EXPERIMENTAL RESEARCH OF THE HEAT TRANSFER LIQUID METAL DOWNWARD FLOW IN RECTANGULAR DUCT IN MAGNETIC FIELD

PODDUBNYI[1] I., RAZUVANOV[2] N., SVIRIDOV[1] V., IVOCHKIN[2] YU.
[1] National Research University "Moscow Power Engineering Institute", 14 Krasnokazarmennaya str., Moscow, Russia
[2] Joint Institute of High Temperatures of the Russian Academy of Science, 13/19 Igorskaya str., Moscow, Russia
E-mail: poddubnyyii@gmail.com

Abstract This work contains the results of experimental research and numerical simulation of heat transfer of the liquid metal (LM) downward flow in rectangular duct (with a side's ration 3/1) under coplanar magnetic field (MF). A temperature fields have been measured in condition of a one-sided and double-sided heating. The averaged fields of temperature, distributions of the wall temperatures and statistical characteristics of fluctuating part of the temperature have been obtained. A numerical simulation of hydrodynamic and heat transfer of LM flow in the conditions of the experiment has been performed.

1. Introduction

Liquid metals are used as a coolant for several projects of ITER Test Blanket Module [1, 2], essentially this is LiPb eutectic. This eutectic can be the coolant agent and neutron multiplier. In addition there are a lot of projects when LMs are used for cooling different parts of heat exchanger. For designing of new projects engineers who work in fission or fusion spheres should well know the laws of heat transfer of LM in magnetic field in a channel with different cross section. By the way rectangular ducts are widely used in applications. So that is why the task of investigation of the heat transfer laws of liquid metal (LM) in rectangular duct is very claim.

2. Governing equations

Test configuration of LM flow in a field of mass forces is shown in figure 1. Steady –state flow and heat transfer of mercury in vertical rectangular duct in a coplanar (a vector magnetic field **B** is directed along long side of duct cross section $B_x \neq 0$) MF. A ration a sides in duct cross section: a/b=56/17. The walls of duct are made from Russian stainless steel 12X18H10T with wall thickness dw/b=2.5/17. Liquid metal flows along a gravity vector with creation of adverse heat - gravitational convection.

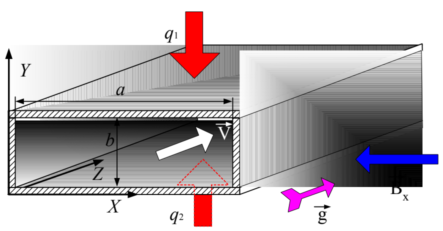

Figure 1. Investigated flow scheme

A double width of duct $d=2b$ took in as a characteristic size. There is a zone of hydrodynamic stabilization on a duct input Z_0=20 d, after that there is a heating zone with a heat - flux density on a both sides of duct q_1 and q_2. A zone of magnetic field is coincidences with heating zone, with length 25 d. The duct walls are electrically conducting. A ratio of steel's electrical conductivity to mercury electrical conductivity is 9.8/75.

The system of dimensionless equations consists from the conservation of the mass, momentum, energy and charge equations [3]. The equations in non-inductive approach (magnetic Reynolds number R_m <<1) are presented below.

$$\nabla \cdot \mathbf{V} = 0 \quad (1)$$

$$(\mathbf{V} \cdot \nabla)\, \mathbf{V} = -\nabla p^* + \frac{1}{\mathrm{Re}}(\nabla \cdot (1+\frac{\varepsilon_t}{\upsilon})\nabla\ )\, \mathbf{V} + \mathbf{F} \quad (2)$$

$$(\mathbf{V}\cdot\nabla)\,\Theta = -\frac{1}{\mathrm{Re}\,\mathrm{Pr}}\nabla\cdot(1+\frac{\mathrm{Pr}}{\mathrm{Pr}_t}\varepsilon_t)\nabla\,\Theta \tag{3}$$

