LIQUID METAL HEAT TRANSFER IN A TOKAMAK REACTOR

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Complex experimental study and numerical simulation of liquid metal (LM) flow and heat transfer in various MHD configurations affected by longitudinal or transverse magnetic field (MF) have been performed [1]. The experimental studies are conducted in MHD facility by a joint team of MPEI-JIHT RAS. The MHD facility combines two mercury loops, where investigations in a longitudinal and in a transverse MF are available (Fig.1). It is well known that mercury is not considered as a possible coolant in energetics. However, mercury is, undoubtedly, the best of the working media for experiments on the MHD heat transfer.

Figure 1: MPEI and JIHT RAS loop for investigations of mercury flow and heat transfer in the longitudinal and transverse magnetic field.

Flow in horizontal, vertical and inclined tubes have been considered. Examined configurations are shown in Fig. 2, where outlined vectors: V - the velocity of the flow, g - the free fall acceleration, B – the MF induction. Heating is uniform in length, and, in general case, heterogeneous on the perimeter of the cross-section of the tube or channel (Fig. 3). The geometry of the flow and MHD convective heat exchange correspond to the various situations of the cooling channels in blanket and divertor of a tokamak- reactor.

The length of the heating zone and the uniform MF area are, respectively, 42d and 29d, where the tube diameter d=19mm.Channel section is 16x56. mm. Measurements in the mercury flow have been provided by probe methods using various sensors: thermocouples, correlation and electromagnetic velocity sensors. With the help of micro thermocouples, three-dimensional (3D) fields of average temperature and temperature fluctuations were measured, then local (along the perimeter and the length of the tube) and average heat transfer coefficients were defined. The probe technique for wall temperature measurements made in possible to eliminate the error associated with the thermal contact resistance at the liquid metal-solid wall boundary. Correlation and electromagnetic sensors were used to measure longitudinal and transverse components of local velocity. Experiments were fully automated.

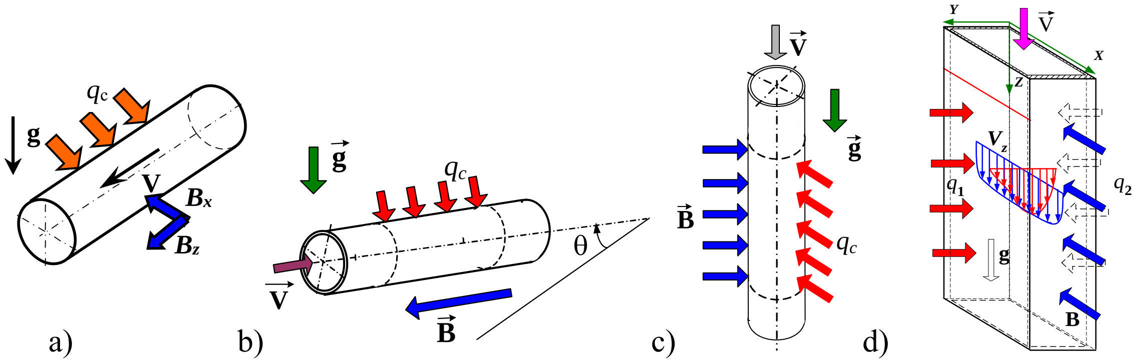


Figure 2: Flow configuration: a) horizontal heated tube in the longitudinal or transverse MF, b) down flow in an inclined to the horizon tube in the longitudinal MF, c) down flow in the vertical tube in transverse MF, d) down flow in the vertical rectangular channel in transverse MF.

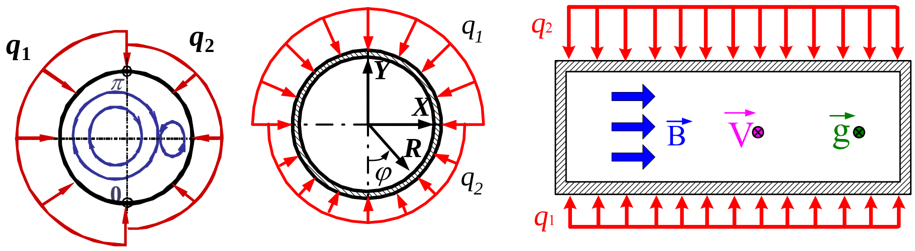


Figure 3: Heating configurations.

Table 1.Criteria in experiments.

