SPECIFIC FEATURES OF LIQUID METAL HEAT TRANSFER IN A TOKAMAK REACTOR

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Complex experimental study and numerical simulation of liquid metal flow and heat transfer in various configurations affected by longitudinal or transverse magnetic fields under conditions close to the tokamak reactor have been performed. A specific feature of the heat transfer under these conditions is the combined exposure of a strong magnetic field and thermogravitational forces, which manifests itself in previously unknown effects. Among these effects are the existence, in some modes, of MHD heat transfer areas of “degraded” heat transfer, the extremely uneven distribution of heat transfer coefficients along the perimeter of the tube and abnormally high temperature fluctuations near the wall. These phenomena including negative ones should be considered in the further designs.

Introduction. Liquid metals (LM), as a nuclear power plant coolant, have been studied in details by specialists of SSC RF-IPPE [1, 2]. However, LM is considered as a promising coolant and working environment for thermonuclear devices. LM can be used for cooling the first wall, the blanket and the divertor of a tokamak. Lithium or lithium alloys are necessary for the production of tritium in the reactor. Different configurations of LM flow can be used, such as forced convection in tubes and channels, volume circulation, films and free jets. The tokamak reactor specific feature is that liquid metal is exposed to strong magnetic fields.

It seems that the LM flows in the tube affected by longitudinal or transverse magnetic fields (MF) are sufficiently well studied. Many researches had been made, especially, in the USSR in the 1970–1980s [3–5].

Let us consider a LM flow in a longitudinal magnetic field. The advantage of this configuration is that the longitudinal component of the velocity vector is parallel to the magnetic field and does not interact with the MF. However, the longitudinal MF alters the flow pattern, i.e. it suppresses turbulence and leads to laminar flow. Respectively, with an increase of the MF induction (the Hartmann criterion Ha) the value of the critical Reynolds number increases. Hydraulic resistance and heat transfer tend to laminar values. It was observed in experiments carried out separately at MAI and MPEI [5, 6].

It is also known that the transverse MF, more than the longitudinal one, suppresses turbulence. But in contrast to the longitudinal MF, the transverse MF leads to a Hartmann effect, and, if the tube wall is not insulated, to a bulk retarding force, which results in a sharp increase in hydraulic resistance.

However, these experimental results were obtained under laboratory conditions with the minimized influence of thermogravitational convection and, thus,
Fig. 1. The MPEI loop to investigate mercury flow and heat transfer in a longitudinal magnetic field.

Fig. 2. The JIHT RAS loop to investigate mercury flow and heat transfer in a transverse magnetic field.

do not provide a complete picture of MHD effects in liquid metal systems of fusion reactors.

1. Research conditions. The MPEI research team has been performing modelling experiments on the LM heat transfer in tubes relevant to the tokamak cooling channels for many years. The present experimental studies are conducted in a magnetohydrodynamic (MHD) setup by a joint team of MPEI-JIHT RAS. The MHD facility combines two mercury loops, where investigations in a longitudinal (Fig. 1) and in a transverse magnetic field (Fig. 2) are available [7].

It is well known that mercury is not considered as a possible coolant in the energy sector. However, mercury is, undoubtedly, the best of the working media
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Fig. 3. Flow configuration: (a) horizontal heated tube in a longitudinal or in a transverse MF, (b) vertical downward flow in a transverse MF, (c) downward flow in an inclined to the horizon tube in a longitudinal MF (θ denotes inclination to the horizon).

Fig. 4. The studied heating configurations and the characteristic lines of the secondary TGC flow vortices.

Table 1. Experimental criteria.

<table>
<thead>
<tr>
<th>Criterion Value</th>
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<tr>
<td>Re = ( \frac{wd}{\nu} )</td>
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<tr>
<td>Ha = ( Bd\sqrt{\frac{\sigma}{\mu}} )</td>
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<tr>
<td>Gr = ( \frac{g\beta q d^4}{(\lambda \nu^2)} )</td>
</tr>
<tr>
<td>C = ( \frac{\sigma w L_w}{(\sigma d)} )</td>
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for experiments on the MHD heat transfer. It allows to use effectively the probe measurement methods and ensures a sufficiently high accuracy of measurements of local and average characteristics of the flow and heat transfer.

