RAPPORTEUR REPORT ON SESSION 14: GENERATOR PERFORMANCE
SUB-SESSION 14[E]: MHD FLOW

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1. Introduction

Although the four papers to be reported here all fit under the broad heading of "MHD Flow", they deal with a wide range of subjects, both theoretical and experimental. It is therefore appropriate to review the papers separately.

2. "Secondary Flow in a Linear MHD Channel with Applied Axial Current" by S.L. Girshick and C.H. Kruger

The authors describe an experimental investigation of secondary flows set up in a linear MHD channel by Lorentz forces. Such flows are likely to have important effects in commercial generators, yet there has been very little relevant experimental research to date. This work makes a strong contribution, presenting direct, detailed measurements of secondary flow velocities in a channel with interaction scaled to be comparable to a commercial generator.

An axial Hall current was deliberately introduced into the plasma to produce the desired $\underline{J}x\underline{B}$ force in the negative y-direction (figure 1). The magnitude of the current was such that the Lorentz force acting on the plasma during its passage along the channel was approximately equal to the axial inertia of the flow. At the end of the active channel, where velocities were measured, this resulted in a peak value of transverse velocity v equal to 15% of the average flow velocity in the x-direction U_b. (U_b was calculated from the total mass flow.)

The principal channel diagnostic was Laser Doppler Anemometry, which gave information about both x- and y-components of velocity, and turbulence intensity. A Faraday discharge could be applied at one electrode pair in the channel. At this location, the authors measured potentials across the electrode boundary layers with probes and determined the electrode surface temperatures with thermocouples.

2.1 Transverse velocity

Figure 2 shows experimental profiles of the y-component of velocity as a function of z (position in the direction of the magnetic field). Curves are shown for a series of y-locations in the channel. From this data, the authors infer the presence of two vortices in the y-z plane as expected (figure 1). However, instead of being symmetrically located in the channel, the vortices appear to be displaced upward and to the right. The asymmetry along the magnetic field (z-direction) is explained as an artifact of the measurement, not a real feature. However, the vertical displacement of the vortices (y-direction) is a real MHD effect which has been predicted theoretically [2].

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During flow along the channel, the distributions of plasma temperature and electrical conductivity in the transverse plane are affected by the vortices. This modifies the distribution of the Hall current density, and hence the Lorentz force, in such a way that the vortices migrate upwards.

2.2 Axial velocity

The effect of the vortices on the axial velocity was to strongly skew the distribution between the electrode walls, with the maximum axial velocity shifted down to y/H=0.3 (H - channel height) for the conditions of figure 2. This is effect arises because the vortices convect fluid downward, introducing plasma at the top of the channel which has come from the boundary layers and has a low axial velocity.

2.3 Turbulence

Turbulence intensities in both the x- and y-directions were measured. In both cases, the region of minimum turbulence was shifted downward from the channel centre, consistent with the axial velocity measurements.

2.4 Electrode temperature/boundary layer conductivity

These measurements gave an indication of the important effects that secondary flow can have on generator performance. The vortices circulate cold plasma from the sidewalls over the anodes, and warm core plasma over the cathodes (figure 1). This led to a measured difference in temperature of about 120K between the electrode surfaces, with the heat flux to the anode increased by 12% and the heat flux to the cathode decreased by 5%. The effect on conductivity was found from probe data with the Faraday discharge: the anode boundary layer was measured to be about twice as resistive as the cathode boundary layer.

3. "Pre-Ionization of the Non-Equilibrium MHD Generation Plasma by Diagonally Arranged Wedges" by M. Miyata and M. Tamaki

In this paper, the authors present data from a shock-tube driven MHD experiment. The working gas is pure argon (unseeded), so that a relatively high temperature is necessary to achieve a satisfactory electrical conductivity. In order to increase the plasma temperature from its low value of 3 000K at the generator inlet, wedges were used to deliberately introduce shock waves in the flow, heating the plasma.