Criterion	JIHT Loop	MPEI Loop
$\mathrm{Re} = \frac{wd}{\nu}$	$5 \cdot 10^3 \div 1.2 \cdot 10^5$	$5 \cdot 10^3 \div 7 \cdot 10^4$
$\mathrm{Ha} = Bd\sqrt{\frac{\sigma}{\mu}}$	Transverse MF 0÷500	Longitudinal MF 0-480
$\mathrm{Gr_q} = \frac{g\beta q d^4}{\lambda \nu^2}$	$0 \div 10^8$	

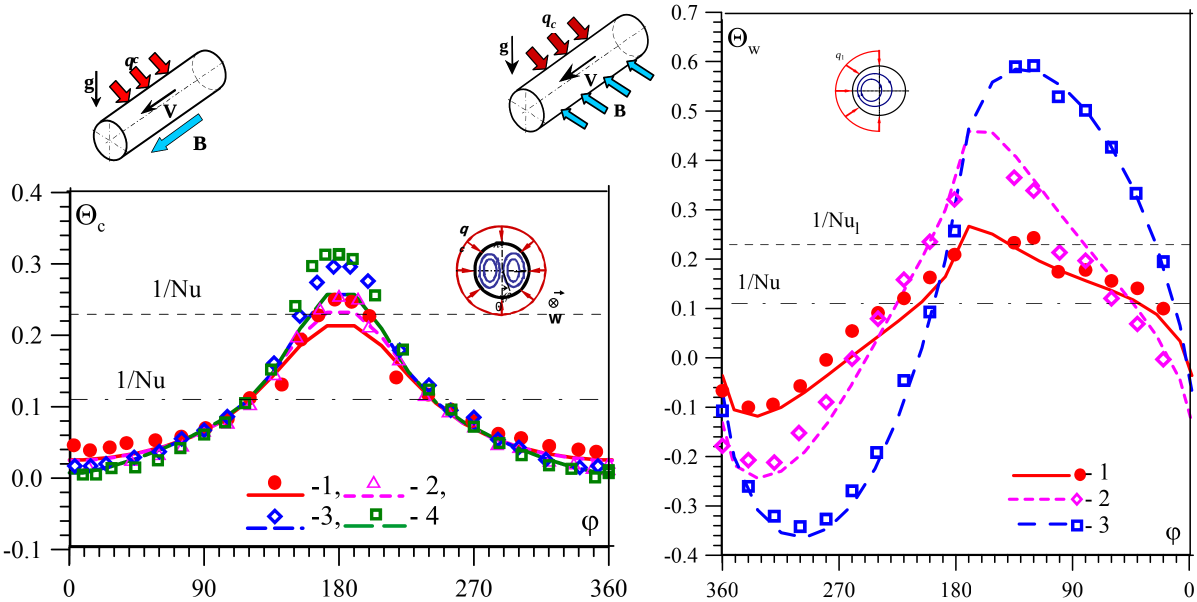
Along with the experiments, numerical simulation of MHD heat transfer has been developed. The basic of the estimated model is a system of Reynolds averaged Navier-Stocks(RANS) equations. The Boussinesq approximation and the authors model of MF affect on the turbulent transfer of momentum and heat were used.

Analysis of all the experimental data taken together allows us to make two general conclusions about the nature of the joint effect of the MF and thermo gravitational convection (TGC) on the flow and heat transfer of the LM in the tube.

The first one is the existence, in some modes, the areas of "degraded" local heat transfer and, as a result, the extremely nonuniform distribution of mean wall temperature along the perimeter of tube cross section.

For example, in horizontal tube affected by longitudinal MF TGC manifests itself in the form of large longitudinal vortices (Fig. 3) with axes parallel to the vector of the MF induction. MF stabilizes these vortices. As a result, flow loses axial symmetry, heat distribution becomes inhomogeneous in the tube cross-section, with the formation of zones of «degraded» and «enhanced» heat transfer. We call heat transfer «degraded » when local Nusselt criteria are below laminar values $\mathrm{Nu_L}= 4.36$ [2].

It is an frequent situation when the designers of heat exchangers, in case of lack preliminary information on heat transfer, use the laminar value Nu_L = 4.36 as «the lowest possible». As it can be seen for example in Fig. 3, this cannot be done, because the local Nusselt criteria can be significantly lower.



a) longitudinal MF, homogeneous heating b) transverse MF, inhomogeneous heating

Figure 3: Dimensionless wall temperature Θ along the perimeter of the horizontal tube cross section *z/d*=37, points – experiment, lines – calculation Re = 10000, *q* = 35 kW/m^2(Gr_q = 0.8·10^8): 1) Ha = 0; 2) 150; 3) 300; 4) 450;

In the vertical tube affected by transverse MF there is also heterogeneity of the wall temperature along the perimeter of the tube section (Fig. 4) [3]. However, physical reason in this case is different. The matter is in the presence of Hartman effect in the transverse MF. This effect leads to a flattening of velocity profile in the direction of the magnetic induction vector, while in the perpendicular direction speed profiles have an elongated shape, typical for laminar flow. Strong axial asymmetry of the velocity profile and reinforced counter TGC leads to the heterogeneity of local heat transfer coefficients and wall temperature along the perimeter of the tube cross section.

