MHD and heat transfer in downflow and upflow of a liquid metal in the vertical pipe applied to tokamak reactor blanket module

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Abstract. The studies of hydrodynamics and heat transfer were carried out with the upflow and downflow of liquid metal in a vertical pipe with one-sided heating affected by a transverse magnetic field. The task simulates a liquid metal flow in a cooling system channel of a TOKAMAK type fusion reactor blanket. The experimental data on heat transfer provided by detailed probe measurements were obtained using mercury MHD facility.

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

The peculiarity of heat transfer of a fusion reactor is a presence of zones with high specific heat loads. In this case, a non-isothermal flow of LM is subject to intense secondary flows caused by thermo-gravitational convection (TGC). The development of TGC in a MHD flow at the same time leads to unexpected effects: strong heterogeneity in the temperature distribution in a flow and on the channel wall, appearance of zones of degraded heat transfer, generation of low-frequency temperature fluctuations of anomalously high intensity.

The flow of LM in pipes and channels, applied to ITER, is the subject of a large number of studies at present, for example [2,3]. In the main, these are numerical research of hydraulics of the channels of various design of blanket module. Experimental investigation are much rarer. As a rule, the authors pay attention to magnetohydrodynamics (MHD), without considering the influence of TGC, or did not notice its manifestation due to imperfection of measurement technique. Experiments on the basis of mercury MHD facilities conducted by research group of the MPEI – JIHT RAS [4, 5] showed that the effect of TGC on MHD and heat transfer in the channels is significant and can lead to undesirable and even dangerous phenomena.

To investigate the effects of TGC, it is convenient to use the detailed probe measurements acquiring fields of velocity and temperature, which is possible for mercury as the fluid model.

This paper presents the results of experimental studies of heat transfer in a vertical pipe under conditions of joint influence of transverse magnetic field (MF) and TGC in modes close to the real ones in a fusion reactor.

2. Problem formulation and research methodology
Investigated configuration of LM flow is shown in figure. 1. An upflow and downflow of mercury in a vertical pipe of stainless steel with an internal diameter d =19 mm and wall thickness of 0.4 mm are
considered. The two-piece heater of indirect heating provides independent heating of pipe semi-perimeter with constant heat flux on the wall \( q_1 \) and \( q_2 \) (figure. 1). The heat flux density can reach \( q_1 \) and \( q_2 \) in the range of 35÷55 kW/m². Heating area with a length of 1.4 m is located between the poles of the electromagnet. The area of uniform heating of 0.9 m coincides with the area of uniform magnetic field of 0.6 m.

![Figure 1](image1.png)

Figure 1. Investigated configuration of MHD and heat transfer of LM in the pipe.

Measurements of the temperature and velocity fields in cross-section of the pipe at a distance from the entrance to the heating zone were performed using a hinged probe [6]. 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 leads to electric current generation, altering flow hydrodynamics significantly. This affect leads to the Hartmann effect [7,8]: 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 [8].

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 \( Gr/Re^2 \). The buoyancy forces are greatest near a heated side of pipe, they are directed upwards in an upflow and accelerate flow or restrain a downflow. In both cases, this leads to the development of flow instability. The effect of TGC in vertical pipes has been well studied on non-metallic heat-transfer agents [9]. The question of the joint influence of TGC and MF is ambiguous and substantially depends on a flow configuration.

Let us consider the extreme version of two-sided asymmetric heating: one-sided heating \( q_2 = 0 \). The considered variant of conditions is possible in channels near the first wall of a fusion reactor blanket.

Figure 2 (a) and (b) shows the data (Re=20000) of primary measurements of temperature fields in the cross-section, taken at a distance of 37d from the entrance to the heating zone in a downflow and upflow, respectively. The profiles along the Y axis of dimensionless temperature \( \Theta=(T-T_b)/(q_w d / \lambda) \) are shown on the right, where \( T_b \) is bulk temperature in this section, \( q_w \) is heat flux at a wall, \( \lambda \) is mercury thermal conductivity. A strong influence of MF, different in the case of an upflow and downflow, is observed.
The most interesting temperature distribution on the wall $T_w$ is in dimensionless form $\Theta_w=(T_w-T_b)/(q_wd/\lambda)$, shown in figure. 3. Dots (1) correspond to temperature in a flow and on the wall in the absence of MF. (Ha=0). For comparison, figure. 3 also shows values $\Theta_w=1/\text{Nu}$ for uniform heating of a pipe: for stabilized turbulent flow, they are calculated by the Lyon’s correlation $\text{Nu}_T=7+0.025\text{Pe}^{0.8}$; for laminar flow, they are calculated by $\text{Nu}_l=4.36$ (Ha=0) and cross-section $\text{Nu}_{l,Ha}=7$, taking into account the Hartmann effect [10]. As one can see, in the downflow, the temperature of the heated wall is at the level of turbulent values $1/\text{Nu}_T$, and in transverse MF, it rises to laminar values $1/\text{Nu}_l$ and even higher. On the contrary, in upflow the wall temperature is above the turbulent level and increases slightly in a MF, stratifying insignificantly according to Hartmann numbers. In both cases, temperature distribution of the wall around perimeter of cross-section is highly inhomogeneous.