In work reported previously, the authors demonstrated the effectiveness of this method of pre-ionization [3]. Here, a comparison is made between two arrangements of 15° wedges: either on the faces of the rectangular channel, or diagonally located in the corners (figure 3). Since there is no external energy source, a trade-off is involved in the technique: the plasma is heated, but it is also decelerated. The authors use the Faraday voltage (dependent on the flow velocity) to evaluate the significance of the deceleration. The Hall voltage developed along the channel depends on the short-circuit Faraday current, and is thus affected by the electrical conductivity; this gives a measure of the success of pre-ionization.

The channel was configured as a Hall generator with 35 octagonal ring electrodes (figure 3). As well as making spectroscopic and pressure measurements, the authors collected extensive electrical data on the generator performance, including Hall and Faraday voltages and currents under various conditions. The Hall field along the channel, deduced from the electrode voltages, is plotted in figure 4 for both wedge arrangements. These values were measured at open-circuit (zero Hall current). It can be seen that the Hall field is lower in the duct with diagonally arranged wedges, particularly in the downstream region. Overall, the result of the comparison was that arranging the wedges diagonally increased the Faraday voltage (less deceleration), but reduced the Hall voltage (less effective pre-ionization), i.e., the shock waves produced by the diagonal wedges were weaker.

The authors also reported an interesting result in measurements of short-circuit Hall current as a function of stagnation temperature: the Hall current rose sharply to about 8A at a stagnation temperature of only 3 000K. The predicted fractional ionization at that temperature is only about 10^{-11}, and the authors attributed the large current to pre-ionization with the wedge arrangement.

4. "Effects of an Applied Magnetic Field on the Natural Convection and Mass Transfer Flow Past a Vertical Porous Plate" by N. Kafousias and N. Nanousis

The authors obtain theoretical solutions to a model problem: the flow of an incompressible, viscous and electrically conductive fluid past a vertical porous plate. The flow is established by

(a) a temperature difference between the plate and the fluid a large distance from the plate, and

(b) for the species under consideration, a differing concentration at the plate and at large distances.

In addition, normal injection or suction of material at the porous plate is allowed for.

The energy balance equation used by the authors is more complete than those considered by some other workers in that both Joule heating and viscous dissipation in the medium are taken into account.

Three partial differential equations describe the variation of the parallel component of fluid velocity, u, the temperature T, and the concentration C. These are functions of the position along the plate x and distance from the plate y. The equations are made dimensionless and a stream function is introduced describing the fluid velocity. With certain assumptions about the spatial variation of fluid properties, a similarity solution is obtained which reduces the problem to a set of three differential equations in the single similarity variable $\eta = ay/x^{\gamma}$. This set of nonlinear differential equations is solved by iteration, applying the Crank-Nicolson finite difference scheme at each step.

The authors carried out numerical calculations for a range of cases: with/without magnetic field; with injection/suction of material or with an impermeable plate; and for different values of the Schmidt number Sc (kinetic viscosity/molecular diffusivity). A table summarizing some of the results is given on the next page.

magnetic field	Sc	impermeable plate		suction		injection	
		f	Q	f	Q	f	Q
no	0.22	0.968	-0.855	0.575	-3.749	0.311	-.0107
no	0.75	0.864	-0.782	0.245	-3.719	0.312	-.0108
yes	0.22	0.920	-0.831	0.557	-3.748	0.307	-.0103
yes	0.75	0.826	-0.760	0.241	-3.719	0.308	-.0104

Here, f is the normalized skin friction at the plate, and Q is the normalized heat flux from the plate (Q is negative because of viscous and Joule dissipation). It can be seen that application of the magnetic field reduces friction in all cases. Particularly in the case of an impermeable plate, application of the magnetic field also decreases the heat flux. This indicates that the resultant Joule heating, which would tend to increase the heat flux, is not as significant as effects due to the changed velocity distribution which decrease the heat flux.

