Correlation analysis for the research of local characteristics of a turbulent flow

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Abstract. The paper describes the temperature-correlation velocimetry technique applied to the flow of water or liquid metal. The method allows simultaneous measurement of temperature signals and local values of a longitudinal velocity component in the flow. This approach is a simple and reliable method for measuring velocity in flows of optically impermeable fluids. At the same flow conditions, different coolants have different spatial-temporal characteristics that are processed using a temperature-correlation technique. This work is devoted to the development of an algorithm for formulating a set of practical recommendations for the use of this technique to measure velocity and to determine a metrological characteristic in various conditions. For calibration, water and mercury are used as model liquids. The data obtained are presented in the form of fields of temperature and intensity of temperature fluctuations. Autocorrelation and cross-correlation functions are compared for two investigated liquids under the same conditions.

1. Introduction

Modern methods of designing heat exchange systems and equipment for nuclear and thermonuclear industries include a rationale of efficiency and safety. To evaluate them, it is necessary to study hydrodynamics and heat transfer, both numerically and experimentally, for each developed configuration of equipment. Information on a distribution of averaged and local characteristics in a flow of studied coolants is required. Numerical research is complicated by high requirements for computing equipment, the complexity of computational models and code verification. Experimental research is complicated by high cost of experimental facility development, the complexity of measurement systems and experimental procedures.

Liquid metals and other promising coolants (for example, molten salts) are used or are considered for use in a number of experimental and already commissioned reactors, such as BN (sodium cooled fast reactor), BREST (lead cooled fast reactor) and test modules of the blanket of TOKAMAK fusion reactors. Joint scientific group of MPEI-JIHT RAS [1] has been carrying out such studies in a flow of promising coolants for many years.

Measurement of velocity in a flow of liquid metal is complicated by a number of factors: high temperature, high electrical conductivity, chemical activity, high density and optical impermeability of a coolant. Information on averaged characteristics of the flow is quite sufficient for calculating the efficiency of systems, however, for calculating a heat transfer coefficient with a significant effect of thermogravitational convection (TGC) on a turbulent flow of liquid metal [2, 3], classical methods are
inapplicable. Therefore, it is necessary to clarify a local value of velocity and temperature with high accuracy. Inhomogeneity and asymmetry of velocity profiles, as well as temperature is of the greatest interest in substantiating stability during long-term stationary operation of power facility.

Most of developed and well-studied methods (PIV, SIV and others) are not applicable in liquid metal flows. A way out of this situation is the promising temperature-correlation method (TCV) [4], which uses temperature signals for further evaluation of longitudinal velocity using a statistical approach. Correlation methods are applied widely using different base signals, including air-water phase optical phase detection [5], images [6], electromagnetic signal [7] and so on.

2. Experimental conditions
Temperature correlation method (TCV) is one of the simplest and most reliable methods used [8–10] to measure velocity in flows of liquid metals. Data are obtained with high accuracy using technology of microthermocouple submersible probes, which allows receiving signals directly from within the flow. The only requirement for the use of immersion probes (Fig. 1, a) is high tightness and durability of thermocouple sensors. TCV is based on temperature measurements at several points of a flow [11, 12] with subsequent signal processing using correlation analysis. This technique provides a detailed picture of state of a flow in a fixed cross-section. A more detailed description of the method and results of first experiments are given in [13].

![Figure 1. Swivel-type probe (a), TCV- basic scheme (b) and TCV sensor (c).](image)

In the course of work, a special microthermocouple TCV-sensor is developed (Fig. 1, c). To improve a measurement accuracy, it is necessary to achieve full hydrodynamic stabilization of a flow at the measured point, and, if possible, to minimize the distance between thermocouples (Fig. 1, b) in order to localize measurements ($l = 5$ mm). This approach was applied in [14–16]. The distance $l$ may vary depending on the used coolant and average flow rates. If measurement points are located at a considerable distance [11, 12, 17], it is necessary to consider changes of a flow (spatial averaging effect), which causes additional problems.
Figure 2. Problem configuration (a); Schematic diagram (b) of RK-3 water loop: (1) storage tank, (2) centrifugal pump, (3) valve, (4) membrane type fluctuation damper, (5) pressure reducer, (6) air-type fluctuation 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.

Figure 3. Schematic diagram of RK-2: 1 – work area; 2 – immersion probe; 3 – electromagnet; 4 – compensation capacity; 5 – “pipe-in-pipe” heat exchangers; 6 – flowmeter; 7 – differential pressure gauge; 8 – electromagnetic pump; 9 – control valve; 10 – storage tank; 11 – thermocouples; 12 – measuring instrument rack; 13 – computer (PC).

To conduct test experiments using a TCV sensor, RK-3 facility is used (Fig. 2); for calibration, water is used as a model liquid (RK-3 is a third-generation facility including separate water and mercury loops, originally created for the study of liquid metal coolants). The electromagnet makes it possible to measure the local velocity in problems with MHD flows. Experiments with liquid metal are carried out at the RK-2 facility (Fig. 3), both facilities being located on the territory of JIHT RAS. Research is performed in a downward flow of water and liquid metal in a vertical pipe with an inner diameter of 19 mm. Design of the working section allows realizing a condition of uniform and non-uniform heating (Fig. 2, a) and provides full hydrodynamic stabilization in a measurement area. Under such conditions, flow regime is controlled by two parameters: Reynolds number $\text{Re} = \frac{ud}{\nu}$ (where $u$ is the average velocity, m/sec; $d$ is the pipe diameter, m; $\nu$ is the kinematic viscosity, m$^2$/sec) and Grashof number $\text{Gr} = \frac{g\beta q_w d^4}{\lambda \nu^2}$ (where $g$ is the acceleration of gravity, m/sec$^2$; $\beta$ is the thermal expansion coefficient, 1/K; $q_w$ is the heat flux density, W/m$^2$; and $\lambda$ is the thermal conductivity, W/(m·K)).

