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KEY CONTRIBUTIONS IN MHD POWER GENERATION

Quarterly Technical Progress Report for the Period September 1—November 30, 1979

By
J. F. Louis

March 1980
Date Prepared

Work Performed Under Contract No. AC01-79ET15518

Massachusetts Institute of Technology
Energy Laboratory
Cambridge, Massachusetts

U. S. DEPARTMENT OF ENERGY

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QUARTERLY TECHNICAL PROGRESS REPORT

for the period

1 September 1979 - 30 November 1979

J. F. Louis,
Principal Investigator

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Energy Laboratory
Cambridge, Massachusetts 02139

Date Prepared - March 1980

PREPARED FOR THE UNITED STATES
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Under Contract No. DE-AC01-79ET15518

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ABSTRACT

Activities during the fourth quarter of the contract period are reported both in summary and in detail. The tasks reported on include: 1) investigation of electrical behavior in the vicinity of electrode and insulating walls; 2) studies of critical performance issues in the development of combustion disk generators; 3) development and testing of electrode modules, including studies of insulator properties; and 4) determination of coal combustion kinetics and ash behavior relevant to two-stage MHD combustors, and investigation of the mixing and flow aerodynamics of a high swirl geometry second stage.

Work carried out under Task 1 includes measurements of simulated slag flow in a glycerin channel; the data indicate that ripples are responsible for essentially all of the mass transport within the slag layer. Surface tension and form drag over the ripples are shown to be the dominant forces controlling the glycerin flow, and non-dimensional correlations of ripple speed, height, separation and width are presented in a form which can be used for estimations of these properties under MHD conditions. Design calculations for laminated electrode configurations for future experiments in the MHD Simulation Facility are discussed; the study emphasizes the need for taking account of the increased heat-flux due to locally high Joule heating in the thermal design of the inter-electrode regions. Other efforts reported under this task include results of tests aimed at improving the present diagnostics in the facility; the initial formulation of a theoretical treatment of slag layer current transport studies is also presented.

Under Task 2, the first set of nonuniformities experiments was completed, and the framework for the analysis of the data was established. The nonuniformities, created by cold blades located in the upstream region of a radial flow disk generator, consisted of well-characterized thermal and velocity wakes with strong variations of the plasma properties in the azimuthal direction. A data base for a fixed set of stagnation conditions and test gas mixture ($T_0 = 2850$ K, $p_0 \approx 4.0$ atm and Ar 80%/CO₂ 20% at room temperature) was obtained for ideal Hall coefficients in the range 2-7 and for configurations having 0, 6, 12, and 24 wakes. Experimental Hall parameter reduction curves (β_{eff} versus β_{ideal}) were established; the data clearly indicate the monotonic degradation of generator performance for this type of nonuniformity (and orientation) with increasing Hall parameter and number of wakes (rms σ). The theoretical framework for an analysis of the data is discussed, and a preliminary comparison of the voltage data for 24 blades at 3.5 Tesla with two theoretical models shows good agreement between theory and experiment.

Work reported under Task 3 includes modifications to the experimental apparatus to permit more accurate control of the surface composition of sample electrodes made from materials in the LaFeO₃ - SrFeO_{3- δ} - SrZrO₃ system. Considerable attention has been paid to minimizing the possible contamination from Si which has been shown to react with the electrode materials and form surface layers of silicates. Other work, on insulator materials, has focussed on obtaining some explanation for the large variations in room temperature breakdown strength observed for numerous specimens of hot pressed silicon nitride. Scanning electron microscopy and other diagnostics have so far failed to yield any reasonable explanation.

Ash vaporization of 26 mineral species has been measured under Task 4, using both oxidizing and reducing atmospheres, and with a range of particle temperatures. Experiments with and without the presence of a carbon matrix indicate that the latter enhances ash vaporization at a rate attributable to reducing reactions. Initial work on analyzing solid pyrolysis and combustion products (chars, tars, soot) is reported, with simultaneous study of physical and chemical surfaces. Direct imaging of internal pore structure ($> 50 \text{ \AA}$) is obtained with transmission electron microscopy. Improvements to the coal combustor model are also discussed.

Results from the computer code SHAPE are presented; these give the stream function, static pressure, and velocity distributions within the second stage nozzle of a high-swirl MHD combustor. Based on limited experimental data obtained in the water model test facility, it appears that the turbulence parameters used by D.G. Lilley yield calculated flow field properties which are qualitatively acceptable; refinement of the choice of these parameters will be based on comparisons with future experimental data.

I. OBJECTIVE AND SCOPE OF WORK

The Department of Energy (DOE) is responsible for a national program for the development of commercial open-cycle MHD power generation with the initial objective of establishing the engineering feasibility of MHD power systems utilizing coal or fuel derived from coal.

Research and development in open-cycle coal-fired MHD power generation has been underway at Massachusetts Institute of Technology (MIT) since 1971, the scope of the effort gradually expanding to its present level. The scope and objectives of the present MHD program are as follows:

1. To carry out an experimental investigation of the mechanisms of near-electrode voltage drops, axial breakdown, onset of transverse arcs, arc damage, slag shorting and related phenomena important for the design of MHD electrode and insulating walls, and to develop analytical models in support of these experiments.

2. To investigate, experimentally and analytically, critical performance issues involved in the development of combustion disk generators. Particular emphasis will be given to determination of the effective plasma properties and generator performance as affected by (a) plasma nonuniformities, (b) chemical nonequilibrium, (c) unsteady flow phenomena, (d) boundary layers and slag, and (e) inviscid flow distortion.

3. To perform the engineering design, construction and testing of electrode modules. This work will include: (a) a laboratory-based materials selection investigation, (b) electrode/insulator fabrication, and (c)

performance measurements. In addition, a model of the time-dependent performance based on measured module data will be developed. The major emphasis of the task will be on development of super-hot electrode modules and measurement of dielectric breakdown of insulator materials and coal slag.

4. To research the coal combustion kinetics relevant to the two-stage MHD combustor, focussing on two problem areas: (a) coal oxidation kinetics under fuel-rich conditions, and (b) ash behavior in an MHD combustion environment. This task will also include study of the mixing and flow aerodynamics behavior in a high swirl geometry intended for the second stage of an MHD combustor, using a simple water model test facility.

II. SUMMARY OF PROGRESS TO DATE

TASK 1, ARCING PHENOMENA IN MHD GENERATORS

Preparations for a second major experiment related to transverse discharges were completed in the previous reporting period; however, failure of the main air compressor has prevented the running of that experiment. In the present reporting period preparations for an axial breakdown experiment have progressed significantly. One run, using the MHD Simulation Facility, operating with pure oxygen, has been made to help in the development of instrumentation required for the main experiments.

Preparations for detailed electrical tests on slagging wall channels have been initiated, with the main emphasis on design of the sidewalls and voltage probes. In addition, an existing two-dimensional electrodynamics code is being modified for use in the modeling of wall-slag-current interactions including polarization effects.

Measurements of isothermal layer characteristics in the slag flow simulation rig have been completed. Emphasis is now being placed on data analysis and formulation of simple models of the ripple flow.

Availability of a 4 Tesla superconducting magnet has caused some rethinking of the Channel II Facility. The main thrust of the experimental program for Channel II has been specified and the overall characteristics of the channel itself have been defined.

TASK 2, OPEN CYCLE DISK GENERATOR PROGRAM

During this quarter, the first set of nonuniformities experiments was completed, and the framework for the analysis of the data was established. The nonuniformities consisted of well-characterized thermal and velocity wakes with strong variations of the plasma properties in the direction normal to the magnetic field and the flow. The wakes were created by cold blades located in the subsonic (upstream) region of a radial flow equilibrium disk generator. A data base for a fixed set of stagnation conditions and test gas mixture (i.e. $T_0 = 2850$ K, $p_0 \approx 4.0$ atm and Ar 80%/CO₂ 20% at room temperature) was obtained for ideal Hall coefficients in the range 2-7 and for configurations having 0, 6, 12, and 24 wakes. The development and key results of this work (accomplished this quarter) are as follows:

1. Additional reference flow tests (without wakes) were made in order to establish the flow uniformity and confirm the validity of the equilibrium plasma assumption. Electron density measurements were made and compared with theoretical (1-D) predictions; Saha equilibrium was verified.
2. The effective Hall parameter, β_{eff} , profiles in the generator were determined from local open-circuit E-field measurements for the various configurations (number of blades/wakes) and compared with the uniform reference flow results. Experimental reduction curves (β_{eff} versus β_{ideal}) were established. A summary of the data (as given in Figures 10 and 13 of the main text) clearly indicates the monotonic degradation of generator performance for this type of nonuniformity (and orientation) with increasing Hall parameter and number of wakes (rms σ).

3. The theoretical framework for analysis of the data was accomplished. The two-dimensional electrodynamics wake code^{[1]*} was extensively modified; a variable grid was included to handle narrow wakes and/or regions of strong gradients of the plasma properties. An "engineering" layered model, based on the formulation of Rosa,^[3] was developed to account for secondary effects due to the radial variation of the plasma properties.
4. A preliminary comparison of the voltage data for 24 blades at 3.5 Tesla with both theoretical models shows good agreement between theory and experiment. The "engineering" model slightly overpredicts the voltage reduction, most likely due to the uniformizing effect of the plasma boundaries (for the experiments). A complete analysis of the overall data base is underway.

The major theoretical modeling effort this quarter has been directed/ associated with the nonuniformities experiment described above. In addition, property files were created for Ar/CO_2 and $\text{Ar}/\text{CO}_2/\text{H}_2$ mixtures for use with the one-dimensional chemical kinetics code. The code will be used primarily for the design and assessment of a high performance swirl generator of small-scale (to be tested in the disk facility).

* See References for Task 2, page 77.

TASK 3, ELECTRODE MODULE DEVELOPMENT AND TESTING

Part A.

The source of variability of breakdown strength in silicon nitride has not been identified.

Work is proceeding to prepare three sets of electrode modules for testing at MIT next quarter.

Work is proceeding to prepare electrodes for a test at Westinghouse.

Part B.

The MHD Test Facility Complex

Lubricating oil from the air compressor contaminated the oil-free air lines. This major failure of the air compressor and the cleaning of the air lines are receiving priority attention from the Institute in an effort to re-commission the oil-free compressed air system back into operation as expeditiously as possible.

Some modifications to the oxidizer system were designed at the request of the Safety Officer as an added precaution against the possibility of oxygen coming in contact with lubricating compressor oil.

A few instrumentation development tests were conducted burning only pure oxygen.

TASK 4a, COAL COMBUSTION STUDIES

A program for analyzing solid pyrolysis and combustion products (chars, tars, soot) has been organized. The overall approach is to study physical and chemical changes simultaneously. Preparation of microtomed samples permits direct imaging of the internal pore structure (greater than 50 Å) using the transmission electron microscope. A recently installed Quantachrome Surface Analyzer will furnish additional measurements of pore structure (i.e., accessible pore volume and pore size distribution).

Ash vaporization of 26 mineral species has been experimentally measured in a reducing and an oxidizing atmosphere as a function of particle temperature. Measurements were made for mineral matter within a carbon matrix (coal) and for free ash (generated from coal according to ASTM ash analysis). Results indicate that ash vaporization is greater in a carbon matrix than for free ash. This phenomenon is attributed to reducing reactions.

Work continues on the coal combustor computer model. The model is now in a second generation phase. Recent improvements include: 1) allowance for a distribution of particle sizes; 2) calculation of ash vaporization as a function of particle size; and 3) better and faster convergence schemes. The new ash vaporization model has been corroborated with experimental data. Results show that previous calculations (from the first generation model, based solely on oxidation by O_2) predicted excessive residence times for burnout and excessive ash vaporization.

Overall progress of Task 4a has proceeded according to schedule.

TASK 4b, COMBUSTION AERODYNAMICS AND FLUID MECHANICS OF HIGH-SWIRL SECOND STAGE

The theoretical model, code named SHAPE, is now operational and calculates the stream function, static pressure, axial and swirl velocity distribution within the second stage nozzle of the MHD combustor for the effects of input swirl number and Reynolds number. The program SHAPE has been tested for its sensitivity to the boundary conditions and the constants employed in the turbulence equations and wall functions. The values of the constants which provide the experimentally observed results are being used in the code. The program has been revised to account for the presence of a flat plate located at the downstream end of the nozzle section. An experimental run was made to compare the theoretical predictions with the observed flow pattern in the second stage swirl combustor.

III. DETAILED DESCRIPTION OF TECHNICAL PROGRESS

TASK 1, ARCING PHENOMENA IN MHD GENERATORS

1. Introduction

Successful application of MHD power generation requires efficient and long-lasting channel wall designs. To effect such designs it is necessary to have a good understanding of the mechanisms of current transport in the vicinity of the wall and to develop models capable of predicting, for example, the conditions for which electrical arcing occurs. In addition, it is important to develop techniques to determine the performance degradation from arcs and the extent of damage to the channel walls. The present task addresses the general problem of current transport to electrodes through a combined experimental and analytical study which includes problems specific to slagging wall operation and non-slagging wall operation. The initial studies, which are of a fundamental nature, are being performed without the complication of a magnetic field. However, the task also includes the designing of a sub-atmospheric channel and the installation of a superconducting magnet. This sub-atmospheric facility will allow extension of the experimental work to conditions typical of a full-scale generator operating at high Hall parameter. The task is divided into several subtasks and, where possible, progress in each subtask is reported separately.

2. Diffuse Discharge and Transition to Arc Experiments

Failure of the main air compressor for the MHD Simulation Facility has prevented running of any of the main Task 1 experiments. The thermal design of the channel components has been made assuming an N/O ratio in the range of 0.7 to 1.0. The electrodes and sidewalls are not capable of withstanding the heat fluxes which would be experienced with the facility oper-

ating close to stoichiometric ratios and with pure oxygen. The channel was completely assembled and all instrumentation installed when the air compressor failure occurred. The channel and instrumentation have been removed and stored for later testing. Work on the air compressor is described elsewhere in this report.

To make some use of the facility during the compressor down time, three secondary experiments which were to be "piggy-backed" on the main transverse discharge experiment were performed in the facility. Water cooled copper electrode modules were installed in the facility and seeded plasma conditions established using pure oxygen. The specific experiments performed were: a) the testing of an automated extrapolation technique to determine plasma temperature to replace the direct line reversal technique used in the past; b) the testing of a water cooled Pitot probe to measure velocity; and c) the testing of an optical probe to measure the flight time of convected plasma non-uniformities. Ability to measure temperature and velocity is important in establishing the conditions for the calculation procedures used to compare with the experimental results in this task. Preparations for a voltage probe experiment in the facility operating on oxygen were also completed in this reporting period.

