Peculiarities of heat transfer at the liquid metal flow in a vertical channel in a coplanar magnetic field

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Abstract. The research of hydrodynamics and heat transfer at the liquid metal (LM) downward flow and upflow in a vertical duct of a rectangular cross section with a ratio of sides ~1/3 in a coplanar magnetic field (MF) under conditions of bilateral symmetrical heating is performed. The problem simulates the LM flow in the heat exchange channels for cooling the liquid metal module of the blanket of the thermonuclear reactor (TNR) of the TOKAMAK type. The experiments were carried out on the basis of the mercury magnetohydrodynamic test-bed (MHD) Moscow Power Engineering Institute (MPEI) – Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS). The probe measurement technique was used in the flow. Profiles of averaged velocity and averaged temperature, as well as profiles of temperature pulsations in the axial planes of the channel cross-section, are obtained; the distribution of the dimensionless wall temperature along the perimeter unfolding of the channel in the section and along the length of the channel. A significant effect of thermogravitational convection (TGC), which leads to unexpected effects, is found. At the downflow in a magnetic field, in some modes, low-frequency pulsations of anomalously high intensity occur.

1. Description of the experimental setup
Liquid materials (LM), mainly lithium lead eutectic Pb-Li [1], are considered as a coolant in a number of test blanket modules of the International Thermonuclear Reactor (TNR) ITER. Due to the electrical conductivity of media, the flow and heat transfer of the LM in the TNR channels is determined by the influence of the magnetic field and TGC. The identification of these differences requires experimental studies.

Complex studies of various configurations of hydrodynamics and heat transfer during the flow of mercury in pipes and channels are conducted at the Laboratory of thermophysical problems of nuclear and thermonuclear energy at mercury magnetohydrodynamic test-beds MPEI - JIHT RAS [2]. One of the test-beds is shown in figure 1.

The scheme of the LM flow in a straight vertical channel is shown in figure 2. The downflow and upflow of mercury in a channel of a rectangular cross-section with a side ratio of ~1/3 (section $a \times b = 56 \times 17$ mm) and a wall thickness of 2.5 mm was considered. The material of the channel wall is stainless steel 12X18H10T. The heating mode is bilateral symmetrical with a heat flow density $q_c = 20 \pm 25$ kW/m$^2$ on each wall. The working area is located between poles of an electromagnet with a length of a homogeneous MF of 600 mm and coincides with an area of homogeneous heating. The Reynolds, Grashof, Prandtl, Rayleigh and Peclet numbers had the following values in the experiments:
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Re = \frac{\bar{V}d}{\nu} = 10\,000 \div 55\,000; \quad Gr_q = \frac{g\beta \rho c d^4}{\lambda \nu^2} = 0 \div 6 \cdot 10^8; \quad Ha = Bd \frac{\sigma}{\mu} = 0 \div 800; \\
Pe = Re \cdot Pr = 50 \div 1400.
\]

\(\bar{V}\) is the average mass velocity; a characteristic dimension of \(d = 2b\) corresponding to the equivalent hydraulic diameter of a flat channel; \(g\) is gravitational acceleration; \(q_c = 0.5(q_1 + q_2)\) is the average arithmetic density of the heat flow; \(\nu\) and \(\mu\) are the kinematic and dynamic viscosity coefficients, respectively; \(\sigma\) is the electrical conductivity of mercury; \(\beta\) is coefficient of volumetric thermal expansion of mercury; \(\lambda\) is the coefficient of thermal conductivity of mercury; \(B\) is the magnetic field induction module.

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\[\begin{align*}
\text{Figure 1. Magnetohydrodynamic test-bed} \\
\text{MPEI - JIHT RAS}
\end{align*}\]

\[\begin{align*}
\text{Figure 2. Flow pattern in the channel section} \\
\text{that is being studied}
\end{align*}\]

Measurement of temperature and velocity fields in the cross section of the channel at a distance of \(21d\) from the entrance to the heating zone was performed using a swivel probe [3]. Measurements of the temperature fields were performed by a single-thermocouple sensor; the velocity fields were measured by the correlation method using a two-thermocouple sensor [3]. To measure the local characteristics along the length of the channel, a longitudinal probe of the “comb”-type was used [2]. The temperature of the channel wall was measured by touching the wall with a thermocouple of the probe, by extrapolating the thermocouple indications to the wall.

2. Results of measurements

Below there are the characteristic results in the mode: \(Re = 20\,000;\ q_1/q_2 = 20/20\ \text{kW/m}^2\). The measurements were made at the section of the channel remote from the entrance to the heating zone at \(Z = 21d\), which, as shown by length measurements, corresponds to the stabilized area of heat exchange.

On the figures 3-4 in the axial planes \(X = x/b\) and \(Y = y/b\) the profiles of the averaged dimensionless temperature \(\Theta = (T - \bar{T})/(q_c d / \lambda)\) are shown, where \(T\) is average mass temperature in a given section. It can be seen that under both the downflow and upflow, the profiles are symmetric, homogeneous along the \(X\) axis and heterogeneous along the \(Y\) axis. In the coplanar MF the profiles almost coincide – the delamination for different Hartmann numbers \(Ha\) is insignificant.

