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TECHNIQUES FOR MEASUREMENT OF VELOCITY IN LIQUID-METAL MHD FLOWS^a

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ABSTRACT

Three instruments for measuring local velocities in liquid-metal MHD experiments for fusion blanket applications are being evaluated. The devices are used in room-temperature NaK experiments to measure three-dimensional flow field patterns anticipated in complex blanket geometries. Hot film anemometry, a standard technique in ordinary fluids, is being used, as well as two developmental devices. One is called the Liquid Metal Electromagnetic Velocity Instrument (LEVI), and performs essentially as a local DC electromagnetic flow meter. The third device, a Thermal Transient Anemometer (TTA) is a rugged, yet relatively simple device, which measures local velocity through the mechanism of convective heat transfer, in some ways similar to hot-film anemometry. Results are presented showing the kinds of data collected thus far with each instrument. Measurements include both local velocity measurements and some preliminary frequency analyses of the fluctuating signals from both a hot-film sensor and the LEVI device.

INTRODUCTION

Recent blanket studies have demonstrated that MHD presents a critical feasibility issue for liquid-metal self-cooled Tokamak blankets.¹ Although successful designs have been developed using available theory and data on liquid metal MHD, a number of uncertainties related to MHD effects remain unresolved.^{1,2} To improve the level of understanding of the details of MHD flows as they apply to magnetically confined fusion blankets, an experimental program is being carried out in a facility at Argonne National Laboratory (ANL). The experimental facility (Argonne's Liquid-Metal Engineering Experiment (ALEX) described in detail elsewhere³) is capable of attaining maximum Hartmann numbers (M) and interaction parameters (N) in the range of 10^3 - 10^4 , which is close to the range of 10^4 - 10^5 that these parameters attain in the reactor blanket.

The experimental program is aimed towards measurement of detailed flow structure characteristics. This is of fundamental importance because existing theories predict, in the cases where 3-D effects become dominant, unconventional velocity profiles with high velocity wall jets and low velocity core regions. Since 3-D effects are virtually unavoidable in the blanket, and because the flow profiles have a strong influence on heat transfer and corrosion rates, data validating existing theories are indispensable to design efforts seeking to either minimize or take advantage of such effects.

Local velocity measurements have been made previously in a number of room temperature liquid-metal MHD experiments. In these experiments mercury has been the working fluid of choice, although one paper⁴ gives very qualitative results in room temperature NaK. Although hot-film anemometry has been used to collect most relevant local velocity data, difficulties associated with operating this instrument in mercury suggest that additional means should be developed for acquiring the necessary local velocity data.

To this end, an instrumentation development program is being carried out at ALEX, in parallel with the baseline experimental program on MHD effects. Three distinct instruments are being used or developed at this time, i.e., the hot-film anemometer (HFA), the liquid-metal electromagnetic velocity instrument (LEVI), and the thermal transient anemometer (TTA). Only HFA has been widely used previously; the other two devices are undergoing significant development work for the first time.

Hot Film Anemometry

Hot film anemometry has been used in similar liquid-metal applications previously, but sensor fouling and calibration stability problems make its use very tedious and time consuming. Nevertheless, previous successes with HFA in room temperature liquid-metal MHD experiments⁵ dictated that its development be pursued in this application. Ordinary, commercially available, hot-film electronic equipment and quartz coated hot-film sensors were used in the

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present investigation. Figure 1 shows a typical cylindrical HFA sensor and probe. A further description of HFA can be found in numerous texts and publications.

Liquid Metal Electromagnetic Velocity Instrument

The LEVI is essentially a miniature local electromagnetic flowmeter; a device that can measure the local component of the velocity, u , normal to an applied magnetic field, by measuring the magnitude of the local voltage gradient. The LEVI used here requires an applied magnetic field and that the local current density, j , be much smaller than σB . Here σ is the fluid's conductivity and B the magnetic flux density of the externally applied field. Fortunately, the latter condition on the magnitude of j is satisfied in virtually all cases of MHD flows in thin-walled and insulating wall ducts. The measured velocity component is related to other measured quantities as follows:

$$u = \frac{\Delta\phi}{d \cdot B}$$

where $\Delta\phi$ is the local voltage difference, and d is the LEVI electrode separation. A sketch of the LEVI geometry used here is shown in Fig. 2. These instruments were fabricated from HFA probes, similar to the one shown in Fig. 1, from which the cylindrical hot film sensor had been removed. The two probe tips were each hand-worked to produce a bare metal tip which comprised the two instrument electrodes. Typical electrode separations were ~ 1.5 mm. Voltages produced by the LEVI were measured with a 12-bit A/D converter system having 2.44 μV resolution.

