tesla and a constant load factor of 0.75 was modeled. Properties used for the calculation were for coal combustion products in preheated air, and were obtained from curve fits performed by Rankin [3.14].

To highlight the effect of the current and magnetic field interactions in the boundary layer, an alternative calculation was performed that eliminated the interaction terms in the boundary layer. This was accomplished by replacing the terms J^2/σ and $J_y u B$ in the boundary layer energy equation with the values of the terms averaged in the y

direction. The effect of these modifications is that the overall Joule heating and MHD work was properly calculated, but the effects are distributed throughout the generator rather than being concentrated in the boundary layer.

The results of these calculations are shown in Fig. 3.18. Turbulence parameters appropriate for an external boundary layer were used in the calculations. A length scale is defined which characterizes the electrical losses in the boundary layer and may be considered as the length of core plasma necessary to give losses equal to those of the boundary layer. This concept is useful in evaluating losses and is described fully in Reference [3.9]. It is seen that the principal effect of the boundary layer interaction terms is to greatly diminish the value of g_T , particularly toward the downstream end of the generator. That is the boundary layer voltage drop is decreased from that estimated with Joule heating averaged in the y direction. This effect is caused principally by the thinning of the thermal boundary layer. The heat transfer is also affected by the interaction. The Stanton number rises markedly toward the downstream end of the generator. This increase is caused principally by a local temperature rise occurring very near the wall, due to the low conductivity near the wall. Thus it appears that the current and magnetic field interactions with the boundary layer are important effects to consider.

To demonstrate the possible importance of core turbulence in large generators, calculations were performed that used a value of the turbulence parameter A_c of 0.005, which is appropriate for pipe flow. See Reference [3.9] for a definition of A_c . (This parameter essentially establishes the turbulence eddy viscosity in the core of the channel.) The turbulence model which uses the parameter A_c assumes that the core eddy viscosity scales with the hydraulic Reynolds number of the channel. This assumption is probably only valid for fully developed duct flow, and boundary layers in large-scale MHD generators would not be fully developed. However, the combustor can generate core fluctuations which may influence the boundary layers. Although more work is required to determine the sources and effects of free stream turbulence in MHD channels, the present calculations provide some insight into what parameters might be affected by free stream turbulence, and to very roughly estimate the magnitude of those effects.

Figure 3.18 Comparisons of MHD generator calculations with (line) and without (points) boundary layer current interaction.

Figure 3.19 shows comparisons of a channel calculation performed with $A_c = 0.005$ to the calculation described in the beginning of this section which used $A_c = 0.0$, appropriate for an external boundary layer. The free stream turbulence causes an increase in Stanton number and skin friction coefficient of about 15%. The overall electrical loss length scale g_T is decreased by about the same amount. Thus it appears that free stream turbulence effects are probably not dramatic but may need to be included in calculations where high accuracy is needed.

3.4.2 Sidewall Boundary Layers

To determine the importance of extended Hartmann flow and turbulence damping on a larger-scale generator, calculations were performed for a 250 MW (th) pilot plant generator burning coal in preheated air. A segmented Faraday generator operating subsonically at a constant velocity and a magnetic field strength of 6 Tesla was modeled. An insulator wall temperature of 2000 K was assumed for the calculations.

A one-dimensional MHD computer program was run to determine the operating conditions for high enthalpy extraction. The generator conditions used by the boundary layer program are summarized in Table 3.4. The power output of this channel is calculated to be 32 MW for a 13 percent enthalpy extraction and a 61 percent turbine efficiency, as opposed to 40.7 MW or 16 percent enthalpy extraction obtained in Reference [3.22] in a similar calculation which excluded electrode voltage drops. The current density obtained in these calculations served as input for the boundary layer code.

For the generator case presented, two calculations were made. The first calculation for the insulator wall boundary layer was computed according to the present model where the current density varies across the channel. For the second calculation, called the "control calculation", the current density is held constant across the channel such that the average current density is the same in both calculations. This form of control calculation was chosen in preference to letting either the current or the magnetic field go to zero because in the latter cases the conditions in the generator would be significantly different. The control calculation and the variable current calculation have the same

Figure 3.19 Comparisons of MHD generator calculations with core turbulence parameter $A_c = 0$ (line) and $A_c = 0.005$ (points).

Table 3.4

Pilot Plant Generator Conditions

B = 6 Tesla		U = 800 m/sec		Height = 0.5 m		T(electrode) = 2000 K		
x m	p atm	T K	A m ²	E _x kv/m	V _{out} volt	V _{loss} volt	J _y ² A/cm ²	P _{out} Mw
0.20	5.00	2835	0.079	----	----	----	----	0.0
0.46	4.73	2821	0.084	0.93	1673	121	1.67	1.2
0.98	4.47	2807	0.089	0.96	1670	131	1.54	2.4
2.02	3.28	2735	0.119	1.20	1655	176	1.19	8.4
3.06	2.50	2673	0.154	1.41	1644	220	0.96	13.4
4.10	1.87	2608	0.201	1.62	1632	277	0.74	18.4
5.14	1.39	2542	0.264	1.75	1620	351	0.53	23.3
5.92	1.13	2494	0.320	1.76	1610	409	0.39	26.7
6.96	0.87	2436	0.404	1.69	1597	478	0.25	30.4
7.48	0.78	2409	0.448	1.63	1590	505	0.20	32.0

average momentum loss due to the interaction of the current with the magnetic field. Thus the flow conditions along the channel are approximately the same for both the variable current and control calculations. In these calculations, a simple integral expression is used to compute the electrode wall displacement thickness which is then used in the core program to determine the effective area. The normally accepted values of the turbulence parameters were used for the pilot plant generator calculations. Thus 0.41, 0.085 and 26 were assigned for κ , λ and A^+ .

The skin friction coefficient computed for the pilot plant generator case is presented in Fig. 3.20. The effect of extended Hartmann flow is seen to significantly increase the skin friction by up to about 140 percent over that for the control case.

The Stanton number for the pilot plant generator is shown in Fig. 3.20. The increase in heat transfer is about 53 percent over the uniform current case, which is more modest than the increase in the skin friction. This increase in heat transfer is due primarily to the steepening of the velocity profile which results in increased convection of energy toward the wall and thus steepening of the temperature gradient at the wall. Joule heating effects are minimal in the insulating wall boundary layer since the current is shunted around the low conductivity region near the wall.

Figure 3.20 Pilot plant generator skin friction and Stanton number comparisons.

4.0 HALL FIELD BREAKDOWN

4.1 Objectives of the Present Investigation

The purpose of this research was to produce and study axial voltage breakdown under non-slugging, combustion MHD conditions. Although the work reported here focussed on slag-free conditions, the understanding and predictive ability gained in studying breakdown along non-slugging walls presents, at the least, a beginning for the understanding of the slugging wall behavior. Specifically the objectives of the investigation were:

- a) to identify the mechanism responsible for axial voltage breakdown and to identify the parameters of importance,
- b) to propose and to verify a theoretical model capable of predicting whether breakdown will occur,
- c) to use experience gained to propose and evaluate possible solutions to the problem of breakdown.

The present report emphasizes the experimental aspects of the research. A thorough discussion of the theoretical model, as well as further details of the experimental procedure and results are given in Reference [4.1].

To facilitate a rapid development of the diagnostic and calculation techniques, experimental and analytical efforts were directed initially toward a simplified configuration, shown schematically in Fig. 4.1, where an external voltage is applied to a pair of adjacent electrodes, rather than being induced by the Hall effect. Although the magnetic field is absent in this configuration, the important features of Joule heating in the plasma and thermal and electrical conduction in the inter-electrode insulator are retained, suggesting that strong similarities, at least of a quantitative nature, should exist between the two cases. Breakdown was first observed in the applied field experiments and the understanding of the breakdown process gained through the applied field work was used to determine conditions favorable for breakdown in the subsequent induced field experiments. Further, the diagnostic techniques developed in the applied field experimental work were used in the final induced field experiments with only relatively minor modifications required.

Figure 4.1 Schematic of applied field configuration.

4.2 Diagnostic Development

Several diagnostic techniques were developed with the overall goal of identifying the mechanisms responsible for breakdown, providing detailed measurements for comparison with the calculations and yielding general information helpful to the modeling process. A dual-filter cine-photographic technique was used to monitor the inter-electrode region and to provide separate records of the plasma and the insulator behavior. In particular, with this technique it was possible to monitor the formation of current constructions and deduce whether the dominant current transfer was through the plasma or the insulator. The insulator record was calibrated such that an estimate of the surface temperature could be obtained. The photographic record of the plasma response was not calibrated to yield plasma temperature; however, a semi-quantitative measurement of the plasma temperature in the region above the inter-electrode insulator was provided by a simple measurement of the total emission intensity of a spectral line. A quantitative measurement of the current distribution at the electrode was provided by a subdivided electrode. Voltage probes were used to determine the behavior of the near anode and near cathode voltage drops during pre-breakdown and post-breakdown times, to determine whether variations in these quantities might be important in the breakdown process. Finally, large scale fluctuations in plasma temperature or seed fraction were monitored by optical emission techniques to determine if these fluctuations played a role in the breakdown process.

Optical access was provided to the channel looking down on the inter-electrode region and movies were taken during operation with current. The field of view provided by the window assembly extended far enough in the flow direction to observe the edges of both electrodes and the entire inter-electrode insulator, and extended across the entire channel width. The inter-electrode region was viewed through a special optical set-up, shown schematically in Fig. 4.2, which formed a dual image of the region on each frame of the film. One of the images was formed through a red cutoff filter which, together with the spectral sensitivity of the film (Kodak, High Speed Ektachrome) isolated a relatively narrow wavelength region from $\approx 6500 \text{ \AA}$ to $\approx 7000 \text{ \AA}$. No strong spectral lines are

Figure 4.2 Schematic of dual-filter photographic device, detailing the various light paths and components.

observed from the plasma in this spectral range, so the film exposure from this image responds primarily to the intensity of radiation emitted by the wall. The second image was formed through a bandpass filter centered near the potassium doublet at $4044\text{--}4047\text{ \AA}$. Exposure from this image, which appears blue on the film, responds strongly to the intensity of radiation from the plasma, although significant sensitivity to radiation emitted by the wall will result if the bandpass of the filter is too broad or the surface temperature very high.

A calibration technique was used to allow the determination of insulator surface temperature from the red image as formed on the film. The image of a five region neutral density step filter, illuminated from the rear by a tungsten lamp, was formed on the film through the main optical train. The transmittance of each of the regions was determined by calibration, such that a knowledge of the brightness temperature of the lamp and the emissivity of MgO allowed a determination of the "effective MgO temperature" for each region of the step filter. For a typical tungsten lamp current, the five regions represented surface temperatures from $\approx 2500^{\circ}\text{K}$ to 1700°K . Comparison of the exposure of a region of the insulator on the red image, with the regions of the step filter as seen through the red filter, allowed a determination of the surface temperatures. An image of the step filter was also formed through the blue filter, as an indicator of the sensitivity of this image to wall emission. It was found that a very narrow bandpass filter ($\approx 10\text{ \AA}$ bandwidth) was required to reduce the interference to acceptable levels.

4.3 Measurement of Hall Field Limitation in Applied Field Experiments

Inter-electrode insulator gaps from 1 mm to 19 mm were studied in the several applied field experiments. Dense MgO was used as the insulator material for these experiments. The effects of plasma flow conditions and of electrode polarity were studied in two of the experiments. The insulator surface temperatures (as measured by an optical pyrometer) approached or exceeded 2000°K in all experiments.