$$\Delta\psi^* = \nabla(\mathbf{V}\times\mathbf{B}^*) \tag{4}$$

and by the Ohm's law for the moving media

$$\mathbf{j}^* = \mathbf{E}^* + \mathbf{V}\times\mathbf{B}^* \tag{5}$$

In these equations $\mathbf{V}(u_x,u_y,u_z)$, $\mathbf{j^*}(j_x,j_y,j_z)$, $\mathbf{B^*}(B_x,B_y,B_z)$, $\mathbf{E^*}(E_x,E_y,E_z)$, ψ^*, p^*, $\mathbf{F}(F_x,F_y,F_z)$ and ε_t denote the dimensionless velocity, current density, magnetic field, and electrical field, electric potential, pressure, vector of source of volumetric force and turbulent viscosity. In presented system of equations coordinates have been related to *d=2b (b* – width of duct*),* velocity V has been related to average velocity, pressure p^* to ρV_0^2; temperature $\Theta=(T-T_0)$ to $q_c d/\lambda$, ^{0}C (where T_0- intake temperature and $q_c=0.5(q_1+q_2)$.); $\mathbf{B}^*$ to magnetic field of external field B_0; current density $\mathbf{j}^*$ to a value $\sigma\ V_0B_0$; electric field поля $\mathbf{E}^*=-\nabla\psi$ to V_0B_0; $\mathbf{g}^*$ to intensity of gravity g_0. In momentum equation the volumetric force is equal

$$\mathbf{F} = \frac{\mathrm{Gr}_q}{\mathrm{Re}^2}\Theta\mathbf{g}^* + \frac{\mathrm{Ha}^2}{\mathrm{Re}}\left(\mathbf{j}^*\times\mathbf{B}^*\right) \tag{6}$$

The non-dimensional boundary conditions are presented below:

- on the duct input applied uniform velocity and input temperature $Z=0$: $V_z = 1, \Theta = 0$;
- on bottom duct wall: $V_i=0$, $\frac{\partial\Theta}{\partial n} = 1$;
- on upper duct wall: $V_i=0$, $\frac{\partial\Theta}{\partial n} = -1$;
- on all duct walls: $\frac{\partial\Psi^*}{\partial n} = 0$

This equation system is solved in a packet for numerical simulation of processes of hydrodynamic and heat transfer ANES20XE [4].

3. Experimental facility

The experimental facility is mercury close – loop system (figure 2). Parameters of test facility are presented in table 1. The geometry of duct and test facility parameters allows performing the experiments by follow dimensionless numbers which determine of flow characteristics: Reynolds number 5000÷55000; Hartmann number up to 800; Grashof number up to 8e+8.

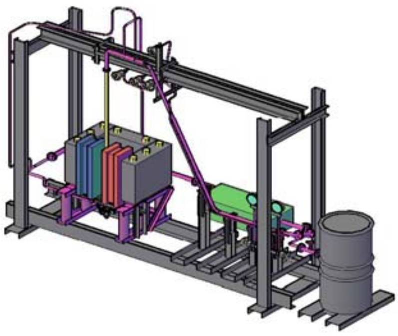

Figure 2: Model of the test facility.

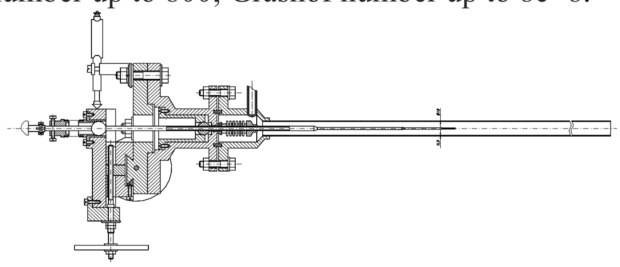

Figure 3: A microthermocouple lever-type probe.

The measurement of temperature field in a section which located on distance 20*d* from input of duct made using a microthermocouple lever-tipe probe for 2-dimensional measurement in LM flow (figure 3), which install on butt end of working section. A copper – constantan micro thermocouple with junction size 0.25 mm locates on end-on of probe. This thermocouple has an inaccuracy 0.2 ^{0}C. The probe coordinates determine based on detection device displacement with accuracy 0.03 mm. The duct wall temperature has been measured by probe in a moment of touch wall and further the field of flow temperature is interpolated on wall. The test facility is automated with using of measuring and computing complex, which has been created basically on modern hardware and software envelopes.

Table 1 – Test facility parameters

Length of gage section, m	2.0
Heat flux density, кW/m^2	0 - 45
Length of heated section, m	0.8
Magnetic field, T	0 – 1.0
Length of electromagnet, m	0.7
Length of uniform magnetic field, m	0.6

4. Results

The results for two character flowing scenarios are presented in this chapter: a scenario with slight impact of heat – gravitational convection (Re= 50000) and strong impact (Re=30 000) ones. All results are presented for case of one side wall heating, q_2=0.