5. "Shock Wave Cancellation by Lorenz Force Action" by J.P. Petit and B. Lebrun

In this paper, the authors discuss a novel application of MHD principles: the elimination of shock waves by an appropriate arrangement of Lorentz $\underline{J}\times\underline{B}$ forces in a gas. Hydraulic simulations have already been carried out [4]; shock tube experiments in argon are now planned to test the concept.

As well as the Lorentz force, current flow through the medium gives rise to Joule heating. This leads to pressure gradients which can nullify the $\underline{J}\times\underline{B}$ effect. The authors find that acceleration is possible if

$$\frac{\sigma B^2 L}{\rho V(\gamma-1)} > 1$$

with V, the flow speed, L, the characteristic length over which current is present, and γ, the ratio of specific heats. For a magnetic field as high as 4 tesla, the authors find that shock wave cancellation could even be achieved in atmospheric air at normal temperatures, using strong $\underline{E}$-fields or microwaves to achieve the required electrical conductivity.

The authors derive two-dimensional models of both internal and external flows using the method of characteristics. In channel flows, the $\underline{J}\times\underline{B}$ forces must be arranged to accelerate the fluid in convergent sections (MHD motor) and decelerate it in divergent sections (MHD generator).

Shock wave cancellation in a external flow is illustrated in figures 5 and 6. Crossing of the characteristic lines in figure 5 shows where shock waves would arise in the absence of Lorentz forces. Figure 6 shows the arrangement of $\underline{J}\times\underline{B}$ force which would be necessary to maintain parallel characteristic lines and avoid shock waves. The inset shows the associated arrangement of electrodes and magnetic field.

Non-equilibrium ionization would be required to achieve adequate electrical conductivity at low gas temperatures. Since the Hall parameter will also be high, the ionization instability is likely to occur, leading to large amplitude, uncontrolled fluctuations in electron density. To avoid this complication, the authors suggest the deliberate introduction of nonuniformities in the magnetic field. These would be in the form of low-$\underline{B}$ paths along which stable streamers of current-carrying plasma should form. This principle has already been demonstrated experimentally [5].

References

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2. Maxwell, C.D., Early, D.W. and Demetriades, S.T., "Predicted Strength and Influence of MHD-induced Secondary Flows in Recent Experiments", 23rd Symp. on Engineering Aspects of MHD, Somerset, Penn., 1985, pp.173-192.

3. Miyata, M. and Tsuboi, H., "Non-equilibrium Hall MHD Generation Experiments with an Inlet Shock Wave Pre-ionization. (Effects of the Shock Wave Angle on the Performance)", 22nd Symp. on Engineering Aspects of MHD, Starkville, Miss., 1984, pp.7.5.1-7.5.15.

4. Petit, J-P., "Is Supersonic Flight, Without Shock Wave, Possible?", Eighth Int. Conf. MHD Electrical Power Generation, Moscow, 1983, Vol. 2, pp.74-77.

5. Petit, J-P., "Cancellation of th Velikhov Instability by Magnetic Confinement", Eighth Int. Conf. MHD Power Generation, Moscow, 1983, Vol. 4, pp.207-209.