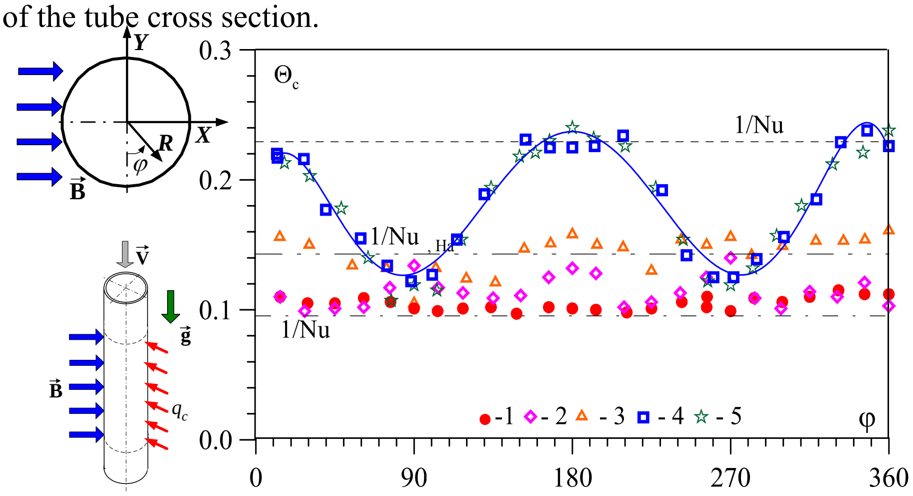


Figure 4: Dimensionless wall temperature Θ along the perimeter of the vertical tube cross section z/d = 37 affected by the transverse MF with the homogeneous heating Re = 20000, q = 55 kW/m^2: 1) Ha = 0; 2) 100; 3) 220; 4) 320; 5) 500. Points – experiment, lines – experiment data approximation.

The second effect is the presence of extremely high temperature fluctuation of low frequency in the core of MHD flow and near the wall. Example of such fluctuations observed in one of examined configurations is shown on Fig.5. This effect present itself when TGC forces compete with MF forces. Such a situations develops in heated vertical tubes with downflow affected by transverse [4] or longitudinal [1] MF and in horizontal tubes affected by transverse MF when heating configuration produces unstable density stratification due to thermo gravitation [5]. The physical cause of both effects is the same: the joint affect of MF and TGC upon the nonisothermal MHD LM flow, which results in generation of stable large-scale quasi-2D vortices with the axes parallel to MF vector. The affect of MF upon the LM mean velocity profile is also essential. Both of these effects are dangerous for wall material.

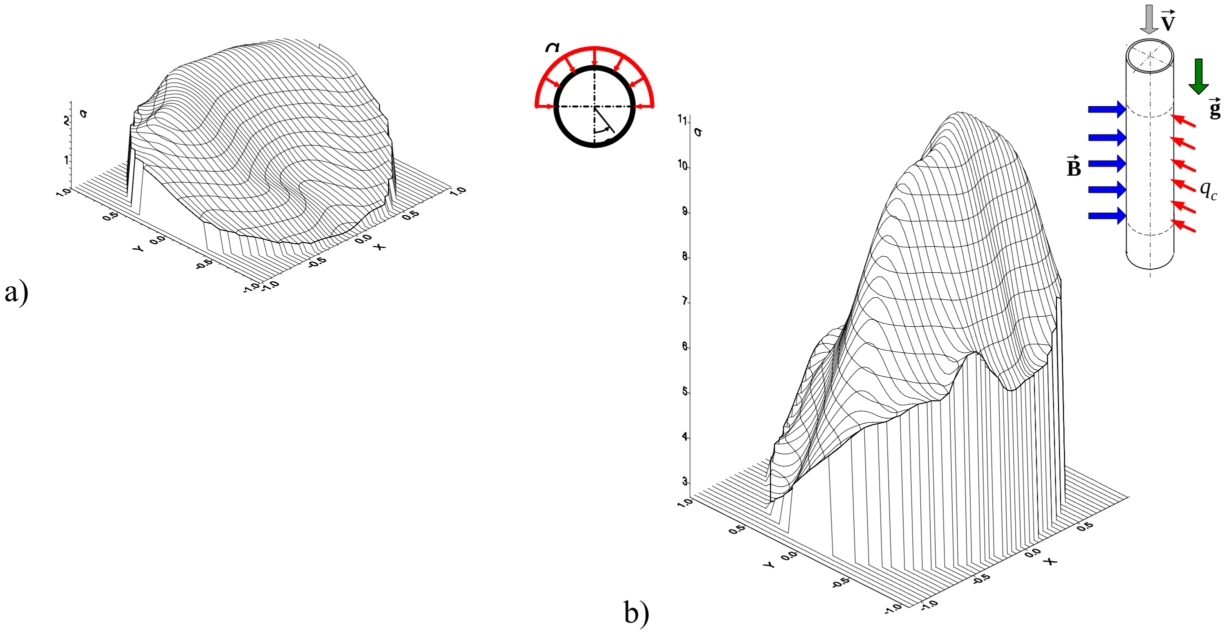


Figure 5: Temperature fluctuation intensity field in the vertical tube cross-section z/d = 37, q_1/q_2= 55/0 W/m^2 (Gr$_q$ = 1.25·10^8), Re = 20000: a) Ha = 0; b) 300.

