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DISCLAIMER

EXPERIMENTAL INVESTIGATION OF 3-D MHD FLOWS AT HIGH HARTMANN NUMBER AND INTERACTION PARAMETERS*

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ABSTRACT. Experimental investigations of 3-D MHD flows in uniform thin conducting wall ducts of circular and square cross section, conducted at Argonne National Laboratory's ALEX facility, are reported. The three-dimensional nature of the flow arises from the spacial variation of the applied transverse magnetic field. Measurements were performed at several Hartmann numbers, M, and interaction parameters, N, with the peak value for M exceeding 6×10^3 and the peak value for N exceeding 10^5. Typical results and their comparison to numerical analysis reported in a companion paper are given, as is a brief description of the ALEX facility and the experimental methods employed. Ongoing activities and plans for future experiments are also discussed.

1. INTRODUCTION

In 1984, the Blanket Comparison and Selection Study (BCSS) [1], an activity that spanned two years and involved the entire fusion technology community of the United States, reached the conclusion that liquid metal cooled blankets represent one of the most attractive design options for tokamak power reactors. In addition, the BCSS identified liquid metal MHD as a feasibility issue for such blankets. This is because, at least for the reactor parameters and the proposed blanket design of the BCSS, uncertainties in the MHD analysis threatened the viability of liquid metal cooled blankets. The uncertainties were brought about by the limited capability for analyzing MHD flows for blanket relevant geometries coupled with a complete lack of detailed experimental data that could be used to support a thermal hydraulic analysis of the blanket.

Given the promise of liquid metal cooled blankets, a liquid metal MHD program was established at Argonne National Laboratory (ANL) for the purpose of developing the analytical tools and providing the experimental data necessary for tokamak blanket design and development. A summary of the analytical work carried out within ANL's MHD program is

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given in a companion paper [2]. Detailed description of the ALEX (Argonne Liquid Metal Experiment) facility, specifically designed and built to accomplish the experimental goals of the program, and some experimental results have been presented previously [3], [4], [5], [6].

In the following, the specific goals of our experimental program are reiterated, the capabilities of the ALEX facility and the associated instrumentation system are summarized, the experimental methods used in our investigations are discussed, and representative results from the first two test series are presented. Finally, both ongoing investigations and plans for future experiments are discussed.

2. TEST OBJECTIVES AND THE ALEX FACILITY

The goals of the experimental investigations carried out at ALEX are (a) to provide data of sufficient breadth, resolution, and accuracy for validation of analytical tools and establishing the region of their applicability, and (b) to provide empirical correlations of parameters of engineering importance for these cases which may prove to defy analysis as a result of their geometric complexity or the presence of unusual or unanticipated flow phenomena (e.g., flow instability).

If these goals are to be meaningfully satisifed, both theoretical and experimental investigations should be carried out as close to the prevailing blanket conditions as possible. For ducts in lithium-cooled tokamak blankets, the Hartmann number, M, and interaction parameter, N, are $O(10^3)$-$O(10^5)$ depending on the size of the duct, its orientation with respect to the toroidal magnetic flux density, and the required coolant velocity. It is important to note that, if attention is confined only to first wall coolant channels where the surface heat flux and the high volumetric heat flux deposition make detailed knowledge of the flow structure all the more important, the range of relevant M and N will only extend from $O(10^3)$ to $O(10^4)$. The practical implication of this is that heat transfer experiments involving surface heat fluxes need only cover this smaller range. Single duct isothermal experiments in this range have already been carried out at ALEX.

An additional parameter of paramount importance to the MHD flows under consideration is the wall conductance ratio $c = \sigma_w t_w/\sigma L$, where σ_w, σ are the electrical conductivities of the wall and the liquid metal, and t_w and L are the wall thickness and the characteristic transverse dimension of the duct. For blanket ducts, $c = O(10^{-1})$-$O(10^{-2})$. Also, insulating wall ducts remain a possible option for blanket design and as such need to be investigated. Achieving prototypic values for the wall conductance ratio or using insulating wall ducts in the ALEX experiments is straightforward.

The working fluid for ALEX is the 22Na78K eutectic alloy of sodium and potassium. Not only does it have room temperature properties relevant to MHD thermal hydraulics which are reasonably close to those of lithium at 500°C, but more importantly, it allows testing at room temperature which is essential for detailed local velocity measurements. Such measurements of the flow structure are most important because 3-D

MHD flows at high interaction parameters exhibit unconventional velocity profiles which have a profound effect on heat transfer.