Extrapolated Line Reversal Technique

The previous technique used for temperature measurement in the MHD Simulation Facility was a direct "reversal" of the sodium doublet. The small quantity of sodium in the potassium seed provided the main source of sodium in the flow, as there was little in the fuel and sodium salts were not added directly. The maximum plasma temperature which can be measured with the reversal technique is limited by the brightness temperature of the lamp, after accounting for all losses through lenses, windows, etc. For

the system used previously a maximum temperature of ~2500 could be successfully reversed.

Extrapolation techniques (see Reference [1]) use measurements of plasma alone and lamp as seen through the plasma to determine the reversal condition. To correct for continuum radiation and detector offsets and to remove the need to know the optical depth, lamp plus plasma and plasma alone signals should be obtained at two wavelengths. The main inaccuracies in such measurement (other than noise separation) stem from not measuring the four signals at the same time and/or for the same line of sight. The preliminary set-up to implement the extrapolation technique is shown in Figure 1. A high speed chopper was used to block light from the lamp, and a multiplexer, synchronized to the chopper motion, was used to separate the two signals (plasma alone and lamp plus plasma) at the detector end. In these preliminary experiments, measurements were taken for a single wavelength region at a time. The optics and electronics were assembled to allow comparison of results from the new technique with those from the old technique, at least for low plasma temperature. To achieve low plasma temperatures with pure oxygen, the combustor was operated considerably fuel lean.

The experimental results indicated that the plasma alone signal was unreliable. Extrapolation of the reversal condition from data at two different lamp temperatures (one higher than the temperature indicated by the conventional technique and one lower) gave considerably different results, all of which indicated temperatures considerably lower than those measured by the old technique. There were also several minor problems with the electronics.

Bench top experiments have been initiated to speed the development of this technique, and a usable system is expected in time for the next major experiment.

Water-Cooled Pitot Probe to Measure Plasma Velocity

A simple water-cooled stagnation probe was assembled and installed at the exit of the combustor. Although the probe was purged when measurements were not being taken, plugging of the probe hole resulted shortly after seed was introduced to the flow system.

Optical Probe to Measure Flight Time of Convected Plasma Non-Uniformities

Measurements of fluctuating plasma intensity using a simple light tube for spatial filtering and a photo-diode detector were made in previous experiments. As discussed in the previous progress report, by correlating fluctuations in intensity at two axial locations the delay time of the convected fluctuations can be determined; this delay time can be related to the probe separation and the gas velocity. A dual probe was constructed and installed at the exit of the combustor. The high speed data acquisition system was interfaced with the diode output. A separation of 10 cm and a light tube size of 3 mm were used. Few usable results were obtained because the plasma light intensity was too low for the detector sensitivity, especially since cross-correlation of two signals is required.

Voltage Probe Experiment

As discussed in the previous progress report, there is a potential measurement error associated with the voltage probes used in the channel walls. It was planned to perform some detailed probe response measurements during the main transverse discharge experiments. A single water-cooled brick wall with four voltage probes has been assembled to allow these measurements to be made in the facility operating on oxygen. This test will be run in the next reporting period.

3. Breakdown Experiments and New Insulator Designs

Experimental and analytical work relating to axial breakdown has established that breakdown can be initiated in the plasma or in the insulator. For many electrode wall designs, the threshold voltage for insulator-initiated breakdown is considerably lower than that required for formation of an axial arc through the plasma. Therefore, the development of electrode wall designs with higher threshold levels is clearly desirable. The particular design considered is a "laminated" design, shown schematically in Figure 2.

In the present reporting period the thermal analysis of the insulator region has been completed and the detailed design of the inter-electrode region components finalized. In addition, rough cutting of the brick liner and assembly of the main diagnostics were completed.

3a. Thermal Analysis

The components of a heat transfer analysis of the inter-electrode region have been described in a previous progress report. The analysis consists of an approximate solution for the heat transfer to a wall with variable temperature coupled to a two-dimensional conduction solution for the inter-electrode wall. A coupled solution is required since the wall temperature distribution affects the heat transfer coefficient. The additional heat transfer due to Joule heating in the plasma is estimated from representative numerical calculations of Reference [2]. The analytical model has been used to evaluate the performance of the laminated electrode configuration and to fix an acceptable thermal design. The main parameters which can be controlled are the insulator material and the extent of cooling of the components. The most important parameter not easily controlled

is the thermal contact resistance between the ceramic components and the metallic components.

The initial design evaluated used alumina for the small insulators and magnesia for the large insulator. A relatively low thermal contact resistance was assumed and the electrode was designed to operate at a uniform level of $\sim 1100^{\circ}\text{K}$ in the absence of Joule heating. The analysis indicated that the thermal "choking" of the downstream edge of the upstream stainless steel electrode was required to achieve the uniform temperature. In an attempt to keep the alumina cool, the intermediate cooler piece was assumed to be copper all the way to the plasma surface. Nevertheless, as shown by the solid line in Figure 3, even in the absence of Joule heating the alumina surface temperature exceeded 1100 K. The effect of Joule heating (corresponding to a plasma current of ~ 40 amps) shown as the dashed line in Figure 3 is to increase the operating temperature of the alumina and the downstream edge of the electrode. Increasing the thermal contact resistance between the alumina and the copper results in only slight improvements as shown in the figure. The electrode and alumina temperatures are unacceptably high. Note that in most electrode wall designs the local Joule heating is not considered. The magnesia surface temperature is relatively low due to the assumed good thermal contact with the cooler piece and, since it is not close to the region of high Joule heating, experiences only moderate increase in temperature. To take advantage of the fact that the magnesia is little affected by the Joule heating, the contact between the magnesia and the cooler can be made intentionally poor such that the magnesia surface temperature is high; this results in a reasonable average wall temperature.

Following the success of Avco with boron-nitride inter-electrode insulators, boron-nitride was used for the small gaps. Further, the thermal design was performed for a relatively high value of thermal contact resistance (i.e, poor contact) and the heat transfer rates with Joule heating were used. The resulting design is shown as the solid line in Figure 4. Note that, rather than thermal choking of the downstream edge of the stainless steel electrode, it is necessary for the copper base to extend a considerable distance toward the surface. Reasonable boron-nitride surface temperatures can be obtained with cooler pieces which are mostly stainless steel. The magnesia surface temperature is maintained at a high value by providing poor contact with the cooler pieces. The temperature distribution in the absence of Joule heating is shown as the dashed line in Figure 4. As can be seen, the surface temperatures are considerably lower, but are maintained well above the level where water condensation could affect the boron-nitride. Resistive seed compound condensation could however be significant.

While detailed insulator calculations with current transport have not been performed, the experience of Reference [2] indicates that, if the temperature is maintained within the limits described above, insulator initiated breakdown should not be a difficulty.

Preparations for Testing the Laminated Inter-Electrode Design

A copper shell similar to that used in the transverse discharge experiments was constructed in the previous reporting period. The basic experimental setup is shown in Figure 5. In the present reporting period rough cutting of the ceramic liner pieces has been completed and design and construction of the two optical ports completed. With the completion of the analytical calculation the final design of the inter-electrode components was performed and those parts sent out to be machined.

4. Arc Damage in Inter-Electrode Insulators

Inter-electrode arcs have the potential to cause considerable damage to the generator wall. In some experiments (such as on the U25-B) such arcs were observed to be driven into the anode wall (presumably under the influence of the $\mathbf{J} \times \mathbf{B}$ force) and extinguished only upon reaching a well cooled containment shell and only after causing significant damage to the generator. In other experiments, inter-electrode arcing occurs without widespread damage even after relatively long term operation. Early considerations at Avco established some rules of thumb about the arc power level required to produce damage to their type of electrode wall. The purpose of the experiments and analysis in this subtask is to study the extent of damage to the walls from inter-electrode arcs and to develop designs and techniques to minimize the effects of such arcing.

In this reporting period, substantial improvements were made to the facility. The first of these was the installation of the D.C. contactor to allow operation of the magnet at higher currents. In addition, manifolds have been added to the system and heat loss measurements are now incorporated into the system. Previous experiments have used a piece of steel wool bridging the gap to start the arc. This was found to be unsatisfactory because of the need to anchor the steel wool; wedging of the steel wool resulted in poor thermal contact of the insulator and the steel electrode caps. To overcome these problems a high-frequency discharge is used to initiate the main arc. The electrode module has been modified such that pressure can be applied to force the electrodes into good contact with the insulator. Preliminary runs indicate that the improved contact may significantly reduce the potential for arc damage. Extensive experiments will be performed in the next reporting period.

5a. Modeling of Slag Flow with Ripples

In all modeling of the fluid and electrical characteristics of slag flow in MHD generators, simple smooth film models have been used. However, experiments have clearly established that the smooth film is not stable and that transverse ripples are formed in the flowing slag layer. These ripples can be responsible for a significant portion of the mass transport and can affect the plasma velocity profile and wall skin friction coefficient. In addition, since the ripple surface can be considerably higher than the surrounding slag, it is possible that the electrical current transport characteristics can also be affected. Some evidence of this is indicated by visual measurements by the Soviets^[3] which show arcs striking preferentially to the ripple crests. The objective of this subtask is to obtain experimental data and develop predictive capabilities for the fluid mechanical aspects of the slag flow problem. To avoid the complexities of measurements associated with the actual slag flow, a suitably scaled flow of air over glycerine is used to simulate the actual slag flow.

In the present reporting period all measurements relating to isothermal viscous films have been completed and data analysis has progressed considerably. Experimental data obtained with the preliminary rig was correlated by using a smooth layer-like gas side shear stress for the driving force of the ripples. Experiments on "fixed ripples" performed in the previous reporting period strongly suggested that the pressure or "form" drag around the ripples was the dominant driving force rather than a smooth wall type shear stress. The results from the new experiment, which cover a wider Reynolds number range than the preliminary experiments, confirm this; that is, the previous smooth shear correlations do not fit the data very well. The results of the experiments and the dimensional analysis of the data are presented in detail in the sections below.

Experimental Results

The main experimental results consist of measurements of the characteristics of the thin isothermal viscous film flow for a variety of mass flow rates, air speeds and for two fluid viscosities. The experimental apparatus has been described in a previous progress report.^[4] In addition, measurements of the velocity profile in the channel and of the pressure and velocity fields in the vicinity of fixed ripples are also of importance and are presented in this section. Following a presentation of the data correlations of the data using dimensional analysis are presented and a simple semi-empirical model proposed.

Thin Film Results

Measurements of film characteristics were made for a range of film mass flowrates from 3×10^{-4} kg/m/s to 1×10^{-2} kg/m/s, a range of air speeds from 8 m/s to 30 m/s and for film viscosities of 0.14 kg/m/s and 1.25 kg/m/s. Over this range of parameters, stable flows and flows with transverse disturbances were observed. For some conditions the disturbances were sinusoidal in character, while for other conditions, the disturbances took the form of transverse ripples similar to those observed in MHD slag flows. The mode of flow observed for combinations of mass flow rates and air speeds is displayed in Figure 6; only a slight dependence on mass flow rate is observed.

The behavior of the stable film was consistent with a shear driven film, with the layer thickening and the surface velocity decreasing in the downstream direction. With increased air speeds the film was no longer stable and, as can be seen in Figure 7, sinusoidal waves similar to free-surface gravity waves were observed. The wave peaks extended the full width of the channel and moved with almost constant speed for distances

exceeding 25 cm. The runoff at the channel exit varied with the motion of the waves. Increasing the air flow rate somewhat destroyed the uniformity of the waves, but the wavelength remained roughly equal to the wave width. Representative photographs of sinusoidal waves are shown in Figures 7 and 8. Accounting for the distortion of perspective due to the camera optics, the wave ridges are observed to propagate in parallel rows in Figure 7, while in Figure 8, which corresponds to a higher air velocity, some three-dimensional disturbances can be observed.

For higher speeds, the shape of the waves was altered, with the width of the wave becoming significantly smaller than the separation between crests. Representative photographs of the flow in this regime are shown in Figures 9 and 10. In this regime, the waves did not usually extend the full channel width as can be seen in the figures. In this regime the waves, or ripples, are less periodic and take on almost a solitary character. Ripples were observed to "catch" and pass other ripples and to "capture" ripples occupying different portions of the channel width. These observations and in fact the photographs of Figures 9 and 10 are in agreement with slag flows behavior measured by Rodgers,^[5] by the Soviets,^[3] and others.

For all regions where transverse disturbances were observed, wave trough and crest heights, wave speed, crest separation and wave shape were recorded. The variation of wave speed with mass flowrate and airside velocity is shown in Figures 11-14. Wave speed increases with mass flowrate for all air speed values. With the exception of the results for the lowest speed value, the curves extrapolate to zero velocity as the mass flow is reduced to zero. This difference is not surprising since, for the lowest air speed, sinusoidal waves were observed at all mass flow rates.

The variations of wave crest height, width and separation with the parameters of interest are shown later in dimensionless form.

Fixed Ripple Measurements

Simple estimates of the forces on a fully developed ripple flow, shown schematically in Figure 15, indicate that the pressure or "form" drag force on the ripple will exceed the force from the shear on the trough region of the film. Relative to the air speed (> 10 m/s) the ripples move very slowly ($< .10$ m/s) and present a relatively steady disturbance to the airside flow. To provide more quantitative data for the shapes typical of the observed ripples, experiments were performed for fixed ripples. Clay "ripples" were constructed on a special plate (as indicated in Figure 15) and pressure taps inserted at strategic locations along the contour of the ripple. The shape of the ripple was characterized by its length L and height h as indicated in Figure 16 and otherwise shaped to follow the shape of the ripples photographed for various conditions. The pressure measurements for two clay ripples are shown in Figures 17a-f. The data indicate a profile similar to that obtained for an airfoil (or cylindrical body) with separation at the trailing edge. The size of the ripples does not allow pressure measurements to be made at many locations and therefore it is not possible to obtain detailed distributions of pressure around the ripple. Approximate values of the drag force on the ripple can be obtained using the measured pressure at three points to define a reasonably shaped pressure distribution and using an approximate ripple contour. In the present experiments the pressure was measured at the point of inflection of the upstream side of the ripple and in the separated region of the downstream.

section of the ripple. The length of the separation region was also measured and the pressure at that point taken equal to the static pressure as measured in the opposite wall. These pressure values were used to define the piecewise linear pressure function shown in Figure 18. A sinusoidal wave shape was chosen and the drag force computed as

$$\frac{F_D}{\text{depth}} = \int_0^h P \frac{dy}{dx} \cdot dx$$

where the terms are defined in Figure 21. The drag coefficient is defined as the drag force per frontal surface of the ripple divided by the kinetic energy per unit volume based on the free stream velocity, that is,

$$C_D = \frac{F_{D/\text{length}}}{h \left[\frac{1}{2} \rho_a U_a^2 \right]}$$

The variation of the drag coefficient with airside Reynolds number for the two wave shapes studied is shown in Figure 19a. Little effect of Reynolds number (based on L_x) on drag coefficient as defined would be expected for the turbulent, separated flow and the experimental results confirm this. The drag coefficient increases with ripple height as shown in Figure 19b. The separation distance is considerably affected by airside Reynolds number based on ripple height for the lower Reynolds numbers, but for Reynolds numbers greater than $\sim 3 \times 10^3$ shows only a slight dependence (see Figure 20).

