A technique of hydrodynamics and heat transfer research during the flow of liquid metals in channels of various forms

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Abstract. This paper presents probe techniques and sensors used in experimental studies of MHD-flow and heat transfer of liquid metal (LM) in pipes and channels, hosted by the mercury stands, which is part of the MHD complex of MPEI-JIHT RAS. A detailed description of the correlation and conduction velocity measurement methods, as well as the results obtained with their use, are given.

1. Introduction

Local measurements in the environment of a liquid metal (LM) are not an easy task - one has to overcome a number of difficulties [1, 2]. When choosing a technique we must be considered that LMs have a number of features, such as: high density, high electrical conductivity, high melting point (except for mercury and some other metals or alloys), aggressive and toxic environment that can dissolve other metals, the presence of oxides and contaminants, the presence of a "front track" when the flow bypass the probe in a magnetic field (MF).

Methods that are widely used for local measurements of thermophysical quantities in non-conductive liquids and gases are often not applicable in fluid flows, or require modification. It should be noted that LM is an opaque environment, which is an additional obstacle to the use of contactless methods for measuring temperature and speed. In such cases, it is advisable to use sensors like as thermocouples, resistance thermometers. They can be laid in the wall and take measurements, but then, we will receive only limited information about the wall temperature, but not about the whole flow. Among other things, the implantation of thermocouples or other sensors in the wall, can greatly distort the results. In such tasks, the probe measurement technique is preferable to others.

2. Probe method of measurements.

The probe measurement technique is based on direct temperature measurement from the stream by insertion various measuring sensors into the test area. A detailed description of this technique and the main types of construction is given in [3]. We give a description of the swivel probe, because it is the most versatile. This type of probe is a lever capable of turning around a ball-on-cone hinge. The longer lever arm is a variable-section rod or, in other words, a telescopic tube that is inserted into the test section tightly towards the flow (Fig. 1). Depending on the characteristic under study, a specific sensor is installed at the end of the rod. The other lever arm is connected with the coordinate mechanism, which allows the sensor to be moved in the pipe cross section. The length of the probe rod is chosen so
that it is 15 ~ 20 times longer than the channel cross section; thus, when the thermocouple rod turns, moving along the radius, it remains almost in the same plane perpendicular to the channel axis.

![Figure 1. Swivel-type probe in 3D projection.](image)

Moving the probe across the channel section has been done using the coordinate mechanism. It consists of two calipers with stepper motors, allowing us to move the tip of the probe in two mutually perpendicular planes (horizontal and vertical). Such a mechanism ensures that the sensor is positioned at any point in the cross section. Two digital dial indicators allow you to install the probe tip with an accuracy of 10 microns, this accuracy is due to the hinge backlash. The preliminary calibration of the coordinate mechanism is carried out by optical means.

3. Main types of measurement sensors in LM environment.
Over the years, using the hinge technique, many modifications of this probe have been developed using various sensors to measure temperature, speed, etc. (Fig. 2).

![Figure 2. Measurement sensors: a) thermocouple for temperature measurement; b) conduction speed sensor [4]; c) correlation speed sensor [5]; d) sensor for transverse correlations [6].](image)

The versatility of the probe lies in the fact that the length of the rod and the size of the sensitive element can be chosen for any geometry of the studied area. At the same time, depending on the selected sensor, it is possible to conduct parallel measurements of temperature and speed, more on this in section 3.2.

3.1. Temperature sensors
A copper-constantan microthermocouple with a junction diameter of 50–100 μm is usually used as a temperature measurement sensor. The thermocouple juncture is fixed with epoxy resin at the end of the stainless capillary with an outer diameter of 0.3 mm so that the wires located inside the capillary.
The last one, in its turn, is also glued with epoxy resin into a capillary of a larger diameter (0.7 mm), and then this structure is fixed at the probe end. All measurement results using the described sensors will be presented for the case of mercury flow in a rectangular vertical channel under the action of a coplanar MF with different heating conditions. Fig. 3 shows the profiles of the dimensionless temperature in cross section along the long (X) and short (Y) side of the channel.

![Figure 3. Profiles of dimensionless temperature in axis planes X(a) and Y(b) in channel cross section, $q_w=35/0$ kW/m$^2$, Re =30 000: 1) Ha=0; 2) 300; 3) 500; 4) 800.](image)

All presented sensors used in our experiments with next regime parameters of Reynolds, Hartmann, and Grashof number $Re = 10000–50000$, $Ha = 0–800$, $Gr_q=10^8–10^9$. Wherein

$$Re = \frac{V_0 \cdot d}{\nu}$$

where $V_0$ is the average velocity by the cross-section, $d$ is the double width of the channel, and $\nu$ is the kinematic viscosity

$$Ha = B_0 d \sqrt{\frac{\sigma}{\mu}}$$

Where $B_0$ is the magnetic induction, $\sigma$ is the electric conductivity, $\mu$ is the dynamic viscosity

$$Gr_q = \frac{g \beta d^4 q_w}{\lambda \nu^2}$$

where $g$ is the acceleration of gravity, $\beta$ is the volume thermal expansion coefficient, $q_w$ is the heat flow on the wall, $\lambda$ and $\nu$ is the thermal conductivity.

### 3.2. Velocity sensors

The traditional method that can be used is a pitot tube. The method disadvantage is that the sensor (steel or glass capillary) cannot be made miniature, with a diameter of less than 0.3÷0.5 mm. Another difficulty is associated with low measurement accuracy: the speed is determined by the dynamic head, which in turn is determined by the difference in levels of mercury in the differential pressure gauge, and this difference in the experiments was a fraction of a millimetre. Despite these difficulties, it was possible to obtain satisfactory measurement results in the flow of mercury in the pipe using the above-mentioned method [7].