During testing, a variety of flow rates and magnetic flux densities is employed. The NaK working fluid is circulated at flow rates continuously adjustable from 4 to more than 400 liters per minute. The available pressure drop through the test section at 40 ℓ/min is 0.7 MPa. The test articles are located within the highly uniform dipole field of a 2 T conventional electromagnet. The gap between the 0.76 m x 1.83 m pole faces is 20.3 cm. The generous dimension of 0.76 m in the direction transverse to main flow direction allows the use of probe traversing mechanisms and heaters for heat flux experiments simulating first wall heating. The design of the magnet allows the future use of pole face inserts to achieve a variety of magnetic field distributions. The magnet can be moved along the axis of the test article by ±1.22 m from its center position at predetermined constant velocities. This capability not only facilitates servicing of the test section and mounting instrumentation on it but also allows a single instrument to gather data corresponding to any location along the magnet's fringing field.

Although all the tests were conducted at room temperature, the capability of operating the loop at 300°C for a period of several hours to condition the stainless steel test articles after their installation has been proven indispensable. The high temperature operation eliminates the interfacial electrical resistance by reducing the chromium oxide at the inner surfaces. Our experience indicates that errors in excess of 50% can result from lack of such a conditioning.

3. EXPERIMENTAL METHODS

For both the round and square ducts the following measurements were made:

(a) Circumferential distribution of wall potential as function of X/L (X is measured from the edge of the magnet pole face with positive X directed away from the magnet). These measurements are of great diagnostic value because, for the flows under investigation, voltages are essentially constant along magnetic field lines. Hence, wall voltage distributions are translated into voltage distributions in the fluid.

(b) Axial pressure gradient as function of X/L. This is a parameter of engineering importance in that, when integrated along the duct, it provides the overall MHD pressure drop.

(c) Transverse pressure difference as function of X/L. This is the pressure difference developed between the centerline of the duct and the wall in the direction perpendicular to both the magnetic field and the flow. It is the result of axial currents in the fluid driven by 3-D MHD effects. As such, this parameter is a sensitive measure of 3-D effects and its comparison with theoretical predictions is used to ascertain the capability of the latter to model such effects.

(d) Axial velocity at selected transverse locations as a function of X/L. This measurement is made by setting the velocity probe at a fixed transverse location and gathering data while moving the magnet.

(c) Transverse velocity profiles at selected Z/L locations. This measurement is made by traversing the velocity measuring probe across the duct while the magnet is stationary.

Measurement of wall voltages is made by stationary electrodes welded on the wall surface or movable spring-loaded electrodes pressed against the wall surface. Measurement of pressures is made with a system of pressure lines, manifolds, and valves using a single pressure transducer. Measurement of velocity is accomplished with a LEVI (Liquid-metal Electromagnetic Velocimeter Instrument) probe. The probe consists of two electrodes whose separation distance of about 1.5 mm is perpendicular to the magnetic field. It is based on a direct application of Ohm's law in moving media and provides accurate measurement of velocity when the current density is much smaller than its short-circuit value. This, of course, is precisely the case for the high Hartmann number flows in thin conducting or insulating wall ducts which are the object of our investigations. The LEVI has proven to be an extremely valuable instrument. It requires no calibration, it is very easy to use, and it has a very fast time response limited only by the response of the voltage measuring instrumentation. Its spacial resolution is determined by the electrode tip separation (1.5 mm in our case). Its output is proportional to the velocity component normal to the distance between the electrode tips averaged over that distance.

4. RESULTS AND DISCUSSION

The computer-driven data acquisition system, and the capability of automated data collection tied to continuous movement of the magnet relative to the instrumented locations of the test article, have been used to collect extensive data at a variety of M and N. Approximately, the range for M extends from 3×10^3 to 6×10^3 for both ducts, whereas the range for N extends from 6×10^2 to 10^4 for the round duct, and 5.5×10^2 to 1.3×10^5 for the square duct. Comprehensive reporting of the results will be given elsewhere. Here, only a small sample of the results is given to provide a demonstration of the variety of data gathered at ALEX and a measure of their quality and resolution.

Figure 1 presents data on the axial pressure gradient along the round duct in the region of the fringing transverse magnetic field. A theoretical prediction for the measured quantity, provided by a fully 3-D numerical solution implemented at ANL [2], is also shown. The numerical solution is based on the equations governing inertialess and inviscid MHD flow ($M, N \to \infty$). The only other assumption made is that $t_w \ll L$, so that the electric potential gradient normal to the surface is negligible in the duct wall. The solution contains no adjustable constants. The only input is the distribution of the measured transverse magnetic field, the wall conductance ratio, and the appropriate upstream and downstream boundary conditions (fully developed flow boundary conditions in this case).

