Spatial-temporal characteristics of temperature fluctuations of turbulent fluid flow and velocity measurements based on them

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Abstract. The paper describes the temperature cross-correlation velocimetry method applied to flows of water or liquid metal. The technique allows us to measure temperature waveforms and averaged longitudinal velocity in a flow simultaneously. This approach is a simple and reliable method for measuring the velocity in flows of opaque coolants. At the same flow parameters, liquids of different origins provide non-similar spatial-temporal characteristics having a different impact on the applicability of the temperature correlation method. This work is devoted to the development of practical methods allowing to form a set of specific recommendations on the application of the technique of temperature correlation velocimetry and to determine the metrological characteristics of the technique in various conditions. Calibration was carried out using water and mercury as a model liquid. Used experimental facility and measuring system are described, accompanied by a detailed description of the developed temperature-correlation sensor. Measuring directly from within a flow is made possible by a unique micro thermocouple immersion probes technique. Data obtained are presented as fields of temperature and intensity of temperature fluctuations. Autocorrelation and cross-correlation functions are compared and analysed for two studied fluids under identical conditions.

1. Introduction
Investigations of hydrodynamics and heat transfer, in conditions close modern energy plants, are an integral part of substantiating efficiency and safety of such facilities. Liquid metals and other promising coolants (for example, molten salts) are used or considered for application in a number of experimental and already commissioned reactors, such as BN (sodium-cooled fast breeder reactor), BREST (lead-cooled fast reactor), and test modules of the blanket of TOKAMAK-type thermonuclear reactors.

Information about averaged flow characteristics is sufficient to calculate efficiency of systems with fewer complicating factors. However, calculation of heat transfer coefficients is difficult when influence of thermogravitational convection (TGC) on a turbulent flow of liquid metal is significant. In this case, one need to know the local values of velocity and temperature with high accuracy. Inhomogeneity and asymmetry in velocity profiles, and accordingly in temperature, is of greatest interest in issue of substantiating stability during long-term, stationary operation of power plants.
Velocity measurements in a liquid metal flow are complicated by several factors: high temperature, high electrical conductivity, chemical activity, high density, and optical impermeability of a coolant. Many of developed and well-studied methods are not available for research because of these factors. An alternative is promising temperature-correlation method [1], which uses temperature signals to further evaluate a longitudinal velocity by statistical methods. Correlation methods are applied widely using different base signals, including air-water phase optical phase detection [2], images [3], electromagnetic signal [4] and so on.

Experimental studies of hydrodynamics and heat transfer under conditions of high thermal loads in configurations similar to those of modern power plants require special diagnostics. Special interest is to perform acquisition of detailed profiles of local velocities and temperatures on the wall and statistical characteristics of fluctuations in a flow. Receiving such a data with high accuracy is possible by unique immersion probes technique. The probe can be equipped with a special microthermocouple correlation sensor, designed and manufactured by our team.

2. Method description
The use of immersion probes makes rather high demands on a tightness and durability of the sensor. However, other methods of measuring a velocity are not applicable or require significant modification for use in liquid metal flows. Temperature-correlation method (TCV) is one of the simplest and most reliable methods used [5-7] to measure velocity in such conditions. Method is based on temperature measurements at several points [8, 9] with further signal processing using the autocorrelation function (1). The autocorrelation function characterizes a degree of correlation between individual values of measured parameters of a centered signal.

For discrete signal, typical for measurements:

\[ R_{11}(\tau) = \frac{1}{n} \sum_{i=1}^{n} T_1(i \cdot \Delta \tau)T_1(i \cdot \Delta \tau + s) \]  

where \( s \) – time shifting, \( s=j \cdot \Delta \tau \), \( j = 0, 1,.., \text{sec} \); \( \Delta \tau \) – time step, sec; \( n \) – sampling size.

![Figure 1. TCV- basic scheme.](image)

To improve measurement accuracy, we tried to achieve full hydrodynamic stabilization and possible flow fluctuations in the measured cross-section, as well as to minimize the distance between thermocouples (figure 1) in order to localize measurements \( (l = 5 \text{ mm}) \). Such an approach was discussed in [10-12], however, if the measurement points are located at a considerable distance[8, 9, 13], it is necessary to take into account changes in a flow itself (effect of spatial averaging), which causes additional difficulties. We consider TCV as a method for measuring the profiles of longitudinal velocity component in the channel cross-section, without significant disturbance of a flow.

Since TCV method is based on use of natural background of turbulent fluctuations, knowing delay time of second signal, it is possible to determine time-averaged value of local flow velocity.

