Measurement of velocity in swirling flows of liquid metals in the presence of a magnetic field

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Abstract. Studies of the dynamics of a round submerged jet of liquid metal in a transverse magnetic field. The experiments were performed in the range of Reynolds numbers up to 1000 and Hartmann numbers up to 1300 using a probe technique for measuring velocity using potential sensors. Detailed three-dimensional flow structures are visualized using a direct numerical simulation method independent of the experiment. The paper presents data on the averaged velocity field and statistical characteristics of the flow, reproducing the complex nature of a substantially unsteady flow, in which zones of reverse fluid flows are detected and a significant heterogeneity of the velocity field is observed.

1. Introduction

Electrically conductive liquids interacting with a magnetic field are an essential element of many industrial processes, for example, liquid metal circuits in thermonuclear reactors \cite{1}, control in crystal growing technologies \cite{2}, continuous casting of steel in metallurgical processes \cite{3}, liquid metal batteries \cite{4}, etc. Ensuring the feasibility of such processes requires a fundamental understanding of the influence of the magnetic field on the flow of an electrically conductive liquid.

Recent studies show that the magnetic field completely changes the properties of the flow \cite{5}. At high values of similarity criteria, such as the Reynolds or Rayleigh number, flows become unstable even in very strong magnetic fields, which leads to the development of large-scale, quasi-two-dimensional disturbances dominating flows, such as, for example, shear layers or jets. The behavior of such structures is often unsteady and leads to high-amplitude pulsations of velocity, pressure and temperature. These phenomena are poorly studied and have both fundamental and practical significance. Quasi-two-dimensional structures completely change the mode of heat and mass transfer, and can lead to the formation of stagnant zones, reverse flow areas, concentrated hot or cold jets, abnormal temperature fluctuations, cyclic mechanical stresses in the walls, etc.

Of particular interest are jet streams that occur, for example, in streams with sudden expansions or during mixing, heating, or cooling of liquid. There are factors that limit the use of experimental methods for studying such tasks. The opacity of liquid metals practically excludes the use of optical measurement and control methods in the flow. Therefore, contactless methods of measuring velocity and temperature...
in the flow (UDV, MIT, LFV discussed in [6]) are considered the most preferable, however, at the current level of development, these methods do not make it possible to obtain three-dimensional velocity and temperature fields. An alternative is contact methods, when various miniature sensors are immersed into the flow (microthermocouples; correlation, electromagnetic and fiber-optic velocity sensors; thin-film thermoanemometers) and probes with coordinate mechanisms for local measurements, adapted, as a rule, for low-temperature or isothermal three-dimensional measurements.

This paper discusses the features of using a four-electrode conduction anemometer (potential sensor) to measure the flow characteristics of a circular submerged jet in a transverse magnetic field. This technique, which was developed back in the 70s of the last century [8], is based on the generalized Ohm's law, according to which an electric field arises in the flow of an electrically conductive medium moving in a magnetic field

\[ \frac{j}{\sigma} = -\nabla \varphi + \mathbf{V} \times \mathbf{B} \] (1)

Therefore, under these conditions, the local components of the velocity vector field \( \mathbf{V} \{V_x, V_y, V_z\} \) can be calculated if the gradient of the electric field potential \( \varphi \) and the current density \( j \) are measured locally. In the external applied transverse magnetic field \( \mathbf{B} \{0, B_y, 0\} \) (figure 1a), then the following relations will be valid for the components of the electric potential gradient:

\[ \frac{\partial \varphi}{\partial x} = E_x = B_y V_z - j_x / \sigma \] (2)
\[ \frac{\partial \varphi}{\partial y} = E_y = 0 - j_y / \sigma \] (3)
\[ \frac{\partial \varphi}{\partial z} = E_z = B_y V_x - j_z / \sigma \] (4)

Further, as it was shown in [8], it is possible to obtain an approximation away from the walls and in a sufficiently strong magnetic field, according to which, in equations (2) and (4), the second terms in the right part can be neglected and considered:

\[ E_x \approx \frac{\Delta \varphi}{\Delta x} \approx B_y V_z \] (5)
\[ E_z \approx \frac{\Delta \varphi}{\Delta z} \approx B_y V_x \] (6)

from where, by estimating the gradient of the electric potential, it is possible to determine the components of the flow velocity that are perpendicular to the induction of the magnetic field. Subsequent studies, however, have shown that to ensure acceptable accuracy, this method requires special calibration and compliance with a number of conditions in the experiment [9].