Thermal Transient Anemometer

The thermal transient anemometer (TTA) is a velocity measurement device that is based on established thermal anemometry principles. However, by applying a pulsed heat input to the sensor, several significant advantages result when compared to conventional

steady state thermal anemometers, perhaps the most important of which is a far simpler and more durable sensor.

The device consists of a sensor located in the flow path of the fluid and externally located support electronics. The sensor is essentially a sheathed thermocouple that is alternately heated and cooled; heated by pulsing an electric current through its hot junction and then convectively cooled by the moving fluid. The cooling rate is measured and then, using a microprocessor algorithm, is correlated to the local flow velocity. A schematic of the TTA system is shown in Fig. 3.

Motivation for development of the TTA in liquid metal flows is primarily based on two functional considerations. First, the TTA probe is easily configured to measure local velocity in a very small flow cross section. This high resolution is advantageous to flow measurements in the ALEX tests where large velocity gradients are encountered. Secondly, the TTA probe has good corrosion resistance in the NaK fluid environment both at ambient temperature as well as at the elevated temperature conditions anticipated for future tests.

INSTRUMENT DESCRIPTIONS AND RESULTS

HFA

Because of its previous widespread use in a number of R&D applications, a detailed description of the theory and operation of HFA will not be given here. The primary questions that arise when considering HFA for liquid-metal MHD (LMMHD) application in NaK are: chemical compatibility, surface effects, and heat transfer effects related to the fluid properties of the liquid metal. Chemical compatibility questions were favorably resolved by testing commercially available hot-film sensors in a quiescent pool of NaK inside a glove box. No evidence of degradation of either the quartz coating or of the organic

Fig. 1. Hot-film probe and cross section of hot-film sensor.

Fig. 2. LEVI geometry.

Fig. 3. Schematic of the TTA system.

electrical insulating material on the sensor support fingers was observed following as many as 67 days of powered operation at overheat ratios (OHR)^a of up to 1.4. Cylindrical sensors, similar to that shown in Fig. 1, operated up to 31 days at power with OHR up to 1.2. Hence, it was established that no fundamental chemical incompatibility exists between ordinary commercially available hot-film sensors and room temperature NaK under operating conditions of interest for fusion applications.

Surface effects are responsible for the commonly encountered erratic behavior of HFA in liquid metals. These surface effects have been reported almost exclusively in the working fluid mercury and include poor wetting of the sensor heat transfer surfaces and buildup of impurities on these surfaces. The impurity issue is handled in the present experiments by routinely filtering the NaK in both the large ALEX loop and in the instrumentation development loop. In the large loop, both 100 μ and 40 μ elements are used; in the small loop, 40 μ . Additionally, the strong reactivity of NaK dictates that a

^aThe sensor OHR is defined as $OHR = R_{hot}/R_{cold}$, where R_{hot} and R_{cold} are the operating and ambient resistances, respectively, of the sensor.

very clean system be maintained. Here, an argon covergas having less than 1 ppm of O_2 and water vapor is used. This feature minimizes the formation of oxides and other impurities which exacerbate the surface effects problem.

Heat transfer considerations associated with hot-film sensors in liquid metals are related to the low Prandtl number (Pr) of NaK (~ 0.04) and its high boiling point. The low Pr translates to a reduced sensitivity to convective cooling of the sensor, compared to conductive cooling. The high boiling point makes possible higher sensor operating temperatures, thus improving measurement sensitivity and reducing the influence of environmental temperature changes. This gain in performance, however, comes at the expense of sensor longevity. Data presented here were collected at an OHR of 1.05, a modest value intended to avoid sensor failure in these initial investigations. Future work will be carried out at higher OHR.

