LIQUID METAL DOWNFLOW IN AN INCLINED HEATED TUBE AFFECTED BY LONGITUDINAL MAGNETIC FIELD

BELYAEV I.A., SVIRIDOV V.G., ZAGORSKY V.S.
[1] 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: iabelyaev@gmail.com

Abstract: Experimental study of heat transfer liquid metal downflow in inclined heated tube (inclination 11º; 30º; 45º to the horizon) under the influence of a longitudinal magnetic field has been done. Mercury was used as a model liquid. The test section is a steel tube with inner diameter 19 mm and approximately 100 calibers length, last 40 calibers are heated. MF is homogenous at calibers. Modes of the parameters: Stuart number $N = Ha^2/Re = 0 \div 23$, Richardson number $Ri = Gr/Re^2 = 0 \div 0.8$ in the case of uniform heating were investigated. The studies were conducted using a probe method with the use of microthermocouples. Fields of averaged longitudinal velocity, average temperature and temperature fluctuations have been measured; local and average Nusselt number on the tube perimeter than have been calculated.

1. Introduction

Liquid metals (LM) are considered as a coolant or working media in advanced fission and fusion devices. In the latter case, considering tokamak concept, the LM flow will be affected by strong magnetic field (MF), which can lead to a catastrophic increase of hydraulic resistance. However, reasonable arrangement of heat exchange channels can minimize the negative effects that are presenting themselves in the MF. Direction of the flow along the lines of magnetic induction is capable to remove a significant portion of the MHD interaction complexities. However, the impact of MF on a flow with presence of high heat fluxes, that give rise to buoyancy forces, is ambiguous and cannot be reduced only to the suppression of secondary flows and turbulence [1] In any tokamak reactor MF is a result of toroidal and poloidal components. So MF is directed at some angle to the horizon. In ITER TBM projects [2] this angle is about 11º. In more compact devices (such as fusion neutron sources (FSN) [3]) it can be up to 45º. Straight inclined tube configuration (Fig 1) is considered as a first approximation to design with LM flow directed along with MF.

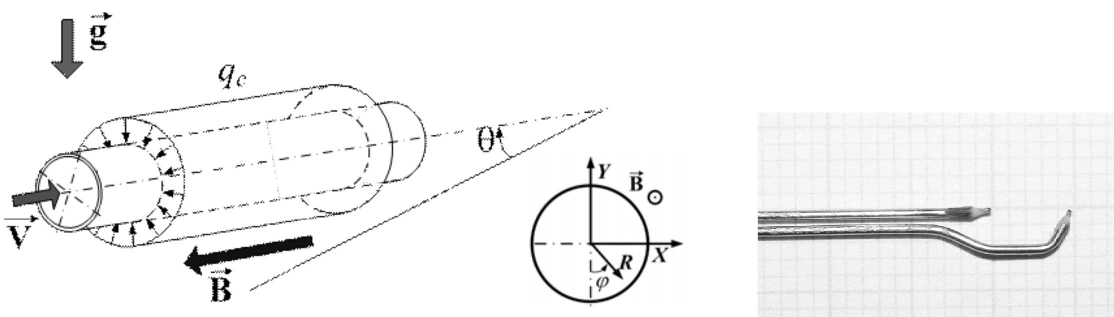


Figure 1: Flow configuration, coordinate system
and the correlation thermocouple probe construction.

Experimental study of this configuration have been made using MPEI mercury loop [1]. Criteria ranges that have been investigated during research are shown in Table 1.