In these flow regimes, the data on the fluctuations temperature are even more interesting. Figure 4 shows intensity profiles of temperature fluctuations $\sigma$ in a dimensionless form $\sigma^*=\sigma/(q_wd/\lambda)$ in the cross-section of the pipe for the downflow. The intensity of fluctuations in the MF increases by 8–9 times in comparison with the turbulent level (Ha=0). A different picture is observed in the upflow: figure 5 shows intensity distribution along a length of the pipe near a maximum temperature in cross-section at a distance $Y=0.8$. If at small Hartmann numbers (Ha=150, 300) turbulence is suppressed, then at large values (Ha=350÷550) the intensity of fluctuations can exceed a turbulent level.
**Figure 3.** Distribution of dimensionless wall temperature at $Re=20000$ and $q_w=55$ kW/m$^2$ along perimeter in cross-section in the downflow (a): 1) $Ha=0$, 2) 120, 3) 210, 4) 330, 5) 500; in the upflow $q_w=35$ kW/m$^2$ (b): 1) $Ha = 0$, 2) 150, 3) 350, 4) 450, 5) 550.

**Figure 4.** Distribution of intensity of fluctuations at the downflow in a cross-section along $X$ axis (a), along $Y$ axis (b) $Re=20000$, $q_w=55$ kW/m$^2$: 1) $Ha = 0$, 2) 150, 3) 330, 4) 420, 5) 550.

**Figure 5.** Distribution of intensity of fluctuations near the heated wall ($X=0$, $Y=0.8$) for an upflow, $Re=20000$, $q_w=35$ kW/m$^2$: 1) $Ha = 0$, 2) 150, 3) 350, 4) 450, 5) 550.
Typical waveforms of temperature fluctuations at an upflow and a downflow in a pipe are shown below in figure 6. The results were obtained in cross-section z/d=37 near a point corresponding to maximum wall temperature $T_w$ ($X=0, Y=0.7$).

In the absence of MF, a turbulent signal is observed, where a high-frequency components of fluctuations prevail. In a MF with a downflow, and to a lesser extent in an upflow, observed effect is associated with an effect of TGC on the flow: emergence of low-frequency peak fluctuations of abnormally high amplitude.

According to estimates of the critical Reynolds number in a pipe in transverse MF [9], complete suppression of turbulence is expected for a pipe with $Ha>50$, that is, in almost all presented regimes in the MF. The fluctuations developing in the MHD flow are of a non-turbulent nature. This behavior of temperature fluctuations is explained by the influence of buoyancy forces leading to formation of secondary flows in the form of large-scale TGC vortices near the wall. The MF, suppressing turbulence, at the same time does not prevent formation of vortex structures with axes parallel to magnetic induction.

Phenomena of TGC directly affect heat transfer. Let us consider the heat transfer coefficients (HTC, i.e the Nusselt number averaged at semiperimeter) in the area of stabilized heat transfer in flow cross-section z/d=37 in the pipe for different Reynolds numbers (Peclet numbers). Experimental points without MF in the case of a downflow are lower than the $Nu$ dependence and with an increase in Peclet number, they approach it. In the MF, Nusselt numbers decrease to laminar $Nu_l$ values and increase with Peclet number, Nusselt numbers significantly exceeding a laminar value $Nu_{l,Ha}=7$. This is the result of manifestation of TGC effects. A different situation is with an upflow: experimental points without MF first turn out to be at the level of $Nu_l$ and, with increasing Peclet number, they are lower than the Lyon’s correlation. In MF, heat transfer decreases to laminar values $Nu_{l,Ha}=7$, the Nusselt numbers slightly increase at $Pe=1100$ ($Re\geq60000$).
Figure 7. Dependence of the Nusselt number (Nu) on the Peclet number (Pe) for downflow (a): 1) Ha=0; 2) 120; 3) 210; 4) 330; 5) 500; for upflow (b): 1) Ha = 0; 2) 160; 3) 300; 4) 450; 5) 550.

Conclusions
Experimental data have been obtained on heat transfer of a LM in a pipe with an upflow and a downflow in a transverse magnetic field with non-uniform (semiperimeter) heating.

In the investigated configuration of the upflow and downflow, strong non-uniformity is found in temperature distribution on a wall, which increases in a magnetic field. This fact must be taken into account in engineering and design of a fusion reactor, since non-uniformity of heating leads to additional thermal stresses.

In a non-isothermal flow under transverse magnetic field conditions, the effects of TGC occur: appearance and growth of temperature fluctuations in a magnetic field, significant contribution of secondary eddy flows to the values of HTC, that compensates the decreasing of turbulent transport affected by a strong MF. The strongest factors of influence of TGC on heat transfer are shown in a downflow.

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