Investigation of heat transfer in a liquid metal upflow in the MHD-channels applied to tokamak reactor blanket module

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Abstract. This article is devoted to experimental investigation of hydrodynamics and heat transfer in MHD flow configuration: upflow of mercury in a vertical round tube and rectangular duct with non-uniform heating in the transverse (coplanar) magnetic field. The problem is of interest for developing fusion reactor’s cooling systems. The liquid metal flow, in this case, will be complicated by influence of electromagnetic and thermogravitation forces. The experimental data were obtained by a proven probe technique for temperature measurements. The average temperature fields, wall temperature distributions, heat transfer coefficients and statistical characteristics of temperature fluctuations have been obtained and compared throughout the length of test section (pipe or duct) detecting the channel geometry influence.

1. Introduction
Liquid metals (LM) are regarded as promising working environment for fusion reactor engineering applications. In tokamaks, it is planned to use mostly lithium-lead eutectic Pb-Li as a tritium breeder and coolant [1].

Experimental studies of different configurations within LM in pipes and channels with different orientations of the magnetic field (MF) and the gravity are conducted by research group MPEI-JIHT based on mercury magnetohydrodynamics (MHD) facilities [2, 3]. Investigation of an upflow in the channel is closest to the conditions in the projected modules of the ITER blanket, where such a flow configuration is often found [1, 4]. The flow LM (typically Pb-Li) in pipes and channels is the subject of most studies in relation to magnetohydrodynamic effects, pressure loss, flow pattern changes and the effect of these factors on heat transfer, examples are given in [5, 6]. Typically, the authors tried to tune away from the influence of thermo-gravitational convection (TGC), or did not notice its manifestation due to the imperfection of the measurement technique. To investigate the effects of TGC it is convenient to use detailed probe measurements acquiring fields of velocity and temperature, which is possible for mercury as the fluid model.

2. Problem statement and research methodology
Experimental studies were conducted on mercury facility of JIHT RAS. Investigated configuration flow LM shown in fig. 1. An upflow of mercury in a vertical duct of stainless steel with an aspect ratio a×b=56×17 mm and a wall thickness of 2.5 mm, as well as in a pipe with an internal diameter of d=19 mm and a wall thickness of 0.5 mm. The heating mode is non-uniform: one of the wide sides of the channel or half of the cross-section of the pipe is heated. The heat flux density can reach, Qw=55 kW/m² heating area (in the channel or the pipe) with a length of 1.5 m is located between the poles of the
electromagnet. The area of uniform heating of 0.8 m coincides with the area of uniform magnetic field of 0.6 m.

Figure 1. Investigated configuration.

Measurements of the temperature and velocity fields in the duct at a distance from the entrance to the heating zone were performed using a hinged probe [7]. To measure the temperature profiles along the channel length, a probe of the “comb” type was used [3].

A more detailed description of these probes, experimental facility and measurement technique can be found in [3] and [7].

3. Experimental results

A flow of electrically conductive fluid in a transverse MF for a pipe and in a coplanar (magnetic induction vector along the wide side of the channel) MF for a duct leads to electric currents generation, significantly altering flow hydrodynamics. This affect leads to the Hartmann effect [8]: flattening of the velocity profiles along the induction of MF and increase in the hydraulic resistance. In addition, the MF suppresses turbulence and turns the flow into laminar. All these facts are well known and investigated in detail earlier [9].

In a non-isothermal flow, thermo-gravitational convection (TGC) is superimposed on the turbulent flow, the effect of this imposition is determined by the ratio $\frac{Ra}{Re^2}$. The buoyancy forces are greatest near the heated walls, they are directed upwards and during the upflow they accelerate the flow in this area. The effect of TGC in vertical pipes has been well studied on non-metallic heat-transfer agents [10].

The question of the joint influence of TGC and MF is ambiguous and substantially depends on a flow configuration.