As part of the measurements of separation distance, and to provide some general information, velocity profiles were measured at distances behind the ripples. Typical results are shown in Figure 21. While these measurements are by no means extensive or extremely accurate, the trends and values of drag coefficient and separation distance can be used in the simple analyses of the ripple behavior.

Dimensional Analysis Considerations

This section presents the dimensional analysis of the slag flow problem. The large number of dimensionless groups, however, renders the analysis rather difficult to use without introducing some physical insight into the problem to help define which dimensionless groups to focus on.

Rodgers^[5] suggested a correlation based on a smooth film shear stress and this approach is tested against the data first. A different approach where the form drag on the ripples and the surface tension of the interface are considered as the dominant quantities is then presented. Correlations based on such assumptions are then evaluated against the data.

The gas-side can be characterized by the quantities:

ρ_a - air density

$\bar{U}_a$ - air velocity averaged over the cross section

μ_a - absolute viscosity of the air

H - channel height

L - distance from the start of the channel.

The liquid film can be characterized by the quantities:

ρ - liquid density

μ - absolute viscosity of the fluid

$\dot{m}'$ - mass flowrate per unit width

and the interface characterized by:

σ - surface tension.

The final parameter to be considered is g, the acceleration of gravity. In relating one of the dependent quantities, such as the ripple speed V_r , dimensional considerations would have

$$\pi_{V_r} = \frac{V_r}{\bar{U}_a} = f_n \left(\frac{\rho_a \bar{U}_a L}{\mu_a}, \frac{H}{L}, \frac{\mu}{\mu_a}, \frac{\dot{m}'}{\mu}, \frac{\rho}{\rho_a}, \frac{\sigma}{\mu \bar{U}_a}, \frac{gL}{\bar{U}_a^2} \right)$$

for example. Without some insight to eliminate some of the dimensionless groups this is not particularly useful. Rodgers^[5] correlated his ripple speed data, measured for actual MHD slag flow experiments, in dimensionless form as

$$\frac{V_r}{\sqrt{\tau/\rho}} = \text{fn} \left(\frac{\dot{m}'}{\mu} \right)$$

where τ was viewed as an effective shear dependent on the gas side Reynolds number. For the limited amount of data Rodgers could obtain this was satisfactory; however, as seen in Figure 22, the correlation is inadequate for the present results, especially in correlating data for the two viscosities investigated. Rodgers chose the above correlation by considering a shear driven liquid film, that is assuming that the driving force for the ripples varies as $\tau \propto 1/2 \rho V^2 f(\text{Re}_L)$ for example. From the poor correlation of the present data it would appear that these ideas are not correct.

Examination of the qualitative features of the main experimental results and of the supplementary results suggest the following:

- a) Pressure or form drag is likely to be the dominant force from the gas side. This is suggested by the fixed wave measurements which showed separation lengths behind the ripples which were comparable to spacing between the ripples. The fixed wave results can be used if helpful.
- b) Surface tension rather than gravity is the restraining force for the ripple behavior. This is supported by comparison of gravity and surface tension forces for a typical measured ripple and both these forces against the form drag which is the main driving force. For example, for a ripple height of $\sim .75 \times 10^{-3}$ m and a surface tension of $\sigma = 70 \times 10^{-3}$ N/m, $\sigma/\bar{r}$ is ~ 90 N/m² while $\rho g \bar{r}$

is $\sim 8 \mu/m^2$. The drag force per unit area is of order $100 \mu/m^2$.

The poor correlation of the sinusoidal data also supports this contention.

- c) the fluid in between ripples is almost stagnant. This is supported by observations of the motion of sawdust mixed with the glycerin and by the measured separation behind the clay ripples.

Simple Model

Using the above information a simple, semi-empirical model can be developed to display the most important physics and to correlate the data. As shown in Figure 23, the ripple is assumed to transport all the mass. Conservation of mass relates the mass flowrate per width to the ripple mass per unit length, m'_r , velocity, V_r , and the average spacing, S_r , as

$$\dot{m}' = m'_r V_r / S_r$$

The mass per unit length is taken to be

$$m'_r = \rho \text{Area} = \rho \alpha_f h L$$

where h is the ripple height, L is the ripple length and α_f is a constant that relates the area to the product hL ; that is, changes in shape are not considered. Combining the equations yields

$$\dot{m}' = \rho h L \alpha_f V_r / S_r$$

The momentum equation in the x-direction balances the form drag against the viscous shear. This can be expressed as

$$\frac{1}{2} \rho_a U_a^2 h C_D = \mu \frac{V_r}{h} L \alpha_m$$

where C_D is the drag coefficient and α_m is a constant which reflects the actual internal motion of the ripple as it resists the force from the airside. From the fixed wave experiments it is reasonable to assume C_D to be independent of Reynolds number but depending on the ripple height to length ratio as

$$C_D = \alpha_c \left(\frac{h}{L}\right)^n$$

where α_c and n are constants, determined from the fixed wave experiments.

The clay waves also indicate a separation distance which is roughly proportional to the ripple height and independent of Reynolds number.

Definition of the spacing between ripples is the most difficult part. It is somewhat reasonable to associate the spacing with the separation distance behind the ripple, but it must be recognized that this is approximate at best. Let us then take

$$S_r = \alpha_s h$$

where again α_s is taken from the fixed wave experiments and the Reynolds number dependence ignored. The final relationship relates the surface tension force to the driving force of the droplet. To see how this balance comes about it is useful to consider a simple problem where there is no internal motion. So, as shown in Figure 24, consider a thin membrane which can sustain a force per unit length of σ , containing an incompressible fluid to a region near the wall. As the air velocity is increased the surface would deform as indicated. If the force in the membrane were increased the bubble would flatten out. The incompressible Bernoulli equation written for a stream line between points 1_a and 2_a in the gas is

$$P_{2a} + \frac{\rho_a V_{2a}^2}{2} = P_{1a} + \frac{\rho_a V_{1a}^2}{2}$$

or

$$P_{1a} - P_{2a} = \frac{\rho_a}{2} (V_{2a}^2 - V_{1a}^2) = \frac{\rho_a}{2} V_{1a}^2 \left(\frac{V_{2a}}{V_{1a}} \right)^2 - 1$$

Since the fluid interior to the membrane is stationary, and assuming gravity to be negligible, the interior pressures at $1a$ and $2a$ are equal; that is,

$$P_{1a} = P_{2a}$$

Two interface conditions relate the liquid pressures to the external pressures. Assume that point 1 has been chosen far enough from the ripple that the curvature is large and $P_{1a} \approx P_{1a}$. At point 2 the length scale L can be used to characterize the curvature resulting in the relationship

$$P_{2a} + \frac{\sigma}{L} = P_{1a} = P_{1a}$$

Combining the relations yields

$$\frac{\sigma}{L} = \frac{\rho_a}{2} v_{1a}^2 \left(\frac{v_{2a}}{v_1} \right)^2 - 1$$

In the spirit of the other equations let us take

$$\frac{\sigma}{L} = \left(\frac{\rho_a U_a^2}{2} \right) \alpha_t$$

where we will take α_t to be a constant (the data confirms this).

There are now enough equations to solve for the unknowns; and, after some manipulation, we have (for $n = 1$, which is roughly consistent with the clay wave data)

$$h = 3 \left(\frac{2\alpha_s \alpha_m}{\alpha_c \alpha_f \alpha_t} \right) \left(\frac{\mu \dot{m}' \sigma}{\rho (\rho_a U_a^2)^2} \right)^{1/3} \quad (1a)$$

$$v_r = \left(\frac{\alpha_s \alpha_t}{\alpha_f} \right) \left(\frac{\dot{m}' \rho_a U_a^2}{\sigma \rho} \right) \quad (1b)$$

$$L = \frac{\sigma}{\rho_a U_a^2 \alpha_t} \quad (1c)$$

$$\text{and } S_r = \alpha_s h \quad (1d)$$

With the exception of the first relationship (Equation (1a)), which is difficult to either prove or disprove due to data scatter, the relations developed are consistent with the dimensionless plots shown in Figures 25a-d.

5b. Slagging Wall Electrical Studies

(a) Current Transport Studies

The detailed mechanisms of current transfer through slag layers in MHD generators have attracted increased attention in the last few years, due to the potential for electrochemical corrosion and polarization effects. One of the most striking manifestations of these effects is the observation of "staircase" voltage distributions in the cathode wall of slagging channels.^[6] The voltage current distributions were found to evolve with time and to develop in about 30 minutes into a periodic pattern where 3 to 5 cathodes became nearly shorted together, the Hall voltage of the group being then sustained by a single gap; "healing" in periods of 5 to 10 minutes occurred after power interruption.

Reference [5] discusses in detail these and other observations and advances tentative explanations for their occurrence. The mechanism by which the one active gap can sustain 100 - 120 volts with no apparent breakdown is described as purely thermal, arising from the thinning of the slag layer over that gap, which itself is due to the Faraday current concentration on the edge of the adjacent upstream electrode. It is also pointed out, however, that this cannot by itself explain the slow evolution into the final pattern and the slow healing or recovery of the shorted gaps after power. These phenomena and the clearly polar character of the overall phenomenon (the anode wall does not sustain such nonuniformities) point toward ion transport and slag polarization as the underlying agents. However, the very complex situation at the cathode wall, along with a clearly two (or three) dimensional current pattern at the interface of plasma, slag and metal and the poorly understood physics of slag conduction, have prevented so far any quantitative analysis that could serve as a basis for extrapolation and scaling laws.

We have initiated a program of theoretical and experimental work aimed at clarifying this and related problems. On the theoretical side, we are developing computer programs for a two-dimensional model of the current transport in the cathodic slag layer. The experiments will involve measurements of AC and DC conductivities versus cumulative current and will serve to establish the values of the critical model parameters. A brief description of the mathematical model follows.

Let n_k^z be the number density of a species k of interest, with charge z (electrons, holes, O^- , Fe^{++} , Fe , O_2 , FeO are examples), and let B_k be its mobility and $\vec{E}$ and T the electric field and temperature respectively. The flux of this species can in general be expressed as

$$\vec{\Gamma}_k = n_k^z(\vec{u} + B_k \vec{E}) - \frac{B_k z}{ze} \nabla n_k^z \quad (2)$$

where $\vec{u}$ is the bulk velocity. For charged species, their contribution to current is $\vec{J}_k = ez\vec{\Gamma}_k$. For uncharged species ($z = 0$), we use Einstein's equation $B_k/ze = D_k$ (diffusivity) and set $B_k = 0$ (but $D_k \neq 0$).

Among the M species present, we can identify L elementary (atomic) species, including electrons. Thus, for the species listed above, electrons, atomic oxygen and atomic iron are the elementary species. For each of these a conservation equation exists of the form

$$\frac{\partial}{\partial t} \left(\sum_k \alpha_{lk} n_k^z \right) + \nabla \cdot \left(\sum_k \alpha_{lk} \vec{\Gamma}_k \right) = 0 \quad (l = 1, 2, \dots, L) \quad (3)$$

where α_{lk} is the number of l -atoms per k -molecule. For the particular case of electrons as "atoms," the first parenthesis is the net charge density, which must be zero; the α_{lk} coefficients are then simply the z values.

$$\sum_k z_k n_k^z = 0 \quad (4)$$

In this case, the conservation Equation (3) becomes the current conservation equation

$$\nabla \cdot \vec{J} = 0; \quad \vec{J} = \sum_k e z_k \vec{f}_k \quad (5)$$

Equations (3) and (4) apply quite generally. Beyond this, kinetic equations would be needed to relate the production and accumulation rates of the species. However, we will assume fast reactions in this condensed medium at high temperature and assume chemical equilibrium throughout. Thus, among the M molecular species, we identify $M - L$ independent chemical reactions, and the law of mass action applies to each. Examples are

$$\begin{aligned} N_e N_{\text{hole}} &= K_1(T) \\ N_{O_2}^{1/2} N_e^2 &= K_2(T) N_O = \text{etc.} \end{aligned}$$

We now have L conservation equations, $M - L$ equilibrium equations and one neutrality equation ($M + 1$ equations) for the M molecular concentrations, plus the electric potential ($\vec{E} = -\nabla\phi$). In addition, an energy equation is needed to find T ; neglecting heats of reaction, this is

$$\frac{\partial}{\partial t} (\rho c_p T) + \nabla \cdot (\rho c_p T \vec{u} - k \nabla T) = \vec{E} \cdot \vec{J} \quad (5)$$

Due to the diffusion terms in the fluxes, Equation (3) is an elliptic partial differential equation in the concentrations and the potential, which makes solution laborious. In many cases, these diffusion terms are unimportant, except in thin layers with voltages of about kT/e across them (~ 0.1 volts) adjacent to discontinuities. Even in these cases, the time to establish a steady diffusion (in balance with field drive) is likely to be longer than either the convective time or the experimental time of interest, resulting in either field-convection balance or unsteady gradual accumulation. We will neglect diffusion in what follows, at least for a first approximation; indeed, accumulation of either high or low conductivity materials in selective regions of the slag layer is probably the mechanism behind the slow trends observed in MHD slag polarization.

The elliptic nature of the current conservation equation (Equation (5)), however, is inescapable. A two-dimensional code adapted to the thin region in and around the slag-covered electrode wall is under construction. Stretching functions are used in both coordinate directions to emphasize regions of interest, and six electrode-insulator pitches are treated, in an attempt to allow periodicity with either one, two, three or six electrodes per period.

The current conservation equation can be regarded as an instantaneous readjustment of the potentials. The remaining equations then will be solved for the concentrations by time-marching at the slow time scale of the polarization, with one potential recalculation after each step. The energy equation will also be updated simultaneously with the current equation, since the heat diffusion term is also essential.