For voltage exceeding a threshold level the discharge between the electrodes (see Fig. 4.1) was not steady, and following a delay period a rapid and significant decline in voltage was observed. This behavior was termed axial voltage breakdown. While many characteristics were common to all the breakdowns, the experiments distinguished between two types of breakdowns and these types are discussed separately. Representative total-voltage versus total-current characteristics showing the behavior during breakdown are displayed in Fig. 4.3, with breakdowns of both types shown and identified. The non-breakdown behavior is represented by a solid line on the figure. As can be observed in the figure, breakdown occurs only for voltages exceeding a threshold level and has the main characteristic of a significant reduction in voltage.

Plasma Breakdown The experimental evidence established that breakdown characterized by a very short delay time are dominated by events in the plasma. Figure 4.4 is representative of plasma breakdown as observed for several experimental conditions. The timescale over which the majority of the breakdown occurs is less than a millisecond; however, the time separating the initiation of current and the breakdown is considerably different for the various cases. Delay times as short as a few milliseconds and as long as a few hundreds of milliseconds were observed for breakdowns of the plasma type. The data taken during these experiments demonstrate that the breakdown is accompanied by a constriction of the current, such that after breakdown a small portion of the electrode carries the majority of the current passing between the two electrodes. Photo-diode emission intensity measurements indicate extremely high temperatures in the plasma region close to the inter-electrode region, while the emission intensity in the region away from the inter-electrode region does not change.

A qualitative, overall understanding of the breakdown process may be obtained by examination of the photographic records taken during a run in which breakdown occurred. A few frames taken from runs in which plasma breakdown occurred are displayed in Fig. 4.5. In the first frame of Fig. 4.5, taken just after the breakdown, an intense region bridges the gap from anode to cathode in the plasma image and

Figure 4.3 Voltage-current characteristic displaying behavior for axial breakdown. Both types of breakdown are shown and labeled.

Figure 4.4 Voltage-current characteristic displaying behavior plasma breakdown. Solid line represents non-breakdown behavior.

Photograph taken ≈ 15 msec
after initiation of current.

Photograph taken ≈ 30 msec
after initiation of current.

Photograph taken ≈ 60 msec
after initiation of current.
Frame immediately prior to
stopping of current.

Photograph taken just after
current stopped.

Figure 4.5 Sequence of frames of the movies showing the behavior of the inter-electrode region for a fast breakdown. The gap is 7.5 mm. Note that the plasma image shows an intense region bridging the gap in the first frame and the intense region disappears as soon as the current is stopped. The insulator beneath, however, remains heated for a considerable time.

the insulator beneath the discharge is significantly heated. As can be observed, the insulator beneath the discharge increases with time and when the current is stopped the intense region in the plasma image is immediately extinguished while the insulator slowly cools. The intense region in the plasma was observed to be extremely mobile in several cases.

The data clearly establish that this type of breakdown is caused by a constriction of the current passing through the plasma in the region directly above the inter-electrode insulator.

Insulator Breakdown. Many of the breakdowns observed were characterized by a delay time greater than a second and by a timescale of about 1 second for the breakdown itself. As with plasma breakdown, this type of breakdown is characterized by a significant decline in voltage, and breakdown occurs only when a threshold voltage is exceeded. The total axial voltage versus total axial current behavior for a breakdown of this type is shown by the lower voltage breakdown in Fig. 4.3. Breakdown is accompanied by a constriction of the current such that after breakdown a small region of the electrode carries most of the total current passing between the electrodes. As in the case of plasma breakdown, both near-electrode voltage drops decline significantly when breakdown occurs. For this type of breakdown, little or no increase in emission intensity was observed for any of the locations monitored by the photo/diode.

A qualitative, overall understanding of the insulator breakdown process may be obtained by an examination of the photographic records taken during the breakdown described above. Several frames from the movies are reproduced in Fig. 4.6. The early frames for both sequences show little activity other than a few hotspots on or near cathode. The later frames in the sequences show the formation of relatively broad heated regions in the insulator image at one or both edges of the inter-electrode insulator. These regions slowly grow in the axial direction and breakdown is observed when the gap is bridged by a narrow channel in the insulator. Temperatures well in excess of 2500°K are indicated by comparison of the channel region and the intensity standards in the photographs. As the breakdown develops further, the channel widens and molten insulator material is observed to flow downstream. As can be observed in the figure, no activity is recorded in the plasma image on the film during the development of the breakdown.

Photograph taken ~13.5 seconds
after initiation of current.

Photograph taken ~16.4 seconds
after initiation of current.

Photograph taken ~17.4 seconds
after initiation of current.

Photograph taken ~17.7 seconds
after initiation of current.

Photograph taken ~18.2 seconds
after initiation of current.

Figure 4.6 Sequence of frames of the movies showing the development of a slow (insulator) breakdown. Data is taken from Run Series 0.75-A; the gap is 7.5 mm. Note that no activity is observed in the "plasma" image.

The above data clearly indicate that this type of breakdown results from the formation of a constricted current path through the inter-electrode insulator.

Breakdown Threshold Voltage. As demonstrated by the preceding discussion, a stable and diffuse discharge was observed for total axial voltage below a threshold level; however, when this threshold voltage was exceeded, breakdown resulted. When plasma and insulator breakdown were observed in the same experiments, the threshold voltage for the plasma breakdown was higher. A summary of the breakdown behavior for these experiments is given by Fig. 4.7. In the figure, the lowest voltage for which breakdown was observed and the highest voltage for which breakdown was not observed are given for plasma and insulator breakdown. These points identify the breakdown regimes in terms of threshold voltage as a function of insulator gap size. The data indicate a region of insulator breakdown, with threshold voltage increasing roughly linearly, with gap size, and above that a region of plasma breakdown again with the threshold voltage increasing with gap size. Little variation of the threshold voltage with plasma flow conditions was observed and little effect of electrode polarity was evident in the experiments. It is interesting to note that the threshold voltage for both plasma and insulator breakdown extrapolate to non-zero voltages at small gap size.

4.4 Measurement of Hall Field Limitation in Induced Field Experiments

Inter-electrode insulator gaps from 2.5 mm to 19 mm were studied in the induced field experiments. The induced field experiments were divided into five run series, representing the different experimental conditions. The MHD channel was operated subsonically with the mass flow to the burner fixed. The MHD generator was run in the segmented-Faraday configuration for all runs.

Breakdown Behavior. For Hall voltages exceeding a threshold level, the electrical behavior of the generator was not steady in time and following a delay period a rapid and significant decline in Hall voltage across one or more of the insulator gaps was observed. In general, the delay time was at least a second and that timescale of the breakdown itself was on the order of a second. In addition to the decline in Hall voltage, a change in the output terminal behavior (Faraday voltage and current) usually occurred when more than one gap suffered breakdown. Representative Hall voltage and Faraday current

Figure 4.7 Threshold voltage as a function of insulator gap size. Figure shows the highest voltage for which no breakdown occurred and the lowest voltage for which breakdown occurred, thus establishing the breakdown threshold for plasma and insulator breakdown. All insulators were MgO except the 1 mm gap, which was dense alumina.

behavior for breakdown are displayed in Fig. 4.8. The non-breakdown behavior is represented by a solid curve. Several frames of the movies taken for this run provide a good overall understanding of the breakdown process and are displayed in Fig. 4.9. The initial frame taken soon after the initiation of current shows some heating of the inter-electrode insulator. In the second frame, taken ≈ 0.5 second after initiation of current, a local heated region can be observed near the downstream edge of the insulator. In subsequent frames this region grows and breakdown occurs when the gap is bridged by a narrow channel in the insulator. It should be noted that no activity is observed in the plasma image during breakdown. Subsequent to the breakdown, the heated region widens with a moderate, further decline in Hall voltage across the test gap.

The evidence from these experiments indicates that the Hall voltage breakdowns, observed for three gap sizes and for gaps on both walls of the generator, were caused by a constriction of the current passing through the inter-electrode insulator. No breakdown of the plasma type was observed for these experiments.

Breakdown Threshold Voltage. As demonstrated by the previous discussion the generator electrical parameters remained steady only when the Hall voltages were below a threshold level. A summary of the breakdown behavior as determined by the induced field results described above and by previously reported induced field experiments is presented in Fig. 4.10. Data from the Soviet experiments using their U-02 facility are also shown, although no breakdown was observed in those experiments. In the figure the lowest Hall voltages which resulted in breakdown for particular conditions and the highest voltage not resulting in breakdown are plotted as a function of inter-electrode gap size. While the separation between breakdown and non-breakdown conditions is not as distinct as it was for the applied field experiments a non-breakdown region is identified in the figure. Inter-electrode gap size appears to be an important parameter although the figure indicates that other factors are most likely of importance as well. It should be noted that the Soviet data were obtained at considerably lower current density levels than the data reported here and the electrode wall construction was considerably different. In interpreting the presently reported data, it should be kept in mind that several of the breakdowns observed

Figure 4.8 Hall voltage versus Faraday current behavior for breakdown. Non-breakdown data is represented by the solid line. Data is taken from Run 0.75-A, for the 0.75 cm gap operating on the anode wall of the generator.

Figure 4.9 Sequence of the frames of the movies showing the development of a slow (insulator) breakdown. The gap suffering breakdown is 7.5 mm. Note that no activity is observed in the "plasma" image.

Figure 4.10 Plot of breakdown threshold voltage for induced field configuration versus inter-electrode gap size. Figure shows highest voltage for which breakdown did not occur. Data from references [4.2] and [4.3] also shown.

involved breakdown at more than one gap and were obtained under conditions of extremely high transverse currents.

Comparison of Induced Field and Applied Field Breakdown. The overall manifestation of breakdown for both configurations is a rapid and significant reduction in axial voltage accompanied by the formation of a constricted current path joining the adjacent electrodes. Current distribution measurements and photographic records show that in the induced field configuration a portion of the transverse current passes to the adjacent electrode prior to passing to the opposite electrode. For both configurations breakdown occurred only when a threshold level was exceeded and the insulator gap size was an important parameter affecting the threshold voltage. Applied field experiments demonstrated that the constricted current path could form either in the plasma or in the inter-electrode insulator, with a somewhat higher threshold voltage indicated for breakdown through the plasma. Induced field breakdowns for present conditions were of the insulator type and displayed characteristics close to the insulator breakdown observed in the applied field experiments. In particular, for both configurations of a delay of about 1 second or more separated the initiation of current and the insulator breakdown. The photographic records show that small hotspots originally located on the insulator edges grow during this delay period and breakdown is observed when the insulator gap becomes completely bridged by a heated channel in the insulator. The majority of the voltage decline occurs over a period of ≈ 1 second. The threshold voltage for insulator breakdown for the induced field configuration is somewhat lower than those observed for the same gap size for the applied field configuration, however, the trend of increased threshold voltage with increased gap size is evident in both cases. The absence of breakdown of the plasma type in the induced field experiments is not surprising considering the significantly higher threshold voltages required for plasma breakdown in the applied field experiments.

The good qualitative similarity between induced field and applied field breakdown indicates that the understanding and successful modeling of the applied field behavior would represent a significant step toward the solution of the problem of Hall voltage breakdown.

4.5 Implication in MHD Generator Design

Design philosophies regarding the problem of Hall voltage breakdown might be characterized as:

Philosophy 1) Assume breakdown will occur and design the generator wall and generator electrical controls to minimize the damage to the generator, while introducing the minimum detrimental effect on generator power output and efficiency,

and

Philosophy 2) Design the generator wall and generator controls to prevent breakdown from occurring.