Fig. 2 (a) and (b) shows the data of primary measurements for one-sided heating: isotherms in the section of the pipe and channel and profiles of dimensionless temperature $\Theta=(T-T_b)/(q_w d/\lambda)$, where $T_b$ – bulk temperature in this section, $q_w$ – heat flux at a wall, $\lambda$ – mercury thermal conductivity. The considered variant of non-uniform heating is possible in channels near the first wall of the ITER blanket. The profiles along the Y axis are strongly non-uniform with a maximum gradient on the wall for both the pipe and the channel. In MF, there is some separation of profiles according to Hartmann numbers, the isotherms are thickening, due to the suppression of turbulence and flow laminarization.

Fig. 3 shows a dimensionless wall temperature distribution around the perimeter of the channel. In these figures, the round dots (1) show wall temperature in absence of a magnetic field ($Ha=0$). For comparison, graphs in fig. 3 (a) also shows the values $\Theta_w=1/Nu$ for infinite plates channel: for a developed turbulent flow, calculated by the formula $Nu_T=4.9+0.017Pe^{0.8}$; for stabilized laminar flow $Nu_l=5.38$ in case of one-sided heating [10]. For a pipe in the case of non-uniform heating, there are no such dependencies; therefore, the comparison is given for uniform heating using the Lyon formula $Nu_T=7+0.025Pe^{0.8}$ and $Nu_l=4.36$, respectively for turbulent and laminar flow [10].
Figure 2. Fields and profiles of dimensionless temperature in channel (а): 1) $Ha=0$; 2) 120; 3) 300; 4) 500; 5) 800; for pipe (б): $Ha=0$; 2) 160; 3) 350; 4) 450; 5) 550. $Re = 30000$, $q_w=q_{1}=35$ kW/m².

Figure 3. Distribution of dimensionless wall temperature at $Re=30000$ and $q_w=35$ kW/m² along perimeter for a duct (а): 1) $Ha=0$; 2) 120; 3) 300; 4) 500; 5) 800; for pipe (б): $Ha=0$; 2) 160; 3) 350; 4) 450; 5) 550.

It can be seen that in both cases, a wall temperature distribution around the perimeter of the cross-section is highly non-uniform, stratified by Hartmann numbers, so that the highest wall temperature approaches laminar values with increasing of Hartmann number.

Fig. 4 (а) and (б) shows the longitudinal wall temperature distribution, measured along the duct length using a multi-thermocouple special probe in the plane of the greatest temperature gradient in the channel and in the pipe, respectively. In the duct, temperature distribution for the heated wall monotonously increases, and reaches a stabilized value, stratifies weakly according to Hartmann numbers and coincides with the dependence for a turbulent flow. Another results were obtained in the pipe: in the absence of MF, heat transfer stabilization is not observed, and dimensionless wall
temperature monotonically increases until the end of a heating section; in MF, some stabilization takes place, but the points are stratified by Hartmann numbers, so that wall temperature increases, approaching a laminar value.

Inhomogeneity during a heating of the channel can lead to additional thermal stresses in channels of fusion reactor. This heterogeneity is observed along entire length of the channels.

![Figure 4](image)

**Figure 4.** Temperature distribution along length of the channel on the generatrix of heated (closed symbols) and unheated (not closed symbols) walls. Designations are the same as on fig. 3.

Typical waveforms of temperature fluctuations in the flow are shown below in fig. 5. The figure shows waveforms of fluctuations in the channel section $z/d=21$ and pipe section $z/d=38$ near generatrix, corresponding to the maximum wall temperature $T_w$. With $Ha=0$ we have a turbulent form of signal. With an increase in the Hartmann number, the level of fluctuations decreases slightly. However, with a further growth of a MF, the form of the waveforms changes. High-frequency fluctuations are suppressed; intense low-frequency bursts appear. A frequency of these bursts decreases with increasing of Hartmann number.

Another situation is in the pipe. In the absence of MF, a turbulent signal is observed, where high-frequency components of fluctuations prevail. In a MF, the high-frequency component is suppressed, and the amplitude of the fluctuations is also reduced.