To date, only the energy equation and segments of the electrodynamic code are implemented. Test runs have been made with prescribed current patterns to study the convergence of the algorithms in the energy equation. Results are satisfactory, but some reduction in the number of time steps (dictated by the convective terms) is desirable. Completion of the electrodynamic code is expected shortly. A literature search is underway on the mobilities and equilibrium constants needed.

(b) Design Studies for Slagging Sidewalls

In preparation for the experimental studies of arcing and breakdown on slagging generators planned to follow the clean-wall test series, design studies are underway to develop a suitable sidewall concept which could also be adapted to the higher field conditions of the future Channel II.

A large (2" x 2") ceramic flame-sprayed "peg wall" design is being considered for the applied field experiments. Sample modules have been

prepared with 1.5 mm coatings of Ca and Sr zirconates and magnesium aluminate on stainless steel bases. The steel pieces are grooved for heat transfer control and cooled by copper blocks brazed to their backs. Thermal tests have been carried out in a furnace and under a torch flame. The layers of magnesium aluminate showed very poor bonding and spilled off easily under moderate thermal shock. The zirconates are mechanically sound, but the thermal impedance measured in the course of the tests still shows indications of incomplete bonding. More rigid tests are planned, and the electrical resistivity of the ceramic will be evaluated. Literature values for the crystalline zirconates show a steep temperature dependence, raising the possibility of a thermal runaway or of excessive current leaks, although the design top temperature is only 1400 K.

6. Design of Channel 2

Plans for a second channel have progressed, with definition of the experimental thrusts of the work and definition of the basic characteristics of the channel itself. In addition, the availability of a 4 Tesla superconducting magnet has caused some reevaluation of the flow train and other facility requirements.

The main purpose of Channel 2 is to provide high Hall parameter conditions in which detailed generator studies can be performed. In the original design with a conventional magnet, moderately high Hall parameters were to be obtained by running the facility at low pressure (≤ 3 atm). With the 4 Tesla magnet very high Hall parameters should be possible, and the experiments possible even more interesting. Consistent with the definition of Task 1, the main experimental thrusts for Channel 2 are:

- a) Transverse discharge experiments;

b) Hall voltage breakdown experiments; and

c) MHD interaction experiments, in particular turbulence damping.

These experiments require only a short test section with "transition" channel sections upstream and downstream to moderate the end effects. To avoid excessively high Hall voltages it is proposed that quenching of the flow be performed inside the active magnetic field region. While this poses possible electrical insulation problems at the point of quenching, these are likely easier to deal with than the greater than 10 Kvolts which could be generated with a channel length of only ~1 m.

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Figure 1. Schematic of Optical System used for Extrapolated Line Reveal Technique.

Figure 2. Schematic of laminated electrode design to alleviate heating problems at points of maximum heat flux from Joule heating in plasma.

Figure 3. Wall temperature distribution for laminated electrode design using alumina for the thin insulator. Wall components designed to give the shown distribution in the absence of Joule heating. The temperature distribution with Joule heating is also shown. (h_{eff} is the effective thermal contact conductants)

Figure 4. Wall temperature distribution for laminated electrode design using boron-nitride as the thin insulator. Wall components have been designed to give the shown temperature distribution with Joule heating. The temperature distribution in the absence of Joule heating is also shown.

Figure 5. Schematic of experimental test laminated electrode design.

Figure 6. Slag-flow modes for various airspeeds and slag flow rates.

Figure 7. Simulated slag film showing sinusoidal wave structure. Note the regularity of the waves and that the crest width is approximately half the wavelength.

Figure 8. Simulated slag film showing sinusoidal wave structure with three-dimensional disturbances.

Figure 9. Simulated slag flow showing the fully developed ripple mode with relatively long spacing between the ripples.

Figure 10. Simulated slag flow showing the fully developed ripple mode with short spacing between the ripples.

Figure 11. Variation of ripple crest velocity with glycerine mass flow rate per unit width for a gas side Reynolds number, based on the channel height, of 4.4×10^4 . Note that sinusoidal waves were observed for this air speed.

Figure 12a. Variation of ripple crest velocity with glycerine mass flow rate per unit width, for a gas-side Reynolds number, based on channel height, of 5.4×10^4 . Fully developed ripples were observed for this air speed.

Figure 12b. Variation of ripple crest velocity with glycerine mass flow rate per unit width, for a gas-side Reynolds number, based on channel height, of 6.3×10^4 . Fully developed ripples were observed for this air speed.

Figure 13a. Variation of ripple crest velocity with glycerine mass flow rate per unit width, for a gas-side Reynolds number, based on channel height, of 7.3×10^4 . Fully developed ripples were observed for this air speed.

Figure 13b, Variation of ripple crest velocity with glycerine mass flow rate per unit width, for a gas-side Reynolds number, based on channel height, of 8.2×10^4 . Fully developed ripples were observed for this air speed.

Figure 14. Variation of ripple crest velocity with glycerine mass flow rate per unit width, for a gas-side Reynolds number, based on channel height, of 8.9×10^4 . Fully developed ripples were observed for this air speed.

Figure 15. Schematic of clay wave experimental configuration showing typical locations of static pressure taps. Characteristic velocity profiles at various axial stations are shown. Pitot tube measurements were used to determine the extent of the separation region.

Figure 16. Flow configuration for the simplified drag model.
The drag coefficient is defined as:

$$C_D = \frac{F_D / (\text{depth} \cdot h)}{\frac{1}{2} \rho_a U_a^2}$$

Figure 17a. Plot of static pressure at several locations in the vicinity of the clay ripple. Results for two ripple height to length ratios are shown.

Figure 17b. Plot of static pressure at several locations in the vicinity of the clay ripple. Results for two ripple height to length ratios are shown.

Figure 17c. Plot of static pressure at several locations in the vicinity of the clay ripple. Results for two ripple height to length ratios are shown.

Figure 17d. Plot of static pressure at several locations in the vicinity of the clay ripple. Results for two ripple height to length ratios are shown.

Figure 17e. Plot of static pressure at several locations in the vicinity of the clay ripple. Results for two ripple height to length ratios are shown.

Figure 17f. Plot of static pressure at several locations in the vicinity of the clay ripple. Results for two ripple height to length ratios are shown.

Figure 18. Clay-wave geometry and idealized pressure distribution.

Figure 19a. Plot of drag coefficient of ripple as a function of Reynolds number based on length from the nozzle exit. Results for two different ripple heights are shown.

Figure 19b. Variation of drag coefficient with ripple height to length ratio. Data for all length Reynolds numbers are indicated within the indicated regions.

Figure 20. Plot of separation distance divided by ripple height as a function of Reynolds number based on ripple height. Results for two different ripple heights and two axial locations are shown.

Figure 21a. Velocity Profile above the clay-wave plate for three air speeds.

Figure 21b. Velocity Profile above the clay-wave plate for three air speeds.

Figure 22. Ripple velocity divided by shear velocity as a function of fluid Reynolds number ($\bar{m}/\mu$) as suggested by Rodgers. Note the poor correlation of the data for the two fluid viscosities.

Figure 23. Schematic sketch of ripple flow situation used in simple ripple analysis.

Figure 24. Identification of points on the streamlines for the balance of surface tension and pressure forces.

Figure 25a. Non-dimensional ripple speed as a function of non-dimensional surface tension parameters.

Figure 25b. Non-dimensional Wave Width as a Function of Non-dimensional Surface Tension Parameter

Figure 25c. Plot of non-dimensional ripple amplitude as a function of non-dimensional surface tension parameter.

Figure 25d. Non-dimensional ripple spacing as a function of non-dimensional surface-tension parameter.

TASK 2, OPEN CYCLE DISK GENERATOR PROGRAM

During this quarter, the first set of nonuniformities experiments, in which wake nonuniformities provided strong variations of the plasma properties in the direction normal to the magnetic field and the flow, were completed. A uniform reference plasma in equilibrium (without ionizational instabilities) was first established. Subsequently, local thermal and velocity deficits/wakes were created by cold blades located in the subsonic region and parallel to the flow. A comparison between this well identified/characterized nonuniform plasma with the reference flow results was established.

A radial flow generator with convergent walls (in order to maintain nearly constant plasma properties) was used and is shown in Figure 1.

Experiments with different numbers of equally spaced radial blades, starting from the center of the stagnation region and extending to the sonic point, were conducted for various magnetic field intensities. The reduction of the Hall coefficient was measured, and a preliminary comparison of the experimental voltage data with a modified two-dimensional theory^[1] and with an "engineering" layered model was made for the case of 24 blades at 3.5 Tesla.

Description of the Experiments

(a) Reference Flow Tests

Several tests for the uniform reference case (no wakes) were conducted for different magnetic field intensities (1.0, 2.0, 2.6, 3.0 and 3.5 Tesla) to complete the data base (for the effective Hall coefficient as a function of the ideal) reported in Reference [2]. Good agreement between the mea-

ured Hall parameter and the calculated values was obtained for all cases (see upper curves of Figures 11-12 and Figure 13).

The calculated pressure as a function of radius, and five measured values, are shown in Figure 2. The electron density is in Saha equilibrium, and measurements of the free-bound continuum at $4900 \text{ \AA}$ were made and are compared with theoretical results in Figure 3. Figure 4 shows the "measured" and theoretical conductivity as a function of the radius; the latter is an average for all the applied magnetic field intensities. In the last portion of the generator, for B-fields higher than 3.0 Tesla, a slight increase in conductivity is predicted which was not observed in the experiment. However, for these operating conditions the interaction is low and variations of the properties with B-field are within the experimental uncertainty (given as error bars in Figures 2-4). The "measured" conductivity was obtained by using the following expression: $\sigma_{\text{meas}} = (N_e)_{\text{meas}} \beta_{\text{eff}} e/B$, where e is the electronic charge and B is the magnetic field intensity. Profiles of the effective Hall parameter for two different B-field intensities, 3.5 and 2.0 Tesla, are shown in Figures 11 and 12, respectively. The upper curves correspond to the uniform reference flow case.

The theoretical profiles were obtained using the two-temperature quasi-one-dimensional model described in Reference [2], with heavy gas components included as indicated in Table I. This table is a review of the operating conditions used for both the uniform and nonuniform (with blades) cases.

TABLE I

Summary of Test Conditions

Mixture of Gases (room temperature)	Ar 80%/CO ₂ 20%
Species Concentration at Stagnation Conditions (mole fraction)	Ar .80/CO ₂ .126/CO .074/O ₂ .037
Stagnation Temperature (K)	T ₀ = 2850
Stagnation Pressure (atm)	3.5 < p ₀ < 4.2
Minimum Area A* (cm ²)	78
Cesium Seed Fraction	.20% < SF < .30%
Mass Flow (kg/sec)	3.0
<u>Test Section</u>	
Mach Number <M>	1.40
Test Time (msec)	.7 - .8
<σ> (mho/m)	30
<β> @ B = 3.5 Tesla	6.5

A gas mixture of Ar 80%/CO₂ 20%, at room temperature, was used for these experiments. The higher specific heat ratio of argon, acting like a buffer, provides longer test time, which is a shock tube limitation for pure molecular gases. This choice of test gas provides some degree of simulation of combustion gases. The CO₂ (dissociated as shown in the table) concentration is sufficient to suppress the ionizational instability.

(b) Wake experiments

As mentioned above, well characterized nonuniformities were produced by the insertion (along the flow) of different numbers of equally spaced cold blades, T_w = 300 K, emanating from the center of the generator and extending to r* = 7.7 cm where M = 1. The blades are 1.0 mm thick stain-

extending to $r^* = 7.7$ cm where $M = 1$. The blades are 1.0 mm thick stainless steel with a trailing edge of .33 mm. The number (25) and thickness of the blades previously used were modified.^[2] The current blade location relative to the shock tube and nozzle is indicated in Figure 5. Photographs of a partial assembly are shown in Figure 6. A set of experiments was performed for 6, 12 and 24 blades. The wakes created in the latter case can be observed in the photograph of Figure 7.

Figures 8 and 9 show the open circuit voltage as a function of the radius for different numbers of blades and magnetic field intensities. At 3.5 Tesla (see Figure 8), the ratio of the average electric field to the reference flow value is .77 for the 6 blades case. For 24 blades, the ratio drops to .46. No remarkable experimental differences were detected between the 24 blade (present tests) and the previous 25 blade test results.^[2] Figure 10 shows the electric field ratio as a function of the ideal Hall parameter for the different configurations at two different locations (9.5 cm and 15.2 cm).

Figures 11 and 12 show the measured Hall parameter (dashed curves) as a function of distance for different numbers of blades at 3.5 and 2.0 Tesla, respectively. The error bars for the uniform reference case reflect the run-to-run variation in pressure, as shown in Figure 2. The complete set of data for the effective Hall coefficient as a function of the ideal Hall parameter for each configuration is shown in Figure 13. The data summarized in Figures 10 and 13 clearly indicate the monotonic degradation of generator performance for this type of nonuniformity (and orientation) with increasing Hall parameter and number of wakes ($\text{rms}\sigma$).

Description of the Theoretical Models

In order to analyze and compare the complete set of experimental data, it was necessary to develop/modify the electrodynamics code to handle narrower wakes. The modified code has the feature of a variable grid which allows the adjustment of the number of grid points in places of sharp gradients of the flow properties. The code is designed to accept variable conductivity, Hall parameter and velocity profiles in both the radial and the azimuthal directions.

The "engineering" model for narrow radial wakes considers the plasma to be of the layered type (in the azimuthal direction) and hence one can use, in the limit, Rosa's one-dimensional approach. However, it is necessary to account for the secondary effects due to the radial variation of the plasma properties. This is accomplished as follows.