![Figure 1. Method for determining the velocity in the flow of an electrically conductive medium using a conduction anemometer.](image)
Note that directly determining the velocity component $V_y$, coinciding in the direction with the induction of the magnetic field, is problematic, nevertheless, statistical characteristics associated with this component can be obtained using current fluctuations measurement data $j'_y$. Moreover, as shown in the work [9], using the data of measurements of the potential gradient, it is possible to estimate the statistical parameters of turbulence in the flow.

A conduction anemometer can have different design options that implement (with some variations) the same idea. Figure 1b, for example, shows one of these options, a four-electrode sensor, involving the measurement of two components of the velocity vector transverse to the externally applied magnetic field:

$$V_x = \frac{\psi_a - \psi_b}{c_1 B \Delta l_x}$$  \hspace{1cm} (7)

$$V_z = \frac{\psi_d - \psi_c}{c_2 B \Delta l_x}$$ \hspace{1cm} (8)

The influence of induced currents $j_x$ and $j_z$ on the error of determining the velocity components when measuring the electric potential is determined by the coefficients $c_1$ and $c_2$. With forced flow in the channel, away from the walls and at small values of the external applied magnetic field $B$ ($Ha = B a (\sigma / \eta)^{1/2} < 100$, where $a$ is the half-height of the channel, $\sigma$ is the electrical conductivity, $\eta$ is the dynamic viscosity coefficient), the values of the coefficients can be determined by calibration, and at large values $B$ ($Ha > 100$), their values can be taken equal to one, while the expected uncertainty of velocity measurements will not exceed 10%. Nevertheless, the issues of applicability of this technique for measurements in substantially unsteady flows, for example, during flow in jets or sudden channel expansions, as well as the influence of channel walls on measurement accuracy, remain not fully investigated, what have motivated this study.

2. Problem formulation

The scheme of the flow under consideration is shown in figure 2. The submerged jet is formed when liquid metal flows out of a tube with a diameter of 6 mm in a channel 56x56 mm located in the region of a electromagnet that creates a magnetic field transverse to the flow. The probe, with a conduction anemometer fixed at its end (see figure 3), is inserted into the flow against the flow, fixed in the selected cross-section and, using coordinate mechanism, can move in a plane perpendicular to the magnetic field, thus measuring the flow velocity profile.

Figure 2. Schematic representation of the flow.

To measure the readings of the conduction anemometer, 3xNI-4071 modules are used, which record rapidly alternating pairwise signals from the electrodes in a time-synchronous mode within the framework of an automated measuring PXI system.
One of the stages of optimization of the method of velocity measurements using a conduction anemometer can be a comparison of the experimental results with the results of direct numerical simulation (DNS) of the flow in the configuration under consideration. DNS is performed using a technique calculated for rectangular and cylindrical geometries, which has shown its effectiveness in modeling MHD flows at high Reynolds and Hartmann numbers [10], as well as submerged jets in a transverse magnetic field [11].

3. Problem formulation

For a submerged circular jet propagating in a square channel in the presence of a transverse magnetic field (figure 2), calculations were carried out by direct numerical simulation (DNS) to identify patterns of flow development and transformation. The transverse magnetic field has a strong influence on the jet stream. At relatively low Reynolds numbers ($Re=V_o a/\nu=800$) and already at moderate Hartmann numbers (on the order of 100-200), a very rapid transformation from the output occurs into a flat jet elongated along the magnetic field due to the action of electromagnetic forces (figure 4). At the same time, the flow becomes unsteady and unstable with tendencies to separation of quasi-two-dimensional structures stretched in the direction of the magnetic field and twisted along it.