![Figure 5](image)

**Figure 5.** Waveforms of temperature fluctuations $Re = 30000$ near heated wall of channel: a) $Ha=0$, b) 500; and pipe: c) $Ha=0$; d) 550.

Generally, we can conclude that MF does not only decrease an intensity of fluctuations. In some modes it can lead to development of fluctuations exceeding turbulent values without MF. On the contrary, in the pipe, temperature fluctuations mostly decrease, but full suppression have not been
observed. In the mode presented above, even with $Ha = 550$, a noticeable level of fluctuations is presented in a flow. Although for the shown flow regimes, according to estimates of a critical Reynolds number in MF [9], complete suppression of turbulence is expected for the channel at $Ha > 200$, and for the pipe $Ha > 50$, which is true for all presented regimes in a MF.

This behavior of temperature fluctuations is explained by the influence of buoyancy forces, which lead to the formation of secondary flows in the form of large-scale vortices near the wall. MF suppressing turbulence, however, does not prevent the formation of vortex structures with axes parallel to magnetic induction. Similar effects were observed in the channel and pipe downflow [7]. Phenomenon of TGC directly affect a heat transfer.

Let us consider how a heat transfer coefficient (averaged Nusselt numbers) behave at stabilized heat exchange in flow cross-section $z/d=21$ in the channel and $z/d=38$ in the pipe for different Reynolds numbers (Peclet numbers). For the pipe, in case of one-sided heating and the absence of MF, the numbers $Nu$ are located near the Lyon dependence $Nu_{T}$, and, in the presence of MF, they decrease values $Nu_{H}, Ha=7$, corresponding to heat transfer in a transverse MF taking into account Hartmann effect.

![Figure 6](image-url) Dependence of Nusselt number ($Nu$) on Peclet number ($Pe$) for one-sided heating of a duct (a): 1) $Ha=0$; 2) 120; 3) 300; 4) 500; 5) 800; for pipe (b): $Ha=0$; 2) 160; 3) 350; 4) 450; 5) 550.

Another situation is in the channel with one-sided heating. In absence of MF (round symbols), with relatively large Reynolds numbers ($Re=40000–50000$) values of the relative Nusselt number turn out to be close to the turbulent $Nu_{T}$ values. As the Reynolds number decreases (and $Ra/Re^2$, therefore, become larger) heat transfer coefficients increase. This suggests that a buoyancy force, accelerating a flow near the heated wall and improves heat transfer. Similar patterns of mixed convection effects on heat transfer are well known for a flow of non-metallic fluids in pipes — for example [10].

In the channel, the nature of the Nusselt numbers dependence in a MF is generally the same as in the case without a MF, but the experimental points are slightly lower than the values at $Ha=0$. In spite of MF suppresses the turbulence, the buoyancy forces accelerate the flow near the wall, which leads to instability of the flow (generation of turbulence) and, accordingly, to the heat transfer increase.

**Conclusions**

MHD flow in a vertical pipe and duct under conditions of transverse(coplanar) MF have been investigated. Using the thermocouple probe technique heat transfer and flow structure characteristics have been received. Longitudinal measurements allowed us to examine the flow stabilization under the magnetic field and thermogravitation joint influence.

Two vital features were found. One of them is strong non-uniformity in the wall temperature distribution, increasing in a MF. The second one is caused by thermogravitation influence: the appearance and growth of temperature fluctuations in a magnetic field. Full turbulence suppression in both of MHD configurations has not been observed. Temperature fluctuations in the pipe flow become lower (excepting some regimes) with the Hartmann number increasing. On the contrary, temperature
fluctuations increased, in the duct under the magnetic field, with intensity exceeding the turbulence intensity level.

Based on the measurements along the pipe we did not observe high level temperature fluctuations which has been observed previously in downward configurations, which means that steady-state numerical simulations can be used for upflow. In the duct, on the contrary, a more complex picture of temperature fluctuations should be considered.

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