For narrow radial wakes, one can assume, approximately, that: $E_r = E_r(r)$, $J_\theta = J_\theta(r)$, and $\langle E_\theta \rangle = 0$. Therefore, Ohm's law can be averaged in the azimuthal direction, with the result (for $u_\theta = 0$)

$$\begin{aligned} \langle J_r \rangle_\theta + \langle \beta \rangle_\theta J_\theta &= \langle \sigma \rangle_\theta E_r \\ \left\langle \frac{1 + \beta^2}{\sigma} \right\rangle_\theta J_\theta &= -\langle u_r \rangle_\theta B + \langle \beta \rangle_\theta E_r, \end{aligned}$$

where all averages can still depend on r . Using current conservation,

$$\langle J_r \rangle_\theta = \frac{I}{2\pi r h(r)},$$

where I is the total current, and $h(r)$ is the generator height, one can solve for the radial field E_r :

$$E_r(r) = \frac{\left\langle \frac{1 + \beta^2}{\sigma} \right\rangle_\theta \frac{I}{2\pi r h(r)} - \langle \beta \rangle_\theta \langle u_r \rangle_\theta B}{G(r)}.$$

Here $G(r)$ is Rosa's nonuniformity factor

$$G(r) = \langle \sigma \rangle_{\theta} \left\langle \frac{1 + \beta^2}{\sigma} \right\rangle_{\theta} - \langle \beta \rangle_{\theta}^2 \geq 1.$$

Integration from inlet to outlet gives the generator load line:

$$V = \int_{r_1}^{r_2} \frac{\langle \beta \rangle_{\theta} \langle \mu_r \rangle_{\theta} B}{G(r)} dr - I \int_{r_1}^{r_2} \frac{\left\langle \frac{1 + \beta^2}{\sigma} \right\rangle_{\theta}}{2\pi r h G(r)} dr,$$

from which the open circuit voltage and the short circuit current follow immediately. For our experiment in the open circuit case, one gets:

$$\beta_{\text{eff}}(r) = \frac{\langle \beta \rangle_{\theta}}{G(r)}.$$

Figure 8 shows the preliminary theoretical results for 24 blades at 3.5 Tesla derived from the two-dimensional analysis and the "engineering" model. Good agreement with the experimental data is obtained. The "engineering" model slightly overpredicts the voltage reduction, most likely due to the uniformizing effect of the plasma boundaries (for the experiment). The input conditions for the near wake, at $r = 7.7$ cm, for the conductivity defect is $\sigma/\sigma_{\infty} = .12$ and is $\sigma/\sigma_{\infty} = .47$ at $r = 15.2$ cm (generator exit); the width of the wake is 1.5 mm and 9.1 mm, respectively. Wakes appeared printed on the generator plexiglass wall, as is indicated in Figure 7, and several measurements of the width were made along the radius (for separate tests). Conductivity and velocity wakes were imposed in the form of modeled and extrapolated profiles which agree with the following simplified treatment of turbulent wake formation far away (1.5 cm) from the trailing edge: the Schlichting model^[4] for the spread of two-dimensional turbulent velocity-defect wakes was adopted, using as initial values the results of thermal and velocity boundary layer calculations^[5] over the blade surfaces. The enthalpy defect profiles were related to the velocity defect profiles using an empirical relation derived by Reichardt.^[4]

Assuming Saha equilibrium for the electrons, the conductivity defect was then obtained.

A complete analysis of the overall data base is underway.

Other Theoretical Work

The major theoretical modeling effort this quarter has been directed/ associated with the nonuniformities experiment described above. In addition, some modifications to the chemical kinetics program were made to accomodate thermodynamic and transport property calculations for mixtures of Ar/CO₂ and Ar/CO₂/H₂. This will enable an assessment of the measured β_{eff} and voltage for the reference flow results for the nonuniformities study (in the past, a crude thermodynamics model was used only to assess the extent of chemical nonequilibrium^[2]), as well as provide the basis for designing a high performance channel with swirl for tests in the disk facility.

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Figure 1 . Drawing of the radial flow generator.

Figure 2. Calculated and measured static pressure in the disk. Gas mixture at room temperature: Ar80%/CO₂20%, $T_0 = 2850$ K, $3.5 < p_{0\text{exp}} < 4.5$ atm, .20% < SF < .30%, $\dot{m} = 3.0$ kg/sec, $A^* = 78$ cm².

Figure 3. Calculated and measured electron density in the disk. Electrons are in Saha equilibrium. Gas mixture at room temperature: Ar80%/CO₂20%, $T_0 = 2850$ K, $p_0 = 4.0$ atm, SF=.25%.

Figure 4. Calculated (average for different magnetic field intensities) and "measured" conductivity:
 $\sigma_{\text{meas}} = (Ne)_{\text{meas}} e \beta_{\text{eff}} / B$. Gas mixture at room temp.
Ar80%/CO₂20%, $T_0 = 2850$ K, $p_0 = 4.0$ atm, SF = .25%,
 $\dot{m} = 3.0$ kg/sec.

Figure 5, Drawing in the r - z plane which illustrates blades location relative to shock tube, nozzle and generator.

Figure 6. Photographs of the blades assembly; up-downstream plexiglass nozzle; 24 blades and parts.

Figure 7. Plasma luminosity photograph for 24 blades at 3.5 Tesla.

Figure 8. Experimental voltage profile in the disk for all blade configurations at 3.5 Tesla, and theoretical comparison for the 24 blades case.

Figure 9. Experimental voltage profile in the disk; average on several runs, for the uniform reference case and for the different blades configurations. Gas mixture at room temperature: Ar80%/CO₂20%, $T_0 = 2850$ K, $p_0 = 4.0$ atm, $SF = .25\%$, $\dot{m} = 3.0$ Kg/sec, $B = 3.0$ Tesla.

Figure 10. Electric field, normalized to the uniform reference case, for the different blade configurations as function of the ideal Hall parameter. Gas mixture Ar80%/CO₂20%, $T_0 = 2850$ K, $p_0 = 4.0$ atm, $SF = .25\%$, $\dot{m} = 3.0$ Kg/sec, $A^* = 78$ cm².

Figure 11. Comparison of the measured effective Hall parameter in the disk. Error bars represent the ideal Hall parameter following the run to run pressure variations. Broken profiles represent the effective Hall parameter for the different blades configurations (several runs average) Gas mixture at room temp. Ar80%/CO₂20%, T₀= 2850 K, p₀= 4.0 atm, SF= .25 , $\dot{m}$ = 3.0 kg/sec, B= 3.5 Tesla.

Figure 12. Comparison of the measured Hall parameter in the disk for all blade configurations at $B = 2.0$ Tesla.

Figure 13. Comparison of the effective Hall parameter with the ideal at two different locations in the disk, for the several blades configurations:
 ○ □ at $r = 9.5$ cm and ● ■ at $r = 15.2$ cm
 △ ▽

TASK 3. ELECTRODE MODULE DEVELOPMENT AND TESTING

Part A.

Insulator Materials

Insulator studies during this quarter focused primarily on hot pressed silicon nitride. As mentioned in last quarter's report, preliminary measurements of room temperature breakdown strength showed large variations among samples. More data were obtained from specimens from various locations within the hot pressed billet, and no correlation was found between breakdown strength and position. Breakdown strength measurements within any one specimen varied only a slight amount. These facts lead us to believe that the silicon nitride material is most likely homogeneous, and that the variation in breakdown strength is probably related to the technique used to prepare the specimens. However, the specimens are all prepared in the same manner, the only difference being that some are ground more to make thinner pieces. The data show no correlation between breakdown strength and thickness, so there is no definitive answer for the variation of breakdown strength, as yet.

In pursuit of the source of the variation of breakdown strength, specimens were examined by scanning electron microscopy. There was no difference of microstructural features in the specimens of low breakdown strength relative to those of high breakdown strength. Likewise, there was no apparent difference in the appearance of the breakdown arc "tracks" for the high and low strength specimens. This microscopical examination

seems to indicate that they are not "singular" type defects which are causing the low values of breakdown strength.

So, at this time, the cause of the variation of breakdown strength in hot pressed silicon nitride is still a "mystery."

Electrode Modules

Present plans are for testing three sets of electrode modules at the M.I.T. MHD Simulation Facility and one set at the Westinghouse MHD Materials Test Facility. These tests would most likely take place next quarter. Forty-two electrode bases are presently available, which we will fabricate into modules for the next three tests at M.I.T. This will deplete the inventory and necessitate fabrication of more electrode bases.

Fabrication of fourteen electrode modules depleted the existing supply of SZSFLF-6 electrode material. Work has started to prepare two new batches of material. One batch will be for arc plasma spraying of the "standard" electrode modules tested at the M.I.T. MHD Simulation Facility; the other batch will be used to fabricate specimens for the test at Westinghouse.

The electrode specimens for the Westinghouse test will be fabricated by pressing and sintering, to form an electrode material of low porosity. Samples of this material were prepared and sent to Battelle Northwest for thermal properties testing and measurement. The thermal properties data was sent directly to Westinghouse for design of the electrode modules.

Experiments were performed to determine if the SZSFLF-6 electrode material could be "brazed" to metal bases using "Ticusil" alloy. The only furnace which was at all suitable for this type of experiment was the argon atmosphere carbon tube. Samples prepared in this furnace were not very good, due to incomplete wetting of the joint by the braze alloy.

Subsequent tests at Westinghouse, in a vacuum furnace, produced good joints; indicating that the carbon tube furnace probably has a "dirty" atmosphere. The electrode modules will be assembled at Westinghouse, since they do have the facilities to make the brazed joints.

Summary of Work Accomplished on Electron Emission of Electrodes

We have discovered that materials in the system $\text{LaFeO}_3\text{-SrFeO}_{3-\delta}\text{-SrZrO}_3$ react at elevated temperatures with trace quantities of Si in their environment to form surface layers of silicates. Because of the crucial role that surface composition plays in electron emission, considerable work has been done to build a new experimental apparatus which eliminates unwanted surface silicate formation and hence allows accurate control of the surface composition of our samples.

The heart of this new apparatus is a sapphire chamber which replaces the polycrystalline alumina chamber of our earlier apparatus. Sapphire possesses two distinct advantages over polycrystalline alumina with regards to providing a silicon-free environment. First of all, sapphire itself is practically silicon-free, whereas high-purity polycrystalline alumina typically contains at least hundred of ppm SiO_2 . Second of all, sapphire provides much better protection against the diffusion of impurities from outside of the chamber. Polycrystalline alumina becomes particularly permeable to impurities after extended periods in high-temperature, low- P_{O_2} environments, which tend to create porosity. A third advantage of sapphire is that it is transparent, which allows visual inspection of the inside of the chamber before and after a run. Sapphire tubes, however, are only available with much smaller dimensions than the 36" x 1" size of the polycrystalline alumina tube, which we had used. Hence, we were required to extensively redesign and rebuild our apparatus. The sapphire tube used is 12" x 1/2" in size.

In addition to the sapphire chamber, many other improvements were incorporated into the new apparatus. First of all, we sought to remove all potential sources of silicon contamination. This included replacing polycrys-

talline alumina parts with sapphire parts, eliminating the use of ceramic cements, replacing silicone vacuum grease with hydrocarbon vacuum grease, eliminating the use of silicone rubber tubing except downstream from the liquid nitrogen trap, and installing a valve so that the zirconia cell (which has a quartz envelope) need only be connected into the system when actually making a measurement. Another improvement in the new system was to install a liquid nitrogen trap to prevent the backstreaming of hydrocarbons from the pump oil into the sample chamber, where they would tend to make the control and measurement of low oxygen partial pressures difficult. Another improvement was to make the collector and the guard annulus surrounding the collector out of platinum sheet rather than platinum paint, which tends to peel. A final improvement was to design the sample assembly so that the sample-to-collector distance is both smaller (about .7 mm) and more stable than before.

Figures 1, 2, 3, show the details of the new apparatus. The sample and collector-guard assembly are designed to fit quite snugly into the sapphire tube, and thus the tube is pumped from both the top and the bottom to avoid pressure differences from one end of the tube to the other. Also, the sample has six holes drilled near its outer circumference which permits the small, but crucial space between the sample and the collector-guard assembly to equilibrate rapidly with the rest of the chamber.

Our initial run with the new apparatus was on a sample of $\text{La}_{.9}\text{Sr}_{.1}\text{FeO}_3$ at 1300°C for 116 hours, and the new apparatus performed very well. Good current saturation was obtained and saturation currents were quite stable over time. Auger analyses done on the sample before and after the run showed no significant change in surface composition, which confirms that we now have

good control over the surface composition of our samples. The saturation current densities measured were $13.5 \mu\text{a}/\text{cm}^2$ at $\log P_{\text{O}_2} = -4.3$ and $4.7 \mu\text{a}/\text{cm}^2$ at $\log P_{\text{O}_2} = -3.4$. This initial data indicates that the thermionic emission from a clean surface is greater than from a silicate-covered surface. We now expect to promptly obtain further data over a wide range of oxygen partial pressures and temperatures and for a variety of compositions.

Figure 1. Schematic drawing of overall thermionic emission apparatus.

Figure 2. Scale drawing of main furnace and chamber for thermionic emission experiment.

Figure 3. Detailed drawing of three sections of the thermionic emission apparatus. With reference to Figure 2, the top section is located in the hot zone of the main furnace, the middle section is located just below the bottom of the main furnace, and the bottom section is located just above where the aluminum plug inserts into the lower fitting.

Tape Casting of Electrode Materials

MHD electrodes and insulators are presently fabricated by plasma spraying a ceramic powder onto a metal blank and then grinding the resulting surface flat and smooth. An alternative processing technique is that of tape casting. In comparison to other ceramic forming techniques, tape casting is the best means of forming large flat articles of uniform high density and flatness.¹ The process entails the formulation of a suspension of finely divided inorganic powders, in an aqueous or nonaqueous liquid, composed of solvents, plasticizers and binders which may be cast onto a carrier surface. During the casting operation, the slurry passes beneath the knife edge of a blade that levels it into a layer of controlled thickness and width. Upon solvent evaporation, the solid particles coalesce to form a relatively dense flexible sheet which can subsequently be sintered. Fabrication of MHD components by tape casting and sintering results in denser materials of more controlled microstructure and thickness than plasma spraying and grinding.

The composition $.75\text{SrZrO}_3 \cdot .25\text{La}_{.75}\text{Sr}_{.25}\text{FeO}_3$ was used in a study of the tape casting process. This composition has been shown to possess properties which makes it desirable for use as an MHD electrode material.² For use in tape casting experiments this material was used in the form of a finely divided powder with a BET surface area of approximately $1.0 \text{ m}^2/\text{g}$.

The formulation used for tape casting is seen in Table I. The mixing process was done in two stages. In the first stage the ceramic powder, solvent and deflocculant were mixed together in a ball mill. Addition of the deflocculant during the initial stage was necessary in order to keep the powder particles evenly dispersed in the solvent. The second stage of mixing was done with the addition of plasticizer and binder to the slurry. The slurry was cast using a small lab caster manufactured by Cladan, Inc.

