Investigating heat transfer in an upward flow of liquid metal in the mercury facility with a loop of natural circulation

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Abstract. Research of heat transfer is performed in an upward flow of liquid metal in a vertical channel of rectangular cross-section under the condition of one-sided heating and in a vertical pipe in a mercury circuit with a natural circulation loop. Natural circulation loop enables measurements in mixed turbulent convection modes, which are inaccessible on a contour with a forced convection, that is, in the region of small Reynolds (Peclet) numbers of characteristics. Using a two-coordinate probe with a microthermocouple correlation sensor, profiles of averaged velocity and temperature and distribution of a wall temperature are obtained, and heat transfer coefficients are determined. Criterion dependences of Nusselt number on Peclet and Richardson are built. Experimental data on heat transfer are compared with similar data obtained earlier in a loop with a forced flow of mercury.

1. Introduction
In natural circulation, a flow pattern is of great importance in the design of power equipment. This is essential in nuclear power engineering, in a design of cooling circuits for fast reactors with liquid metal cooling. Lead and its alloys are the most promising as a coolant in nuclear power. Transition to a natural circulation mode in such facilities is possible in emergency situations - in case of failure of a circulation pump.

Research of features of heat transfer during a flow of liquid metals in pipes and channels of various orientations (horizontal, vertical, inclined) as applied to cooling systems for nuclear reactors is carried out on the basis of the mercury facility of JIHT RAS [1].

Heat transfer under mixed turbulent convection has been studied in most detail for non-metallic liquids [2], and for liquid metals (LM) it is insufficiently presented in the literature. Studies have been carried out mainly for sodium [3, 4]. From a class of heavy liquid metals, mercury has always been considered as a model liquid [5, 6]. The early studies reveal that during LM flow in a vertical heated pipe and channel, natural or thermogravitational convection (TGC) has a strong effect on characteristics of turbulent heat transfer in a forced flow. In recent experiments, detailed characteristics of heat transfer are obtained for mixed turbulent convection with an upward flow of mercury in a pipe [7]. A found decrease in heat transfer in comparison with turbulent convection is consistent with general laws of heat transfer with mixed convection and the data presented for mercury [5–7].

Natural circulation loop raises possibilities of the existing facility to obtain stable regimes with low Reynolds numbers and to enter a region of large Richardson numbers Ri=Gr/Re², which was previously inapproachable.
2. Problem conditions and research methods

Experimental study was carried out at the mercury facility of JIHT RAS. Problem configuration and schematic diagram of the loop are shown in Fig. 1. A natural circulation loop was installed on the existing facility. The loop included two vertical pipes: one mounted on a heater (0.8 m long) of indirect heating, providing the condition of \( q_w = \text{const} \), and another one was on a cooler of “pipe-in-pipe” type with water cooling and a control valve. An upward flow of mercury in a heated pipe with an inner diameter \( d = 18 \) mm and a wall thickness of 1.0 mm was considered. Heat flux density was achieved in experiments with \( q_w = 25 \) kW/m².

Figure 1. Problem configuration (a); Schematic diagram (b) of RK-2 with natural circulation loop:
(1) working area with heater, (2) thermocouples, (3) immersion probe, (4) compensation tank,
(5) heat exchangers-refrigerators, (6) flowmeter, (7) mercury differential pressure gauge,
(8) electromagnetic pump, (9) control valve, (10) storage tank, (11) measuring lines,
(12) instrument rack, (13) personal computer with instrument interface.

Temperature and velocity fields in the channel cross-section at a distance from the entrance to the heating zone were measured using a lever-type articulated probe [8]. Measurements were carried out in a heated pipe by the probe method, for which a swivel probe with a correlation microthermocouple sensor at the end was introduced at the exit from a working section [8]. The probe allowed scanning the profile of longitudinal averaged velocity and temperature in a flow, in a section at a distance of 38 diameters from the beginning of heating. Velocity and temperature profiles were used to calculate an average mass temperature in a cross-section \( T_b \), and average heat transfer coefficients were determined from temperature distributions on the wall.

3. Experimental results

A series of experiments was carried out to study characteristics of heat transfer during an LM flow in the facility with a loop of natural circulation during an upward flow in a vertical pipe with uniform heating and with heat flux densities on a semi-perimeter \( q = 2000 \text{–} 25000 \) W/m².

Swivel lever-type probe served to obtain velocity and intensity fields of temperature fluctuations in a pipe section, a distance of \( z = 38d \) from the beginning of heating.

Experiments realized under the conditions of natural convection allowed obtaining data for small Reynolds numbers \( Re = 1700 \text{–} 10500 \). Modes were varied with maintaining the fixed position of shut-off control valve and power of heater.