Local velocity measurements comprise most of the HFA results presented here, but some turbulence measurements collected with HFA are presented later. Figure 4 shows HFA bridge voltage variations along the length of the ALEX thin-walled, round test section; further details of the test section and experimental arrangement are given in Refs. 3 and 7. The figure is centered on the corner of the magnet pole face, showing variations up- and downstream from the pole face corner ($X=0.0$). Upstream is negative and downstream is positive in X. The hot-film sensor is positioned at the pipe centerline and M and N are as shown on the figure. Since the anemometer bridge voltage, E_b , is related to the local velocity in the following way:

$$E_b^2 = A + B\sqrt{u},$$

the bridge voltage follows the velocity. One can see that the HFA reveals trends in the local flow velocity in the vicinity of the inlet (or outlet, shown

Fig. 4. Hot-film voltage axial variation, $N = 10,000$; $r/a = 0.0$.

here) of the magnetic field at M and N values of interest in fusion reactor blanket design. For example, Fig. 4 shows the voltage (velocity) at the centerline decreasing as the outlet of the magnet is approached, reaching a minimum before fully exiting the field, and finally increasing toward the centerline flow velocity. Figure 5 shows similar behavior at the test section centerline for M = 3,500 and N = 3,050, with one notable exception, i.e., the hot-film data suggest that the distance downstream from the edge of the pole face, over which the centerline velocity is influenced by the magnetic field is less for the lower values of M and N than for the high.

An additional example of the kinds of results the HFA can produce is shown in Fig. 6. Here the probe is placed at 90% of the distance from the pipe centerline to the wall, $r/a = 0.9$ (the centerline being $r/a = 0.0$, the wall being $r/a = 1.0$). The probe is in the horizontal plane of symmetry for the pipe. It can be seen that the HFA indicates first a

Fig. 5. Hot-film voltage axial variation, $N = 3,050$; $r/a = 0.0$.

Fig. 6. Hot-film voltage axial variation, $N = 10,300$; $r/a = 0.0$.

rise and then a fall in velocity as the wall jets are first formed and then die out on exiting the magnet. Further details on the method of data acquisition and interpretation of the results can be found in Ref. 7.

LEVI

Ohm's law for a moving conductor is

$$\vec{j} = \sigma(\vec{E} + \vec{u} \times \vec{B})$$

neglecting the Hall effect. In all cases of interest for liquid-metal cooled fusion blankets, the MHD flows will be confined to thin-walled or insulated ducts where

$$c \ll 1.$$

In these cases, it can be shown that

$$\vec{j} \ll \sigma \vec{u} \times \vec{B}.$$

Hence, Ohm's law reduces to

$$\vec{E} = -\vec{u} \times \vec{B}.$$

Dropping the vector notation, expressing the electric field E as $\Delta\phi/d$, and solving for u , we have

$$u = \frac{\Delta\phi}{d \cdot B}.$$

This argument forms the theoretical basis for use of the LEVI probe, but experimental verification of its performance is required. Figure 7 shows a velocity profile across the horizontal midplane of the ALEX test section inside the magnetic field obtained with a LEVI. (The asymmetries of the profile are associated with some early difficulties in completely and uniformly removing the Cr_2O_3 layer from the inside surface of the stainless steel test section.) Nevertheless, the average velocity was known from loop flow meters and should agree with the

Fig. 7. LEVI velocity profile integration.

value obtained by integrating the velocity profile across the pipe. Care was taken to observe the fact that the flow is uniform along magnetic field lines in the presence of a transverse magnetic field as shown in Fig. 7. Comparison of the average velocity obtained by graphical integration of Fig. 7 to that given by the loop flow meter yielded 0.72 m/s and 0.70 m/s, respectively; a roughly 3% difference.

Since resolving the Cr_2O_3 surface layer problem, a number of additional velocity profiles have been collected in the round test section using the LEVI. All LEVI velocity profiles obtained have been graphically integrated and compared with the known average velocity reading. Table 1 summarizes the results of this comparison. It can be seen that with the exception of the two profiles taken in the far fringes of the B-field (E and H), all comparisons are within very respectable limits. An example profile (F) is shown in Fig. 8.

In Fig. 9 velocity variations in the axial direction, as measured by the LEVI, are shown. This figure is to be compared with Fig. 4, taken with the HFA at the same conditions. It can be seen that the LEVI gives good quantitative information until it gets outside the B-field where the LEVI measurement goes to unrealistically high values. There are a number of possible explanations for this behavior, among them the decrease in both the applied field and in the induced voltage to levels which may be below reliable limits of the instrumentation. Another possible cause of this behavior could be the presence of B-field gradients across the width of the pipe, which undoubtedly increase in the fringing areas.