Sintered densities of about 97% of theoretical were achieved in $.75\text{SrZrO}_3 \cdot .25\text{La}_{.75}\text{Sr}_{.25}\text{FeO}_3$ tapes fired to 1350°C . Scanning electron microscope examination of green tapes revealed a gradation of particle size between the top and bottom surfaces of cast tapes. This phenomenon emphasizes the need for a narrow particle size distribution in the starting powder and that good dispersion of the powder in the liquid vehicle is imperative in obtaining tapes of uniform high green density.

Since good powder dispersion is a key to successful casting operations, it is desirable to study the dispersion process in greater depth. Studies are underway to learn of the mechanism of deflocculation in dispersions of ceramic powders in organic media.

Charge repulsion and steric stabilization are the two models commonly used to explain the mechanisms involved in dispersion stabilization.¹ Aqueous systems are well described by the double layer electrostatic repulsion model, also known as DLVD theory.^{3,4} In organic media of low dielectric constant, the number of charges per unit volume is lower than in aqueous systems, and ionic stabilization is less likely to be operative.^{5,6} In many nonaqueous systems it is believed that stabilization results from the repulsion between interacting molecules adsorbed onto particle surfaces, commonly referred to as steric stabilization.⁷

Regardless of the mechanism, the adsorption of a surface active agent (deflocculant) from the liquid onto the solid surfaces is a prime requirement for the dispersion of solids in liquids.^{4,5} The type of adsorption relevant to this study is that which is usually physical, and occurs from a binary mixture of a surface active agent and an organic solvent onto the powder surfaces.

Surface active agents are generally organic materials which are amphipathic in nature.^{4,5} This means that they contain a hydrocarbon group which is nonpolar and also a polar group. In relatively nonpolar organic solvents, one would expect adsorption of such a surfactant to occur such that the hydrocarbon groups are oriented toward the solvent and the polar groups away from it.

Glycerol trioleate and menhaden fish oil are two substances which have been found to be effective deflocculants for tape casting ceramics.¹

Glycerol trioleate is a synthetic oil, composed of triglyceride molecules derived from the combination of oleic acid with the alcohol, glycerol. The general formula of a triglyceride is:⁸

For glycerol trioleate, $\text{R} = \text{R}' = \text{R}'' = (\text{CH}_2)_7\text{CH} : \text{CH}(\text{CH}_2)_7\text{CH}_3$. The primary functional group in these ester molecules is the carbonyl ($\text{C} : \text{O}$) group, the presence of which makes them polar.

Menhaden fish oil is a naturally occurring oil which is composed of a mixture of carboxylic ester molecules, including esters of normal monohydric alcohols and triglycerides.⁸ The fish oil differs from the glycerol trioleate in that it is composed of triglycerides derived from many different carboxylic acids. The carboxylic acids which make it up are straight chain compounds ranging in chain length from fourteen to twenty-two carbons,

including both saturated and unsaturated acids.⁸ According to a supplier, the fish oil also has present in it a small percentage of free fatty acids.

Infrared spectroscopy is being used to measure the adsorption of these two deflocculants onto powder surfaces from solutions of an organic solvent. Initial adsorption studies have been performed using an alumina powder dispersed in toluene solutions. The powder is 100% alpha phase, has a BET surface area of about $8.5 \text{ m}^2/\text{g}$ and a median particle size of less than one micron. In the adsorption experiments 30.0 grams of alumina were combined with 20.0 grams of solution of known concentration and mixed for 16 hours at room temperature; repeating this procedure for a series of solutions of different concentrations. After mixing, the dispersions were centrifuged and the supernatant solutions analyzed for concentrations using an infrared spectrometer. A separate series of blank solutions of known concentration were also analyzed in order to plot a calibration curve of absorbance versus concentration. The calibration plot was used to determine the concentration of the supernatant solutions. The peak at $1740 - 1745 \text{ cm}^{-1}$, due to the stretching vibration of the C : O group of the ester molecules was used in the analysis of the infrared spectra of the solutions. In each case, the absorbance at the peak maximum was used as a measure of the concentration.

The isotherms for the adsorption of fish oil and glycerol trioleate onto alumina from toluene solutions have been constructed in Figure 1. The isotherms are plotted in terms of the adsorption ($\Delta c W_o/m$) in mg/g versus the concentration of the equilibrium solution, where Δc is the change in concentration between the original and equilibrium solution,

W_0 is the weight of solution and m is the weight of adsorbent.

Though glycerol trioleate and menhaden fish oil are composed of the same types of chemical functional groups, their adsorption patterns onto an alumina powder from toluene solutions are quite different. The adsorption isotherms differ in both shape and extent of adsorption. The menhaden fish oil is adsorbed to a much greater extent than the glycerol trioleate and its isotherm rises to a peak before leveling off. The calibration curve for a series of fish oil in toluene solutions is seen in Figure II. It is of interest to note that the peak in the adsorption isotherm corresponds to the abrupt change in slope in the adsorbance versus concentration curve.

Many factors influence the adsorption from solution, but the most important ones are the adsorbent-adsorbate interactions and interactions between the components of the solution.⁹ The interaction of the solute with the solvent has an effect on adsorption in terms of the extent of adsorption and the shape of the isotherm.⁹ In general, a given solute is more strongly adsorbed from a poor solvent than a good one.

The differences in the adsorption behavior of these two deflocculants onto alumina must lie in the differences between the specific types and structures of the molecules which comprise them, and thus the manner in which they interact with the solvent, toluene. The abrupt change in shape in the calibration curve of the fish oil/toluene solutions is an indication of some type of interaction between the fish oil and toluene in solution, which has an effect on the adsorption. It seems that the glycerol trioleate is more soluble in toluene than fish oil, and is thus adsorbed from solution to a lesser extent. The calibration curve of the glycerol trioleate/toluene solutions is a smooth curve with no abrupt slope changes.

In addition to alumina, other compositions will be used in adsorption studies with these deflocculants, including the one used in tape casting experiments. The measurement of electrokinetic phenomena is another technique commonly used in the study of dispersions. Electrophoretic techniques may be used to determine whether or not a charge repulsion mechanism is operative in the systems used in adsorption studies.

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TABLE I
Tape Casting Formulation

<u>Material</u>	<u>Function</u>	<u>Amount</u>
$.75\text{SrZrO}_3 \cdot .25\text{La}_{.75}\text{Sr}_{.25}\text{FeO}_3$	Ceramic powder	300.00 g
Toluene	Solvent	85.80 g
Menhaden fish oil	Deflocculant	2.40 g
Polyvinyl butyral	Binder	7.50 g
Polyethylene glycol	Plasticizer	10.20 g

Casting surface: cellulose triacetate film

Casting speed: about 17"/min

Doctor blade setting: 0.040"

Figure 1. Isotherms for the adsorption of menhaden fish oil (opened circles) and glycerol trioleate (closed circles) onto alumina from toluene solutions.

Figure II. Calibration curve for menhaden fish oil/toluene blank solutions.

Part B. The MHD Test Facility Complex

The MHD Small Scale Simulation Facility, designed exclusively for electrode development testing and used extensively for other MHD related tests as well, was used in the reporting period in the development of plasma temperature and particle velocity instrumentation.

A mechanical failure of the oil-free air compressor has interrupted the test program.

Facility Development

Infrastructure

Lubricating oil from the air compressor was discovered in the compressed air line on the eve of an extensive series of tests. Inspection of the compressor revealed a major compressor failure. Steps were immediately taken by the Institute to find a contractor capable of cleaning the complete network of oil-free air piping which supplies compressed oil-free air to a number of laboratories in the building. The cleaning task was undertaken by the Dow Company using Chlorothene Nu as the solvent in nitrogen suspension. Repair of the compressor has been undertaken by the compressor manufacturer for which replacement parts are being made to special order; hence the extended time it is taking to recommission the compressor back into operation.

As a precautionary measure, a tell-tale oil separator will be incorporated in the oil-free compressed air system.

Facility Components

As an added precaution against compressor oil ever coming into contact

with pure oxygen, the Safety Officer required a re-design of the oxidizer system section outside the test tank. Included in the re-design is the replacement of the check valves with no-leak check valves. The Circle Seal no-leak check valves being installed should prevent oxygen from ever migrating upstream into the compressed air line, which could carry oil if the compressor should contaminate the air with oil again.

Facility Operations

A few tests were performed using pure oxygen, as compressed air was unavailable for proper operation of the Facility. A limited degree of control over the test conditions was possible by varying the flow rate and the stoichiometric ratio within safe bounds.

The only tests that could be performed under the above conditions were developmental tests on a plasma temperature and pressure survey probe under development for use in the December 1979 tests of the USSR/IVTAN U-25B MHD channel in Moscow. The tests served to confirm the thermal integrity of the probe, and the operation of the fiber optics system and of the intermittently purged pressure ports. This probe system and the results obtained with it will be described in the next progress report.

One other test was conducted as a preliminary check on the design of a brightness detector which is being developed to be used in measuring plasma flow velocity.

A list of the tests performed during the reporting period appears in Table F-1 indicating representative test parameters.

TABLE F1 ELECTRODE DEVELOPMENT AND ELECTRO-FLUID MECHANICS TESTS IN MHD SIMULATION FACILITY

Test Sequence No.	Electrode Stack Nos.	Date	Total Durtn. (h)	Seed Durtn. (h)	Current Durtn. (h)	$\dot{m}$ Total (kg/s)	N_2/O_2	ϕ_{O_2}	Seed (XK)	Slag (kg/s)	Current Density (A/cm ²) max	T_o (K)	P_o (atm)	Mach No.	$\dot{Q}_{hot}$ (W/cm ²)	$\dot{Q}_{cold}$ (W/cm ²)	σ (mho/m)	Remarks
294	Probe	10/31	.90	.13		.154	0	.787	1.38			2877	1.080	.343			26.05	Radiation Probe
295	Probe	11/7	.53	.31		.418	0	.623	1.276			2803	1.002	.379			19.08	Radiation Probe
296	B-1	11/21	1.10	1.03		.158	0	.785	1.533			2883	1.064	.320			27.97	Temp. & Velocity

TASK 4a, COAL COMBUSTION STUDIES

I. Analysis of Coal and Char (From Pyrolysis)

A. Background

Researchers have been unable to satisfactorily model coal pyrolysis based on weight loss of the resulting char. This is not surprising when one considers the complex chemical composition and physical structure of coal. The behavior of coal during pyrolysis depends on multiple factors: coal type, reactor type, temperature, residence time, etc. To help visualize the pyrolysis process, consider the schematic in Figure 1. Simpler and more complex models have been proposed. The one in Figure 1 was chosen because it shows that both kinetic and mass transfer limitations may be important. Bear in mind that this model has not been verified. Some of the paths may be negligible, while others may be oversimplified. Researchers have clearly shown, however, that a realistic pyrolysis model should consider multiple pathways.

Traditionally, researchers have studied coal devolatilization external to the coal particle by measuring weight loss of the original coal gas product composition. The bulk of the literature deals primarily with kinetic schemes based on weight loss of the original coal. A small portion of the literature examines mass transfer effects. Unfortunately, most of the papers in this latter group assume well-characterized reaction rates and physical parameters which either cannot or have not been measured. The two competing effects of kinetics and mass transfer are seldom combined. Experimental measurements, such as weight loss and gas product composition, are important in that they provide checks on the material balance. However, we believe that substantial gains may be made by studying pyrolysis

internal to the coal particle. In this effort we have been developing new methodologies (see below) and acquiring new equipment, such as the Quanta-chrome Surface Analyzer, to measure porosity and pore size distribution. (See the section on Pore Measurements.)

During the past reporting period we have looked at several analytical techniques for investigating coal structure and coal chemistry. Among the techniques considered were nuclear magnetic resonance (^{13}C and proton) (NMR), Fourier transform infra-red spectroscopy (FTIR), x-ray diffraction, successive extraction by solvents, supercritical extraction, liquid chromatography, Raman spectroscopy, Mossbauer spectrometry, electron spin resonance (ESR), the proton probe, the electron probe, and the ion probe. The most suitable techniques for chemical studies are FTIR and NMR for chemical functionality studies and the proton probe for direct measurement of oxygen in solids (usually determined in coal by difference with H, C, N, S and ash content). Transmission electron microscopy (TEM) shows good potential in aiding studies of the coal and char microstructure. TEM may also greatly enhance the chemical techniques, such as FTIR or the proton probe. Preliminary results using the TEM are presented below.

Currently, the popular trend in models which include mass transfer effect is to assume a branching tree pore structure (see Figure 2), whereby the base of the tree trunk is located at the particle surface with the branches protruding inward. This idea is attractive because it takes into account the fact that a wide range of pore sizes exist and that the pores interconnect. Moreover, the pore sizes and pore size distribution can be measured experimentally using BET and mercury porosimetry apparatus. However, this idea is not necessarily realistic. It is entirely conceivable that a pore can be constricted or even inaccessible altogether. The re-

quired techniques and skills are being developed to experimentally determine the inaccessible pore volume. This can be accomplished using the TEM for total pore volume and the Quantachrome Surface Analyzer for accessible pore volume.

B. Results

Provided that samples are sufficiently electron transparent, the TEM can have a resolution as low as $3\text{\AA}$. Thus, the TEM is ideal for directly imaging the pore structure of coal, which typically ranges from $8 - 300\text{\AA}$. However, most samples, including coal and char, are not sufficiently electron transparent or thin in their original state, but they can be made so by microtoming. Microtoming involves making an ultrathin slice of a sample using a freshly cut glass knife or a diamond knife. We have been successful in sectioning a 200 mesh Montana lignite coal particle. A TEM picture using a Phillips 200 microscope is shown in Figure 3. The microtoming thickness was set at $100\text{\AA}$. However, such settings are not always accurate; the actual sample thickness is between $50 - 200\text{\AA}$. We believe that the lighter areas are pores. The pores are greater than $50\text{\AA}$. This is significant since researchers report that most product gases are transported in pores of comparable size. Smaller pores have been obscured by the thickness of the sample. Better resolution may be possible with improved microtoming techniques and a better TEM microscope. The dark glob in Figure 3 may be mineral matter. One could determine its composition by using a scanning transmission electron microscope (STEM) rather than a TEM microscope, which was used in this case. The STEM is equipped with x-ray diffraction for metals.

One can determine the porosity of the sample with an image analyzer. The image analyzer distinguishes areas of contrast; it has capabilities for

determining image number, area, perimeter, size distribution, etc. In this case we used the image analyzer to measure total pore area within the box of Figure 3. The photo as viewed by the image analyzer is shown in Figure 4a. The area which the analyzer saw as pore volume is shown by the bright white areas in Figure 4b. The total area viewed was 295 square microns, of which 2.89 square microns or approximately 1% was pores. Thus, assuming the pores are randomly distributed, the porosity of the coal (for pores greater than 50Å) is roughly 1%.