The choice of the first philosophy by many generator designers may result from the lack of knowledge to effectively implement the second philosophy, or the belief that the second philosophy is not practically realizable. While the present study does not answer all questions regarding the prevention of breakdown, it does provide some information to evaluate the gains by following the second philosophy and some indications of how to successfully prevent breakdown.

A channel designer has many parameters to choose, the most important of which, for breakdown considerations, might be:

- a) electrode pitch
- b) inter-electrode insulator gap
- c) average axial (Hall) field (dependent on generator length and magnetic field strength)
- d) electrode configuration (window frame, V-wall, etc.)
- e) electrode wall component materials and design temperatures.

Design philosophy 1 has lead to:

- a) electrode configurations where the current which can be coupled to a single arc is limited
- b) active electrical controls on the generator to limit the Hall voltage per pair to levels below the steady burning voltage of a breakdown arc, and
- c) limits on the average Hall field commensurate with b)

For the relatively large gaps (7.5 mm and 19.1 mm) in the present studies an electric field of ~ 40 volts/cm is exhibited by the well-developed breakdown; this value agrees well with the value advanced by others. To first approximation, this result is roughly independent

of electrode configuration, electrode wall materials, or component temperatures. Further, the steady-arcing field is not likely to be dependent on insulator material or whether or not the wall is covered with slag, as most insulator material and slag have comparable high temperature properties. The main parameters available to the designer are the average electric field, the electrode pitch and insulator gap size. For a given average axial electric field in the core, the average field across the insulator will be

$$E_{x\text{insulator}} \sim \left(\frac{\text{pitch}}{\text{gap}} \right) E_{x\text{core}} .$$

Thus if the maximum electric field at the insulator is limited to the steady arcing value of 40 volts/cm,

$$E_{x\text{core}} < \left(\frac{\text{gap}}{\text{pitch}} \right) E_{x\text{insulator maximum}}$$

$$< 40 \text{ volts/cm} \left(\frac{\text{gap}}{\text{pitch}} \right) .$$

Thus, to a first approximation, the first design philosophy results in a limitation on the core axial field which depends only on the gap to pitch ratio. This indicates that improvements with respect to maximum Hall field can be achieved only with increases in average current density to the electrode. The desire to limit the maximum current to be coupled to a breakdown arc would indicate that a small pitch is desirable, although subdivision of the electrodes in the magnetic field direction and active controls would also seem required to limit damage.

The present study has demonstrated that a threshold voltage must be exceeded if breakdown is to occur, and that the threshold voltage is considerably higher than the voltage maintained after breakdown is well developed. The threshold voltage for insulator breakdown was lower than that for plasma initiated breakdown, however, it would appear that by careful thermal design insulator initiated breakdown could be prevented for clean wall generators. On the other hand, the experimentally measured threshold voltage for plasma initiated breakdown was only moderately affected by any of the parameters studied except gap size. The threshold electric field for plasma initiated breakdown increased with decreasing

gap size in the applied field experiments and might be expressed as

$$E_{x_{\text{insulator threshold}}} = \frac{130 \text{ volts}}{\text{gap (in cm)}} + 70 \frac{\text{volts}}{\text{cm}} \frac{\text{gap}}{\text{pitch}} .$$

The maximum core axial electric field becomes

$$E_{x_{\text{core threshold}}} < \frac{130 \text{ volts}}{\text{pitch}} + 70 \frac{\text{volts}}{\text{cm}} \frac{\text{gap}}{\text{pitch}} .$$

For fixed gap/pitch ratio, that is for fixed average current density at the electrode, substantial increases in core axial field can be obtained by a reduction in electrode pitch. For example, at a gap to pitch ratio of 0.25, the maximum core field is 83 volts/cm at a 2 cm pitch and 148 volts/cm at a 1 cm pitch. Thus for the same average current density (gap/pitch = 0.25) and the same electrode pitch (pitch = 1 cm) the maximum allowable axial field based on the threshold level is ~ 150 volts/cm or ~15 times the value based on the steady arcing level. Although threshold voltage levels for plasma initiated breakdown are likely to be lower for the generator configuration than were measured for the applied field configuration the above estimates do indicate that substantial gains can be achieved by the prevention of breakdown.

Presence of a slag layer on the electrode wall could significantly alter the breakdown characteristics of the inter-electrode gap, as well as lead to a long term degradation of the electrode wall components. While the present study does not consider such a layer, it would appear that the slag layer will behave much as the inter-electrode insulator and that inasmuch as the thermal state of the slag is more difficult to control, slag initiated breakdown may dominate the problem. Obviously, in view of the significant possible gains indicated above, analytical and experimental work relating to the slagging wall configuration is desirable.

5.0 ELECTRODE CONFIGURATION AND CURRENT CONCENTRATIONS

Two research programs investigated electrode configurations and current patterns in MHD channels. The first has been described in Section 4.0 and in the course of the study of Hall field breakdown phenomena, segmented electrodes were used to measure current distribution. The second program is an investigation of electrode configurations which have the potential to decrease current concentrations by providing conducting surfaces normal to the magnetic field. This work has only been theoretical in nature with future plans for experimental work dependent on the results of the computed improvement potential.

5.1 Measurements of Current Concentrations Near Incipient Hall Field Breakdown

As part of the investigation of Hall field breakdown described in Section 4.0, a special segmented electrode was constructed, Figs. 5.1 and 5.2. This electrode provided a means of measuring current distributions for nonuniform currents in both the x and z directions. Measurements were made for the case of $B = 0$ with applied electric field in the axial direction and for $B = 2.6$ tesla with induced and augmented voltage in the Hall direction.

Typical results for applied field measurements are shown in Fig. 5.3 where the fraction of total current carried by the front segments of the electrode is seen to increase with total axial current. In Fig. 5.4 is shown the transverse distribution of current for the front row of pegs with applied electric field.

Generally similar results were obtained for induced voltages with $B = 2.6$ tesla as shown in Fig. 5.5. Measurements were also made of the current distribution in the x direction with induced (Faraday) currents. Typical results are shown in Fig. 5.6.

Detailed discussion of these measurements is given in reference [5.1].

Figure 5.1 Schematic of electrode module which allowed pre-assembly of the inter-electrode wall.

Figure 5.2 Photograph of electrode wall of applied field test section.

Figure 5.3a Current distribution in axial direction as a function of total axial current. Fraction of current leaving the downstream edge of the upstream electrode is used to represent the axial current distribution. Data taken from Run 1.9-A.

Figure 5.3b Current distribution in axial direction as a function of total axial current. Fraction of current leaving the downstream edge of the upstream electrode is used to represent the axial current distribution. Data taken from Run 1.9-B.

Figure 5.4a Current distribution in transverse direction for non-breakdown conditions. Current from individual pegs plotted as a fraction of the total current to the row of pegs. All data from Run 1.9-A are represented in the figure. Electrode was operating as an anode.

Figure 5.4b Current distribution in transverse direction for non-breakdown conditions. Current from individual pegs plotted as a fraction of total current to the row of pegs. All data from Run 1.9-B are represented in the figure. As indicated the electrode was operated as an anode and as a cathode.

Figure 5.5a. Distribution of Faraday current in the magnetic field direction for non-breakdown conditions. Figure shows the fraction of current leaving individual pegs along the electrode edge where the current concentrates due to the Hall effect. Data is taken from Run .75-A. Average Faraday currents as high as 4 A/cm^2 are represented for this anode.

Figure 5.5b. Distribution of Faraday current in the magnetic field direction for non-breakdown conditions. Figure shows the fraction of current leaving individual pegs along the electrode edge where the current concentrates due to the Hall effect. Data is taken from Run 1.0-AP. Average Faraday currents as high as 2 A/cm^2 are represented for this anode.

Figure 5.6a Fraction of current leaving 1/4" strip on edge of electrode where the current is concentrated due to the Hall effect. Key identifies the conditions for each set of data. The 1/4" strip represents approximately 20% of the total electrode surface area.

Figure 5.6b Fraction of current leaving 1/4" strip on edge of electrode where the current is not concentrated due to the Hall effect. Key identifies conditions for each set of data. The 1/4" strip represents approximately 20% of the total electrode surface area.

5.2 Calculation of Effects of Three-Dimensional Surfaces on Electrode Current Concentration

In segmented Faraday channels, local shorting of the axial electric field near the electrode leads to an asymmetrical distribution of current with concentrations at the upstream edge of the anode and downstream edge of the cathode. This results in a significant reduction in maximum power output from the case of a "finely" segmented channel with uniform current density. The asymmetry and power reduction become worse with increasing Hall parameter.

In addition, the current concentrations can severely erode the electrode surface. Also, under certain conditions, notably high current density and large Hall parameter, arcing between adjacent electrodes can occur. Not only does this reduce channel performance by further breaking down the axial field, it also can seriously damage both electrodes and insulators.

In an effort to alleviate these problems, alternative electrode shapes are being considered. A three-dimensional electrode can promote a more uniform current distribution if sufficient surface is provided for current flow parallel to the direction of the magnetic field. To study the effects of a change in electrode shape, a 3-D finite difference code has been written which solves for the potential and current distribution within the generator.

The channel geometry is shown in Fig. 5.7. The physical dimensions are approximately those of the Stanford M-2 generator. Velocity and thermal boundary layers of equal size have been assumed. In the thermal boundary layer the freestream conductivity decreases by a factor of ten.

In dealing with 3-D data and the fully three-dimensional effects associated with any electrode which is not flat, it is important to have a graphics capability in order to understand the enormous quantity of computer output. Figure 5.8a shows the normal components of the current density vectors on a flat electrode (cathode). Figures 5.8b and 5.8c show the same data using a 3-D contour surface and shading, respectively. All three figures indicate the heavy concentration of current on the downstream edge.

Figure 5.7 Channel geometry and flow conditions.

Figure 5.8a Normal components of current density vectors on flat electrode.

Figures 5.8b&c Distribution of current on a flat electrode as shown by a three-dimensional contour surface and shading.

Figure 5.9 shows the current distribution on an electrode with 3 cm sidewalls (total channel height = 10 cm). For the assumed conditions the sidewalls carry more than 50% of the total current. It is this strong affinity of the current for sidewalls and other extended electrode surfaces that

In Fig. 5.10 the flat portion of the electrode remains unchanged while the sidewalls have been shortened. The shading shows that the sidewalls still carry a significant amount of current. This idea can be extrapolated: smaller "fins" with surface parallel to the magnetic field can be added in the flow stream to draw current off the front edge of the electrode. These fins will have an additional advantage in that they will be surrounded by relatively small velocity and thermal boundary layers.

Figure 5.11 shows quantitatively the effect of a change in electrode shape. Numerical results for three cases are presented. Each line represents the total electrode current up to the given axial point along the electrode. Curve 1 shows that, as a result of the current concentration, nearly 45% of the current into a flat electrode is in the last 10% of its length. The electrode with conducting sidewalls reduces the current in the final 10% of the electrode length to approximately 30% of the total. The "abbreviated sidewall" electrode, with the sidewall portions "clipped" in the direction of the current concentration, reduces this figure to approximately 25%. These percentages are of course dependent upon the assumed conditions within the channel, but the trend is clear.

The analytical program will be continued under a following contract, and experimental investigations will be conducted in the Stanford M-2 MHD channel.

(a)

(b)

(c)

Figure 5.9 (a) Distribution of current on electrode with sidewalls.
 (b) Using three-dimensional contour surface.
 (c) Using shading.

Figure 5.10 Distribution of current on electrode with shortened sidewalls.