Further examples of LEVI velocity distributions in the axial direction are shown in Figs. 10 and 11. These two figures complement Figs. 5 and 6, respectively. At this point, the LEVI has given very good quantitative velocity data inside the field and partially into the fringing region. The HFA currently

Fig. 8. LEVI velocity profile in fringing magnetic field.

Fig. 9. LEVI velocity axial variation, $N = 10,000$; $r/a = 0.0$.

Table 1. LEVI Velocity Profile Integral Summary

ID	Location ^a	B_0 (T)	B/B_0	N_0	M_0	$\frac{\bar{u}_{LEVI}}{\bar{u}_{flowmeter}}$
A	mid-plane	2	1	10^4	6500	1.03
B	mid-plane	2	1	10^4	6500	0.92
C	mid-plane	1	1	3×10^3	3250	0.88
D	inlet	2	0.5	10^4	6500	0.96
E	inlet	2	0.1	10^4	6500	1.17
F	inlet	1	0.5	3×10^3	3250	0.88
G	outlet	2	0.5	10^4	6500	0.95
H	outlet	2	0.1	10^4	6500	1.35
I	outlet	1	0.5	3×10^3	3250	0.95

^aProfile Location W.R.T. Magnet.

Fig. 10. LEVI velocity axial variation, $N = 3,050$; $r/a = 0.0$.

Fig. 11. LEVI velocity axial variation, $N = 10,000$; $r/a = 0.9$.

gives qualitative velocity information in the entire inlet/outlet region of the magnet, showing the extent of the three-dimensional region both inside and outside the field. The HFA also shows regions of rising or falling velocity inside and outside the field.

TTA

A schematic of the TTA system is shown in Fig. 3. The system consists of a sensor located in the flow path of the fluid and externally located support electronics. The sensor is essentially a sheathed thermocouple that is alternately heated and cooled; heated by pulsing an electric current through its hot junction and then convectively cooled by the moving fluid. The cooling rate is measured and then, using a microprocessor algorithm, is correlated to the local flow velocity over the probe.

Referring to Fig. 12, the operation of the probe can be described as follows:

- At time t_{-1} , a constant, relatively high, voltage (10-30 V) is applied directly across the calibration wires for a time $(t_0 - t_{-1})$. Hence, by resistance heating, the temperature of thermocouple junction is raised above the bulk fluid temperature. This power pulse (voltage) does not have to be accurately controlled or measured.
- At time t_0 , the power pulse is switched off and the temperature distribution in the thermocouple begins to relax.
- At time t_1 , an instantaneous junction temperature is recorded, T_1 .
- At time t_2 , a second instantaneous junction temperature is recorded, T_2 .
- Then, using readings T_1 and T_2 , the preprogrammed microprocessor calculates the corresponding flow velocity.
- At time t_3 , the power pulse is reapplied and the cycle is repeated.

After the initial cooldown time, $t_0 - t_{-1}$, the

Fig. 12. Cyclic operation of the TTA probe.

temperature decay of the thermocouple junction is characterized by:

$$T = A_1 e^{-k\alpha_1^2 t} \quad (1)$$

where

T = temperature at a given time,
 t = time,
 H = convective coefficient at a cylinder surface,
 K = thermal conductivity within the cylinder,
 $k = K/\rho c$, ρ = density and c = heat capacity of the cylinder,

and α_1 is a function of H only, for a given probe. A_1 is a constant for fixed initial conditions and probe thermal properties.

A semilog plot of Eq. (1) starting at time, t_1 , and normalized to temperature, T_1 , is shown in Fig. 13. The slope of this curve is constant and approximated by:

Fig. 13 Normalized TTA temperature decay starting from time t_1 .

$$\frac{\ln T_2/T_1}{t_2 - t_1} = -k\alpha_1^2 \quad (2)$$

Thus with measured temperature values, T_1 and T_2 , at a given time interval, $t_2 - t_1$, the slope is calculated using Eq. (2) and, from the calculated H , the local fluid velocity is determined.

Testing to date in air and water have established feasibility of the TTA device. Typical results are shown in Fig. 14 for two sizes of thermocouple sensor. The anticipated operating region for NaK is also identified. Presently, flow tests are being performed at ALEX using a test arrangement and test procedures similar to those for the air and water tests. Results to date in NaK have been reasonably successful. However, the very high thermal convection encountered in NaK flow requires higher magnitude power pulses and faster response thermocouples to achieve good data resolution. A normalized log plot of the NaK flow test results is shown in Fig. 15. Note the fast temperature decay and the scattering of the data.