The preliminary results using the TEM are promising. It will be interesting to compare the TEM porosities with the Quantachrome porosities. In addition to aiding our study of pore structure, the thin samples may also be used for FTIR analysis. This approach may provide a significant improvement over the traditional KBr preparation for solid samples for FTIR since grinding and overpowering signals from water would be eliminated. Thus, if the TEM and FTIR techniques are combined, it will be possible to make detailed chemical functional analyses and structural analyses of the same sample.

While we are pleased with the initial TEM results, the technique has not been perfected. Most of the problems involve sample preparation. Standard procedures have been developed for biological applications. However, very little is known about preparation of non-biological samples, such as coal. Following the procedures for biological applications the sample preparation typically involves fixation, staining, washing, dehydration, embedding, microtoming, relaxation, and post-staining. Tonicity, osmolality, and Ph of the solutions can also play an important part in the machinability and contrast of samples. We have not yet determined which of the above steps are truly important for coal and chars. A systematic study

needs to be made to determine the optimal stains and embedding mixtures. Deformation of the pore structure during microtoming, extraction or dissolution by the embedding media, and sublimation in the TEM microscope are also problems which have not been investigated. However, these issues will be pursued in the future.

II. Quantachrome Surface Analyzer

Two mass flow controllers have been installed on the Quantachrome Surface Analyzer to regulate nitrogen and carbon dioxide. This addition permits measurement of pore size distribution in coal and char samples. Previous measurements were limited to total pore volume. Calibrations of the equipment for nitrogen are complete; those for carbon dioxide will be done soon.

III. Modifications to the Pyrolysis Furnace

The pyrolysis furnace was previously mounted too close to the floor. One could not use the centripeter in series with the cascade impactor, which is necessary for complete soot and char separation. Consequently, the furnace was elevated. During downtime the vacuum pumps were replaced by a single pump. A flow-controlling vacuum pump was installed to maintain constant flow through the center nozzle of the centripeter as solids accumulate on the filter. Several electrical wires were also rerouted and/or replaced. A pressure controller for the furnace is being constructed now; it will operate using differential heat sensors and a motor-operated solenoid valve installed at the vacuum pump inlet.

IV. Experimental Ash Vaporization Studies*

A. Background

The vaporization model discussed in Section V.A.4 indicates the importance of particle temperature and the surface vapor pressure of the mineral species in determining the vaporization of ash from a burning coal char particle. The surface vapor pressure is a function not only of temperature, but also of the chemical state of the species concerned. Thus, one might expect different vaporization behavior depending on whether the local surface conditions are reducing or oxidizing. For example, in the presence of carbon, silicon is vaporized not as SiO_2 , but rather as the more volatile nonoxide SiO .^[1,2]

To investigate further the influence of chemical environment on coal ash vaporization, a series of experiments have been performed in which the average vaporization rates from ash in coal and from free ash were compared. Some preliminary results are presented here.

B. Experimental

Ash, free of organic material, was produced by the ASTM procedure and fed to a laminar flow furnace^[3] in an inert (argon) atmosphere at temperatures up to 2500 K. Sized coal particles (either 38/45 μm or 75/90 μm) were also fed to this furnace under the same conditions.

In a separate series of experiments, coal particles were burnt in mixtures of O_2/Ar to produce particle temperatures between 1800 and 2700 K. As described earlier,^[4] the particle temperature attained is a function of the oxygen partial pressure in these experiments.

In all of these experiments, the material which vaporizes recondenses to form a fine particle fume (typical diameters range from 100 to 400 $\text{\AA}$)

* This work was carried out jointly with EPRI Project No. RP 121212-3.

which is then collected on a final filter after char and residual ash particles have been removed by an Anderson impactor. Analysis of this fume by neutron activation analysis yields the amount of material vaporized and hence, since the quantity of material fed is known, the fractional vaporization, ϕ .

C. Results

Results obtained for the vaporization of Al, Ca, Mn and Na are shown in Figures 5 through 8, respectively, expressed as an average fractional vaporization rate, ϕ/t_b . The appropriate time, t_b , is either the particle burnout time (in the combustion experiments) or the total residence time (in the inert pyrolysis experiments). In all cases, it is clear that vaporization of ash contained in the coal carbon matrix is substantially augmented over that from the free ash. As shown in the case of aluminum, it makes no difference whether the coal is pyrolyzed in an inert atmosphere or is burnt out in an oxidizing atmosphere--presumably because particle combustion is largely diffusion-controlled under the present conditions.

D. Discussion

The chemical environment in which an ash particle finds itself at high temperatures is obviously of great importance in determining the extent of vaporization of the ash minerals. In the case of species such as aluminum, it can be shown that, under sufficiently reducing conditions, species such as AlO and AlO_2 have higher equilibrium vapor pressures in the presence of $Al_2O_3(s)$ than does $Al_2O_3(g)$ at the same temperature. Of course, ash is a complex mixture of species and phases so that it is difficult to apply thermodynamics for pure species quantitatively. Nevertheless, it is clear that the activities of the various vaporizing species are augmented in a reducing environment and that this effect is important when considering the

extent of vaporization under given conditions. Further, more quantitative studies of this problem are planned.

V. Coal Combustion Model

A. Improvements in Computer Model

A detailed computer program for coal combustion was presented in an earlier report.^[5] Since that time, considerable improvements have been made to increase both the capabilities and flexibility of the program. The improvements also provide more meaningful results. There are four areas where changes have been made: 1) reaction rate calculations; 2) gas phase equilibrium calculations; 3) overall convergence scheme; and 4) ash vaporization kinetics. Other miscellaneous changes were made to enable smoother operation and interactive capabilities, but these will not be discussed here.

A.1. Reaction rate calculations

A kinetic model was presented in our last report^[4] for calculating the steady state reaction rate for single particles under fuel-rich combustion conditions. This model considers the effects of internal reaction within the porous structure of the char, pore diffusion, and external diffusion for each of the five reactive species CO_2 , H_2O , O_2 , O , and OH ; it also performs an energy balance for the particle, thereby allowing the particle temperature to differ from the gas temperature.

This single particle model was used to replace the previous model, which only considered the reaction with O_2 and which did not allow for differences in the temperatures of various particle size groups from the gas temperature. The coal combustion model now calculates contributions to the total rate for each reactant and for each of fifteen particle size groups,

and sums up the contributions to arrive at an overall char consumption rate.

A.2. Gas phase equilibrium

The convergence scheme in the old equilibrium routine was based on a correlation between the amounts of CO and CO₂. Difficulties in obtaining rapid convergence (and at times the inability to attain convergence at all) necessitated a better computational scheme. The new method is based on the technique of minimization of Gibbs free energy, and, although it involves lengthier calculations than the simple routine it replaces, there are no problems in obtaining convergence.

A.3. Overall convergence scheme

The above rate and equilibrium calculations and ash vaporization calculations (which will be discussed subsequently) require much more computer time than previous versions. These calculations are repeated in the overall iterative loop for each plug flow section in the combustor. Therefore, it was important to change the convergence scheme for this loop to avoid excessive run time. Convergence in this loop is obtained by selecting a value of the section temperature, performing all calculations, and calculating a new temperature from a section energy balance. Rapid convergence is now achieved by basing the new temperature estimate for the current section on a linear interpolation of the temperatures calculated from the previous section in the first iteration and that calculated from the previous section in the last iteration.

A.4. Ash vaporization kinetics

In a recent experimental study at MIT^[6] the rates of vaporization of individual mineral species were measured using two techniques. In the first method coal particles were injected into a high temperature inert at-

mosphere and the char particles were quenched and analyzed for their inorganic constituents, with the amount of vaporization determined by difference. In the second method, coal particles were burned to completion in an oxidizing atmosphere at temperatures up to 3000°K, and the amount and composition of vaporized mineral matter was obtained by analyzing the aerosol produced (using neutron activation).

As indicated in a previous paper, [7] these results can be correlated empirically with a model which assumes that vaporization is controlled by the mass transport resistance in the boundary layer surrounding a single particle. The molar rate of vaporization of species i with a vapor pressure $P_i(T_p)$ at the particle surface is

$$\frac{dn_i}{dt} = \frac{2\pi}{RT_p} \cdot D_i(T_{BL}) \cdot d_p(t) \cdot P_i(T_p)$$

where dn_i is the differential number of moles vaporized in time dt , $D(T_{BL})$ is the diffusivity of i in the boundary layer, R is the gas constant, and $d_p(t)$ is the particle diameter at time t . An alternate formulation for the rate of change of the fraction F_i of species i in the original coal which has vaporized is

$$\frac{dF_i}{dt} = \frac{3}{r_{p_0}^3 C_{i_0} RT} \cdot D_i(T_{BL}) \cdot r_p(t) \cdot P_i(T_p)$$

where $r_p(t)$ is the particle radius at time t , r_{p_0} is the initial particle radius, and C_{i_0} is the initial molar concentration of species i in the coal particle. The temperature dependence of the vapor pressure is

$$P_i(T_p) = A_i \exp\left(\frac{-B_i}{RT_p}\right)$$

where A_i and B_i are empirical factors whose values are shown in Table 1 (below) for Montana lignite coal.

Table 1

Species	A (atm)	(B/R) x 10 ⁻⁴ (°K)
Al ₂ O ₃	2.32	2.93
As ₂ O ₃	1.27 x 10 ⁻⁴	1.55
CaO	.714	1.86
Fe ₂ O ₃	.496	2.26
MgO	24.2	2.34
Na ₂ O	7.77 x 10 ⁻⁴	1.29
SiO ₂	7.67	2.60
ZnO	3.73 x 10 ⁻⁴	2.04

These values were obtained by integration of the above rate expression and regression of the experimental data for oxidizing conditions using an oxygen diffusion-limited combustion model to determine particle temperatures. (The oxygen diffusion-limited combustion model was presented in a previous report, [5] separate from the global combustor program.)

An excellent correlation is obtained for temperatures ranging from 2000 to 3000°K. Corroboration of the ash vaporization model is also found from the agreement between the predicted and experimental dependence of vaporization on particle size. For constant particle temperature, the model predicts that

$$\frac{F_{i1}/t_{p1}}{F_{i2}/t_{p2}} = \left(\frac{d_{p2}}{d_{p1}} \right)^2$$

where t_{p1} and t_{p2} are the burning times for the two sizes. Experimental data for 45 - 90 μm particles were found to satisfy this inverse square relationship.

This simple model was incorporated into the computer model to enable calculations of vaporization which are in line with the experimental data. The parameters A and B must be evaluated for the particular type of coal of interest.

B. Preliminary Results

Presented in Figures 9 through 11 are graphs of the temperature, char fraction remaining, and fractional ash species vaporization versus residence time in the combustor. These results are representative of a fuel-rich case where only the reaction with O_2 is considered. Figures 12 through 14 show similar results for the same conditions, but allowance has been made for reactions with CO_2 , H_2O , O_2 , O and OH . Figure 15 shows the fraction of the total instantaneous char consumption rate for each reactant as a function of the fraction of original char that has burned.

The temperature profiles in Figures 9 (O_2 only) and 12 (multiple reactions) are quite similar for the two cases. It is interesting to see, by comparison of Figure 10 with Figure 4, that when reactions with species other than O_2 are considered, the level of burnout is higher and can be attained more rapidly. This shows that previous estimates of required residence time for coal-fired MHD combustors may have been conservative for fuel-rich combustion conditions. Figure 11 and 15 show the amounts of ash species predicted to be vaporized according to the model. Note that about 80% is vaporized when considering only O_2 , whereas only 70% vaporization is noted when the other reactions are included. Once again, previous estimates may be too high for the amount of vaporization for fuel-rich conditions.

The reason for the differences indicated above is the endothermicity of the CO_2 and H_2O reactions with the char. As seen in Figure 15, these

reactions account for 20% of the total rate at the start of combustion, and when the O_2 level in the reactor falls these reactions become the dominant char gasification reactions.

Subsequent refinements of the model will be directed to the inclusion of a coal heating and pyrolysis model and a well-stirred section.

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Figure 1. Devolatilization Schematic

GT = graphitized tar

TI = internal tar

GI = internal gas

SI = internal soot

GX = external gas

TX = external tar

SX = external soot

Note: During the pyrolysis step coal can react to form internal gases and internal tars (condensed liquids). The tars can then participate in further reactions, termed secondary reactions, to form additional internal gases or graphitized tars. The internal gases may also participate in secondary reactions to form internal soot. Competing with these internal reactions are mass transfer effects (provided by the pore structure). The internal tars and gases can diffuse out of the particle to form external tars and gases. Finally, these external products crack in another secondary reaction to form external soot.

"Branching Tree" Pore Model

Figure 2. Hypothetical Pore Shapes

Figure 3. Microtomed Montana Lignite Coal Particle--200 Mesh

Figure 4a. Box of Figure 3 as viewed by image analyzer.

Figure 4b. Pore structure as determined by image analyzer.

Figure 5.

Figure 6.

Figure 7.

VAPORIZATION OF SODIUM

Figure 8.

Figure 9. $P = 1$ atm, Air Preheat = 1600°K , $\phi = 1.11$, Reaction with O_2 .

Figure 10. $P = 1$ atm, Air Preheat = 1600°K , $\phi = 1.11$, Reaction with O_2 .

CUMULATIVE FRACTIONS ASH VS TIME

Figure 11. $P = 1$ atm, Air Preheat = 1600°K , $\phi = 1.11$, Reaction with O_2 .

Figure 12. $P = 1$ atm, Air Preheat = 1600°K , $\phi = 1.11$, Reaction with 5 species.

Figure 13. $P = 1$ atm, Air Preheat = 1600°K , $\phi = 1.11$, Reaction with 5 species.

Figure 14. $P = 1$ atm, Air Preheat = 1600°K , $\phi = 1.11$, Reaction with 5 species.

Figure 15. $P = 1$ atm, Air Preheat = 1600°K , $\phi = 1.11$, Reaction with 5 species.