![Figure 3](image3.png)

**Figure 3.** Four-electrode conduction anemometer (dimensions are given in millimeters): 1 - tin contact layer; 2 - copper electrode; 3 - epoxy shell of the electrode

In a strong magnetic field ($Ha = 1000$), the effective length of the jet decreases, it loses stability at a sufficiently small distance from the entrance (figure 5) and tends to "stick" to one of the walls of the channel with the formation of a return circulation movement.

The structure of the swirling flow of a submerged jet is successfully reproduced in an experiment using a conduction technique for measuring the flow velocity. For example, figure 6 shows a dimensionless comparison of the measured fields of the averaged longitudinal and transverse velocities in the vertical section $x/a=1.6$ with the calculation data. Their good correspondence can be seen,
demonstrating both the isotropy of the flow along the Y-direction of the magnetic field lines and the changing pattern of the averaged jet flow with an increase in the Hartmann number.

Figure 5. Instantaneous field of the longitudinal velocity field $V_x$ in the vertical section $y=0$. DNS calculation on the grid $N_x\times N_y\times N_z=1536\times 384\times 384$ for $Re=800$, $Ha=1300$.

For the mode with a low Hartmann the waveforms of the dimensionless longitudinal $V_x$ and transverse $V_z$ velocity signals (figure 7), which are recorded simultaneously at a fixed point in the center of the channel ($y=0$), show the oscillatory nature of the jet flow in this section with low-frequency fluctuations (period $\sim 6$ sec). On the waveforms, the time intervals when both velocity components are positive (are in the same phase), which corresponds to the "movement" of the flow to the upper part of the channel, alternate with time intervals when the longitudinal velocity is positive and the transverse velocity is negative (are in the opposite phase), which corresponds to the "movement" of the flow to the lower part of the channel.

Figure 6. Comparison of profiles of dimensionless averaged longitudinal $V_x$ and transverse $V_z$ velocity measured (a,b,c,d) and calculated fields using DNS (e,f,g,h) in vertical section $x/a=1.6$ for $Re=800$, $Ha=200$ (a,b,e,f) and $Re=800$, $Ha=1300$ (c,d,g,h). The scale for the velocity is $V_0$ – mean flowrate velocity, the averaging time in the experiment is 600 seconds.

Figure 8 shows a comparison of the measurement results of the $V_x$ longitudinal velocity waveforms with the results of the DNS calculation. There is a good qualitative and quantitative coincidence of the measurement results and calculations. Some quantitative difference in the results is observed in the time intervals of the signal, in which the presence of a high-frequency component of the flow velocity is
noticeable, in these areas the high-frequency pulsation component of the electric current density $j'_x$ becomes significant, which cannot be obtained by a potential sensor evaluating the derivative $-\frac{\partial \phi}{\partial z}$ and in this connection there is an inaccuracy in determining the longitudinal component of the velocity.

**Figure 7.** Waveforms of dimensionless longitudinal $V_x$ and transverse $V_z$ velocity in the center of the channel ($y=0$, $z=0$) in vertical section $x/a=1.6$, measured using a conduction sensor for Re=800, Ha=200.

**Figure 8.** Waveforms of dimensionless longitudinal velocity $V_x$ in the center of the channel ($y=0$, $z=0$) in vertical section $x/a=1.6$, measured using a conduction sensor (blue line) in comparison with the results of DNS calculation (red line), Re=1000, Ha=500. The graph also shows the values from the DNS calculation $-\frac{\partial \phi}{\partial z}$ the derivative of the electric potential along the Z axis (black line) and the Z component of the current density $j'_z$ (pink line).

**Conclusions**
The results of velocity measurements using a conduction anemometer are compared with the results of direct numerical simulation of submerged jet flow and give a good correspondence both in terms of averaged and statistical characteristics of the flow, reproducing the complex nature of a substantially
unsteady flow in which zones of return fluid currents are detected and a significant inhomogeneity of the velocity field is observed.

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