The flow in horizontal, vertical or inclined tubes is considered. For example, the examined configurations are shown in Fig. 3, with the vectors: \( \mathbf{V} \) is the flow velocity; the free fall acceleration is \( g \), the MF induction is \( \mathbf{B} \). Heating is uniform in length, and, in a general case, uniform over the perimeter of the tube cross-section (Fig. 4). The geometry of the flow and the MHD convective heat exchange, in general, correspond to the various sections of the tokamak cooling channels, for example, the blanket and the divertor.

The length of the heating zone and the uniform MF area are, respectively, 42\( d \) and 29\( d \), where the tube diameter \( d = 19 \) mm. The criteria realized in experiments are presented in Table 1, where Re is the Reynolds number, \( w \) is the mean velocity, \( d \) is the tube inner diameter, \( \nu \) is the kinematic viscosity, Ha is the Hartmann number, \( B \) is the applied magnetic field induction, \( \mu \) denotes dynamic viscosity, \( \sigma \) is the electrical conductivity, Gr is the Grashof number, \( g \) is the acceleration of
gravity, $\beta$ is the volumetric thermal expansion coefficient, $q$ is the heat flux, $\lambda$ is the thermal conductivity, $C$ is the wall conduction ratio, $\sigma_{w}$ is the wall electrical conductivity, $L_{w}$ is the wall thickness.

Measurements in the mercury flow were made by probe methods using various sensors (thermocouples), correlation and electromagnetic velocity sensors. With the help of micro thermocouples, three-dimensional (3D) fields of averaged temperature and temperature fluctuations were measured, then local (at the periphery and over the length of the tube) and average heat transfer coefficients were defined. The used probe technique for wall temperature measurements made it possible to eliminate the error associated with the thermal contact resistance at the liquid metal solid wall boundary. Correlation and electromagnetic sensors sampled the fields of the longitudinal and transverse components of local velocity.

Experiments were automated using modern hardware, software and virtual tool techniques.

All the experimental data in the facility allow to conclude about the nature of the joint effect of MF and thermogravitational convection (TGC) on the LM flow and heat transfer in the tube. The experiments have shown a strong influence of MF and TGC on the fields of temperature, velocity and on the distribution of the heat transfer coefficients along the perimeter.

The TGC secondary flow, in general and on the average, has led to the heat transfer intensification in horizontal tubes [8]. In vertical tubes with the downward TGC flow, in general, the heat transfer decreases [9]. In the inclined downward flow, TGC and the main flow interact in a difficult way, where increasing and decreasing of heat transfer is possible [10].

It is found that the result of the combined action of the two factors (MF and TGC) is complicated and ambiguous, and can lead to unexpected effects. This result depends on the orientation of the tube about the gravity force, on the MF induction vectors, and on the heating configuration as well.

It is assumed that a strong MF (uniform longitudinal or transverse) laminarizes the flow by suppressing turbulence [4]. However, in some cases (if any TGC is present), the MF leads to the unexpected appearance of velocity and temperature fluctuations of abnormally high intensity [11, 12]. The nature of these phenomena is completely different from turbulence. These fluctuations, on the one hand, contribute to the increase of the heat transfer coefficients and, on the other hand, are dangerous for the wall causing its fatigue destruction by pulsating thermal stresses.

Along with the experiments, a technique for numerical simulation of MHD heat exchange has been developed [9]. The basis of the estimated model is a system of average equations of motion and energy. The Boussinesq approximation and our developed model of magnetic field impact on the turbulent transfer of momentum and heat were used. The influence of viscous and Joule dissipation were neglected. Calculations were made using the ANES software [13] developed at the MPEI Department of Engineering Thermal Physics. The results of numerical simulation were then compared with the experimental data. In our opinion, there is a good agreement of calculations and experiment, which demonstrates the adequacy and reliability of the model and allows, in some cases, to avoid physical experiments, using numerical simulation.