TASK 4b. COMBUSTION AERODYNAMICS AND FLUID MECHANICS OF HIGH-SWIRL SECOND

STAGE

Introduction

For any MHD system the overall cycle efficiency of the plant depends upon the relative fraction of power extracted in the MHD generator. The overall efficiency can be increased by minimizing the external losses, including those in the diffuser, and selecting the burner pressure which will maximize the new MHD power. The combustor pressure, ranging from four to nine atmospheres, depends upon the required residence time, the need to achieve supersonic flow at the combustor exit and to maintain continual expansion and acceleration of gas over the length of a standard divergent channel. The diffuser section must allow sufficient pressure recovery to establish near supersonic flow through the generator at the selected combustor pressure. The pressure recovery in the diffuser depends upon the area ratio, length, boundary layer blockage at the entrance and the height to width ratio. For a thin boundary layer the performance increases with an increasing area ratio as long as no separation occurs. Experimental studies reveal that maximum pressure recovery occurs if the diffuser is operated in the transitory stall regime, but without flow separation. Thus we find that it is very important to prevent flow separation if the losses have to be minimized. Secondly, the point of separation gives rise to a hot spot, with consequent damage to the wall material from the 2500 - 3000°F combustion gases. Then again, for a non-separated flow, a stream of cool fluid may be forced to flow along the diffuser surface, thereby insulating the surface and reducing the wall cooling requirements.

The present code is being developed to predict the flow aerodynamics in the nozzle section of the MHD Combustor, and to indicate if any flow

separation occur from the second stage combustor walls. This program is being developed for the water-model, and it computes the two-dimensional, steady-state, swirl flow using the cartesian co-ordinate system. It employs the vorticity-stream function approach together with a two equation ($k-\epsilon$) model of turbulence. This approach reduced the number of equation to be solved, and also eliminated the pressure term. Secondly, the stream function map will visually indicate flow separation. Subsequently, the capability of pressure calculations has been added to the code. However, this calculation is done more easily now as it is based on the converged solution for stream function. A subroutine for calculating the axial velocity has also been added.

Experimental Facility

The experimental facility for the Water-Model Study was extensively modified during the last quarter. The chain drive mechanism employed for the positioning of the vanes was found unsuitable -the chain mechanism bound the vanes and prevented them from moving. This was due to the construction of the vane locating pin and bush, which had excessive play, and also due to the large radius of the driving chain. Various alternate drive mechanism were considered, but were abandoned in favour of individually setting and locking each vane in place. This setting can be done in place for two sets of vanes, while setting of the third set requires that the second stage three concentric annuli assembly incorporating swirl vanes assembly be brought down about 1 foot from its actual location. It was decided to fix the latter set of vanes, governing the swirl in the outermost annulus, to an angle of 70° , corresponding to a swirl number of approximately 1.8. Another difficulty was that there was

no way of determining if a vane moved on its axis during operation. This was overcome by providing eight windows along the periphery of the second stage flow introduction section. It is now possible to check the vanes visually.

An experimental run was made with maximum swirl in the first stage (swirl number of approximately 1.85) and a swirl number of 1.8 in the outermost annulus of the second stage. The flow through the first stage was 94 gpm. corresponding to a flow velocity of 5.7 m/sec, and that through the outermost annulus was also 94 gpm, corresponding to a flow velocity of 4.1 m/sec. There was no flow through the other two annullii. This test showed a strong recirculation zone covering approximately three-quarters of the inlet diameter, with a flow separation occurring approximately three inches from the downstream end of the nozzle. During this test the top plate was located 1.5 inches above the nozzle exit.

An attempt was made to photograph the flow, but the light source employed proved to be too weak. A new light source has now been constructed. This will be located on top of the facility for viewing the longitudinal section of the flow and will provide a slit beam of approximately 64000 lumens. The flow regime is made visible by the use of polystyrene beads.

Theoretical Model

The code 'SHAPE' is now operational. It was initially developed to predict the stream function and swirl velocity distribution, but the addition of new subroutines has added the capability of predicting the axial velocity and pressure distribution also. The pressure calculations are done by successive over-relaxation method as given in "Computational

Fluid Dynamics" by Patrick J. Roach. The equations employed are given below.

At the internal points, at least twice removed from the boundary.

$$P_{ij}^{k+1} = P_{ij}^k (1 - \text{ORF}) + \frac{\text{ORF}}{2(1+\beta^2)} [P_{i+1,j}^k + P_{i-1,j}^{k+1} + \beta^2 P_{i,j+1}^k + \beta^2 P_{i,j-1}^{k+1} - \Delta x^2 S_{ij}]$$

At the points adjacent to the boundary

$$P_{ij}^{k+1} = P_{ij}^k (1 - \text{ORF}) + \frac{\text{ORF}}{2(1+\beta^2)} [P_{i+1,j}^k + P_{i-1,j}^{k+1} + \beta^2 P_{i,j+1}^k + \beta^2 (P_{i,j-1}^{k+1} - \frac{\partial P}{\partial n} |_{ij} \Delta y) - \Delta x^2 S_{ij}]$$

The boundary value is given by

$$P_{i,jw} = P_{i,jw+1} - \frac{\partial P}{\partial n} \Delta y$$

where

$$S_{ij} = \rho [(\frac{\partial^2 \psi}{\partial x^2}) (\frac{\partial^2 \psi}{\partial y^2}) - (\frac{\partial^2 \psi}{\partial x \partial y})^2]$$

$$\beta = \Delta y / \Delta x$$

ORF = over-relaxation factor, which is 1.5 in the present case

$\frac{\partial P}{\partial n}$ = pressure gradient normal to the wall. For a vertical wall

$\frac{\partial P}{\partial n} = \frac{\partial P}{\partial y}$, but over the curved portion $\frac{\partial P}{\partial n} = \frac{\partial P}{\partial y} \sqrt{1+\beta^2}$. The value

of $\frac{\partial P}{\partial n}$ is obtained from

$$\rho \left\{ u \frac{\partial v}{\partial x} + v \frac{\partial u}{\partial y} \right\} = -2 \frac{\partial P}{\partial y} + 2 \left(\frac{\partial u}{\partial y} \frac{\partial v}{\partial y} + \mu \frac{\partial^2 v}{\partial y^2} \right) + \frac{\partial u}{\partial x} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) + \mu \left(\frac{\partial^2 u}{\partial x \partial y} + \frac{\partial^2 v}{\partial x^2} \right)$$

This gives

$$\frac{\partial P}{\partial y} = - \frac{\partial u}{\partial y} \frac{\partial^2 \psi}{\partial x \partial y} + \frac{1}{2} \frac{\partial u}{\partial x} \left(\frac{\partial^2 \psi}{\partial y^2} - \frac{\partial^2 \psi}{\partial x^2} \right) + \frac{\rho}{2} \left(\frac{\partial \psi}{\partial y} \frac{\partial^2 \psi}{\partial x^2} - \frac{\partial \psi}{\partial x} \frac{\partial^2 \psi}{\partial x \partial y} \right)$$

Similarly, for the top plate $\frac{\partial P}{\partial n} = \frac{\partial P}{\partial x}$, and

$$\frac{\partial P}{\partial x} = \frac{\partial u}{\partial x} \frac{\partial^2 \psi}{\partial x \partial y} + \frac{1}{2} \frac{\partial u}{\partial y} \left(\frac{\partial^2 \psi}{\partial y^2} - \frac{\partial^2 \psi}{\partial x^2} \right) + \frac{\rho}{2} \left(\frac{\partial \psi}{\partial x} \frac{\partial^2 \psi}{\partial y^2} - \frac{\partial \psi}{\partial y} \frac{\partial^2 \psi}{\partial x \partial y} \right)$$

A second change that was made to the code was the addition of a plate located 1.5 inches above the nozzle exit. This corresponds to the actual experimental conditions. The code was initially made operational without the top plate, but now is operational with the above two additions. The addition of a top plate required modification of the grid system employed. Currently a grid size of 27x36 is being used. This being the maximum size permitted by the storage in the computer system employed (PDP-11). The present grid system has closely spaced grids both near the wall and the top plate.

During the last quarter efforts were made to check the sensitivity of the code to the boundary conditions and the constants employed in the turbulence equations and the wall functions. The value of the constants as given by M.A. Serag-Eldin and D.B. Spalding in their paper "Computation of Three-Dimensional Gas-Turbine Combustion Chamber Flows" are $C_\mu = 0.09$, $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_k = 1.0$, $\sigma_\epsilon = 1.3$, $\kappa = .40$ and $E = 9.0$. However these values gave results that were contrary to those expected for a swirling flow in an expanding nozzle. The constants now being employed are $C_\mu = 0.09$, $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_k = 1.0$, $\sigma_\epsilon = 1.21$, $\kappa = .4187$ and $E = 9.793$. These constants are given by David G. Lilley in his paper "Primitive Pressure-Velocity Code for the Computation of Strongly Swirling Flows", and used in the code COSMIC (1). These constants gave the expected results for a swirl number of 1.0 (Fig. 1), but did not give the expected results for a swirl number of 2.0 (Fig. 2). The value of the constants C_μ , C_1 , C_2 and σ_k will remain the same as above, but the values for σ_ϵ , κ and E will be completely determined after experimental verifications. The experimental facility was made operational towards the middle of January, 1980, and so many tests could not be run. The tests that were run were at an inlet axial velocity of 7-12 m/sec, which is considerably below the value of 40 m/sec used in the calculations done by the code. The following is a description of some of the predicted results generated by the code. All of these runs were made for an input axial velocity of 40 m/sec.

- (1) A run was made using the constants of Dr. Lilley together with a stream function value of 0.0 at the wall and 1.0 along the center-line and the top plate. This run predicted a re-circulation zone for a swirl number of 1.0, Fig. 1, but no re-circulation for the swirl number of 2.0, Fig. 2. It is felt that the axial velocity is so high that it prevents re-circulation from occurring at the swirl number of 2.0. This will be experimentally checked.
- (2) A run was made using the constants of Dr. Spalding together with a stream function value of 0.0 at the wall and 1.0 along the top plate and the center-line. This run did not predict any re-circulation for either swirl number of 1.0 or 2.0. This is contrary to the expectations for this type of flow.

- (3) A run was made using the constants of Dr. Lilley and determining the value of the stream function at the center-line from

$$\psi_c = \psi_{wall} + UVEL \times RAD$$

where ψ_c is the center-line value for the stream-function, ψ_{wall} is the wall value of the stream function. UVEL is the axial inlet velocity and RAD is the inlet radius (5" is this case). This same value of stream function is used at the top plate. The predicted results did not show any re-circulation for either swirl number of 1.0 or 2.0

- (4) A run was made using the constants of Dr. Spalding and the stream function boundary values given for case 3. The solution diverged instead of converging.
- (5) A run was made using the constants of Dr. Lilley, but changing the value of σ to 1.25. The boundary conditions were the same as for case 1, but no re-circulation was predicted for either a swirl number of 1 or 2.
- (6) It was felt that the value of the stream function along the center-line should vary to depict the increasing radius of the nozzle. A run was made where the value of the stream function along the center-line was calculated from

$$\psi_c = \psi_{wall} + UVEL \times RADIUS$$

where RADIUS is the local value of the radius at the various grid nodes. The top plate had a fixed value of stream function corresponding to the expected velocity at the outlet. The constants employed during the run were those of Dr. Lilley^{2,3} but the predicted results showed no re-circulation for a swirl number of 1 or 2.

Various other runs were made, but the above show the significant trends.

It also became obvious that the final setting of the value for the constants will be done once more experimental data is available.

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Figure 1. Stream Function Map for a Swirl Number of 1.0 with an Axial Inlet Velocity of 40.0 m/sec.

Figure 2. Stream Function Map for a Swirl Number of 2.0 with an Axial Inlet Velocity of 40.0 m/sec.

IV. CONCLUSIONS

TASK 1, ARCING PHENOMENA IN MHD GENERATORS

Calculations relating to the laminated electrode configuration designed to alleviate insulator initiated breakdown have shown the need for designing the inter-electrode region with consideration of the increased heat-flux due to local regions of high Joule heating. Boron-nitride was chosen for the crucial insulator in the design as it has significant advantages over alumina or MgO.

Measurements and simple, semi-empirical models of simulated slag flow indicate that the ripples are responsible for a majority of mass transport. The results show that surface tension and form drag over the ripples are of significant importance. Non-dimensional correlations of ripple speed, height, separation and width are presented and can be used to estimate these values for MHD conditions. These correlations are obtained for the appropriate range of dimensionless parameters, although only preliminary data with transverse viscosity gradients is included.

TASK 2, OPEN CYCLE DISK GENERATOR PROGRAM

A data base has been established for well-characterized thermal and velocity wake nonuniformities; strong variations of the plasma properties were created (with cold blades) in the direction normal to the magnetic field and the flow. The quantitative data clearly indicate the monotonic degradation of generator performance for this type of nonuniformity (and orientation) with increasing Hall parameter and number of wakes (rms). A preliminary examination of the results provides strong support for the validity of both the two-dimensional theoretical model of Dvornik, et al, and the use of simplified layered models for certain limiting conditions.

TASK 3, ELECTRODE MODULE DEVELOPMENT AND TESTING

Part A.

No conclusions were reached under Task 3, Part A. during this quarter.

Part B.

The MHD Test Facility Complex

A breakdown of the oil-free compressor has delayed progress of the test program.

TASK 4a, COAL COMBUSTION STUDIES

A program for analyzing solid pyrolysis and combustion products has been organized. The overall approach is to study physical and chemical changes simultaneously. The applicability of many experimental techniques has been assessed; the most promising methods are IR, NMR, and TEM. Preliminary attempts to examine the internal pore structure of Montana lignite coal using TEM show encouraging results. (Pore structure greater than 50 Å was resolved.) A parametric study is needed to determine the optimal method for sample preparation.

Experimental results from ash vaporization studies indicate that vaporization is enhanced in a carbon matrix (as compared to free ash). This phenomenon is attributed to reducing reactions and is consistent with thermodynamic predictions.

The coal combustor computer model has been modified to include: 1) allowance for a distribution of particle sizes; 2) calculation of ash vaporization as a function of particle temperature; and 3) better and faster convergence schemes. New results indicate that previous results were conservative--i.e., the old model predicted excessive burnout times and ash vaporization. The differences are attributed to the endothermicity of CO_2 and H_2O reactions with the char. Results from the updated model will be presented in a paper at the Seventh International MHD Symposium.

TASK 4b, COMBUSTION AERODYNAMICS AND FLUID MECHANICS OF HIGH-SWIRL SECOND

STAGE

It is apparent that the constants given by Dr. Lilley ($\sigma_g = 1.21$, $\kappa = .4187$, $E = 9.793$) give the expected results and are employed in the code. However, we see that any variations in these constants have a significant affect on the result, and so the final values will be determined after more experimental data is available. Another direction being taken is the development of the code using an orthogonal grid system. This grid system will enable us to place a large number of grid points adjacent to the wall and the top plate, thereby increasing the accuracy of the predicted results.