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EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS OF
MAGNETOHYDRODYNAMIC FLOWS NEAR THE ENTRANCE TO A STRONG MAGNETIC FIELD*

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ABSTRACT

An experimental program on liquid metal MHD phenomena relevant to blanket engineering is being carried out at ANL's ALEX facility. The experiments carried out at the facility are aimed towards detailed measurements of 3-D MHD flow characteristics to enlarge the existing data base and to provide validation of existing analytical approaches. Results of the first series of experiments, dealing with three dimensional MHD effects in a circular thin conducting wall duct in the fringing field of a strong transverse magnetic field, are reported. Comparison of the experimental data with the predictions of pretest analysis both supports the basic premises on which the analysis is based and suggests possible improvements.

INTRODUCTION

Magnetohydrodynamic (MHD) effects have been shown to present major feasibility issues for self-cooled liquid metal blankets of magnetically confined fusion reactors.¹ These issues cannot be resolved and the design of liquid-metal-cooled blankets cannot proceed beyond the conceptual stage before the state-of-the-art of MHD analysis is advanced and data on MHD flows at conditions approaching those prevailing in fusion reactor blankets are obtained.

In order to address this need, a program of analytical and experimental investigations in MHD flows has been established at Argonne National Laboratory within the framework of the

Blanket Technology Program. An experimental facility for such investigations has been built and is being operated at Argonne National Laboratory.² The investigations carried out on the Argonne Liquid Metal Experiment (ALEX) are complemented by analysis carried out at the University of Illinois.

The first phase of the experimental program is devoted to investigations of well defined cases for which analytical solutions exist. Such testing will allow validation and increased confidence in the theory. Because analytical solutions exist for only a few cases, which do not cover the entire range of anticipated flow behavior, confining testing to these cases will not be an adequate validation of the theory. For this reason, this phase involves testing and a companion analytical effort aimed towards a broad range of cases, which, although simple in geometry, are believed to encompass the range of flow phenomena relevant to fusion. This parallel approach is necessary so that analysis will guide and help plan the experiments, whereas the experimental results will provide information needed to validate and/or refine the analysis.

The first case investigated according to this philosophy involves the flow structure inside a circular duct near the entrance to or the exit from a strong transverse magnetic field. This case was chosen to be the first because the magnetic flux density profiles required for such an investigation exist naturally at the ends of the ALEX electromagnet and no special pole face inserts are required. This case is not without relevance, as the inlet and outlet coolant ducts of both Tokamak and Tandem Mirror Devices are subjected to such specially varying magnetic fields.

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Because the existing analytical solution dealing with an abrupt transition between two large values of magnetic flux density³ was not applicable to the gradual decay to a zero value existing in a fringing field, a new solution pertinent to the latter case was developed.⁴ The solution was carried out for the parameters of the experimental test section so that direct comparison between theory and experiment could be made.

The peak Hartmann number, $M = aB\sqrt{\sigma/\mu}$, and interaction parameter, $N = aB^2\sigma/\rho U$, for which experiments are reported here were 6.4×10^3 and 10^4 , respectively. Here, B is the magnetic flux density, " a " is the duct radius, U is the average velocity, and σ , μ and ρ are the fluid's electrical conductivity, viscosity and density. These values are not only more than an order of magnitude higher than the values attained so far for similar local flow structure measurements, but they are close to and in some cases overlap with the values prevailing in a fusion reactor blanket. Measurements were also obtained for other combinations of M and N values to explore the possibility of different behavior and establish the limitations of the analysis.

THEORETICAL CONSIDERATIONS

The uniform motion of a liquid metal in a circular duct through a magnetic field induces a transverse electromotive force proportional to the magnetic flux density. If the magnetic flux density changes along the duct the electromotive force will also change. This sets up axial potential differences which drive currents in the axial direction. These currents result in electromagnetic body forces which force the fluid out of the core of the flow and into high velocity flow regions near the walls tangent to B . The flow redistribution is accompanied by a pressure drop higher than it would have been had the flow remained undisturbed.