The thermoanemometric method for measuring speeds requires a significant modification: the thermoanemometer filament must be electrically insulated. As a rule, thermoanemometers are used in
isothermal LM flows. In non-isothermal flows it is difficult to organize thermal compensation of the sensor signal.

The most promising is the correlation velocity measurement method. The sensor based on this method consists of two microthermocouples whose junctions are located on the probe center line (Fig. 1 (c)).

The velocity profiles are measured by using the natural background of turbulent temperature fluctuations carried by the flow. Velocity measurements are carried out mainly in the core of the stream, at $R<0.9$, since the Taylor hypothesis of “frozen” turbulence, which underlies the correlation method [2], loses validity near the wall.

If $l$ is the distance between thermocouples, and $S$ is the signal lag time from the second thermocouple, then the time-averaged value of the local velocity $V_z$ is calculated simply: $V_z = \frac{l}{\Delta \tau_{\text{max}}}$. The lag time corresponds to the coordinate of the maximum on the space-time correlation function (CF) curve for two stationary random signals of temperature pulsation $X(\tau)$ and $Y(\tau)$ from thermocouples:

$$R_{xy}(\Delta \tau) = \lim_{t \to \infty} \frac{1}{t} \int_{0}^{t} X(\tau)Y(\tau + \Delta \tau) d\tau,$$

where $\Delta \tau$ is the time shift, $t$ is the averaging time.

An example of waveforms of thermocouple signals of the sensor is shown in Fig. 4 (a). It can be seen that the signal from thermocouple 2 repeats signal thermocouple 1 with some delay $\Delta \tau_{\text{max}}$, which is determined by the maximum coordinate of the normalized CF (Fig. 4 (b)).

![Figure 4. An example of waveforms from correlation sensor thermocouples (a) and space-time CF (b).](image)

Fig. 5 presents the results of measuring the velocity by the correlation method. The profiles of the dimensionless averaged longitudinal component of the velocity $V_z$ in two axial planes along the X and Y axes are shown for different values of the Hartmann number. The velocity $V_z$ is related to the average flow velocity in the channel $V_0$.

![Figure 5. Dimensionless longitudinal velocity profiles by axis planes X(a) and Y(b) in channel cross section, $q_w =$35/0 kW/m$^2$, Re =50 000: 1) Ha=0; 2) 300; 3) 500; 4) 800.](image)
There are conditions in which it is best to apply the conduction method (electromagnetic method). A sensor based on this measurement method is used in the presence of a MF. It consists of two copper electrodes located on an axis which perpendicular to the measured velocity and MF direction (Fig. 1 (b)). In the presence of the velocity transverse component and the MF corresponding direction between the sensor electrodes, a potential difference arises, the value of which is proportional to the transverse component of the velocity in the gap between the electrodes.

As an example of measurement using this method, consider the results that were obtained using a combined three-thermocouple sensor. Such a sensor can operate as a correlation and conduction method. Each pair of thermocouples T₁ and T₂, T₂ and T₃ can be simultaneously used as a two-electrode sensor, taking the signal from a pair of copper wires, to measure the fluctuation components \( V_{y}' \) and \( V_{y}' \) in an external MF \( B_x \) (Fig. 6).

The method is based on Ohm's law for a moving electrically conductive environment:

\[
\frac{j}{\sigma} = E + V \times B
\]  

(5)

Or, in the projection on the horizontal axis, perpendicular to the axis of the channel:

\[
\frac{j_z}{\sigma} = E_z + V_y B_x
\]  

(6)

For the fluctuation component of the velocity \( V_{y}' \):

\[
\frac{j_z'}{\sigma} = E_z + V_{y}' B_x
\]  

(7)

![Figure 6. Three-thermocouple velocity sensor in two planes: a) X–Z, b) Y–Z.](image)

We believe that the velocity fluctuation component \( V_{y}' \) caused by vortex structures with axes directed along the MF, that is, along the X axis. We assume that vortex structures have poor conditions for shorting the electric currents generated in a MF, therefore, we neglect the electric current density \( j_x \) on the left side of the equation. We obtain

\[
\frac{u_{12}}{l_{12}} = -E_z = V_{y}' B_x,
\]  

(8)

where \( u_{12} \) is the potential difference between copper electrodes 1 and 2 and from here:

\[
V_{y}' = \frac{u_{12}}{l_{12} B_x},
\]  

(9)

Electromagnetic method is problematic to measure the velocity averaged component \( V_y \) in a MF, since electrical currents are generated in the flow and shunt the useful signal. However, it is possible to measure the fluctuation component \( V_{y}' \), which cannot be done by the correlation method. Since the
fluctuation component $V_y'$ is associated with large-scale vortex structures caused by free convection [8], with axes parallel to the field induction lines, and they, according to the authors, do not lead to the currents generations. Typical waveforms for the transverse velocity component $V_y'$ are shown in Fig. 7. These data on velocity fluctuations are preliminary and require further appropriate statistical processing in order to build and verify numerical computational models.

![waveform]

**Figure 7.** Waveforms of velocity fluctuations $V_y$ near a heated wall. 
Re = 35000, $q_w=35$ kW/m², Ha=800.

**Conclusion**
The versatility of speed sensors is that microthermocouples are used as a sensitive element. Therefore, it is possible simultaneously with the local value of the averaged velocity component to obtain in the measurement zone: averaged and fluctuation temperature characteristics. In addition, it allows us to make temperature compensation of signals, as well as significantly reduces the time spent on experiments.

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