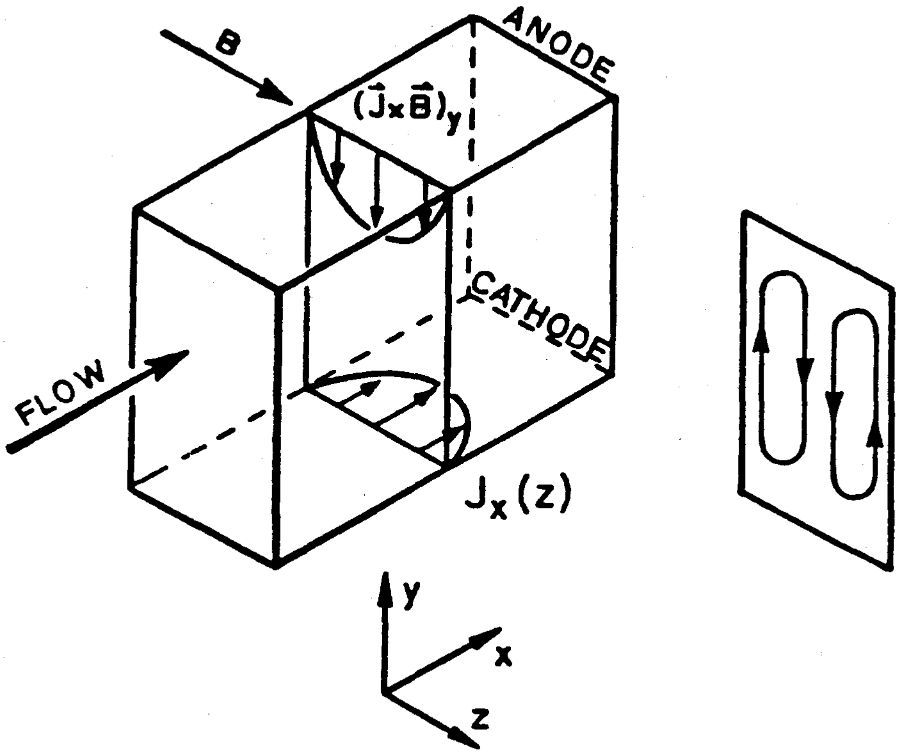


Figure 1. Basic mechanism of secondary flow, from reference [1].

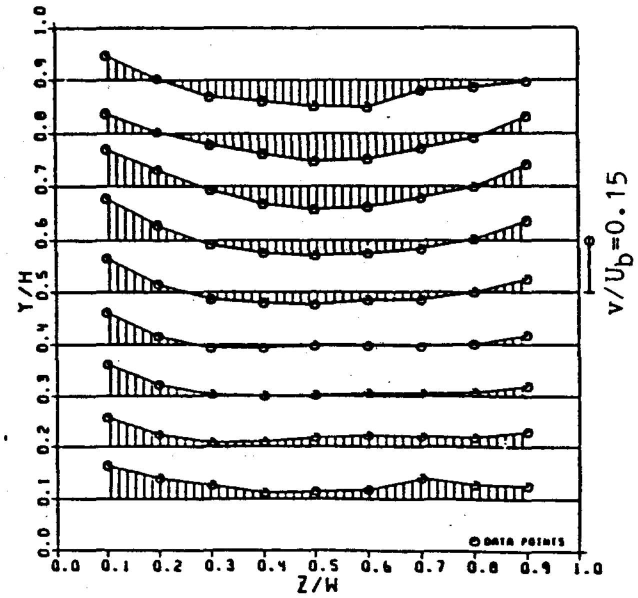
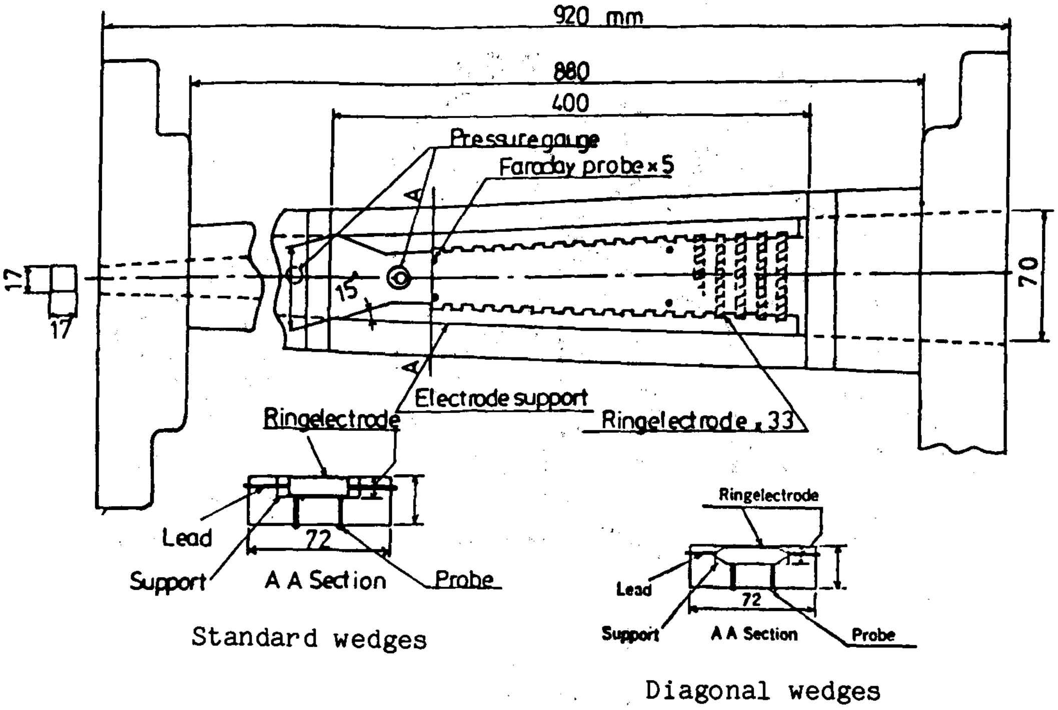