$u_0 = 800 \text{ m/sec}$	$\tau_0 = 10 \text{ mho/m}$
$B = 3.0 \text{ Tesla}$	$\tau_{\text{wall}} = 1 \text{ mho/m}$
$\beta = 2.0$

Figure 5.11 Normalized cumulative current distribution for three types of electrodes.

6.0 INVESTIGATIONS IN 6 TESLA SUPERCONDUCTING MAGNET

In order to begin experiments at high magnetic fields as early as possible a program was planned for the small 6 tesla superconducting magnet available in the Stanford High Temperature Gasdynamics Laboratory. This magnet had been constructed as a split solenoid with room temperature access through the 21 cm diameter bore and through four ports extending radially outward from the base at the central plane, each 5 x 10 cm in cross section. The design made it possible to install a disk generator with combustion gases entering along the base axis and leaving through the four radial ports. Also it is possible to install a linear channel transverse to the base with conducting gases entering and leaving through opposite radial ports.

The limitation of the 6 tesla magnet is its size. As described in the following sections, great care had to be taken to avoid excess heat loss and other boundary layer effects. Both a disk generator and a linear generator were constructed and tested at 5.5 tesla in the magnet. The results of these tests are discussed below.

6.1 Disk Generator Studies

6.1.1 Experimental Investigation of Combustion Disk Generator

During the contract period, the entire disk generator flow train and the cryogenic systems for the superconducting magnet have been developed and operated successfully. Four disk generator experiments, each of several hours' duration, have been conducted to date. A brief description of each component of the apparatus and of experimental results obtained to date is given below.

Disk Generator Channel

A schematic representation of the disk generator flow train with the superconducting magnet is shown in Fig. 6.1. All the flow train components are water cooled stainless steel or copper with MgO liners. The combustor, plenum and test section are assembled as a unit and inserted into the round centerbore of the magnet and bolted to a flange on the magnet iron vacuum tank. Four exit sections are inserted into the rectangular magnet ducts and bolted to other flanges on the magnet vacuum tank. Then a water cooled exhaust manifold torus is connected to the four exit ducts. The hot exhaust gas is quenched in the exhaust manifold and is delivered to the scrubber and exhaust system.

Figure 6.2 shows a cross section of the test section with the electrodes, insulator and some of the instrumentation. A contoured anode 5 cm in diameter on the downstream plate is surrounded by an insulator made of 85% dense high purity fused MgO. Outside the insulator is a segmented stainless steel ring cathode with a diameter of 9.8 cm. This gives an effective channel length of 2.4 cm. The ring cathode is segmented to five cathode elements in order to measure the azimuthal current distribution in the generator channel. Along both the upstream and downstream insulating walls are placed iridium voltage probes which protrude into the plasma to measure plasma potential and allow the calculation of electrode voltage drops. Four other voltage probes are located in the nozzle and allow measurement of plasma electrical conductivity parallel to the magnetic field by measuring the voltage difference when a current

Figure 6.1 Schematic figure of the disk generator flow train with the superconducting magnet.

Figure 6.2 Disk generator test section with a contoured anode, segmented ring cathodes, insulator ceramics and some of the instrumentation.

is passed between the anode and an electrode located upstream in the plenum. Thermocouples placed in the ceramics and cathodes give an estimation of channel heat flux and surface temperatures. Static pressure taps are located in the combustor, plenum, nozzle, test section and in the exit sections.

Superconducting Magnet

The magnet used in this work is a split circular coil superconducting magnet with a design maximum field strength of 6 Tesla (see Fig. 6.1). Room temperature access in the magnet consists of an 18 cm diameter round centerbore intersected midway between the coils by four 5 cm x 10 cm rectangular ducts which are perpendicular to each other and to the centerbore. The magnet was designed to have the generator test section in the center of the round centerbore and the exhaust gases exit through the four rectangular ducts.

During the first magnetization test the magnet quenched at 5.85 Tesla due to excessive charging rates. Operating procedures were changed and more accurate coil voltage monitoring instrumentation installed and 6 Tesla was subsequently achieved successfully. However, just as the magnet was being stabilized at 6 Tesla in a subsequent test, another quench occurred. It was concluded that the superconductor may be operating too close to its design limit so subsequent tests were carried out at 5.5 Tesla.

Problems also arose with the automatic liquid helium fill system, which was designed around an American Magnetics superconducting level probe. A possible combination of thermal and fluid mechanical problems, which have evidently been experienced by others in the cryogenic community, made the probe unreliable in detecting and controlling the liquid helium level. Therefore, a manual backup system using carbon resistors was used.

Extensive experience has been gained in the operation of the magnet. Some representative operating parameters are summarized in Table 6.1, and the measured magnetic field calibration curve is presented in Fig. 6.3.

Table 6.1

Operating Parameters of Superconducting Magnet

Cooldown Time:	1-2 hrs. (from liquid nitrogen temperature)
Charge Time:	1-1/2 hrs. (to 5.5 Tesla)
Liquid Helium Consumption:	30-50 liters/hr during cooldown 15-17 liters/hr during operation
Coil Dewar storage capacity:	12 liters
Inductance:	35 henries
Stored energy:	.5 megajoule (6 Tesla)

Table 6.2

Typical Disk Generator Operating Conditions

Fuel:	Alcohol
Oxydizer:	Oxygen
Diluent:	Nitrogen ($N_2/O_2 \approx 0.25 - 1.5$)
Mass Flow:	0.05 - 0.1 kg/sec
Gas Temperature:	2800 K
Gas Pressure:	≤ 1 atm
Mach Number:	.2 - .6
Plasma Conductivity:	3 - 15 mho/m
Insulator Temperature:	2500 K
Electrode Temperature:	
Anode	1000 K
Cathode	1700 K

Figure 6.3 The B-I characteristic of the 6 Tesla superconducting magnet.

Disk Generator Experiments

Four major disk generator experiments, each of several hours' duration, have been conducted to date: two current discharge experiments at zero magnetic field using external batteries and two power generation experiments at a magnetic field of 5.5 Tesla. A photograph of the experimental facility during one of the experiments is shown in Fig. 6.4.

During each experiment steady state data were obtained for electrode and insulator temperatures, cooling water temperature rise, and plasma pressure. Electrode voltages and currents, measured through each of the 5 cathode segments were obtained for a variety of load conditions. Static and fluctuating plasma potential were measured by the iridium voltage probes. The static data was scanned by a computer-controlled data acquisition system. Some on-line data reduction was done during the experiment with both digital and analog video display. Hard-copy output was also obtained during the test and the raw data was stored on disk for subsequent analysis. Fluctuating voltages and currents were recorded on a high-speed multichannel analog tape recorder for post-test statistical analysis of radial and tangential nonuniformities. Typical operating conditions for the experiment are listed in Table 6.2.

In Fig. 6.5 is presented a steady state electric field including voltage drops, vs. current densities based on flow area for several similar flow conditions for the two 5.5 Tesla experiments. The data show reasonably good behavior for typical V-I characteristics. Maximum power extracted was 70 watts. Before the addition of 1% seed during the electrical tests, sufficient ionization was achieved to give an appreciable Hall parameter. Open circuit electric fields measured during this part of the experiments were much higher than those shown in Fig. 6.5. Based on the open circuit voltage measured before the addition of seed, an effective Hall parameter of 2 was obtained, compared to a theoretical value of 2.14. However, with the addition of seed and an increase in conductivity, the electric field was significantly reduced, indicating internal current leakage within the channel, probably along the insulator surface in the hot boundary layer or in the insulator itself. For a typical curve on Fig. 6.5 the corresponding open circuit voltage was about 30 volts and the short circuit current was about 5 amps. Based on the mass

Figure 6.4 Disk generator experimental facility.
1. M-2 combustor
2. Superconducting magnet
3. Liquid helium dewar
4. Liquid helium transfer line
5. Vacuum pump
6. Exhaust manifold torus
7. Exhaust duct to scrubber

Figure 6.5 Electrical data from similar flow conditions during Tests II and III. Magnetic field was 5.5 Tesla. Static plasma properties were $T \sim 2800^\circ\text{K}$, $p \sim .75 \text{ atm}$, $\sigma \sim 15 \text{ mho/m}$, $M \sim .9$. Open circuit voltages prior to seed addition were 3-4 times higher than values shown, indicating the presence of internal current loops in the flow train which limited electrical performance to less than calculated values.

flow rate, measured static pressure, and using temperatures based on the measured conductivity at the channel inlet, the calculated open circuit voltage was about 500 volts and the calculated short circuit density was about 17 amps. The discrepancy between calculated and experimental values is evidently due to the current leakage problem. Possibilities of current leakage are being investigated.

In Fig. 6.6 is presented the induced steady state electrical data at 5.5 Tesla (the same as in the previous figure) along with the externally augmented data at higher voltages and currents. It can be seen that electrical conditions pertinent to open-cycle application were achieved. Although the resistance appears to decrease at higher electric fields, there was no evidence of arcing or breakdown. Higher electric fields were not attempted due to limitations in the external circuitry.

Statistical analyses were made of the fluctuating quantities of voltage and currents to determine the presence of nonuniformities in the radial outflow geometry in the presence of a high magnetic field. A typical spectral density function plot for a voltage probe signal (measured relative to the anode) is shown in Fig. 6.7. A typical cross correlation function plot for two adjacent voltage probes at different channel locations is shown in Fig. 6.8. No significant correlation between channel loading and fluctuating voltages has been observed in the data obtained and examined to date.

Summary

The entire disk generator flow train with the superconducting magnet has been developed and operated successfully.

Experiments have been conducted with maximum mass flow of 0.1 kg/sec at a magnetic field of 5.5 Tesla.

Voltage-current data obtained in power generation experiments showed ideal straight line characteristics. However, the open circuit voltage and the short circuit current were significantly lower than the calculated values indicating the existence of a current leakage loop. Possibilities of current leakage are being investigated.

Figure 6.6 Electrical data from Fig. 6.5 (open symbols) with externally augmented data (+), both obtained at $B = 5.5$ Tesla. Also shown is data taken at $B = 0$ (x) with externally-applied power. Electrical levels were achieved which are of interest to open-cycle application. Although the applied-field data show leveling off at higher electric fields, there was no evidence of arcing or breakdown.

Figure 6.7 Spectral density function plot for a voltage probe
($r = 2.38$ cm) measured relative to the anode. Run 368.

Figure 6.8 Cross correlation function plot for two adjacent voltage probes
($r = 2.38$ cm, 60° apart). Run 268.

E-field breakdown tests were conducted under applied field mode. Electric field up to 5.2 kV/m was achieved without breakdown.

Potential fluctuation data obtained under power generation conditions did not show any indication of instabilities.

6.1.2 Analytical and Numerical Study on Current Discharge Phenomena in The Disk Generator

Current discharge in the disk generator is subject to different constraints from those of the linear generator. The azimuthal current closes upon itself, thereby eliminating the electrodes which sustain the induced current. The lack of electric field in the azimuthal direction simplifies the structure of the insulator wall as the insulation must be made only in the radial direction. Another important characteristic is that the current flows parallel to the applied magnetic field when it enters or emerges from the electrodes. This effect alleviates the current concentration and is fundamentally different from the current discharge configuration of linear generators. It is expected to be an important advantage of the disk generator regarding the lifetime of the electrodes and for interelectrode breakdown.