3. Experimental results
Autocorrelation function (ACF) characterizes the degree of correlation between individual values of measured parameters of a single centered signal and carries the same information as a spectral energy density. Analysis of the ACF shape allows concluding on the structure of a signal at a point and giving recommendations about the sample length and the required gap between a point of measurement of a cross-correlation function (CCF).
Figure 4. Fields of dimensionless temperature fluctuation intensity. (a) water (b) liquid metal.
Gr=1.1\cdot10^7, Re=10000, fully developed flow in a pipe. Dots are exact point of measurements.

The structure of the flow of water and liquid metal is significantly different, including due to different molecular thermal conductivity. Liquid metal has a high molecular thermal conductivity, which, all other things being equal, provides a greater overheating of a liquid in a cross-section. Then the region of significant temperature fluctuations expands, which allows achieving a higher signal-to-noise ratio when implementing TCV method and facilitates its application. Fields of dimensionless intensity of temperature fluctuations (Fig. 4) are defined as: \( \sigma^* = \sigma \lambda / (q_w d) \), where \( \sigma \) is the intensity of temperature fluctuations, °C. On the other hand, detailed temperature waveforms and their autocorrelation functions (Fig. 5) show that temperature signals for water have a higher frequency, which gives more statistical information for the same measurement length. These data are consistent with early studies of the structure of a flow of liquid metal and water [18, 19].

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

Form of CCF is related to ACF of a basic signal, since in most cases the offset of CCF produces a reflection in ACF (Fig. 6 and 7). To minimize measurement uncertainty of a TCV rate, it is necessary to accurately identify a CCF peak. Calculation of longitudinal component of velocity is carried out by evaluating a displacement of a CCF peak. Received signals are resistant to interference sources (for
example, electromagnetic noise) and filtering is possible using spectral analysis. At the moment, an experimental program with sources of interference is being prepared to test a signal filtering algorithm.

![Figure 6](image-url)  
**Figure 6.** Temperature waveforms for the mercury flow in the pipe center.  
Uniform heating: $Gr = 7 \times 10^7$, (a–d); Non-uniform heating: $Gr = 3.4 \times 10^7$, (e–h).  
Reynolds numbers: (a, e) – $1.2 \times 10^4$, (b, f) – $2 \times 10^4$, (c, g) – $3.5 \times 10^4$, (d, h) – $5 \times 10^4$. 

![Diagram](image-url)
Convergence of a CCF peak over the ordinate axis with an increase in Reynolds number indicates an increase in local velocity, and for regimes Re > 50000 it is required to increase a distance l between thermocouples. ACF analysis is the first step in optimizing TCV method. The conducted experiments significantly expand the experience of using the correlation analysis of temperature signals, which allows us to formulate recommendations for the use of the method in liquid metals and non-metallic liquids.

**Conclusions**

Finding the characteristics of an autocorrelation function of a temperature signal is an important step in determining the applicability of the temperature correlation method. Liquids that are different in nature under the same conditions (at the same Reynolds numbers) are strikingly different when measuring the statistical characteristics of their temperature fluctuations, which is caused both by different dynamics of turbulence in metals and non-metals, and by an inertia of the sensors.

A series of measurements on water and mercury has revealed differences in the requirement for a parameter of an initial pair of temperature signals for cross-correlation measurement of velocity in liquid metals and non-metallic droplet liquids.

This experimental work is devoted to the development of practical methods for formulating a set of simple recommendations for the use of the temperature-correlation method for measuring velocity and determining a metrological characteristic in various conditions.

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**References**

[1] Batenin V M et al. 2015 *High Temperature* **53** 904–7
[2] Sviridov V G 1989 *Investigation of hydrodynamics and heat transfer in channels as applied to the problem of creating a thermonuclear power reactor* (Moscow: MPEI) 438
[3] Ibragimov M Kh et al. 1978 *Turbulent flow structure and heat transfer mechanism in channels* (Moscow: Atomizdat) 296
[4] Belyaev I A et al. 2017 *Flow Measurement and Instrumentation* **55** 37–43
[5] Chanson H et al. 2007 Environmental Fluid Mechanics 6 495–509
[6] Tokumaru P et al. 1995 Experiments in Fluids 19 1–15
[7] Dubovikova N et al. 2016 Measurement Science and Technology 5 055102
[8] Zhilin V G et al. 1989 Magnetohydrodynamics 3 382–5
[9] Ricou R and Vives C 1982 Int. J. Heat. Mass Transf. 25 1579–88
[10] Malcolm D G 1970 Magnetohydrodynamics 2 198–207
[11] Horanyi S et al 1999 Int. J. Heat. Mass Transf. 21 3983–4003
[12] Frick P et al 2015 EPL 1 14002
[13] Sardov P et al 2020 J. Phys.: Conf. Ser. 1689 012037
[14] Rockwell S 2012 Influence of coal dust on premixed turbulent methane-air flames (United Kingdom: Worcester Polytechnic Institute) 263
[15] Motevalli V et al 1992 J. Heat. Transf. 2 331–7
[16] Delarochelambert P 2000 Proceedings of the 3rd ETS Conference 675
[17] Belyaev I A and et al 2017 Therm. Eng. 11 841–8
[18] Ibragimov M K et al 1968 TVT 6 1066
[19] Eyler L and Sesonske A 1980 Int. J. Heat. Mass Transf. 11 1561