The solution of such a 3-D MHD problem which requires, in general, the solution of the equations of motion, coupled with Maxwell's equations and Ohm's law, becomes somewhat tractable when M and N are large and the magnetic Reynolds number is much smaller than one. This, which happens to be the case for all problems related to blanket engineering, makes inertia forces negligible, confines the effect of viscous forces in very thin boundary layers, and assures that the induced magnetic field is negligible. It can be shown that, outside the very thin boundary layers, the pressure, voltage, and velocity are virtually constant along magnetic field lines. Even so, further assumptions must be made to be able to obtain approximate analytic solutions. The solution developed for the conditions of the experiments is such an approximate solution.

The analysis⁴ assumes that the decay of

the magnetic field far beyond the end of the magnet is inversely proportional to the distance from the end of the pole face, x , and treats the flow in the side layers in this decaying field. The thickness of the side layers turns out to be comparable to $ac^{1/3}$ where " a " is the duct radius and $c = t_w\sigma_w/\sigma a$ is the wall conductance ratio (t_w and σ_w are the thickness and electrical conductivity of the duct wall). The results of the analysis indicate that as x is increased, the flow in the side layer is accelerating (and that in the centerline is decelerating) reaches a maximum at an x at which the local B field has decayed to one-half of its peak value, B_0 , and then decelerates as the flow in the entire cross section tends to a uniform flow outside the magnetic field.

In addition, the analysis provides a solution for the region just upstream of the fringing field region, where the circulating currents disturb the fully developed flow. The solutions in the two regions are appropriately matched. In the matching region, neither solution is valid and the analysis is not meant to provide any detailed information there. Nevertheless, the following picture of the disturbed flow emerges. At the duct centerline, ahead of the point where the magnetic field changes appreciably, the velocity rises slightly from its fully developed flow value, U_0 . It then drops to $0.3 U_0$ at $B/B_0 = 0.5$ and gradually recovers towards U_0 away from the magnet. The same behavior is exhibited for all distances from the vertical diameter up to about $0.6a$. As one moves from 0 to $0.6a$, the rises and drops become less pronounced. From $0.6a$ to $1.0a$ the picture is reversed. The flow velocity first drops ahead of the fringing field region, and then accelerates as flow is pushed towards the side layers. For $r = 0.9a$, the peak velocity occurs at $B/B_0 = 0.5$ and has a value of three times the average velocity. Following this maximum, the velocity drops gradually toward U_0 .

The analysis also provides predictions for the axial and transverse pressure gradients and the axial and transverse voltage distributions. The solutions are valid in the aforementioned two regions and their extrapolation into the matching region, where the magnetic field gradients are steep, is not expected to be valid. Despite this shortcoming, the solutions do indicate the overall trend that the data should follow over the entire range of interest.

DESCRIPTION OF THE EXPERIMENTS

The facility, described in detail elsewhere,² delivers a steady flow of isothermal NaK to the test section, shown in Figure 1. The flow rate, Q , and the magnetic flux density, B , were varied independently to provide the four test conditions shown in Table 1. The test section's internal diameters of 11 cm and wall thickness of 0.32 cm yield a wall conductance ratio, c , of 0.027.

Figure 1. Schematic of circular test section.

Table 1. Test Matrix

	Q = 10 gpm	Q = 40 gpm
M	$M = 6.4 \times 10^3$	$M = 6.4 \times 10^3$
N	$N = 10^4$	$N = 2.5 \times 10^3$
Re _D	$Re_D = 8.2 \times 10^3^*$	$Re_D = 3.3 \times 10^4^*$
U _{avg}	$U_{avg} = 7 \text{ cm/s}$	$U_{avg} = 28 \text{ cm/s}$
M	$M = 3.2 \times 10^3$	$M = 3.2 \times 10^3$
N	$N = 2.5 \times 10^3$	$N = 6.2 \times 10^2$
Re _D	$Re_D = 8.2 \times 10^3^*$	$Re_D = 3.3 \times 10^4^*$
U _{avg}	$U_{avg} = 7 \text{ cm/s}$	$U_{avg} = 28 \text{ cm/s}$

*Whereas M and N are based, as is customary, on the duct radius, the Reynolds number, Re_D , given here is based on the duct diameter.