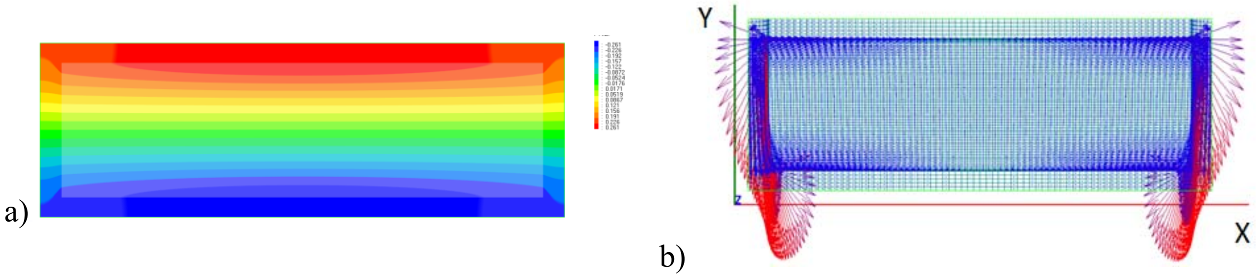

Figure 4. Voltage drop (a) and current density distribution (b) in duct section. Re = 50000, Ha = 800.

A representative distribution of electrical potential in duct section and vector plot of current density which is generated into flow of electrical conductive liquid in coplanar MF are shown in Figure 4. The duct walls are electro conductive in experiment. In this case a bridging of current happens both in short duct walls and in thin near-wall (Hartman) layer. Such distribution of current density on duct cross section explains a presence of decelerating forces near duct walls. This effect brings to deplanation of velocity profile along line of magnetic field, along axis X (figure 4). Also velocity profile in a plane perpendicular to the field is shown in figure 5. The velocity profile in case of low value of Reynolds number is non symmetry. This effect can be explained of influence of heat-gravitational convection – flow is decelerated near hot walls. Velocity profiles along axis *Y* are come to M – shaped form as Magnetic field increases.

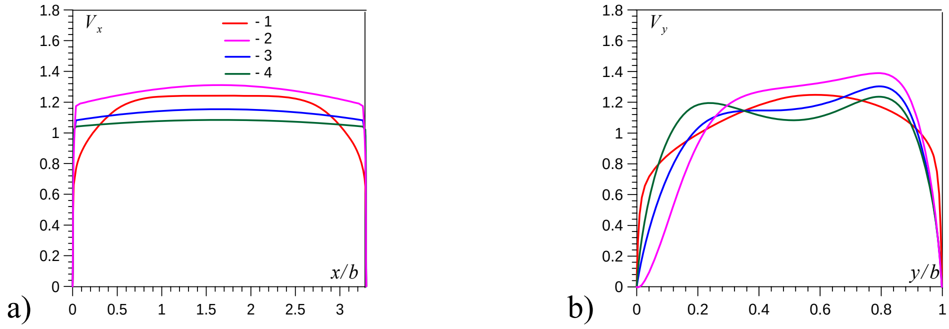

Figure 5: Longitudinal velocity's profiles in along *X* (a) и *Y* (b) axis in a section with coordinate Z = 20, $Gr_q = 4.0{\cdot}10^8$:1) Ha = 0; 2) 300; 3) 500; 4) 800.

The average nondimensional temperature's profiles in two perpendicular planes, along axis X and Y are shown in figure 6. Axis with coordinates *X=x/b* is directed in the line of long duct side and parallel magnetic field. Temperature profile along axis Y (in the line of short duct side) is significant nonuniform with maximal gradient on heated wall.