The purpose of this study is to characterize current discharge phenomena in the disk generator channel under various operating conditions and to assess their effects on the performance of disk generators. During the past contract period two different aspects of the current discharge have been investigated analytically and numerically. One is the current discharge in the r - z plane and the other in the r - θ plane of the generator channel. These two aspects have been treated independent of each other. This may be justified because the physical mechanisms and the consequences of the current discharge in the r - z plane and those in the r - θ plane are distinctly different due to the unique configuration of the disk generator channel. For example, electrode phenomena and the current leakage on the insulator walls are primarily determined by the current discharge pattern in the r - z plane, whereas nonuniformities and instabilities that might decrease the generator performance are expected to take place mainly in the r - θ plane.

During the contract period the current discharge phenomena were studied by means of two numerical computational techniques, the finite difference method (FDM) and the finite element method (FEM) as discussed in the following sections.

Current Discharge in the r-z Plane

The current discharge pattern in the r-z plane of the generator is characterized by the interaction of the plasma with its boundaries, i.e. insulator walls and electrodes. It was shown [6.1] that the current discharge pattern in the r-z plane of the disk generator can be described by the partial differential equation of the elliptic type for the current stream function ψ as

$$\begin{aligned} \frac{\partial^2 \psi}{\partial r^2} + (1 + \beta^2) \frac{\partial^2 \psi}{\partial z^2} - \left(\frac{\partial \ln \sigma}{\partial r} + \frac{1}{r} \right) \frac{\partial \psi}{\partial r} + \sigma \left[\frac{\partial}{\partial z} \left(\frac{1}{\sigma_\beta} \right) \right] \frac{\partial \psi}{\partial z} \\ - \sigma r \frac{\partial}{\partial z} (v_\theta B + \beta v_r B) = 0 \end{aligned} \quad (6.1)$$

where

$$\sigma_\beta = \frac{\sigma}{1 + \beta^2} \quad \text{and} \quad j_r = \frac{1}{r} \frac{\partial \psi}{\partial z}, \quad j_z = -\frac{1}{r} \frac{\partial \psi}{\partial r}.$$

The azimuthal homogeneity,

$$\frac{\partial}{\partial \theta} = 0$$

is assumed in deriving the above equation.

The above equation was solved for a combustion driven disk generator by the finite difference method (FDM). The size of the generator, the mass flow rate and the magnetic field were chosen to simulate the base-load disk generator conditions. The coefficients of the partial differential equation were given by a quasi one-dimensional core flow calculation which was performed separately. For the sake of simplicity the height of the generator was held constant along the radial direction. The boundary layer model employed is the turbulent, one-seventh power law for temperature and velocity distributions. In Fig. 6.9 the result of the computation is given. The generator configuration for this result is the outflow disk generator. Electrodes shown in the figures are the inner cathode (center)

Figure 6.9 The current discharge pattern in the disk generator channel with 2 ring cathodes. $B = 6$ Tesla, mass flow rate = 75 kg/s, alcohol + N_2/O_2 (0.5) + 1% K, inlet temperature = 2600 K, inlet pressure = 1.5 atm, inlet swirl = 1, Mach = .84, $T_w = 2000^\circ K$. Current through the inner cathode = 1526 amp, current through the outer cathode = 1526 amp.

and the outer cathode (right). The central anode is not shown because the current discharge pattern over the anode was shown to be straightforward [6.1]. Detailed current streamlines over the inner and the outer cathodes are shown in Fig. 6.10.

Figures 6.9 and 6.10 indicate that the current discharge pattern in the r-z plane of the disk generator behaves well, i.e. the discharge current fills the entire generator channel volume and flows into and out of the electrode uniformly. It is to be noted that the current streamlines over electrode surfaces for the disk generator are much more uniform than those for linear generators. This will have favorable effects on the electrode lifetime and on the ability of the insulator wall to withstand a high electric field in the channel.

Current Discharge in the r- θ Plane

Current discharge phenomena in the r- θ plane have important effects on the performance of the disk generator. Azimuthal nonuniformities such as wakes from guide vanes degrade macroscopic electrical properties and consequently cause the performance of the generator to deteriorate. For the inflow disk generator, scroll induced nonuniformities as discussed in the next section may contribute to the performance deterioration.

A previous study on the current discharge phenomena in the r- θ plane of the disk generator was conducted mainly for the prescribed nonuniformities [6.2]. In order to study the current discharge phenomena with high MHD interactions, electrical equations and fluid dynamic equations must be solved simultaneously. This could be achieved by step-wise coupling of the electrical equations and fluid dynamic equations as attempted in the work of Dvornik, et al. [6.2]. During the past contract period we have initiated a new approach to the problem, namely to solve the electrical and fluid dynamic equations simultaneously by using the finite element method (FEM).

The electrical and fluid dynamic equations that govern the current discharge phenomena in the r- θ plane of the disk generator under the assumption of axial uniformity ($\frac{\partial}{\partial z} = 0$) are:

The current discharge pattern over the inner cathode.

The current discharge pattern over the outer cathode.

Figure 6.10 Current streamlines over the inner and outer cathodes.
Insulator wall and electrode temperatures are 2000°K.

Energy equation

$$\rho \left(\frac{\partial h_{tot}}{\partial t} + v_r \frac{\partial h_{tot}}{\partial r} + \frac{v_\theta}{r} \cdot \frac{\partial h_{tot}}{\partial \theta} \right) - \frac{\partial p}{\partial t} = - \left[\frac{1}{r} \frac{\partial}{\partial r} (r q_r) + \frac{1}{r} \frac{\partial}{\partial \theta} q_\theta \right] \\ + \sigma_\beta \left[\left(\frac{\partial \phi}{\partial r} \right)^2 + \left(\frac{1}{r} \frac{\partial \phi}{\partial \theta} \right)^2 + (v_\theta B + \beta v_r B) \frac{\partial \phi}{\partial r} + (v_r B - \beta v_\theta B) \frac{1}{r} \frac{\partial \phi}{\partial \theta} \right] \quad (6.2)$$

Momentum equation

$$\rho \left(\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \cdot \frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} \right) = - \frac{\partial p}{\partial r} + \sigma_\beta \left[\left(- \frac{1}{r} \frac{\partial \phi}{\partial \theta} - v_r B \right) \right. \\ \left. + \beta \left(- \frac{\partial \phi}{\partial r} + v_\theta B \right) \right] B \quad (6.3)$$

$$\rho \left(\frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \cdot \frac{\partial v_\theta}{\partial \theta} + \frac{v_r v_\theta}{r} \right) = - \frac{1}{r} \frac{\partial p}{\partial \theta} - \sigma_\beta \left[\left(- \frac{\partial \phi}{\partial r} + v_\theta B \right) \right. \\ \left. - \beta \left(- \frac{1}{r} \frac{\partial \phi}{\partial \theta} - v_r B \right) \right] B \quad (6.4)$$

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (\rho r v_r) + \frac{1}{r} \frac{\partial}{\partial \theta} (\rho v_\theta) = 0 \quad (6.5)$$

Electrical equation

$$\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r^2} \cdot \frac{\partial^2 \phi}{\partial \theta^2} + \left(\frac{\partial \ln \sigma_\beta}{\partial r} + \beta \frac{1}{r} \cdot \frac{\partial \ln \sigma_\beta}{\partial \theta} + \frac{1}{r} \frac{\partial \beta}{\partial \theta} + \frac{1}{r} \right) \frac{\partial \phi}{\partial r} \\ + \left(- \beta \frac{\partial \ln \sigma_\beta}{\partial r} - \frac{\partial \beta}{\partial r} + \frac{1}{r} \frac{\partial \ln \sigma_\beta}{\partial \theta} \right) \frac{1}{r} \frac{\partial \phi}{\partial \theta} - \frac{\partial}{\partial r} (v_\theta B + \beta v_r B) \\ - \frac{1}{r} \frac{\partial}{\partial \theta} (-v_r B + \beta v_\theta B) - (v_\theta B + \beta v_r B) \left(\frac{\partial \ln \sigma_\beta}{\partial r} + \frac{1}{r} \right) \\ - (-v_r B + \beta v_\theta B) \frac{1}{r} \cdot \frac{\partial \ln \sigma_\beta}{\partial \theta} = 0 \quad (6.6)$$

where the electrical potential ϕ is related to the electric field such that

$$E_r = - \frac{\partial \phi}{\partial r} , \quad E_\theta = - \frac{1}{r} \cdot \frac{\partial \phi}{\partial \theta}$$

In the above set of equations, the independent variables are pressure (p), temperature (T), velocity components (v_r , v_θ) and electric potential (ϕ). Other properties, such as density (ρ), enthalpy (h), heat flux components (q_r , q_θ) and electrical conductivity (σ) are determined as functions of the variables. The finite element method allows us to solve the above set of equations simultaneously with given initial and boundary conditions. For example when the inlet thermodynamic conditions with azimuthal nonuniformities are given, the entire flow field and the current discharge pattern can be computed for a given potential difference between the anode and the cathode.

Steps have been taken to develop FEM computer programs that can be used for combustion driven disk generators. A "prototype" FEM computer program which handles simplified forms of Eqs. (6.2 - 6.6) has been developed. In order to keep the required computer relatively short, the program has been tried on a small scale disk generator (5 ~ 8 cm radius) comparable in size to the Stanford experimental disk generator described in the previous section. A wedge shaped (30°) section of the generator was chosen for the computation. The elements are made to take up 1/12 of the section width and the boundary conditions on both sides of the wedge section to be equal (periodicity condition).

The FEM program was checked by running cases for which inlet conditions are azimuthally uniform and comparing the results with those of the one-dimensional iterative program. The FEM results with as few as five elements in the radial direction agreed well with the one-dimensional 4th order Runge-Kutta iteration method. Figures 6.11 - 6.13 show some of the FEM computation results that describe propagation of an inlet azimuthal nonuniformity into the downstream of the generator.

In Fig. 6.11 a cold spot (~ 50 K lower than the rest of the plasma) is specified at the right front edge (inlet) of the channel. We see that the cold spot propagates with the gas along the channel forming a much

T

σ

Figure 6.11 Propagation of cold spot in a small-scale outflow disk generator. Temperature distribution (above) and σ distribution (below). $R_{in} = 5$ cm, $R_{out} = 8$ cm
 $T_{g \text{ inlet}} = 2800^\circ\text{K}$ (cold spot 2760°K), $P_{inlet} = 1$ atm,
 $M = 0.84$, swirl = 1, $B = 6$ Tesla, Montana coal +
 air + 1% K.

steeper canyon in the electrical conductivity plotting. The total current density $\left(\sqrt{j_r^2 + j_\theta^2}\right)$ variation and the current vector components are shown in Fig. 6-12. The fact that the current vector direction does not change appreciably indicates that the reduction of the current is due almost entirely to the lower conductivity of the cooler plasma.

The FEM computer program is now ready to be expanded so as to be used for larger channels and to study transient behavior of the current discharge phenomena in high interaction disk generators.

Summary

Current discharge phenomena in the disk generator channel were investigated using two numerical computational techniques: the finite difference method (FDM) and the finite element method (FEM).

The current discharge pattern in the r-z plane was analyzed by means of the FDM. It was found that the discharge current fills the entire generator channel volume, and flows into and out of the electrode uniformly. This will have favorable effects on the electrode lifetime and on the ability of the insulator wall to withstand high electric fields in the channel.

Current discharge phenomena in the r- θ plane of the channel have been investigated by means of the FEM. In this new approach to the problem a simultaneous solution of electrical and fluid dynamic equations has been attempted. A "prototype" FEM computer program has been developed and has been successfully applied to a small scale disk generator channel. The FEM computer program is now ready to be extended to larger channels.