Measurements were carried out in the three instrumented axial location of the test section. At each location, there is a flange for introducing traversing probes into the flow cross section, pressure taps, and voltage probes. At present, the traversing probes that are used are velocity measuring instruments and traverse along the diameter normal to the B field. The probes are capable of providing both the average and the fluctuating components of the axial velocity.⁵ There are four pressure taps at each station. Three of the taps, separated by 7.6 cm, are located along the generatrix which lies on the horizontal mid plane of the duct. They are used to measure axial pressure differences. The pressure gradient is calculated as p/x where x is either 7.6 cm or 15.2 cm. There is a trade-off between experimental error in measurement of p and error in approximating the local gradient by p/x . The fourth tap is located at 90° from one of the three taps and is used to measure the transverse pressure differences. This pressure difference is zero in fully developed flow and arises as a result of 3-D MHD effects near the fringing fields. The voltage probes are wires welded at 15° intervals on the upper half of the duct circumference.

The three instrumented stations, in conjunction with the capability of the magnet to move axially by 245 cm, allow gathering of complete sets of data at any location between 1 m upstream of the upstream edge of the magnet

pole face to 1 m downstream of the downstream edge (a span of 3.8 m). During the course of a test, the magnet is set to a slow rate of advance and data is logged automatically at predetermined axial intervals (usually 1.25 cm). The one exception is the gathering of velocity profile data, during which the magnet is stationary and a probe is advanced radially by the probe traversing mechanism.

The data is plotted by computer software in the following forms: a) Transverse voltage profiles. These are wall voltages vs distance from the vertical diameter of the duct. These voltage profiles are linear in fully developed flow and are, therefore, a good indicator of the existence of 3-D MHD effects. b) Axial voltage profiles. These are transverse voltage differences (usually over a radius) plotted against the axial position. If the flow is quasi-fully developed, these profiles follow the profile of the transverse magnetic field. c) Axial velocity profiles. These are axial velocities at fixed radial locations plotted against axial position. Any variation of the magnitude of the velocity with axial position indicates 3-D disturbances. d) Axial profiles of pressure gradient. In fully developed flow, the pressure gradient is proportional to the square of the magnetic flux density. When 3-D effects are present, the value of the constant of proportionality changes. e) Axial profiles of transverse pressure differences. As indicated earlier, a non-zero value indicates 3-D MHD flow effects. f) Transverse velocity profiles. The axial profiles are plotted against the distance from the edge of the magnet pole face, with the positive direction pointing away from the magnet. This is done for both the magnet inlet and exit. Significant deviations between the two locations would indicate the existence of inertial effects.

RESULTS AND DISCUSSION

All data indicate that fully developed flow conditions are established in the magnet within 0.35 m from the edge of the pole face, in good agreement with the analytical prediction of 0.25 m. Given the fact that the magnetic field reaches 95% of its constant value at a distance of 0.2 m, it follows that the "entrance" length is effectively 0.15 m, or just three times the pipe radius.

Figure 2 shows transverse voltage profiles for the inlet region to the magnet. The curves are identified by the value of the magnetic flux density at the axial location corresponding to the curve. The curves at $B = 2.088 \text{ T}$ were taken at the magnet center and show the linear distribution characteristic of fully developed flow. As expected, the curves become S-shaped in the fringing field. As the slope of these curves is proportional to the local axial velocity, the fact that these curves become more S-shaped with decreasing B indicates that the core of the flow gets progressively

slower and the wall jets faster. Comparison of the curves in Figure 2 with curves taken at the magnet exit reveals small but well defined differences corresponding to higher core flow at the exit. Such differences between inlet and outlet are attributed to inertia effects. Inertia is expected to become a factor as the local field and the local interaction parameter decrease. The differences between inlet and outlet are more pronounced in the transverse voltage plots than in any of the other plots indicating that they are a particularly sensitive indicator of inlet/outlet asymmetries.

Figure 2. Transverse voltage distribution at the magnet center and inlet region.

Figure 3 shows a plot of the voltage difference between the 12:00 o'clock and the 3:00 o'clock voltage probes with axial position superimposed on the magnetic field distribution. The corresponding curve for the inlet is virtually identical, except that the decay to zero is slightly steeper. It is evident from this curve that uniform conditions are indeed established within 0.35 m from the magnet pole face.