Turbulence Measurements

Power spectral density measurements and RMS measurements were collected from both the HFA and the LEVI. A variable gain, differential amplifier was used to isolate the LEVI from an RMS meter and/or a digital fast Fourier transform spectrum analyzer. Turbulence and energy spectrum studies are not a primary focus of the present work because, based on past LMMHD work in this area at much lower M and N (see Ref. 8 for example), turbulence is expected to play a negligible role in fusion blanket related

issues, if it is present at all. Indeed, the preliminary data gathered thus far from both the HFA and the LEVI indicate that ordinary turbulence is damped by more than two orders of magnitude, to near the noise level of the system. For example, Fig. 16 shows two energy spectra obtained from the HFA at $r/a = 0.9$, the region very near the wall where turbulence production is the strongest. The upper curve represents the amplitude vs frequency of turbulent fluctuations (in arbitrary units) rather far downstream from the exit of the magnet ($X \approx 0.9$ m) where the flow has nearly returned to ordinary turbulent pipe flow. The lower curve represents the turbulent energy spectrum at roughly $X \approx 0$. ($B/B_0 = 0.5$), i.e., near the edge of the B-field. Yet the turbulent spectra is down more than two orders of magnitude, only slightly above the system noise level. The lower curve in Fig. 16 is fully representative of all hot-film spectra obtained once inside the fringing area of the B-field, at all values of r/a . Hence, our conclusion is that turbulence, in the cases of interest for liquid-metal cooled fusion blankets, is of academic interest at most.

It was shown earlier that the LEVI gives meaningful local velocity results away from the edges of the fringing field only. This same result is true of its ability to generate meaningful velocity fluctuation signals as well. A significant number of power spectral density (PSD) measurements were collected from the LEVI probe. LEVI spectra were collected while the mean velocity profiles listed in Table 1 were being taken and while the data in Figs. 9, 10, and 11 were being taken. All these PSD results from the LEVI probe can be represented by the two curves in Fig. 17. The upper curve represents spectra collected from all regions of the pipe within the magnetic field except the two essentially stagnant

Fig. 14. Normalized TTA temperature vs time-theoretical slope comparisons.

Fig. 15. Normalized TTA temperature plot for NaK flow.

Fig. 16. Hot-film power spectra.

Fig. 17. LEVI power spectra.

regions, one at each end of the magnet. In these two central regions of nearly stagnant fluid, not only is the mean velocity very low, but the LEVI fluctuations are also lower (lower curve in Fig. 17), by roughly an order of magnitude than those in the other regions of the pipe.

It is important to put these PSD measurements in perspective. Within the magnetic field, the HFA and the LEVI PSD measurements are essentially consistent. In this preliminary work, the HFA has not been able to resolve the same detail as the LEVI PSD distributions shown by Fig. 17, perhaps because of the influence of the magnetic field on the HFA heat transfer. However, the important picture to keep in mind is that presented in Fig. 16, where it is seen that all the possible fine points in the PSD distributions exhibited by the LEVI data of Fig. 17 are at least two orders of magnitude below the freestream turbulence levels. Hence, our preliminary conclusion is that turbulence is not a major technical issue here.

SUMMARY AND CONCLUSIONS

Three instruments for measuring local velocity in LMHD experiments are being tested and developed. The HFA has proven to be chemically compatible with NaK and thus far a powerful though qualitative tool for the task at hand. It is also useful in over-viewing the importance of turbulence. Future HFA work will focus on increasing the instrument sensitivity by using higher OHR and developing calibration procedures to yield quantitative results as well.

The LEVI has turned out to be a rugged, accurate, reliable, easy to use, and inexpensive instrument. It has become the workhorse of the velocity measuring effort at ALEX and is expected to remain so. Future enhancements will focus on such details as electrode geometry improvements and increasing the adherence of the organic coating.

A methodology for determining performance of a given thermocouple in TTA-NaK applications has been developed using air and water flow measurements to characterize the probe. From these results, baseline decay curves have been calculated which represent the limiting case of the fastest decay for a given probe, i.e., infinite surface conductance. Baselines for 1.66 mm and 0.33 mm diameter probes were presented. At present, 0.25 mm diameter sheathed, ungrounded, BN insulated thermocouples are being baselined. These probes show promise in the TTA velocity measurement system under NaK flow conditions.

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