Cross-correlation function (2) of thermocouple signals of correlation velocity sensor can be determined by formula:
\[ R_{12}(s) = \frac{1}{n} \sum_{i=1}^{n} T_1(i \cdot \Delta \tau)T_2(i \cdot \Delta \tau + s) \]  

(2)

where \( s \) – time shifting, \( s = j \cdot \Delta \tau, j = 0, 1, ..., \) sec; \( \Delta \tau \) – time step, sec; \( n \) – sampling size.

3. Experimental conditions and results

To conduct test experiments using a TCV sensor, RK-3 facility have been used (figure 2); for calibration, water was used as a model liquid (RK-3 is a third generation facility including separate water and mercury loops [13], originally created for study of liquid metal coolants).

Circulation in the loop is provided by a chemical centrifugal pump; Pressure fluctuations after pump are effectively reduced because of combined operation of reducer and systems of membrane and air-type fluctuation damper. As a result, at entrance to test zone (thin-walled pipe with an inner diameter of 19 mm and a wall thickness of 0.5 mm), a flow is supplied, hydrodynamic stabilization of which occurs at first 60 calibers of the experimental section and on next 40 calibers, studied flow develops. At the end of test section, in the heating zone, a swivel-type scanning probe (figure 3) is installed, on tip of which a TCV sensor is fixed.

![Figure 2](image-url)

Figure 2. Schematic diagram of RK-3 water loop: (1) storage tank, (2) centrifugal pump, (3) valve, (4) membrane type pulsation damper, (5) pressure reducer, (6) air-type pulsation damper, (7) working area, (8) electromagnet, (9) pressure sensor, (10) measuring probe, (11) heat exchanger, (12) three-way ball valve, (13) turbine flowmeters TPR-4 and TPR-8, (14) valve, designed for" rough" adjustment, (15) valves designed for" smooth" adjustment, (16) selected cross section, and (17) homogeneous heating of the experimental section.
We have studied basic geometry of a vertical uniformly heated pipe of 19 mm inner diameter. Two general parameters are control the flow regime under these conditions. The Reynolds number $Re = \frac{ud}{\nu}$, where $u$ – average velocity, $d$ – pipe diameter, $\nu$ – kinematic viscosity; and The Grashof number $Gr = \frac{g\beta q d^4}{(\lambda^2 \nu)}$, where $g$ - gravitational acceleration, $m/s^2$; $\beta$ - coefficient of thermal expansion, $1/K$; $q$ - heat flux, $W/m^2$; and $\lambda$ - thermal conductivity, $W/(m\cdot K)$. Described above technic allows to achieve detailed picture of the flow state in the given cross-section. Example is given in figure 4 for water and mercury at the very same flow parameters. Fields of dimensionless temperature fluctuation intensity are given $\sigma^*=\frac{\sigma \lambda}{(qd)}$, where $\sigma$ - intensity of temperature fluctuation, $^\circ C$. Due to different molecular heat conductivity of media ($Pr$ number) the fields differ significantly. Liquid metal provides a much more filled with temperature fluctuations cross-section, which allows one to achieve a higher signal-to-noise ratio, when implementing the TCV technique.

$$Gr=1.1\cdot10^7, \ Re=10000, \ fully \ developed \ flow \ in \ a \ pipe. \ Dots \ are \ exact \ point \ of \ measurements.$$
Form of cross-correlation function (CCF) is strongly connected with auto-correlation function (ACF) of base signals, as basically CCF is shifted and degraded ACF (see example given in figure 6). To minimize the uncertainty of velocity measurements using TCV technique it is necessary to improve CCF peak designation. Analysis of ACF is a first step in optimizing the measurement. Performed experiments allow us to generalize different approaches necessary for liquid metals and non-liquid metals in the same conditions. In the first case one should mostly focus on a sufficiency of the sample’s length. In the latter case noise reduction and signal conditioning becomes more important.

4. Conclusion
Temperature correlation velocimetry is a promising method due to relative simplicity. Its application is constrained by the complexity and low level of sophistication of signal processing, which require not only adaptation of developments from other areas of the statistical theory of signal processing, but also a deep understanding of the flow structure.

Ongoing experimental work is devoted to development of practical methods allowing to form a set of specific recommendations on the application of the technique of temperature correlation velocimetry and to determine the metrological characteristics of the technique in various conditions.

Figure 5. Waveforms and auto-correlation functions in the center and half-radius of the pipe in conditions described in figure 4: (a) liquid metal (b) water.

Figure 6. (a) – Temperature fluctuation signals for mercury flow in a pipe centre in the same conditions as in Fig.4. Measurements are performed using TCV sensor with 5 mm base; (b) – cross-correlation (R12) and autocorrelation (R11) functions of the signals.
At the current stage of research, we have performed series of tests on water and mercury revealing differences in cross-correlation processing expected in liquid metals and non-liquid metal liquids.

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