Figures 4 through 6 present axial profiles of velocity at $r/a = 0.0, 0.7$, and 0.9 . The curve for $r/a = 0.0$, shown in Figure 4, shows the early rise, drop, and recovery predicted by the analysis. Comparison of this curve with a similar one taken at the exit reveals that the two curves are virtually identical except that the plateau at about $x = 0$ is slightly higher at the exit. This indicates a slightly higher core velocity at the exit near 1 T, which is exactly what the detailed profiles, shown in Figure 7, reveal. The curve at $r/a = 0.7$, shown in Figure 5, shows the different character of early drop and subsequent overshoot predicted by the analysis. The corresponding curve at the exit, not shown here, is virtually identical, except that, instead of starting to drop towards the end, it continues increasing beyond 0.15 m/s.

Figure 3. Radial voltage difference as a function of axial position at the exit from the magnet. The solid dots are the corresponding transverse magnetic flux densities.

Figure 4. Axial velocity at centerline as a function of position at the inlet to the magnet. The solid dots are the corresponding transverse magnetic flux densities.

Figure 5. Axial velocity at $r/a = 0.7$ as a function of position at the inlet to the magnet. The solid dots are the corresponding transverse magnetic flux densities.

Figure 6. Axial velocity at $r/a = 0.9$ as a function of position at the inlet to the magnet. The solid dots are the corresponding transverse magnetic flux densities.

It should be noted here that the last few points of all these curves are subject to a large experimental error because the signal output of the velocity measuring probe, which is proportional to the local field, becomes very low. Figure 6 shows the axial profile of the velocity at $r/a = 0.9$. The figure also shows the analytical prediction. Note that the curves for the analysis are not joined because they are not supposed to be valid in the matching region. Comparison on analysis with experiment shows complete qualitative agreement. Analysis shows an earlier and weaker velocity peak but this is to be expected because the assumed variation in the decaying field of $1/x$ gives steeper field gradients for small x than the actual ones. Again curves for the inlet and outlet at $r/a = 0.9$ show virtual coincidence, the only difference being the further increase in velocity beyond 0.3 m/s for the outlet. The same observation can be made for curves taken at other radial locations as well as for curves taken at $M = 3,200$ and $N = 2,500$.

Figure 7 shows comparison of transverse velocity profiles taken at the inlet and outlet and the same value of the fringing magnetic field. Deviation between inlet and outlet is slight but consistent. The analytical prediction superimposed on the data shows excellent qualitative agreement. The analysis, as shown in Figure 6, predicts an earlier peak in wall jet velocity, than was actually measured. Had data been taken at a lower value of $B/B_0 = 0.5$, the comparison would have been much better.

Figure 8 shows comparison of the measured transverse pressure difference with the analytical prediction. Again, as with the axial velocity profiles and for the same reason, the analysis predicts an earlier peak. Also, the

peak appears to occur in the matching region which is not covered by the analysis. Notwithstanding these limitations, the agreement between analysis and experiment is satisfactory.

Figure 7. Transverse velocity profiles at the inlet and exit position corresponding to $B/B_0 = 0.5$. Comparison of analysis and experiment. $M = 6,500$, $N = 10,500$, $U_{avg} = 7.0$ cm/s.

Figure 8. Transverse pressure difference at the inlet to the magnet. Comparison of analysis and experiment. The solid dots are the corresponding transverse magnetic flux densities.

Finally, Figure 9 presents the measured distribution of axial pressure gradient. The analysis predicts for this curve a drop to a minimum for small negative x , a subsequent rise to a peak at about $x = 0$, and a gradual decline. The data indicates a similar trend although the peak has degenerated in the data to a plateau. This is to be expected because the measured pressure gradient is an average value over a

distance of 15 cm and the theoretically predicted drop and peak in pressure gradient extend to about 10 cm each. Note that in the fully developed flow region the measured gradient agrees completely with the theoretical value.

Figure 9. Axial pressure gradient at the inlet to the magnet. The solid dots are the corresponding transverse magnetic flux densities.

CONCLUSIONS

The experimental results give support to the fact that a facility such as ALEX can provide reliable data at M and N values relevant to blanket engineering. The results of the experiments are found in complete qualitative agreement with pretest analysis. It is important to note that no effort has been made to adjust the analysis to improve agreement. It is evident that the physical model on which the analysis is based is valid. Deviations between analysis and experiment are attributed to the approximate representation of the magnetic field used in the analysis in the region of the initial field decay. Plans to extend the analysis to provide solutions for the entire range of a fringing field without resorting to asymptotically valid representations have already been made.

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