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Investigation of the liquid metal flow in a vertical rectangular channel applied to the tokamak reactor cooling system

N Yu Pyatnitskaya 1,2, N G Razuvanov 2, E V Sviridov 1,2 and V G Sviridov 2

1 Moscow Power Engineering Institute (MPEI), Moscow
2 Joint Institute for High Temperatures (JIHT) RAS, Moscow

PiatnitskayaNY@mpei.ru

Abstract. For realization of this project, large-scale studies of heat transfer and hydrodynamics of the flow in the channels, simulating conditions close to real are required. These conditions are primarily the flow of an electrically conducting fluid in a magnetic field and thermo-gravitational convection, emerging due to strong heat fluxes. Recently in our research group in MPEI-JIHT RAS, obtaining experimental data has become possible due to creation of model stands to identify patterns of MHD flow in a magnetic field under the action of heat flux. It is necessary simple algebraic models, resulting the main parameters of the flow and not requiring large computational resources. Besides that, obtaining experimental data will be used for validation and verification of computational codes. This project examines the influence of thermo-gravitational convection on the upward flow of a liquid metal in a rectangular channel (aspect ratio 1:3). This configuration matches to the Russian-Indian project of cooling the ITER blanket. Currently, the participants of the project are creating of a model including the influence of magnetic field on the flow. This work is dedicated to the creation of a model including the influence of thermo-gravitational convection without influence of magnetic field.

1. Introduction
Using liquid metals for TOKAMAK [1] blanket cooling is one of the most debated issues in fusion energy. In fusion reactors of the type "tokamak", flow of the coolant occurs in strong magnetic fields and heat loads. With this configuration the determining factors influencing on the flow are the magnetic field (MF) and thermogravitational convection (TGC). These regularities (MF and TGC) essentially depend on the parameters of the MHD configuration: mutual orientation of the vectors of the flow velocity and of the magnetic field, the shape and geometrical dimensions of the channel, the channel orientation in gravity field, the electrical conductivity of the wall material, the nature of the heating. Therefore, a detailed study of all the possible MHD configurations is an important practical task. Currently it is impossible to talk about the completeness of such data. MHD configuration where a liquid metal circulating in a rectangular channel in a coplanar magnetic field, is implemented in all proposed projects the liquid-metal cooling systems (HCLL, DCLL, WCLL, SCLL) of the core of ITER reactor [2,3]. This article is devoted to the study of the TGC and MF combined and separately action on the flow of liquid metal in a vertical rectangular channel.

2. Experimental setup
A quantitative assessment of influence TGC was obtained by a measurement on united mercury facility MPEI-JIHT RAS (figure 1) [4]. It was studied the upward flow of liquid metal in rectangular
channel (aspect ratio 1:3) in the presence of coplanar MF. Recall that the coplanar MF is a transverse magnetic field but directed along the long side of the channel.

**Figure 1.** Experimental facility. 1 – test section; 2 – swivel type probe; 3 – electromagnet; 4 – compensation tank; 5 – heat exchanger “pipe in pipe”; 6 – flowmeter; 7 – differential pressure gauge; 8 – electromagnet pump; 9 –control valve; 10 – tank with mercury; 11 – overhead thermocouples; 12 – measuring instrument rack; 13 – computer (PC).

The experiments were carried out with the following values of the regime parameters:  Reynolds number $Re = \frac{U_0D}{\nu} = (10 \div 55) \cdot 10^3$; Peclet number $Pe = \frac{U_0D}{a} = 50 \div 1400$; Grashof number $Gr_q = \frac{g\beta q w D^4}{\nu \lambda} = 0 \div 7 \cdot 10^8$; Hartman number $Ha = B_0 D \sqrt{\frac{\sigma_e}{\mu}} = 0 \div 800$; Stuart number $N = \frac{Ha^2}{Re} = \frac{B_0^2 D^2 \sigma_e}{\mu U_0} = 0 \div 11.6$. As a characteristic scale $d$ is used $2b$ (double channel width). The measurements were carried out in area with uniform magnetic field and heat flux at $37d$ distance from the channel beginning.