6.1.3 Performance Prediction Study of Disk Generators for Open-Cycle Power Generation [6.3]

The purpose of this study is to assess the potential of the disk generator for open-cycle, base-load power generation. The steps we have taken to conduct this study are:

1. to review disk generator studies conducted to date.
2. to define optimum operating conditions for base-load disk generators.
3. to compute the performance of disk generators based on combustion-driven, base-load conditions.

Figure 6.12 Propagation of cold spot in a small-scale outflow disk generator. Total current density distribution (above) and the current vector distribution (below).

4. to compare the performance of disk generators with that of linear generators.
5. to identify the advantages and the disadvantages of disk generators.

Disk generator studies conducted to date show that the disk generator is an effective power conversion machine if proper parameters are chosen. The question to be answered is whether the generator operates satisfactorily under conditions for open-cycle, base-load conditions. Previous disk generator studies considered the supersonic operation in the outflow geometry for power generation. However, detailed analyses of local performance characteristics of disk generators operating on combustion gas of Western coal with preheated air showed that subsonic operation is also possible in terms of enthalpy extraction and efficiency. Analyses also showed that, in terms of electrical characteristics, subsonic operation is even more desirable than supersonic operation.

Based on these results the performance of the base-load disk generator was calculated for three different disk generator configurations -- outflow, inflow and inflow-outflow as shown in Fig. 6.13. Operating conditions for these generators are given in Table 6.3.

The results of the calculation showed that the supersonic outflow generator and the subsonic inflow generator will attain about the same level of performance acceptable for base-load application. However, the electric field to be sustained along the generator channel for the supersonic outflow generator will be twice as high as that for the inflow generator. Thus performance deterioration due to current leakage or E-field breakdown will be more severe for the outflow disk generator. Another important point to be noted is that since the outflow generator needs inlet guide vanes to create inlet swirl, the effect of inhomogeneities associated with wakes will decrease the level of performance. The inflow disk generator does not require inlet guide vanes to create swirl. The combustion gas from multiple combustors can be distributed around the outer radius of the channel by a scroll and is injected tangentially inward. In this case there will be gradual, periodic azimuthal variations of thermodynamic and electrical properties due to losses in the scroll. However the effect of such gradual nonuniformities will be much less than those associated with wakes from guide vanes.

Figure 6.13 Three disk generator configurations. Sizes given here are for the outflow (impulse-supersonic), the inflow (reaction-subsonic) and the inflow-outflow (reaction-subsonic) disk generators for base-load application.

Table 6.3

Operating Conditions for Disk Generators

Fuel	Montana Rosebud seam (2% moisture)
Oxidizer	Preheated Air (1750 K)
Seed	K (1% by weight)
Thermal input (MW)	1250
Generator inlet condition	
Enthalpy influx (MW)	2000
P_{tot} (atm)	6.0
T_{tot} (K)	2800
Insulator wall temperature (K)	2000
Diffuser efficiency, η_D	0.80
Diffuser exit pressure (atm)	1.15
Magnetic Field (Tesla)	8.0
Reaction Mode	Constant Mach number, $M = 0.90$
Impulse Mode	$M_{\text{inlet}} = 1.85$

The inflow-outflow generator both for subsonic and supersonic operations may attain higher performance levels than the outflow generator or the inflow generator. The advantage of the inflow-outflow generator is its compactness. The smaller diameter of the channel may reduce the magnet cost. However, its relatively complex flow field in the channel and the fact that it requires a torus to collect the exhaust gas, as in the case of the outflow disk generator, may make this configuration less practical than the inflow generator.

In Fig. 6.14 the performance of disk generators is compared with that of linear generators. Enthalpy extraction and generator isentropic efficiency are chosen here as pertinent criteria for comparison. The performance of the inflow generator (reaction), the outflow generator (impulse) and the inflow-outflow generator (reaction, impulse), though they fall below that of the Faraday generators, are comparable to that of diagonal generators.

The results presented above show that, in terms of enthalpy extraction, generator isentropic efficiency, electric fields to be sustained along the generator channel and simplicity of the generator channel geometry, the inflow disk generator which operates in the reaction mode in the subsonic regime may be preferable for base-load power generation. Under coal-fired, base-load conditions, with the magnetic fields achievable at costs less than that for linear generators, the performance of the inflow disk generator is comparable to that of the diagonal generator.

Some of the advantages and drawbacks of the disk generators identified to date are briefly discussed below.

Surface areas of the generator channel of disk generators are equal to or less than those of linear generators. For example, the surface area of the inflow-reaction disk generator for 2000 MWth range will be 110 m^2 as compared to 120 m^2 for a diagonal linear generator [6.4]. It is to be noted that the electrode surface area of the disk generator is only about three percent of the total surface area and that the power loss associated with electrode voltage drops amount to less than one percent of the electrical output. This means that the temperature of the electrodes has little effect on the generator heat loss. Thus the temperature of the electrodes can be set for minimum electrochemical and structural degradation while keeping the insulator wall hot to minimize heat loss.

- [A] "Optimization Studies of MHD-Steam Plants," T.C. Tsu, W.E. Young, and S. Way, Proceedings of a Symposium on MHD Electrical Power Generation, Salzburg, July 1966, Vol. III, pp. 899-911.
- [B] "Some Design Considerations for a Single-Load Generator," M.W.E. Coney, and J.B. Heywood, Proceedings of a Symposium on MHD Electrical Power Generation, Warsaw, July 1968, Vol. IV, pp. 2687-2702.
- [C] "Cycle Efficiency of Large Scale Open-Cycle MHD Power Plant," Y. Mori, et al., Fifth Intl. Conf. on MHD Electrical Power Generation, Munich, April 1971, Vol. I., pp. 569-584.
- [D] "MHD Power Plant for Early Realization," S. Way, Fifth Intl. Conf. on MHD Electrical Power Generation, Munich, April 1971, Vol. I, pp. 615-628.
- [E] "Calculation of Performances of Large Scale Diagonal MHD-Steam Plants," K. Takano, K. Onda and Y. Mori, 13th Symp. on Engineering Aspects of MHD, Stanford, March 1973, pp. V.6.1-V.6.9.
- [F] "Status of the Reference Dual-Cycle MHD-Steam Power Plant," W. D. Jackson, et al., 16th Symp. on Engineering Aspects of MHD, Pittsburgh, May 1977, pp. X.6.37-X.6.44.

Figure 6.14 Comparison of performance of disk generators with that of linear generators.

When an MHD generator operates in the presence of the slag layer in the channel the leakage current flows along the surface of the slag layer. The disk generator is subject to larger current leakage than linear generators due to its larger surface to volume ratio. A quantitative evaluation, based on the experimental results pertinent to the operating condition of the inflow reaction disk generator [6.5, 6.6] showed that the power loss due to the current leakage in the disk generator channel is still less than 1% of the total enthalpy influx to the generator channel.

An important advantage of the disk generator is that it is not subject to the electrode shorting observed on the cathode wall in linear channels. Recent linear generator experiments showed that the cathode wall of slag-coated linear generators is covered with a current-conducting layer due to slag polarization [6.7, 6.8]. The effect of this cathode shorting on the performance of full-scale MHD generators has not been assessed. It is clear, however, that the cathode shorting phenomena will limit the axial Hall field, i.e., the enthalpy extraction rate, of linear generators. The disk generator is not subject to the cathode shorting problem because of its unique geometry. This is a significant point to be considered because the cathode shorting problem is likely to have more a serious effect on generator performance than the current leakage along the slag surface.

The circular magnetic field volume for the disk generator can be provided either by a single coil magnet or by a solenoidal magnet. However, the cost of the single coil magnet will be less than that of the Helmholtz pair magnet because the support structure of the single coil magnet can be simpler. An analysis based on the single coil magnet indicates that for a disk generator size similar to those studied in this paper, the magnet cost will be less than that for linear generators of equivalent power output [6.9].

A conceptual scheme of the inflow disk generator discussed above is given in Fig. 6.15. The combustion gas from four combustors is distributed around the outer radius of the channel by a scroll and is injected tangentially inward. At the exit of the channel the gas flows axially out into the diffuser. The main load circuit (left) extracts

INFLOW DISK MHD GENERATOR

Figure 6.15 Conceptual scheme of the inflow disk generator. The combustion gas from four combustors is distributed around the outer radius of the channel by a scroll and is injected tangentially inward. At the exit of the channel, the gas flows axially out into the diffuser.

more than 80% of the power while the secondary circuit (right) optimizes the current loading. The magnet shown in the figure is a pair of circular coils. From the structural and slag fluid dynamic considerations, the axis of the generator will be aligned vertical sending the exhaust gas downward to the radiant boiler. The inherent compactness of the inflow disk generator assembly is apparent in the figure.

Summary

Calculation of enthalpy extraction and generator isentropic efficiency showed that three disk generator configurations - outflow (supersonic), inflow (subsonic) and inflow-outflow (subsonic, supersonic) - would attain a performance level comparable to that of the linear diagonal generator.

In terms of the electrical and fluid dynamic operating conditions subsonic inflow disk generator appears to be preferable among three generator configurations mentioned above.

Surface areas of base-load disk generators are equal to or less than those of linear generators. The electrode surface area of the disk generator is about 3% of the total surface area of the generator channel and the power loss associated with electrode voltage drops amount to less than one percent of the electrical output.

The current leakage loss over the slag surface for the disk generator is expected to be larger than that for linear generators. Preliminary calculation showed that the loss may amount to about 1% of the total enthalpy influx to the generator.

Because of its geometry the disk generator is not subject to the cathode shorting due to slag polarization.

The magnet cost for the disk generator will be less than that for linear generators of equivalent power output.

6.2 Linear Generator Design and Status

A small linear generator has been designed and operated in the 6 Tesla magnet. Special problems arise because of the small size, the need for a long lead-in section through the magnet coils and the presence of high electric fields. A pictorial view of the channel, transfer sections and adapters to the combustor plenum and diffuser is shown in Fig. 6.16. Because of the high magnetic field and associated high electric fields, the construction utilizes a peg wall with a fiberglass reinforced plastic backing material. Photos of the construction are shown in Figs. 6.17, 6.18 and 6.19.

A special effort was made to operate with hot walls and electrodes to overcome the problems with cold boundary layers in small channels. The sidewall pegs are copper with MgO brazed to them through a compliant layer of copper mesh. Lanthanum-chromite electrodes were selected for their ability to operate at high temperatures and a lifetime of several hours was expected. This duration is adequate for the initial test program planned.

Detailed consideration has been given to the experimental program for the six Tesla linear channel. It is planned to investigate the following phenomena at magnetic fields up to 6 Tesla:

1. Effective conductivity
2. Effective Hall parameter
3. Effect of β and j on electrode voltage drops
4. Current concentration on electrodes
5. Boundary layer shear stress
6. Time dependent fluctuations

Both the effective conductivity and effective Hall parameter can be found if current and field magnitudes and directions are known in the generator channel. The generator is constructed with segmented electrodes with a pitch of 0.5 cm. By connecting the electrodes together in a continuous configuration and measuring the current to each segment, the current angle (and magnitude) can be ascertained. Probes will be used to measure the electric fields E_x and E_y in the core.

Electrode voltage drops are frequently measured by extrapolating voltage probe measurements in the core to the electrode wall and comparing

Figure 6.16 The near channel flowtrain.

Figure 6.17 Transfer section sidewall.

Figure 6.18 Transfer section sidewall.

Figure 6.19 Assembled electrode wall.

the actual electrode voltage with the extrapolated value [6.10]. Because of the high magnetic field and Hall parameter, it is opportune to examine the effect of these parameters on voltage drops with current density treated as an independent variable. Through the use of the external battery power supplies we expect to make measurements at average current densities up to 2 amps/cm².