Table 1. Criteria ranges

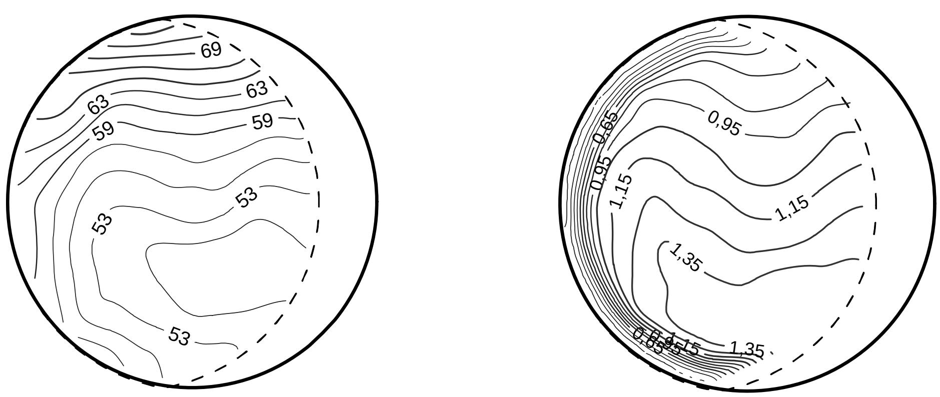
Criterion	Range
$Re=U\ d/\nu$	$5\cdot10^3\div55\cdot10^3$
$Ha=B\ d(\sigma/\mu)^{0.5}$	$0\div480$
$Gr_q=g\ \beta\ q\ d^4/(\lambda\ \nu^2)$	$0\div1.2\cdot10^8$
$C=\sigma_w L_w/(\sigma d)$	0.04
$Nu=(q_c d/\lambda)/(T_w-T_{bulk})$	–

Table 1 legend: Re - Reynolds number, ν - the kinematic viscosity coefficient, Ha - Hartmann number, σ - conductivity of the medium, μ - dynamic viscosity, Gr_q - Grashof number, g – gravity acceleration, C - relative conductivity of the wall, σ_w – wall conductivity, L_w - wall thickness.

2. Experimental results

Fields of temperature and dimensionless longitudinal velocity obtained in section z/d=37 for tube with 45 degrees inclination in one of investigated regimes are shown on fig. 2 and fig. 3. Section z/d=37 is chosen as a last point of homogeneous MF. Construction of correlation thermocouple probe (Fig.1) which is capable to measure temperature and time averaged longitudinal velocity produces area where measurements cannot be made. Fields are constructed from the experimental points by polynomial triangulation.

In regimes without MF, one can see that temperature isolines are curved by secondary TGC vortices. Traditional for horizontal tubes these TGC vortices with axes along the tube are quite significant in inclined tubes too. In addition, we observe velocity suppression near the upper wall and amplification near the lower wall due to counter thermo gravitation. Both of these thermo gravitational effects lead to temperature inhomogeneity along the wall.

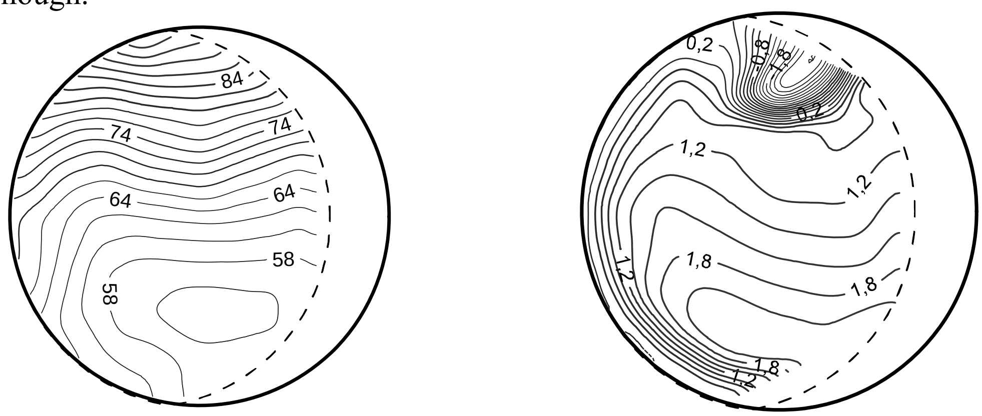


a) Temperature ˚ C b) The dimensionless longitudinal velocity

Figure 2: Fields in section z/d = 37, θ = 45 ˚, Re = $10\cdot10^3$, $Gr_q = 0.8\cdot10^8$, Ha = 0.

In regime with MF strong enough to fully suppress isothermal turbulence one can see area of stable reverse flow near the top of the tube (Fig.3 (b)).

