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Temperature correlation velocimetry technique in liquid metals

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ABSTRACT

The article describes the temperature cross-correlation velocimetry method applied to liquid metal flows. The technique allows to measure temperature waveforms and average longitudinal velocity in a flow simultaneously. The used micro thermocouple sensor and signal processing procedure are described in comparison with other works where the same or a similar approach have been implemented. Examples of experimental results obtained in MPEI[1] – JIHT[2] mercury facilities, are also provided. Method has been successfully used in magnetic fields up to 1 T.

1. Introduction

The local velocity measurement in liquid metal (LM) has been not an easy task since many difficulties have to be addressed. When choosing a measurement method, the following features of liquid metal should be taken into account:

1. High density;
2. High electrical and thermal conductivity;
3. Opacity;
4. High temperatures (except mercury, InGaSn, Na-K and some other alloys);
5. Toxicity;
6. Oxides and contaminants presence;
7. Chemical activity;
8. Electromagnetic issues.

A variety of techniques commonly used to measure flow velocity are not applicable at all or require significant modification to be used in liquid metal flow.

Invasive technique in liquid metal faces high demands on sensor's tightness and durability in conjunction with a reasonably small measuring point localization.

The possible velocimetry methods in relation to conducted research of mercury heat transfer and hydrodynamics in heated channels affected by magnetic field [1], have been considered. The goal is to obtain longitudinal velocity component profiles in the channel’s cross section.

For quite a long time the temperature correlation velocimetry (TCV) had shown itself as one of the simplest and the most reliable among several common methods [2–4] used in MPEI and JIHT researches.

This method is intuitive; it appears naturally in environments with multiple points of temperature measurement [5,6]. Serious development was connected with researches dedicated to the nuclear industry [7–10] in 1970s. However, obtaining high-accurate results was time-consuming. The complexity and big amount of the equipment required for analog signal processing have become a significant barrier to widespread implementation at that time. In the cross-correlation technique, a significant role is given to flowmeters in which a special form of flow tract creates conditions convenient for steady flow measurement by the correlation method [11–13].

The TCV technique discussed herein is fundamentally similar to the approaches developed in the flowmeter solutions design though has significant distinctions. The main one is the desire to achieve complete absence of flow disturbance by the measuring sensor, as well as minimizing the base distance between the temperature sensors aimed at measurement localization. Examples of this approach are given in [14–16] and discussed below in comparison with our own results. It is necessary to emphasize the difference in cases when measurement points are separated by a significant distance [5,6,17]. In this case, the changes of flow itself should be considered (spatial averaging effect) which causes extra difficulties and is not discussed in this paper. There is no clear borderline between the flowmeter technique and more localized measurements. However, we categorized TCV separately as a technique able to measure local velocity using temperature waveforms without significant flow disturbance.

The TCV technique described in the article was used for velocity profile measurements in mercury flow in vertical, horizontal and

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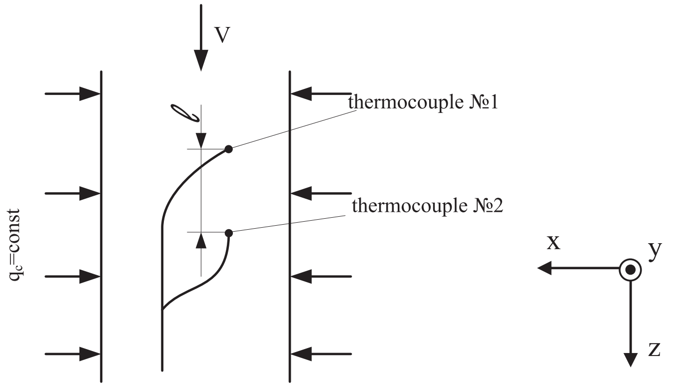

Fig. 1. TCV- basic scheme.

inclined channels affected by thermogravitation and strong magnetic fields of various orientation (transverse, longitudinal) [1].

2. Temperature correlation measurements

2.1. Sensor

To measure the temperature cross-correlation with subsequent achieving the longitudinal velocity component V_z, the authors used a sensor with basics shown in Fig. 1. It consists of two micro thermocouples (in our case type – T) with a fixed distance between them. Thermocouples junction probe is located on the centerline. The actual sensor views are shown in Fig. 2.

Thermocouple hot junction size was δ = 0,2 mm, the distance between thermocouples in most of our experiments was l = 5,0 mm for velocities ranging 1–250 mm/s, and with heat flux q_c through the tube wall. Thermocouples were attached to steel capillaries with high temperature epoxy adhesive. The sensor was mounted on the end of a swivel-type probe (Fig. 3).