3. Result of experiments and compare with dependence of turbulence suppression by coplanar MF

The combined influence of MF and heat load has complex effect on the flow of LM. On the one hand, the MF suppresses turbulent fluctuations, laminarizing the flow. On the other hand, the presence of thermogravitational convection evokes appearing large-scale vortex structures [4]. The study of these effects impact requires a large number of experiments with different parameters and flow modes. For theoretically express the influence of one factor, it is necessary to eliminate the influence of another factor in the experiment and then analyze the obtained data. A series of experiments under different conditions and subsequent results analysis makes it is possible to reflect these effects using simplified correlations.

One of the possible ways to reflect the effect of TGCs and MPs on the flow of liquid metal separately and together it is the analysis of the intensity profiles of temperature fluctuations in the channel section for different flow conditions. The figure 2 shows the development of temperature fluctuations of the intensity profile with increasing Grashof number.
Figure 2. The dimension temperature fluctuations intensity profiles. Re=3·10^4, 1 – Gr_q=1·10^8, 2 – Gr_q=2·10^8, 3 – Gr_q=5·10^8.

As expected, the increase in heat flow leads to an increase in the level of the fluctuations intensity, and this happens evenly along the cross section. This suggests that it is possible to reflect the influence of TGC using a theoretical model, which will depend only on the regime parameters (Gr, Re).

Of particular interest are regimes in which the combined effect of TGC and MF on the flow is manifested. For comparison, the figure 3 shows a mode with a relatively weak influence of thermogravitational convection (a) and strong (b). In both cases, the suppression of fluctuations by a magnetic field occurs in a similar way. The shape of the profiles remains similar in both case a) and b). However, graph b) shows that with complete suppression of turbulence (Ha = 500), the level of fluctuations persists approximately of about 0.6×σ0, where σ0 is the intensity of temperature fluctuations in the absence of a magnetic field. This suggests that in such modes the fluctuations recorded with the complete suppression of turbulence caused by the influence of TGC.

Dimensionless intensity of temperature fluctuations:

\[ \sigma = \frac{\lambda}{Dq_w} \cdot \frac{\sigma^D}{\sigma_w}, \]

where \( \sigma^D \) - dimensional temperature fluctuations intensity.

Figure 3. The dimensionless temperature fluctuations intensity profiles. a) Re=3·10^4, Gr_q=2·10^8; b) Re=4·10^4, Gr_q=5·10^8.
In work [6,7] was obtained a model of the suppression fluctuations degree by the magnetic field with generalization of temperature intensity fluctuations data, which depends only on the regime parameters (number Re and Ha). For a full understanding of the MHD flow, a modification of this model showing the effect of only natural convection is necessary. During the experiments, data on the intensity of temperature fluctuations at different heat flux values were obtained. This was done for modification of model [6, 7].

The figure 4 shows the exponential dependence of turbulence suppression by a coplanar magnetic field, obtained with a negligible effect of TGC (Gr\(_q\)=1\(\cdot\)10\(^8\)) for two flow regimes (downward and upward)

\[
\gamma_e = \frac{\sigma}{\sigma_0} = e^{\left(\frac{1}{2} \frac{Ha^2}{Re}\right)},
\]

where \(\sigma_0\) is a dimensionless temperature fluctuations intense without magnetic field and \(\sigma\) is magnetic field. The graph 4 compares the dependences obtained earlier and the results of experiments obtained for higher Grashof numbers than in the work [6]. For value \(\sigma/\sigma_0\) in figure 4 conforms to the average in the cross-section taken average in cross-section, how it was in [6].

**Figure 4.** Coefficient of turbulence suppression by coplanar magnetic field for different Grashof numbers. 1 – Gr\(_q\)=1\(\cdot\)10\(^8\), 2 – Gr\(_q\)=2\(\cdot\)10\(^8\), 3 – Gr\(_q\)=5\(\cdot\)10\(^8\).

Based on the results, it can be noted that a small increase in the Grashof number does not lead to a discrepancy with exponential dependence. However, when Grashof is increased 5 times, a significant difference can be observed. In this case we can see, that experimental points “stratified” with theoretical dependence. Currently, to determine the exact "beginning" of the discrepancy between the experimental data and the dependence (2), it is necessary to carry out additional experiments with other values of the heat flux.

4. Conclusion
From the obtained results, it can be concluded that the flow is very "sensitive" to changes in the regime parameters, in particular when changing the number Grashof. For practice it would be useful to evaluate the effect of regime parameters (Gr, Re, Ha) separately from each other and together to create a model that allows to quickly assess the heat transfer in the channels modeling the real in the ITER blanket.
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