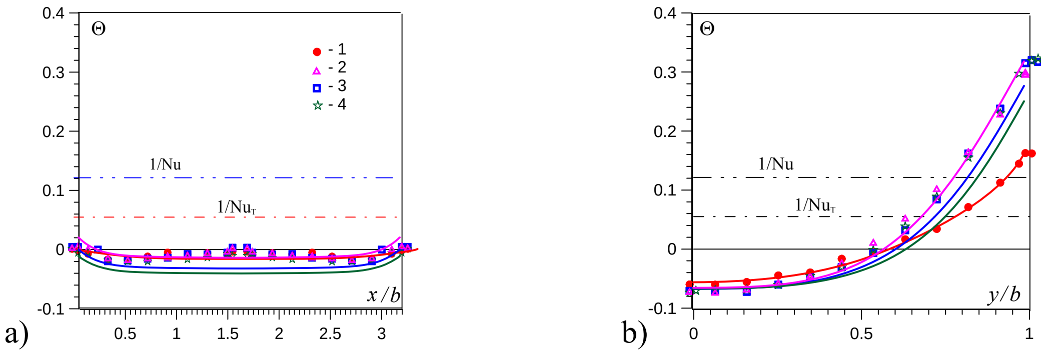

Figure 6: Average nondimentional temperature profiles along axis X (a) and Y (b) in section Z=20d, q_1/q_2= 35/0 kW/m^2, Re = 50000: 1) Ha=0; 2) 300; 3) 500; 4) 800.

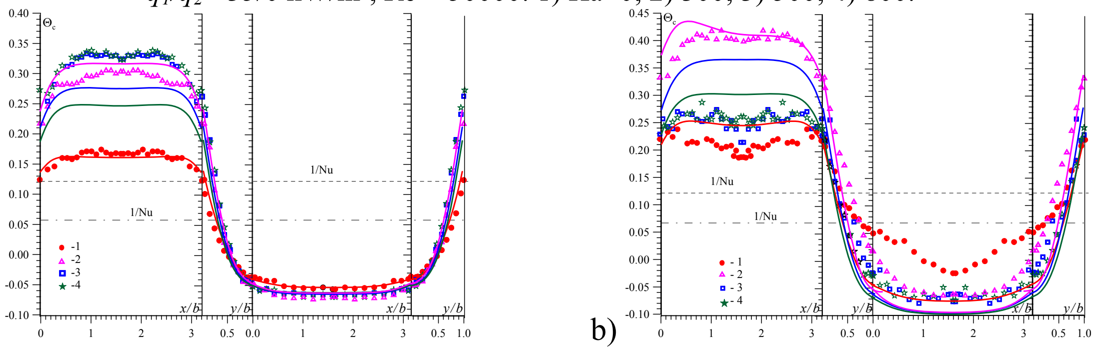

Figure 7: Distribution of nondimentional wall temperature Θ_c on duct perimeter in section Z=20d, q_1/q_2= 35/0 kW/m^2, a)Re = 50000 and b) Re = 30000: 1) Ha = 0; 2) 300; 3) 500; 4) 800.

A plot of variance nondimensional wall temperature of duct on perimeter is presented in figure 7a. For the comparison reciprocal variable of Nusselt numbers (1/Nu) for flat conduit are shown in figure 6: for developed turbulent flow which calculated using Lyon's integral equation $\mathrm{Nu}_T=10+0.025\mathrm{Pe}^{0.8}$ and stabilized laminar flow $\mathrm{Nu}_{Л}=8.24$ in case of single side heating. There is a significant nonuniform in distribution of duct wall temperature in case of single side heating. The results of numerical simulation are also presented in this plot. There is a good coincidence analysis and experimental results.

Analogical measurements have been performed for different values of Reynolds number. For the scenarios with Re<30000 a strong effect of heat – gravitational convection is observed. The experimental results for these scenario show qualitative coincidence of the average temperature of flow with have been described higher. But phenomena is discovered – at the beginning wall temperature goes up with increasing Hartmann number up to Ha=300, as might have been expected. But with a further increase the Hartmann number, wall temperature goes down. It's seen that experimental dates and analysis results are different. This difference in results can be explain effect of developing heat – gravitational convection, which will be describe below and weren't included in analysis model. The plot of variance nondimensional wall temperature of duct on perimeter is presented in figure 7b.

The profiles of intensity temperature fluctuation in dust section in two perpendicular planes are shown in figure 8. Magnetic field drives out the turbulence. Generally, intensity of temperature fluctuation goes down up to zero with increasing Hartmann flow. This effect was observed in experiment with Reynolds number Re=50000. In case of scenario with Re=35000 intensity of temperature fluctuations grow up with increasing Hartmann number and is higher in several times that level of turbulence fluctuation.