Figure 2 presents data on the transverse pressure difference for the square duct. Agreement between analysis and experiment is as exceptional as it was in Fig. 1. It should be pointed out that, in the

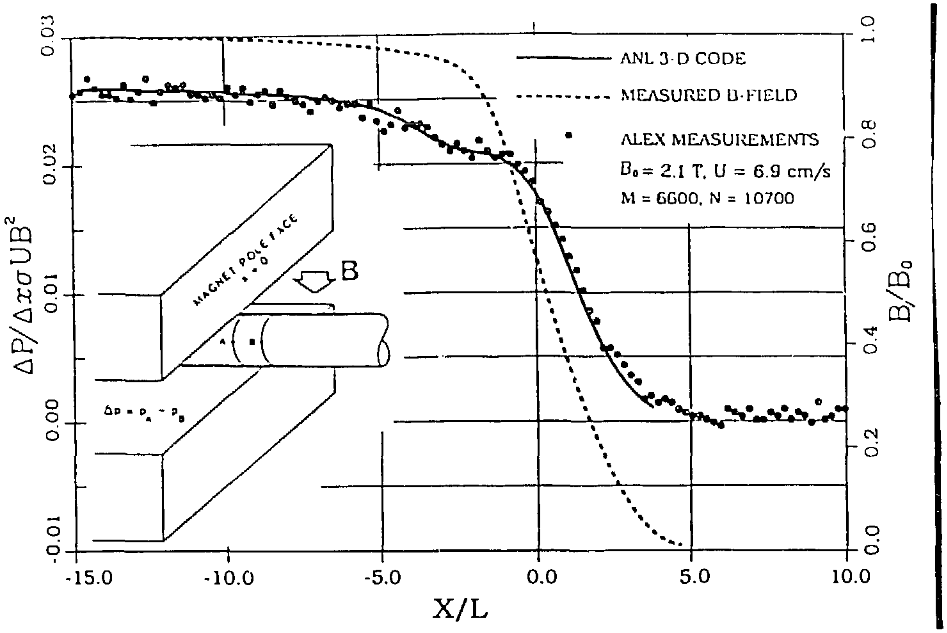

Figure 1. Analysis and experiment for the axial pressure gradient in the the fringing magnetic field. Round duct with c = 0.027, L = 5.4 cm.

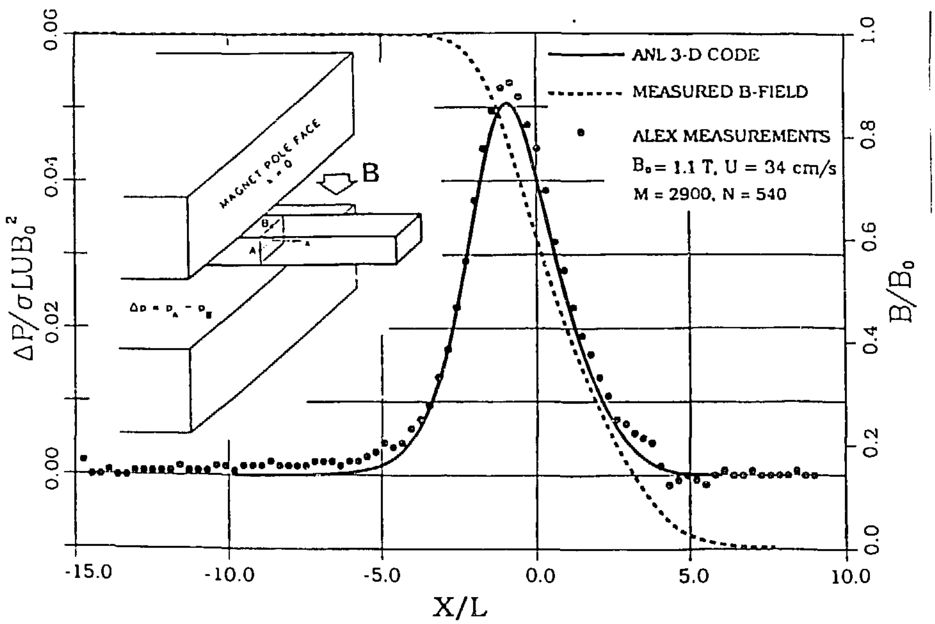

Figure 2. Analysis and experiment for the transverse pressure difference in the fringing magnetic field. Square duct with c = 0.07, L = 4.8 cm.

fringing field region, axial currents flowing in the walls interact with the transverse magnetic field to cause a pressure difference along the column of liquid metal filling the holes drilled in the wall at the pressure measurement locations. This pressure difference, which depends on the wall thickness, the magnitude of the axial currents, and the location of the holes, modifies the fluid pressure measurement. This effect has been taken into account in the analysis shown in Figs. 1 and 2. Moreover, the theoretical prediction for the pressure gradient accounts for the fact that the experimental pressure gradient is derived as a pressure difference over a finite axial distance of 15.2 cm.