2. Results. As a result of the experiments and numerical simulations, it has been found that the LM heat transfer in a strong MF under large thermal loads has some peculiarities determined by the influence of magnetic field and TGC. There are two features, generally.
The first feature is a substantial heterogeneity of the heat transfer coefficients and, hence, of the wall temperature along the perimeter of the tube cross-section, which can, as experiments have shown, lead to unacceptably high thermal stresses in the heat exchanger walls. In Figs. 5–8, one can see examples of the experimental and calculated data: the fields of averaged temperature and longitudinal velocity...
Fig. 6. Dimensionless wall temperature $\Theta$ along the perimeter of the horizontal tube cross-section $z/d = 37$ affected by a longitudinal MF with uniform heating, Re = 10000, $q = 35$ kW/m$^2$ (Gr = 0.8 $\cdot$ 10$^8$); points – experiment, lines – calculation.

Fig. 7. Dimensionless wall temperature $\Theta$ along the perimeter of the inclined tube with downward flow, $z/d = 37$ affected by a longitudinal MF (Ha = 480) under uniform heating; Re = 10000, $q = 15$ kW/m$^2$ (Gr = 0.3 $\cdot$ 10$^8$).

component, the distribution of the dimensionless wall temperature

$$\Theta_w = \frac{T_w(\varphi) - T_b}{q_w d/\lambda} = \frac{1}{Nu}$$

along the perimeter as the difference between the wall temperature $T_w$ and the bulk temperature $T_b$.

This effect can be observed in various configurations of the MHD heat exchange both in the longitudinal and in the transverse MF. However, physical reasons of the wall temperature heterogeneity are different.

In the horizontal tube affected by a longitudinal MF, TGC manifests itself in the form of large longitudinal vortices (Fig. 6) with their axes parallel to the vector of the MF induction. The MF stabilizes these vortices. As a result, the flow loses axial symmetry (Fig. 5a), the heat distribution becomes inhomogeneous in the tube cross-section, with the formation of zones of “degraded” and “enhanced”
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heat transfer. We call the heat transfer “degraded” when the local Nusselt criteria are below the laminar values \( \text{Nu}_L = 4.36 \).

It is a common situation when, in the case of lack of preliminary information on heat transfer, the designers of heat exchangers use the laminar value \( \text{Nu}_L = 4.36 \) as “the lowest possible”. As it can be seen, for example, in Fig. 6, this cannot be done because the local Nusselt criteria might be lower.

In the inclined tube with the downward flow affected by a longitudinal MF with inclinations up to 45 degrees to the horizon, the heterogeneity of the wall temperature in cross-section can be even more significant (see Fig. 7).

In the horizontal tube affected by a transverse MF, the temperature inhomogeneity along the perimeter of the tube cross-section, as assumed, should be less pronounced (Fig. 5c). The transverse MF, in general, must suppress TGC vortices, not allowing them to develop. However, the experiments have shown that in the transverse MF this effect might be significant, for example, in the case of non-uniform heating (Fig. 8).

In the vertical tube affected by a transverse MF, there is also heterogeneity of the wall temperature along the perimeter of the tube cross-section (Fig. 9).

However, the physical reason in this case is different. The point is in the presence of the Hartmann effect in the transverse MF. This effect leads to a flattening of the velocity profile in the direction of the magnetic induction vector, while in the perpendicular direction, the velocity profiles have an elongated shape typical of laminar flow. Strong axial asymmetry of the velocity profile and TGC reinforced counter lead to the heterogeneity of the local heat transfer coefficients and wall temperature along the perimeter of the tube cross-section.

In Figs. 10–11, some results of our experimental data application for the conditions similar to the ITER blanket are illustrated [14].
Fig. 9. Dimensionless wall temperature $\Theta$ along the perimeter of the vertical tube cross-section $z/d = 37$ affected by a transverse MF under uniform heating; $Re = 20000$, $
abla T = 55\text{ kW/m}^2\cdot\text{m}^2$ ($Gr = 1.25 \cdot 10^8$). Points – experiment, lines – experiment approximation.

Fig. 10. The wall temperature distribution along the perimeter of the tube cross-section (length 1 m, $d = 10$ mm, wall width 1 mm; steel 12X18H10T), for Li-Pb coolant $Re = 35000$, $q = 1\text{ MW/m}^2$.

Fig. 10 shows the estimated wall temperature distribution for the lithium-lead eutectic alloy in a flow in a horizontal tube exposed to a longitudinal MF. One can see that in the second case, the heterogeneity in the distribution of the tube wall temperature exceeds a hundred degrees. The temperature in the zone of the “degraded” heat transfer (at an angle of 90 degrees) comes up to the maximum allowed for the tube material (700°C).

