Rotational MHD Flow Under Crossed Electrical and Magnetic Fields

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Abstract

Results of experimental measurements of the azimuthal velocity component of a rotating flow of a conducting fluid in an annular cylindrical cavity under the action of azimuthal electromagnetic force generated at the interaction of a radial electric field with an axial magnetic field are presented. The obtained data are analyzed and compared with computed characteristics.

Introduction

Rotating flows of conducting fluids in an annular gap between coaxial cylinders under an azimuthal electromagnetic force generated at the interaction of a radial electric field with an axial magnetic field have been studied earlier [1-5]. However, the suggested analytical solutions are either obtained for asymptotic modes or derived on the basis of solutions for specific rotating flows, whereas respective experimental data for liquid metals are rather scarce.

The objective of the present paper is experimental study of turbulent rotating flows of such kind and the evaluation of potential use of known analytical solutions for their computation. The paper is concentrated on the azimuthal component of the rotating flow velocity at the ratio of gap height to diameter close to unity.

1. Experimental Setup

The experiments were carried out on a facility (Fig. 1) comprising a copper cylindrical vessel 1 (external electrode with the radius $R_2 = 35$mm) and a coaxial copper rod 2 (inner electrode with the radius $R_1 = 4$mm). The bottom 3 of the vessel is made of electrically insulating material. The annular gap limited by the electrodes and the bottom is filled with a ternary eutectic alloy Indium-Gallium-Tin up to the level H $= 2R_2$ (aspect ratio $\delta_z = H/R_2 = 2$). The vessel with liquid metal is arranged in the cavity of a water-cooled magnet exciting a magnetic field directed along Z axis. When the radial electric field I with the density j_r between the electrodes interacts with vertical magnetic field B_z in the liquid metal volume, azimuthal electromagnetic forces with the density f_φ arise and set the liquid metal into rotation.
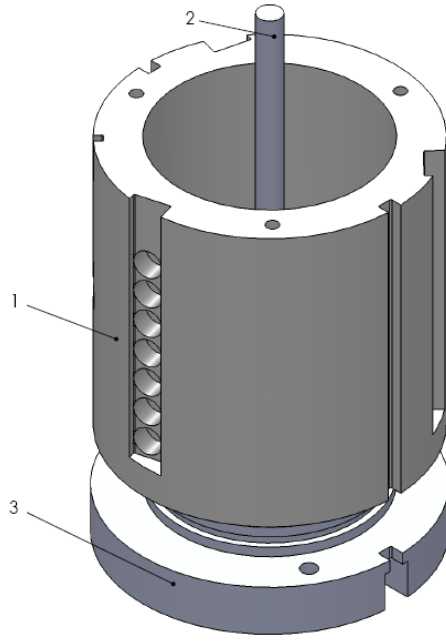
Fig. 1. Schematic view of a vessel with liquid metal

The current circuit and the electromagnet winding were fed by Genesys Programmable DC Power Supplies. Maximal values of the electric current and magnetic induction in the experiments amounted to 120A and 0.15 T, respectively. The magnetic field in the magnet cavity was measured with Teslameter FW Bell, Model 6010, and the field inhomogeneity in the volume occupied with liquid metal did not exceed 8%.

Velocity components of the rotating flow were measured by two methods. To perform measurements using Ultrasonic Doppler Velocimeter DOP-2000, special slots were made with 10 mm spacing throughout the height on the external lateral surface and in the bottom of the experimental vessel for carrying out ultrasound measurements along the vessel radius, chord and height. Velocity profiles were measured by 4 MHz and 10 MHz transducers, and the values of azimuthal velocity component of the rotating flow were recalculated taking into account the radial component value.

Two-electrode conductive velocity probe with the base of 1.5 mm was used for measuring the azimuthal component, together with Stanford Research Systems Low-noise preamplifier, Model SR560 and electronic filters. The analog signal was transformed into digital one using National Instruments DAQ Card-6052E, and the data were processed using National Instruments LabVIEW-8 software.
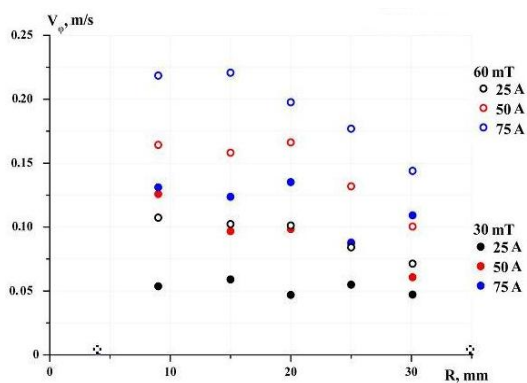
2. Results

Fig. 2. Mean azimuthal velocity radial distribution

Fig. 2 shows typical experimental results of measurements of the rotating flow azimuthal component V_φ with the conductive probe for a certain set of electromagnetic parameters in the cross-section z = 25 mm within the r,φ plane. Liquid metal spin-up, steady-state and spin-down modes were recorded. Mean velocity values (Fig.2) were obtained by averaging the time series within the steady-state flow mode. The electrical and magnetic fields contribution to the flow rate value was estimated on the basis of these data. In particular, it was obtained that the magnetic field has a larger effect on the mean velocity value in the flow region in the vicinity of the central electrode, while in the vicinity of the external electrode the electric field effect became stronger. The analysis of steady-state mode fluctuation characteristics has allowed us to evaluate turbulence level depending on the electric current and magnetic induction