Figure 3 shows a transverse velocity profile for the round duct in the fringing field region. Agreement between analysis and experiment is again outstanding. It is evident that the inertialess inviscid approximation is valid for MHD flows at sufficiently high M and N. The lower limits of M and N for which this approximation is valid will depend on the particular situation, so a general statement cannot be made. Nonetheless, our results indicate that for M and N exceeding 10^3, as they would in most circumstances relevant to fusion blankets, any inertial or viscous effects are likely to be localized.

During our square duct experiments, a laminar instability in the neighborhood of the sidewalls was observed. The presence of the high-velocity jets present in the sidelayers and the associated high velocity gradients are evidently the source of this instability. Full characterization of the instability, and a thorough study of the dependence of its onset on the interaction parameter, Hartmann number, and duct

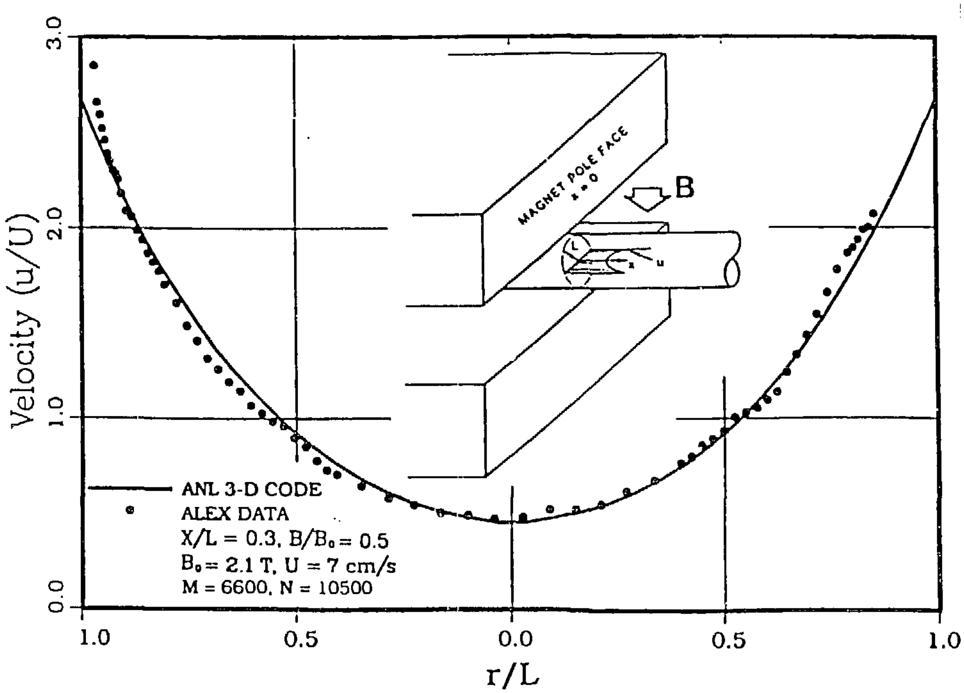

Figure 3. Analysis and experiment for the transverse velocity profile in the fringing magnetic field. Round duct with c = 0.027, L = 5.4 cm.

geometry is an ongoing activity at ALEX. Although the presence of this instability will enhance heat transfer and is therefore desirable, the question about its existence under blanket relevant conditions can only be settled through such thorough study.

Currently, a joint ANL/KfK (Kernforschungszentrum Karlsruhe) activity on proof of principle testing of MHD flow tailoring is being carried out at ALEX. Flow tailoring offers the promise of increased thermal hydraulic performance of the blanket by enhancing desirable features of MHD flows. In the concept under investigation, 3-D MHD flows with high velocities near the sidewalls are created in a uniform magnetic field by variation of the duct geometry (expansions and contractions). Preliminary results support the validity of the concept and are in good agreement with ANL's 3-D MHD code predictions [6].

Following completion of the flow tailoring experiments, extensive investigations of heat transfer in MHD flows in rectangular ducts will be undertaken. In these investigations, uniform heat flux will be applied on a wall parallel to the magnetic field to simulate heating of the first wall in a fusion reactor. ANL's MHD thermal hydraulic code [2] is being used in the detailed design of the test article and its instrumentation. An important objective of the investigations is to gather data on the effect of sidewall instability on heat transfer near fusion reactor relevant conditions.

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