For this case, in Fig. 11, one can see the temperature distribution along the entire length of the tube. Fig. 11 shows the field of thermal stresses and the tube deformation, the bending of which is about 8% of length in the case of a tube free
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Fig. 11. Equivalent stress, Pa in the tube for Li-Pb coolant; homogeneous heat, longitudinal MF ($T_{in} = 350^\circ C$, $T_{out} = 500^\circ C$).

Fig. 12. Downward flow in a longitudinal MF: (a) temperature waveform, $Re = 7500$, $z/d = 35$; (b) temperature fluctuations intensity, $Re = 10000$, $x/d = 35$, $l - Ra/Re = 0.4$, $2 - 0.8$, $l - 1.6$ [12].
at both ends. If the tube is fixed at both ends, additional stress will be even more significant. Failure to incorporate these factors in the heat exchanger design can lead to a dangerous situation. The second main feature of the MHD heat transfer under conditions close to real ones in a reactor-tokamak is the following: at some Reynolds, Hartmann and Grashof criteria ratios (depending on the configuration of MHD heat transfer), dangerous low-frequency temperature fluctuations of an abnormally high amplitude can exist in the LM flow (Figs. 12–18). When penetrating through the wall of the heat exchanger, the temperature fluctuation can cause its thermal fatigue destruction. Note that these fluctuations have no relation to turbulence. The values of the criteria for Re and Ha implemented in our experiments have resulted in turbulence suppression by the MF. The temperature fluctuation is one of the manifestations of TGC secondary vortices developing in the flow.

Such secondary TGC motion exists in the form of stable or quasi-stable large-scale vortices with their axes parallel to the MF vector. Note that under some regimes (Figs. 17, 18) the amplitude of the temperature fluctuations is almost equal to the difference between the wall and the bulk temperature. Hence, the scale of secondary vortices and the tube diameter are of the same order of magnitude.

3. Conclusions. With reference to the results of our experiments, we can conclude that under any configuration of MHD heat exchange (longitudinal and transverse MF, vertical, horizontal and inclined tubes), with a certain ratio of the
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Fig. 14. Temperature fluctuation intensity distribution over the tube length. $Re = 10000$, $Gr = 0.4 \cdot 10^8$; $R = 0.7$ at the tube bottom, $\varphi = 0$.

Fig. 15. Temperature fluctuation intensity distribution in the vertical tube cross-section: (a) along the MF; (b) across the MF. $z/d = 37$, $q_c = 55\, kW/m^2$ ($Gr = 1.25 \cdot 10^8$), $Re = 20000$, transverse MF. Points – experiment, lines – experiment approximation.

operation parameters in the LM flow, TGC secondary flows in the form of large vortices with the axes oriented along the MF can exist.

Patterns of these secondary flows are shown for several different cases of longitudinal (Fig. 12) and transverse (Figs. 13-18) magnetic fields. However, from the practical point of view, two negative effects can exist: the inhomogeneous heat transfer coefficient and wall temperature along the tube perimeter, and the low-frequency high-amplitude temperature fluctuations.

In some cases (Figs. 17, 18), the amplitude is almost equal to the temperature difference between the wall and the LM flow, which can be a hundred degrees and more under the actual conditions of the tokamak. The reason is clear: the development of TGC secondary vortices existing almost over the entire cross-section of the tube.
Fig. 16. Temperature fluctuation intensity field in the vertical tube cross-section $z/d = 37$, $q_c = 55\, \text{kW/m}^2$ ($Gr = 1.25 \cdot 10^8$), $Re = 20000$: (a) $Ha = 0$, (b) $Ha = 300$.

Fig. 17. Characteristic temperature waveforms and their power spectrum in the vertical tube with homogeneous heating: $z/d = 37$, $q_c = 35\, \text{kW/m}^2$ ($Gr = 0.8 \cdot 10^8$), $Re = 12000$; transverse MF; at the flow core.
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Fig. 18. Characteristic temperature waveforms and their power spectrum in the vertical tube with inhomogeneous heating: \( z/d = 37, q_1/q_2 = 55/0 \text{ kW/m}^2, \text{Re} = 20000; \) transverse MF; waveforms are taken at the intensity maximum.

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