Figure 2. Experimental profiles of the y-component of velocity as a function of z (position in the direction of the magnetic field). Profiles are shown for a series of y-locations in the channel. The channel height H and width W normalize the co-ordinates.



Standard wedges

Diagonal wedges

Figure 3. Schematic of shock-tube driven generator showing the standard arrangement of 15° wedges and the diagonal arrangement. (From reference [3] in part.)

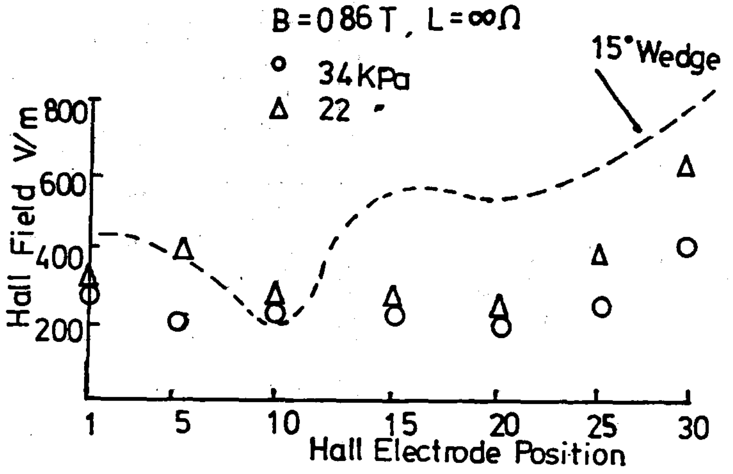


Figure 4. Hall voltage distributions along the channel measured at zero Hall current. The dashed curve is the measured voltage profile for the standard rectangular wedge arrangement at a stagnation pressure of 22kPa. The points show Hall voltages with the diagonal wedge arrangement for two different stagnation pressures.