Some probe measurements were performed with the longitudinal magnetic field presence. This could have an impact on sensor readings associated with conductive fluid flow deceleration in magnetic field. This creates a so-called “front wake” [18]: flow distortion caused by sensor extended in the upstream. The typical size δ_p of the perturbation region in the direction of the average velocity is taken as $\delta_p/d_T = N_T^{0.5}$ [19], where $N_T = \frac{Ha^2}{\mathrm{Re}}$ is a local Stuart number (local MHD parameter) calculated using streamlined body diameter d_T. as a characteristic length. In our case, magnetic induction was up to B = 1T. This fact had been considered in the probes design.

The probe size ratio was chosen in such a way so that probe elements “front track” did not reach the neighboring microthermocouples. Besides, the work [20] has been taken into account and resulted in conclusion that the cylindrical body in a longitudinal magnetic field flowed round about substantially the same as in its absence if $N_T \leq 0, 7$. In most of our experiments this inequality was correct up to B = 0.5 T which gave us less than 1 mm front track.

The above measurement difficulties in liquid metal flows are partly compensated by the following favorable features of temperature fields of liquid metals. Due to the high thermal conductivity the average temperature, profiles and temperature fluctuations statistical characteristics in the flow vary quite smoothly even near the heated wall. Thus, measurements in the mercury flow do not have such high requirements for the thermocouple junction’s size and setting coordinates accuracy, as compared, for example, to measurements performed in a water flow. When using the probe, especially when dealing with complex multi thermocouple probes for dimensional correlation functions research, we have to put up with the inevitable small-scale perturbations of the velocity field. However, in liquid metals these perturbations do not affect the temperature field structure. This happens since only relatively large thermal inhomogeneities may exist in liquid metals, while smaller ones are absorbed due to high molecular thermal conductivity. Indeed, in a non-isothermal isotropic turbulence we have the following ratio between the Taylor microscales for velocityλ_V and temperature λ_T fluctuations:

$$\lambda_V/\lambda_T = \sqrt{\mathrm{Pr}}\,.$$

Taylor time microscales can be found from autocorrelation function of a signal sample:

$$\frac{1}{\lambda^2} = -\frac{1}{2}\left(\frac{\partial^2 R_{xx}(\tau)}{\partial \tau^2}\right)_{\tau=0},$$

where R_{xx}- autocorrelation function.

Our correlation measurements show that time microscales and therefore sizes of temperature fluctuations during our experiments in mercury flow are quite large – sizes are about several millimeters. This confirms our conclusion about the low sensitivity of the temperature field in the liquid metal to the local small-scale velocity perturbations.

The swivel-type probe is basically a rod pivotally mounted on the frame. The probe moves by rotating the cross-pivot caliper screw attached to the end of the probe rod. Movement is controlled by indicators. Each movement is followed with a pause in measurements to stabilize the flow. The probe’s natural frequencies are higher than observed in hydrodynamics air, water, and mercury flow measurements by several orders. The probe positioning in the channel section is ensured by defining the wall touch along the temperature profile fracture (Fig. 4).

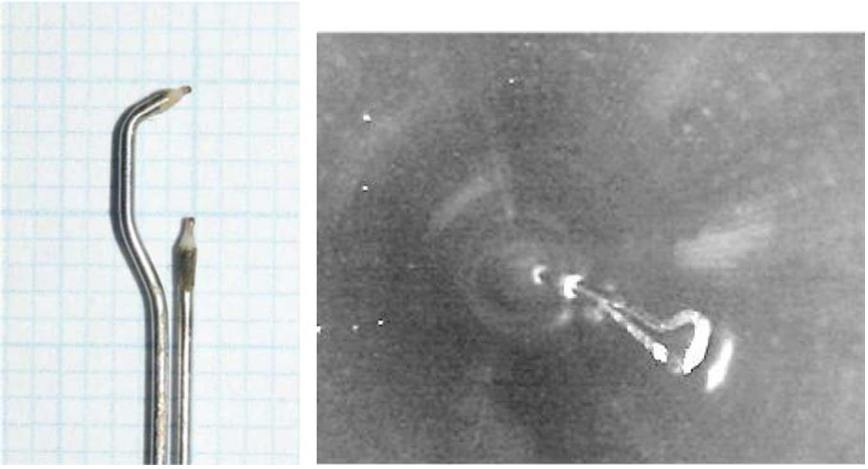

Fig. 2. TCV – sensor: side view and front view inside a tube (19 mm inner diameter).