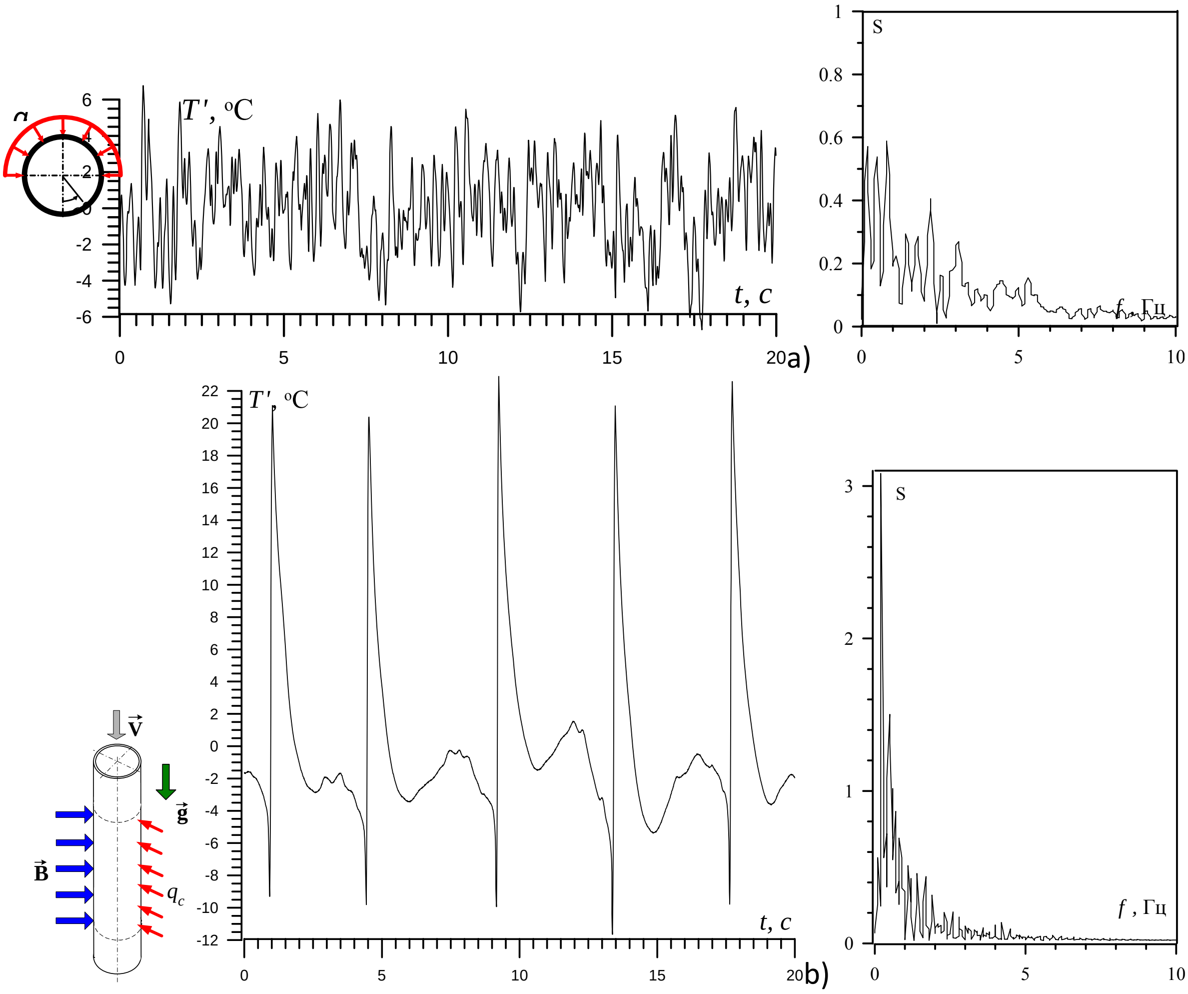


Figure 6: Characteristic temperature fluctuations and its power spectrum in vertical tube with inhomogeneous heating: z/d =37, q1/q2 = 55/0 кW/m2, Re =20000, transverse MF, at intensity maximum) Ha = 0; b) 330.

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