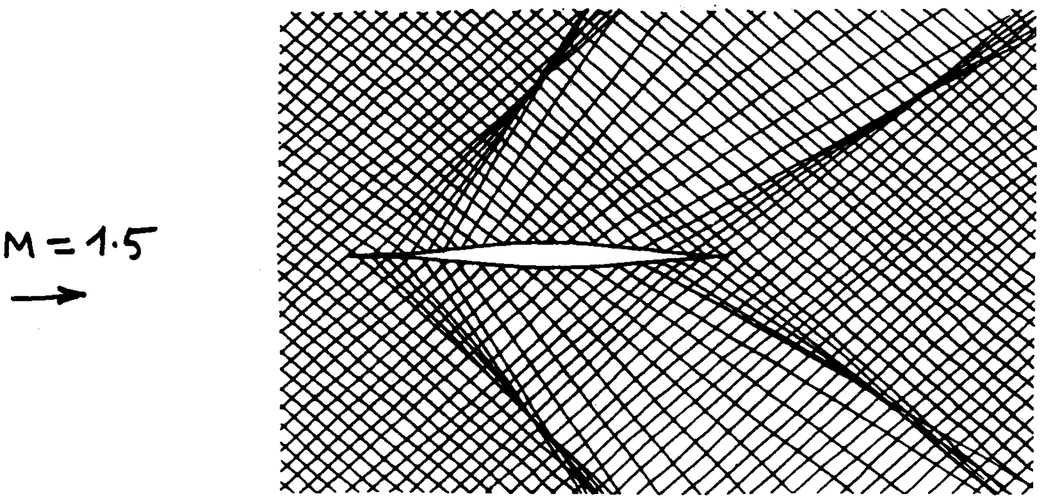


Figure 5. Shock wave formation around a thin model showing characteristic lines.

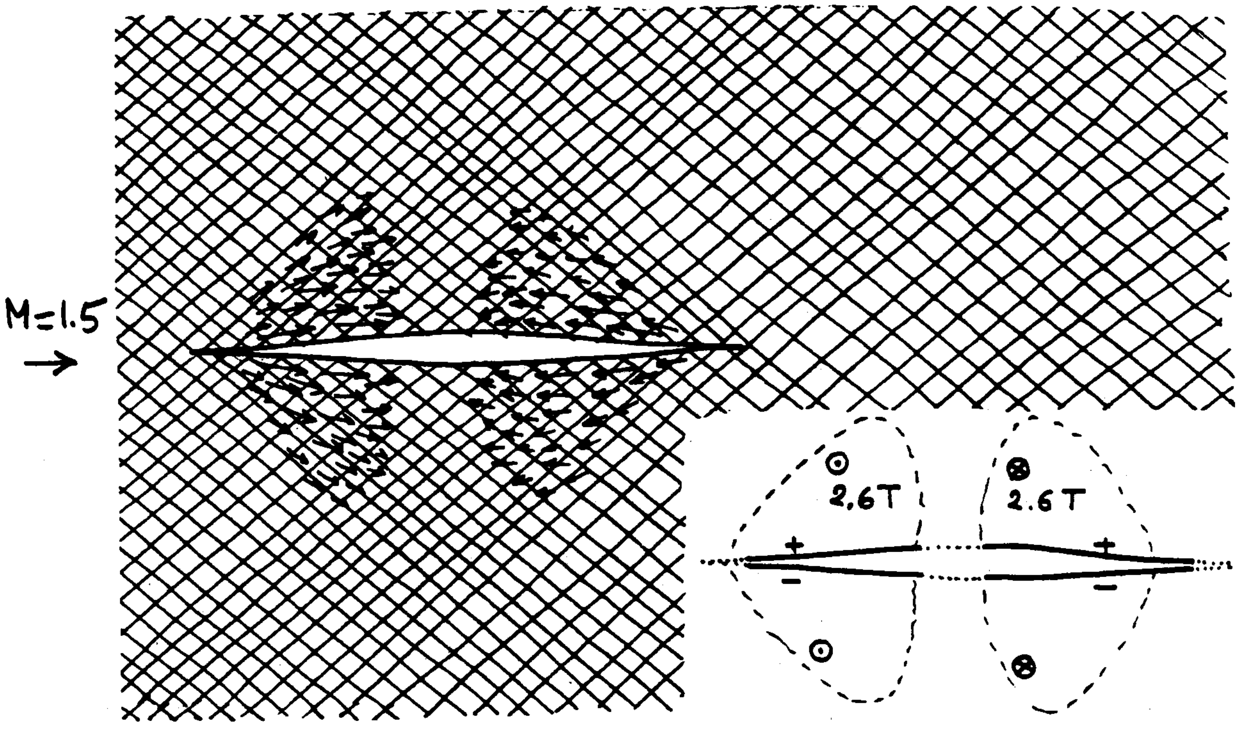


Figure 6. Shock wave cancellation around a thin model. The arrows show the required distribution of $\underline{J}\times\underline{B}$ forces. The inset shows the arrangement of electrodes and magnetic $\underline{\text{field}}$.