Figures 5-6 show the graphs with the wall temperature distributions \(T_c\) in the dimensionless form \(\Theta_c = (T_c - \bar{T})/(q_c d / \lambda)\) in the form of unfolding along the perimeter of the channel section. The dimensionless wall temperature is the reciprocal of the Nusselt number \(Nu\). For comparison, the values of \(\Theta_c = 1/Nu\) for the slit channel are also shown on the graphs: \(Nu_f = 10 + 0.025 Pe^{0.8}\) and \(Nu_L = \)
8.24 [2]. The graphs show a significant heterogeneity in the distribution of the channel wall temperature, which is related to the presence of adiabatic (short) walls.

Figure 3. Profiles of the dimensionless temperature in the axial planes $X$ and $Y$ with the downflow:
1) $Ha = 0$; 2) 300; 3) 500; 4) 800.

Figure 4. Profiles of the dimensionless temperature in the axial planes $X$ and $Y$ with the upflow:
1) $Ha = 0$; 2) 300; 3) 500; 4) 800.

For the downflow (figure 5) without the MF, heat exchange at the level of turbulent values (the red dots in figure). An unexpected and interesting fact in this mode is that in the coplanar MF the wall temperature and the heat exchange coefficients are at the level of turbulent values. It would seem that with complete suppression of turbulence with an increase in the Hartmann number, the heat exchange must be laminar and the wall temperature must grow to laminar values. However, this was not observed in a number of modes with the ratio $Gr_q/Re^2 \geq 1$. For the upflow, the values of $\Theta_c = 1/Nu$ are located between the dependences $1/Nu_T$ and $1/Nu_l$ and weakly depend on the Hartmann number. The reason for this became clear when we studied the structure of the pulsation temperature.

Figures 7 and 8 show the intensity profiles of the temperature pulsations for the downflow and upflow. A characteristic difference between the two modes is that in case of downflow with increasing magnetic field, the pulsation intensity almost doubles, and the signal character changes from the high-frequency turbulent to the periodic low-frequency (figure 9). This effect, which we call the MHD effect, is related to the manifestation of TGC, which leads to a periodic formation on the heated wall and further detachment into the core of the flow of large-scale vortex structures that cause these low-frequency temperature bursts.
In the case of an upflow, we also do not observe a suppression of turbulence. The character of the signal, as well as in the downflow, changes its form from the characteristic turbulent to the periodic low-frequency one. The mechanism of appearance of pulsations in the case of an upflow is different, it is a manifestation of “two-dimensional turbulence”, which was often observed in different MHD studies [6].

Figure 5. The distribution of the dimensionless wall temperature $\Theta_c$ along the perimeter of the channel section at the downflow: 1) $Ha = 0$; 2) 300; 3) 500; 4) 800.

Figure 6. The distribution of the dimensionless wall temperature $\Theta_c$ along the perimeter of the channel section at the upflow: 1) $Ha = 0$; 2) 120; 3) 300; 4) 500; 5) 800.

Figure 7. Profiles of intensity of temperature pulsations in axial planes $X$ and $Y$ for downward flow: 1) $Ha = 0$; 2) 300; 3) 500; 4) 800.
Figure 8. Profiles of intensity of temperature pulsations in axial planes X and Y for upward flow: 1) Ha = 0; 2) 300; 3) 500; 4) 800.

Figure 9. Oscillograms of temperature pulsations in the center of the flow and spectra at downflow: a) Ha = 0; b) 800; c) at upflow Ha = 800.

Figure 10 shows the dependence of the Nusselt number with average width of the heated wall of the channel from the Peclet number. In the case of a downflow, the behavior of Nusselt numbers is ambiguous. Without MF (Ha = 0), with a relatively small Reynolds number (Re = 12 000), the heat exchange is worse than the laminar value $\text{Nu}_L$. There is a very strong influence of counter TGC, which led to the appearance of recurrent flows near the heated walls of the channel, as a result of which the wall temperature increased greatly. In a strong magnetic field with numbers $\text{Ha} \geq 500$, no recurrent flows were observed, but the above-mentioned MHD effect of TGC develops, related to the formation of large-scale vortex structures with axes parallel to the induction of the magnetic field. In this case, the heat transfer increases to turbulent values of $\text{Nu}_\text{t}$ and higher.

With an increase of the Reynolds number (Re = 12 000 ÷ 20 000), heat transfer without MF and in MF at the level of turbulent values $\text{Nu}_\text{t}$. With a further increase of the Reynolds number (Re = 30 000 ÷ 50 000), the Nusselt numbers without the MF remain at the level of turbulent $\text{Nu}_\text{t}$ values, and in the MF they decrease to laminar values $\text{Nu}_L$. This means that the TGC effect decreases and disappears. The area of Reynolds numbers 25 000 ÷ 30 000 is boundary for this effect of TGC. Of course, the boundary of this effect depends on the Grashof number $\text{Gr}_q$, so we built a mode map showing the area of manifestation of the TGC effect.
Figure 10. The average Nusselt numbers on the heated wall for the downflow (a) and the upflow (b):
1) $H_a = 0$; 2) 300; 3) 500; 4) 800.

The discovered MHD effect (the existence of anomalously high intensity in the flow of low-frequency pulsations) together with a significant inhomogeneity of the wall temperature along the perimeter of the channel section in the MF is dangerous for the wall material of the TOKAMAK heat exchangers, and this effect must be taken into account.

The work is supported by a grant from the Government of the Russian Federation no. 14.Z50.31.0042.

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