The oscillograph traces of intensity temperature fluctuations which have been measured in center of duct section for different Hartmann numbers are shown in figure 9. The low-frequency signals are registered. On traces for higher Hartmann values signal is periodical with pronounced peaks. A fluctuation character isn't turbulence. This phenomenon is explained by the generation of large-scale secondary vortices induced by heat – gravitational convection, with axes of rotation parallel to the magnetic field flow, which are carried by the flow and thus causing the temperature fluctuation. The temperature fluctuations can be growing up to 15 ^{0}C in scenario with Hartmann number Ha=800. The value of fluctuation is compatible with temperature drop in duct section.

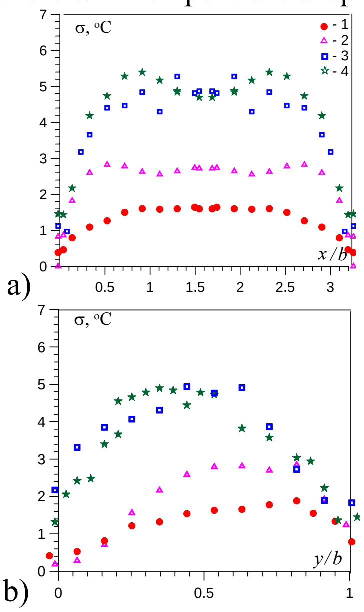

Figure 8: Intensity of temperature fluctuation's profiles along axis X (a) and Y (b) in section Z=20d, Re = 30000: 1) Ha=0; 2) 300; 3) 500; 4) 800.

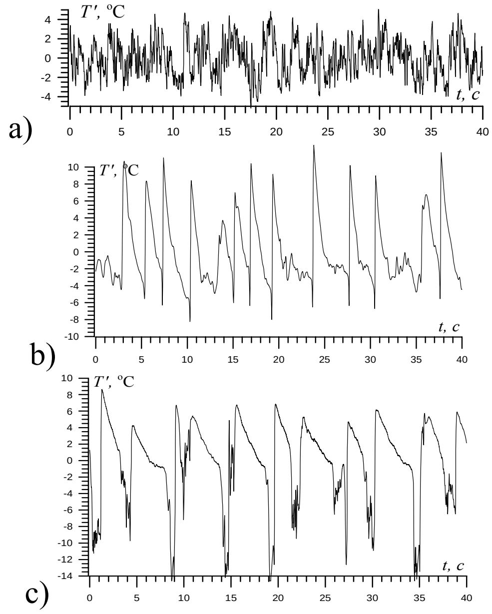

Figure 9: The oscillograph traces of intensity temperature fluctuations in low core: a) Ha = 0; b) 500; c) 800.

5. Conclusions

The significant nonuniform of the temperature distribution in the duct wall section was found in investigated configuration of flow and heating, which increases in the magnetic field. Observed MHD effect associated with the occurrence of the temperature with anomalous amplitude. These fluctuations are the result of development of the secondary flow in large-scale structures, which are the result of joint action for mass, electromagnetic and gravitational forces.

Data on values of temperature fluctuations are practical importance for the calculation of heat exchange's channels of fusion reactor. As walls temperature can change with such intensity. It leads to additional fatigue stresses, which can be causing of premature failure of the structural.

The work is supported by the Russian Fund for Basic Research, RF Ministry of Education and JSC "NIIEFA".

References

[1] Wong C.P.C., Salavy J.-F., Kim Y., Kirillov I., Kumar E.R., Morley N.B., et. al. Overview of liquid metal TBM concepts and programs. Fusion Engineering and Design. 83 (2008) 850-857.

[2] Giancarli L.M., Abdou M., Campbell D.J., Chuyanov V.A., M.Y. Ahn, Enoeda M. et. al. Overview of the ITER TBM Program. Fusion Engineering and Design. 87 (2012) 395-402.

[3] Genin L.G., Sviridov V.G. Hydrodynamic and heat transfer of MHD-flow in channels of reactors. Moscow. Publishing house MPEI 2001.

[4] Artemov V.I., Yankov G.G., Karpov V.E., Makarov M.V. Numerical simulation of heat-and mass transfer processes in parts of thermal and energetic environments. Heat Power Engineering. 7 (2000) 52-59.