Measurement data with \( q_w = 5000 \) W/m², obtained with minimum loop resistance (with valve fully open) are shown below as an example.
Velocity profiles were measured in two mutually perpendicular axial planes along $X = x/r_0$ and $Y = y/r_0$ axes. Experimental points were obtained using a correlation two-thermocouple sensor. Fig. 2 (a) shows as an example of profiles of averaged longitudinal velocity along the X-axis only. Along both X-axis and Y-axis, velocity profiles have the same shape as in the loop with a forced flow with mixed turbulent convection. Velocity profile along the X-axis is symmetrical about a pipe axis and has a weakly expressed “m”-shape, which is explained by the influence of buoyancy forces. Velocity was averaged over the pipe cross-section and dimensionless profiles reduced to $V_0$ were constructed. Results in Fig. 2 (b) show that profiles are almost the same.

Since the velocity sensor consists of two thermocouples, it is possible to obtain average and fluctuation temperature profiles simultaneously with velocity profiles. Fig. 3 (a) shows a profile of dimensionless temperature difference of an isotherm in a section of a pipe and channel and profiles of dimensionless temperature $\Theta=(T-T_b)/(q_0d/l)=1/Nu$, where $T_b$ is the mass-average temperature in a given section, determined by integrating profiles of a superficial velocity and temperature (by definition), and $\lambda$ is the thermal conductivity. All observed flow regimes are turbulent, with distribution of an intensity of temperature fluctuations shown in Fig. 3 (b).

![Figure 2](image1.png)

**Figure 2.** Longitudinal velocity (a) and dimensionless velocity (b) profiles:
1) $q = 5$ kW/m$^2$, 2) 10, 3) 15, 4) 20, 5) 25.

Fig. 4 shows the wall temperature distribution in dimensionless form as a sweep for channel cross-section perimeter. For comparison, the graph shows values $1/Nu_1$ and $1/Nu_2$: for a developed turbulent flow, calculated by the Lyon formula $Nu_1=7+0.025Pe^{0.8}$ for extreme Peclet (Reynolds) numbers corresponding to points 1 and 5; and for a stabilized laminar flow $Nu_1=4.36$ [1].

![Figure 3](image2.png)

**Figure 3.** Profiles of dimensionless temperature (a) and intensity of temperature fluctuations (b) in the pipe cross-section.
Apparently, the temperature distribution is not entirely, but close to be uniform due to insufficient length of a heater to stabilize the flow. Experimental data for local heat transfer are slightly higher or lower than turbulent values determined by the Lyon formula. Results of averaging such distributions are shown below on the data plots presented by criterion dependences.

**Figure 4.** Distribution of dimensionless wall temperature along the pipe perimeter: 1) $q = 5 \text{ kW/m}^2$, 2) 10, 3) 15, 4) 20, 5) 25.

**Figure 5.** Dependence of Nusselt number versus Peclet number (a): 1) $q_w=15 \text{ kW/m}^2$; 2) 22; 3) 30; 4) 42, 5) 50, 6) 5, 7) 10, 8) 15, 9) 20, 10) 25; normalized Nusselt number $Nu/Nu_T$ versus Richardson number (b): 1) data from [7]; 2) [5]; 3) loop of natural circulation.

Fig. 5 (a) contains averaged Nusselt numbers depending on Peclet number obtained in different modes in natural circulation loop (to the left of dashed line $Pe = 270$) and in the loop with a pump, obtained earlier in an upward flow in a pipe with $d = 19 \text{ mm}$ [7]. It can be seen that the points obtained for natural circulation loop are located mainly above the $Nu_T$ Lyon curve and near it. It is interesting to
present these data in the form of normalized Nusselt number $\text{Nu}/\text{Nu}_T$ versus Richardson number $\text{Gr}/\text{Re}^2$ (shown by crosses in Fig. 5 (b)). For comparison, circles show data from [7] and Buhr [5] under the conditions of a forced flow of mercury in a vertical pipe. The data is in good agreement with each other. Experimental points obtained in natural circulation mode supplement the points [7] in a region of large Richardson numbers and are located slightly above the data in [5]. That is, the behavior of experimental points corresponds to general regularities of heat transfer in a mixed turbulent convection in an upward flow in a vertical pipe [2].

Conclusions
Mixed turbulent convection was observed everywhere in a natural circulation loop in a vertical pipe with an upward flow of LM. Natural circulation allowed obtaining regimes with low Reynolds numbers and entering a region of large Richardson numbers $\text{Ri}=\text{Gr}/\text{Re}^2$, which was not approachable in early experiments in the loop with a forced coolant flow. New points obtained in natural circulation loop supplement the data in a forced flow loop and, in general, agree with the expected regularities of heat transfer for mixed turbulent convection in a vertical pipe.

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