The relatively fine segmentation of the electrodes will permit shorting of the segments in twos and threes to measure current distribution as a function of β and j . Computer calculations for an electrode temperature of 2000 K and a core temperature of 2700 K at $B = 6$ Tesla and for the expected flow conditions show a 10% - 20% - 70% distribution of current for the triplet electrode case. Experimental measurements are important because local current densities have very important effects on the operation and lifetimes of electrodes.

A number of thermal tests were made on components and a successful thermal test of the system was made on 8/30/79. The flow train was then disassembled and inspected and installed in the superconducting magnet. A performance test was conducted on 12/20/79, and at the same nominal operating conditions the walls and electrodes ran significantly colder than during the thermal test. Later it was found that the combustor plenum chamber had an intermittent water leak which may have been the cause of the low temperatures. The performance data are not considered representative of normal MHD generator operation at the design conditions and the test will be repeated.

7.0 PUBLICATIONS

J. P. Barton, J. K. Koester, and M. Mitchner, "An Experimental Investigation of Fluctuating Properties within a Combustion MHD Generator," 16th Symposium on Engineering Aspects of MHD, May 1977.

R. R. Rankin, S. A. Self, and R. H. Eustis, "A Study of the MHD Insulating Wall Boundary Layer," 16th Symposium on Engineering Aspects of MHD, May 1977

W. Unkel and C. H. Kruger, "Axial Field Limitations in MHD Generators," 16th Symposium on Engineering Aspects of MHD, May 1977.

R. M. Kowalik and C. H. Kruger, "The Effects of Fluctuations and Non-uniformities on Line-Reversal Temperature Measurements," J. Quant. Spectrosc. Radiat. Transfer, 18, 1977, pp. 627-636.

J. P. Barton, J. K. Koester, and M. Mitchner, "Probe-tube Microphone for Pressure-fluctuation Measurements in Harsh Environments," J. Acoust. Soc. Am., 62, 5 (1977), 1312-1314.

J. P. Barton, J. K. Koester, and M. Mitchner, "An Experimental and Analytical Investigation of Fluctuation Phenomena Within a Subsonic Combustion MHD Generator," 17th Symposium on Engineering Aspects of MHD, March 1978, Stanford.

R. K. James and C. H. Kruger, "Boundary Layer Profile Measurements in the Electrode Wall of a Combustion Driven MHD Channel," 17th Symposium on Engineering Aspects of MHD, March 1978, Stanford.

R. M. Kowalik and C. H. Kruger, "Preliminary Experiments Concerning Inhomogeneities in Combustion MHD Generators," 17th Symposium on Engineering Aspects of MHD, March 1978, Stanford.

R. M. Kowalik and C. H. Kruger, "Laser Fluorescence Temperature Measurements," Western States Section, Combustion Institute, Paper #78-17, April 1978, Boulder, Colorado; Also Combustion and Flame 34, (1979) 135.

R. R. Rankin, "Insulating Wall Boundary Layer in a Faraday MHD Generator," DOE Report #FE-2341-7, April 1978, HTGL Report #106.

W. C. Unkel, "Axial Field Limitations in MHD Generators," DOE Report #FE-2341-8, April 1978, HTGL Report #107.

S. A. Self, "Boundary Layer Velocity Measurements in Combustion MHD Channels," Third International Workshop on Laser Velocimetry, July 1978, Purdue University.

C. H. Kruger, R. M. Kowalik, and R. K. James, "Spectroscopic Measurements of Temperature, Electron Density and Temperature Fluctuations," Fourth US/USSR Colloquium on MHD, October, 1978.

P. Kuzmenko, F. O. Reigel, and S. A. Self, "Measurement of Electron Concentration and Mobility in Slag-Laden MHD Flows by Submillimeter Interferometry," Fourth US/USSR Colloquium on MHD, October, 1978.

S. A. Self, I. A. Vasil'eva, A. P. Nefedov, "Plasma Diagnostics in an MHD Installation," Open-Cycle Magnetohydrodynamic Electrical Power Generation, M. Petrick and B. Ya. Shumyatsky, Argonne National Laboratory, 1978.

S. A. Self, "Diagnostic Techniques in Combustion MHD Flows," Dynamic Flow Conference, September 1978, Baltimore, Maryland.

S. A. Self, "Diagnostic Techniques in Combustion MHD Flows," 10th Materials Research Symposium on Characterization of High Temperature Vapors and Gases, National Bureau of Standards, September 1978.

R. M. Kowalik and C. H. Kruger, "Experiments Concerning Inhomogeneities in Combustion MHD Generators," 18th Symposium on Engineering Aspects of MHD, June 1979, Butte, Montana.

J. P. Barton, J. K. Koester, and M. Mitchner, "Fluctuations in Combustion MHD Generator Systems," 18th Symposium on Engineering Aspects of MHD, June 1979, Butte, Montana.

R. K. James and C. H. Kruger, "Plasma Measurements of Joule Heating Effects in the Near Electrode Region of an Open Cycle MHD Generator," 18th Symposium on Engineering Aspects of MHD, June 1979, Butte, Montana.

Takashi Nakamura and Marion K. Jenkins, "Performance of Disk Generators for Open-Cycle MHD Power Generation," 18th Symposium on Engineering Aspects of MHD, June 1979, Butte, Montana.

R. M. Kowalik, "Measurements of Conductivity Nonuniformities and Fluctuations in Combustion MHD Plasmas," DOE Report FE-2341-14, January 1980, HTGL Report #114.

R. K. James, "Joule Heating Effects in the Electrode Wall Boundary Layer of MHD Generators," DOE Report FE-2341-15, January 1980, HTGL Report 115.

8.0 SUMMARY AND CONCLUSIONS

A theoretical and experimental program has been undertaken to investigate MHD channel phenomena which are expected to be important at high magnetic fields. In most areas, advanced diagnostics were developed to permit experimental measurements which could be compared with theory. Extrapolation of the theory, which had been verified at the laboratory scale, was then used to predict the influence of the phenomena on large scale MHD generators.

The areas studied were:

- inhomogeneity phenomena
- boundary layer phenomena
- Hall field breakdown phenomena
- electrode configuration and current concentrations
- disk generator performance

In the first three areas, important advances in diagnostics occurred. Techniques were developed for measuring pressure fluctuations in a magnetic-field at frequencies to 10 kHz, plasma temperatures with 2-D and 3-D spatial resolution, electron concentration with 2-D and 3-D spatial resolution, velocity by laser doppler anemometry, photographic discrimination of plasma and surface temperatures, and fluctuating voltages by probe.

The study of inhomogeneities in the plasma characterized the flow in the Stanford M-2 facility as having convected streamers of hot or cold plasma generated by combustor variations with superposed pressure standing waves. Spectral distribution curves showed most energy in the low frequencies, less than 1000 Hz, and amplification of the pressure waves with increasing magnetic field was observed when a current was present. This is due to the fluctuating $\bar{j} \times \bar{B}$ influence on the pressure. An analysis which involved linearization of the perturbation equations describes fluctuations in terms of two acoustic waves and a convected entropy wave. This analysis predicted the general character of the fluctuations measured in the M-2 facility and was extended to a full-scale, subsonic MHD generator. Regions of "significant amplification" for a wave were mapped on a plane with coordinates of interaction parameter

and load factor for Hall, Faraday, and diagonal wall electrical configurations. "Significant amplification" was defined as growth of any wave by a factor of 100 during the period it was in the generator channel. The Hall and diagonal wall configurations showed significant growth at any load factor for interaction parameters above about 5 and the Faraday configuration was less sensitive. Proposed full scale facilities will operate at interaction parameters above 5.

Investigations were made of both the electrode wall and the insulator wall of an MHD generator. Measurements were made of the temperature and electron concentration profiles for the electrode boundary layer with a particular interest in Joule heating and non-equilibrium effects. The boundary layers were close to equilibrium although Joule heating was observed at higher current densities. Observations were made as close as 0.5 mm from the wall. Numerical solution of the boundary layer differential equation using a mixing length theory for turbulence parameters gave satisfactory but not complete agreement with the measured profile. Extension of the calculation procedure to large MHD generators showed that Joule heating should be included in boundary layer predictions to prevent large errors in estimated voltage losses and heat transfer. The sidewall or insulated wall boundary layer is important because the velocity and temperature profiles are modified due to the Hartmann effect. Non-uniform current distribution perpendicular to the insulator wall due to both viscosity effects and conductivity variation with temperature causes a variation in the $\bar{j} \times \bar{B}$ force in the boundary layer. A velocity overshoot near the wall was predicted and confirmed experimentally by laser anemometry in an operating MHD generator. Extension of these results to a pilot plant size generator showed that wall friction more than doubles and heat transfer increases about 30 per cent compared to calculation not accounting for non-uniform current distributions.

Hall field breakdown studies were conducted to elucidate the mechanisms of breakdown, to construct a model capable of predicting the onset of breakdown, and to propose possible solutions to the problem. Experiments were conducted with applied electric fields between electrodes which reproduce the important features of plasma and insulator heating. A second

series of experiments was made with induced electric fields which yielded results similar to the applied field tests. It was shown that a threshold voltage exists before breakdown which is higher than the voltage after breakdown. Rapid breakdown was seen to occur in the plasma and a slow breakdown occurred in the insulator. For the induced field experiments only insulator breakdown was observed and for both types of experiments, the insulator breakdown occurred at a lower threshold voltage than for plasma breakdown. The test data show the threshold voltage to vary roughly linearly with gap size. Little variation of the threshold voltage was observed with changes in the plasma flow condition. Designers should consider electrode gap and insulator temperature important variables for controlling Hall voltage breakdown in slag-free flows.

A study of electrode configurations and measurement of current concentrations were made in an effort to find a way to increase the Hall field possible in linear MHD generators. A solution of the three-dimensional equations provided current distribution on electrodes with some surfaces perpendicular to the magnetic field direction. Such electrodes have less current concentration than conventional flat electrodes and may provide a way to increase Hall fields. Configurations studied to date show a decrease in current at the electrode edge of about 30 per cent. Measurements of current distribution over a segmented flat electrode in Hall breakdown experiments were made.

As part of the program in the small 6 Tesla superconducting magnet at Stanford, a disk generator was constructed and operated at 5.5 Tesla. Large Hall radial voltages were sustained even though performance was limited by the small size channel. A study was made to examine the projected performance of inflow and outflow disk configurations operating at subsonic and supersonic velocities. The outflow supersonic and inflow subsonic arrangements give similar performance with the inflow arrangement preferable because of the lack of turning vanes, lesser electrical stress on the insulating wall, and potential arrangement conveniences.