and to analyze the spectra behavior. As a result of such analysis, velocity spectra were obtained, and some of them are presented, by way of example, in Fig. 3, where at $r = 15$mm in the inertial subrange the spectral slope changes from -2 to -2.5 with turbulence level ~3%, and while moving to the external electrode (at $r = 25$mm) it changes from -2 to -2.8 with turbulence level from ~4% to ~7%.
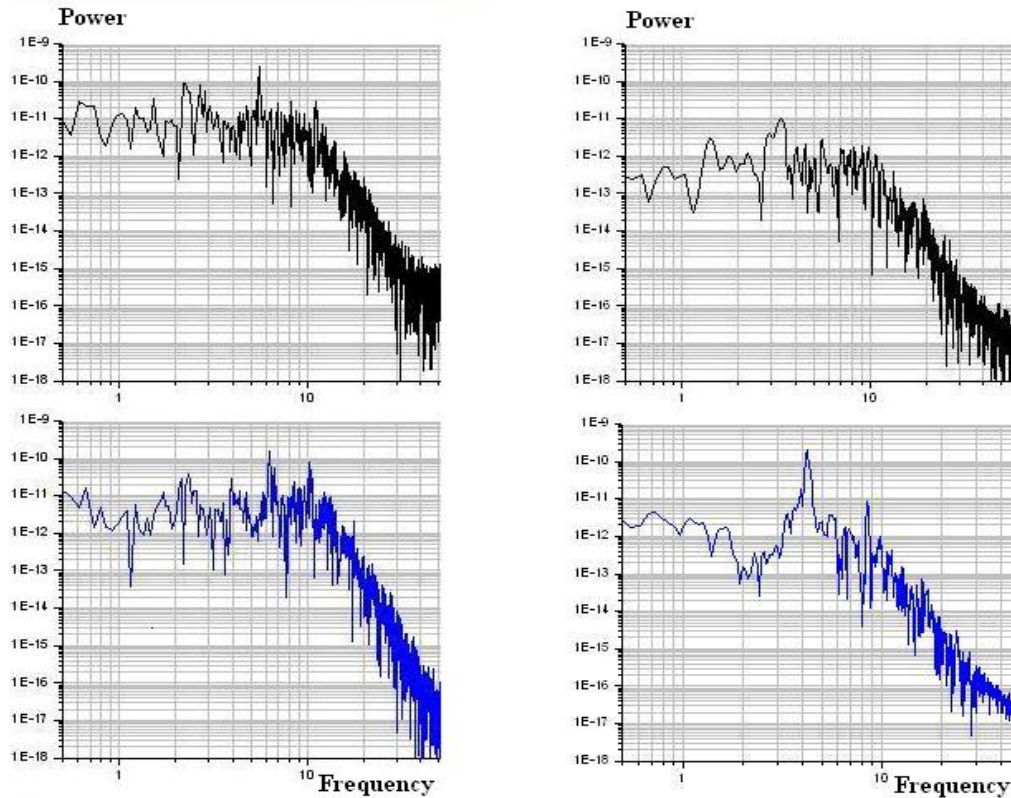

Fig. 3. Spectral characteristics of the flow (log-log scale). 30mT, 100A (black) and 120mT, 25A (blue) modes; $r = 15$mm (left), $r = 25$mm (right)

Ultrasonic UDV measurements have revealed, in certain cases, acoustic contact breaks on cylindrical surfaces caused by the appearance of products of melt interaction with electrodes. Besides, the curvature of the cylindrical walls on the boundary between the solid and liquid media with significantly differing acoustic velocities distorts the ultrasonic signal, which leads to the appearance of flow velocity profile artifacts, so that the data need further correction (see, e.g., [7]).

Conductive probe insertion into the rotating flow causes local hindering of the flow and turbulent wake generation behind the probe. The value of such hindering can be determined by simultaneous measurements using both methods and comparison with the results obtained by UDV only. Simultaneous measurements in the central part of the gap using both methods make it possible to verify the conductive probe calibration.

The comparison of experimental data with calculations according to the "external" friction model [5, 6], which has shown itself in case of rotating flows under the action of rotating magnetic fields, does not provide satisfactory agreement of profiles (results close to experimental data were obtained only for the flow rate). This can be attributed to the absence of a quasi-solid core, which is characteristic of flows under the action of RMF, whereas shear effects play the major role in the flow under study. Note that the obtained experimental data do not confirm the presence of a

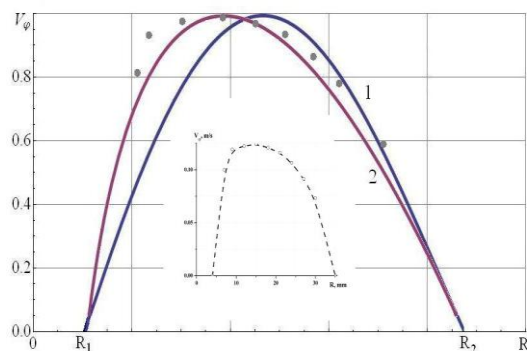potential flow core with the inverse relationship between a flow mean velocity and radius [4].

Fig. 4. Comparison of experimental and estimate

The trend of velocity profiles obtained from analytical solutions [3,4] and normalized to their maxima, which are presented in Fig. 4 (with the polynomial fitting in the insert), is the closest to experimental ones. As follows from the obtained results, the velocity profile maximum is shifted with respect to the center of the annular gap towards the internal electrode, the shift magnitude increasing with growing fields.

Although the respective velocity profiles can be estimated using said formulas with a correction factor, numerical simulation can provide a more detailed flow pattern.

Conclusion

The obtained experimental data give a possibility of flexible control of both mean and fluctuating characteristics of rotating flows by simultaneous variation of electrical and magnetic fields. Nevertheless, the computation of these characteristics calls for further development and respective clarifications.

References

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