9.0 REFERENCES

- [2.1] Daily, J. W., Kruger, C. H., Self, S. A. and Eustis, R. H., "Boundary Layer Profile Measurements in a Combustion-Driven MHD Generator," Sixth International Conference on MHD Electrical Power Generation, Washington, D. C., June, 1975; also AIAA J., Vol. 14, pp. 997-1005, August 1976.
- [2.2] James, R.K. and Kruger, C. H., "Boundary Layer Profile Measurements in the Electrode Wall of a Combustion-Driven MHD Channel," 17th Symposium on Engineering Aspects of MHD, Stanford, 1978.
- [2.3] Daily, J. W. and Kruger, C. H., "Effects of Cold Boundary Layers on Spectroscopic Temperature Measurements in Combustion Gas Flows," J. Quant. Spectrosc. Radiat. Transfer 17, p. 327, 1977.
- [2.4] Kowalik, R. M. and Kruger, C. H., "The Effects of Fluctuations and Nonuniformities on Line-Reversal Temperature Measurements," J. Quant. Spectrosc. Radiat. Transfer 18, p. 627, 1977.
- [2.5] Kowalik, R. M., "Measurements of Conductivity Nonuniformities and Fluctuations in Combustion MHD Plasmas," HTGL Report No. 114 (FE-2341-14), Stanford University, January 1980.
- [2.6] Self, S. A. and Kruger, C. H., "Diagnostic Methods in Combustion MHD Flows," AIAA Paper No. 76-310 presented at the AIAA Ninth Fluid and Plasma Dynamics Conference, San Diego, CA., 1976.
- [2.7] Kowalik, R. M. and Kruger, C. H., "Laser Fluorescence Temperature Measurements," Combust. Flame 34, p. 135, 1979.
- [2.8] Vasil'eva, I. A., Deputotov, L. V. and Nefedov, A. P., "Investigation of the Far Wings of Resonance Lines of Alkaline Metals in Combustion-Products Plasma," Proceedings of the Second US-USSR Colloquium on MHD Electrical Power Generation, Washington, D. C., 1975.
- [2.9] Barton, J. P., Koester, J. K., and Mitchner, M., "A Probe Tube Microphone for Pressure Fluctuation Measurements in Harsh Environments," J. Acoust. Soc. Am. 62, p. 1312, 1977.
- [2.10] Jenkins, M. K., "High Temperature Gasdynamics Laboratory MHD Test Facility General System Description," High Temperature Gasdynamics Laboratory Memorandum Report #6, Stanford University, 1977.
- [2.11] Shamma, S. E., Martinez-Sanchez, M., and Louis, J. F., "Ohm's Law for Plasmas with Non-Isotropic Inhomogeneities and Its Effects on The Performance of MHD Generators," Proceedings of the Sixteenth Symposium on Engineering Aspects of MHD, Pittsburgh, PA., 1977.
- [2.12] Owen, F. K., Sapdaccini, L. J., and Bowman, C. T., "Pollutant Formation and Energy Release in Confined Turbulent Diffusion Flames," Sixteenth Symposium (International) on Combustion, p. 105, The Combustion Institute, Pittsburgh, PA., 1977.

- [2.13] Kerr, N. M., "Swirl. Part II: Effect on Flame Performance and the Modelling of Swirling Flames," J. Inst. Fuel 38, p. 527, 1965.
- [2.14] Barton, J. P., Koester, J. K., and Mitchner, M., "An Experimental Investigation of Fluctuating Properties Within a Combustion MHD Generator," 16th Symposium on Engineering Aspects of MHD, Pittsburgh, PA., 1977.
- [2.15] Barton, J. P., Koester, J. K. and Mitchner, M., "An Experimental and Analytical Investigation of Fluctuating Phenomena Within a Subsonic Combustion MHD Generator," 17th Symposium on Engineering Aspects of MHD, Stanford, 1978.
- [2.16] Barton, J. P., Koester, J. K. and Mitchner, M., "Fluctuations in Combustion MHD Generator Systems," 18th Symposium on Engineering Aspects of MHD, Butte, Montana, 1979.
- [2.17] Barton, J. P., "Fluctuations in Combustion-Driven MHD Generators," report in preparation.
- [2.18] Scott, M. H., "An Experimental Investigation of Fluctuations in a Direct Coal-Fired Open Cycle MHD Generator and a Method for Modeling These Fluctuations," AIAA Paper No. 76-313 presented at the AIAA Ninth Fluid and Plasma Dynamics Conference, San Diego, CA., 1976.
- [3.1] Tourin, R. H., Spectroscopic Gas Temperature Measurements, Elsevier, New York (1966).
- [3.2] Strong, H. M. and Bundy, F. P., "Measurement of Temperatures in Flames of Complex Structure by Resonance Line Radiation. I. General Theory and Application to Sodium Line-Reversal Methods," and "Measurement of Temperatures in Flames of Complex Structure by Resonance Line Radiation. II. Sodium Line Reversal by High-Resolution Spectroscopy," Journal of Applied Physics, Vol. 25, No. 12, December, 1954.
- [3.3] Brederlow, G., Riedmüller, W. and Salvat, M., "On the Applicability of the Line-Reversal Method for Measuring the Electron Temperature in a Weakly Ionized Alkali-Seeded Rare Gas Plasma," Institut für Plasmaphysik, Report IPP 3/69, Garching bei München, Germany, 1968.
- [3.4] Daily, J. W., Kruger, C. H., Self, S. A. and Eastis, R. H., "Boundary Layer Profile Measurements in a Combustion-Driven MHD Generator," Sixth International Conference on MHD Electrical Power Generation, Washington, D. C., June, 1975; also AIAA J., Vol. 14, pp. 997-1005, August 1976.
- [3.5] Kirillov, V. V., Semenov, V. D. and Yundev, D. N., "Measurement of the Temperature Distribution in a Boundary Layer at the Channel Walls of an Open Cycle MHD Generator," High Temperature, 11 (6), November-December 1973.
- [3.6] Vasil'eva, I. A., Kirillov, V. V., Maksimov, I. A., Malyushonok, G. P. and Novosadov, V. B., "Measurement of a Plasma's Temperature by a Spectroscopic Method with Continuous Automatic Detection," High Temperature, Vol. 11, No. 4., July-August 1973.

- [3.7] James, R. K. and Kruger, C. H., "Boundary Layer Profile Measurements in the Electrode Wall of a Combustion-Driven MHD Channel," 17th Symposium on Engineering Aspects of MHD- Stanford, 1978.
- [3.8] Daily, J. W. and Kruger, C. H., "Effects of Cold Boundary Layers on Spectroscopic Temperature Measurements in Combustion Gas Flows," JQSRT, Vol. 17, pp. 327-338, 1977.
- [3.9] James, R. K., "Joule Heating Effects in the Electrode Wall Boundary Layer of MHD Generators," HTGL Report No. 115, January 1980.
- [3.10] McGregor, D. D., "Electron Nonequilibrium in a Supersonic Expansion of Ionized Gas," SU-IPR Report No. 474, Institute for Plasma Research, Stanford University, 1972.
- [3.11] Durst, F. Melling A., and Whitelaw, J. H., Principles and Practice of Laser Anemometry, Academic Press, 1976.
- [3.12] Self, S. A. and Whitelaw, J. D., "Laser Anemometry for Combustion Research," Int. J. Comb. Sci. and Tech. 13, pp. 171-197, 1976.
- [3.13] Self, S. A., "Boundary Layer Measurements in Combustion MHD Channels," 3rd International Workshop on Laser Velocimetry, Purdue University, July 1978.
- [3.14] Rankin, R. R., "Insulating Wall Boundary Layer in a Faraday MHD Generator," Stanford University, HTGL Topical Report #106, April 1978.
- [3.15] James, R. K. and Kruger, C. H., "Plasma Measurements of Joule Heating Effects in the Near Electrode Region of an Open-Cycle MHD Generator," 18th Symposium on Engineering Aspects of MHD, pp. E.4.1-6, June 1979.
- [3.16] Hartmann, J. and Lazarus, R., "Kgl. Danske Videnskag Selskab," Mat.-Fys. Medd., Vol. 15, No. 6, p. 7, 1937.
- [3.17] Murgatroyd, W., Phil. Mag., Vol. 44, p. 1348, 1955.
- [3.18] Sonju, O. K., "Viscous Magnetohydrodynamic Flows," Stanford University, SU-IPR Report No. 245, July 1968.
- [3.19] Pepper, J. W., "Effect of Nitric Oxide Control on MHD Steam Power Plant Economics and Performamnce," Stanford University, SU-IPR No. 614, December 1974.
- [3.20] Kays, W. M., Convective Heat and Mass Transfer, McGraw-Hill, New York, 1966.
- [3.21] Crawford, M. E. and Kays, W. M., "STAN5 - A Program for Numerical Computation of Two-Dimensional Internal/External Boundary Layer Flows," NASA CR-2742, December 1976.

- [3.22] Burton, T., et. al., "CDIF-MHD Generator System Conceptual Design," ERDA Report TID-27150, December 1976.
- [4.1] Unkel, W. C., "Axial Field Limitations in MHD Generators," HTGL Report No. 107, Stanford University, April 1978.
- [4.2] Burenkov, D. K., et. al., "Study of the Maximum Hall Voltages and Interelectrode Breakdown in the Channel of an Open-Cycle MHD Generator: A Joint US-USSR Experiment on the U02 Facility MHD Generator," 16th Symposium on Engineering Aspects of MHD, Pittsburgh, PA., 1977.
- [4.3] Unkel, W., Kruger, C. H. and Koester, J. K., "Axial Field Limitations in MHD Generators," Proceedings of the Sixth International Conference on MHD Power Generation, Washington, D. C., June 1975.
- [5.1] Unkel, W. C., "Axial Field Limitations in MHD Generators," HTGL Report No. 107, Stanford University, April 1978.
- [6.1] Eustis, R. H., Kruger, C. H., Mitchner, M., Self, S. A. and Koester, J. K., "A High Magnetic Field MHD Generator Program," Quarterly Report FE-2341-4, Stanford University, 1977.
- [6.2] Dvore, D. S., Martinez-Sanchez, M., and Shamma, S. E., "Two Dimensional Effects in Disk Generators," 17th Symposium on Engineering Aspects of MHD, Stanford, California, pp. B.2.1-B.2.7, March 1978.
- [6.3] Nakamura, T., Jenkins, M. K., "Performance of Disk Generators for Open-Cycle MHD Power Generation," 18th Symposium on Engineering Aspects of MHD, Butte, Montana, June 1979, also Journal of Energy 3, No. 4, pp. 217-226, July-August 1979.
- [6.4] Jackson, W. D., et al., "Status of the Reference Dual-Cycle MHD-Steam Power Plant," 16th Symposium on Engineering Aspects of MHD, Pittsburgh, pp. X.6.37-X.6.44, May 1977.
- [6.5] Rodgers, M. E., Ariessohn, P. C. and Kruger, C. H., "Comparison of Measurements and Predictions of the Fluid Mechanics and Thermal Behavior of MHD Channel Slag Layers," 16th Symposium on Engineering Aspects of MHD, Pittsburgh, pp. VIII.4.26-VIII.4.31, May 1977.
- [6.6] Rodgers, M. E. and Kruger, C. H., "Fluid Mechanics and Thermal Behavior of MHD Channel Slag Layers," 17th Symposium on Engineering Aspects of MHD, Stanford, California, pp. C.2.1-C.2.6, March 1978.
- [6.7] Koester, J. K. and Nelson, R. M., "Discharge Characteristics of Slagging Metal Electrodes," 17th Symposium on Engineering Aspects of MHD, Stanford, California, pp. C.3.1-C.3.7, March 1978.
- [6.8] Demirjian, A., Petty, S. W. and Solbes, A., "Electrode Development for Coal-Fired MHD Generators," 17th Symposium on Engineering Aspects of MHD, Stanford, California, pp. D.1.1-D.1.6, March 1978.

- [6.9] Marston, P. G., Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA., private communication.
- [6.10] Kessler, R. and Eustis, R. H., "Effects of Electrode and Boundary Layer Temperatures on MHD-Generator Performance," AIAA Journal 6, p. 1640, September 1968; also IEEE Proceedings 56, September 1968; also Ninth Symposium on Engineering Aspects of MHD, Tullahoma, Tennessee, April 1968.