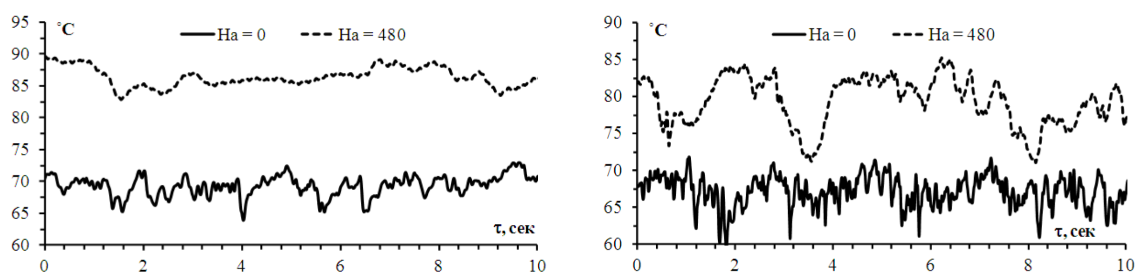
Correlation method, in principle, is a direct method of measuring speed, so it can be applied for the straight and reverse flow, but in the transition region from straight to reverse flow method is not applicable. Also in case of reverse flow probe produces additional disturbance to measurements, which are difficult to compensate. Thus, we assume that the fact of the return flow presence is clear but the region and negative velocity values themselves are defined not precisely enough.



a) Temperature ˚ C b) The dimensionless longitudinal velocity

Figure 3: Fields in section $z/d = 37$, $\theta = 45$ ˚, $Re = 10{\bullet}10^3$, $Gr_q = 0.8{\bullet}10^8$, $Ha = 480$.

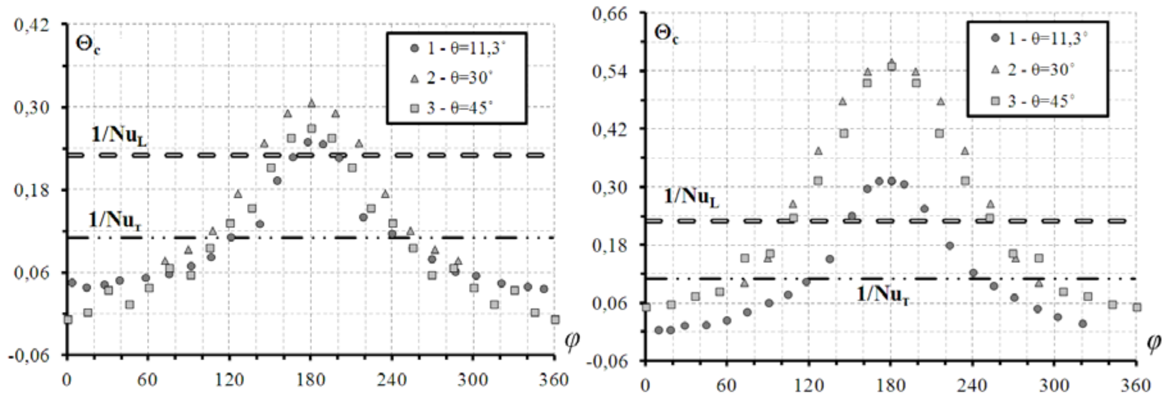
The emergence of the reverse flow in MF is not accompanied by any growth of temperature fluctuations amplitude (Fig. 4(a)). In some regimes where flow have been affected by MF but development of reverse flow have not happened, we observed growth of temperature fluctuation amplitude (Fig. 4(b)).



a) $Gr_q = 0.8 \cdot 10^8$, $Re = 10 \cdot 10^3$ b) $Gr_q = 1.2 \cdot 10^8$, $Re = 20 \cdot 10^3$

Figure 4: Temperature waveforms near the upper generatrix ($R = 0.8$, $\varphi = 180$˚), $z/d = 37$, $\theta = 45$˚.

In case of reverse flow presence temperature fields are quite similar qualitatively (Fig 2(a), Fig.3(a)), but overheating near the top generatrix ($\varphi=180$) is significantly increased quantitatively. This is shown in the form of distributions of local dimensionless temperature ($\square(\varphi) = 1/Nu(\varphi)$) along the perimeter for different inclinations (Fig. 6).

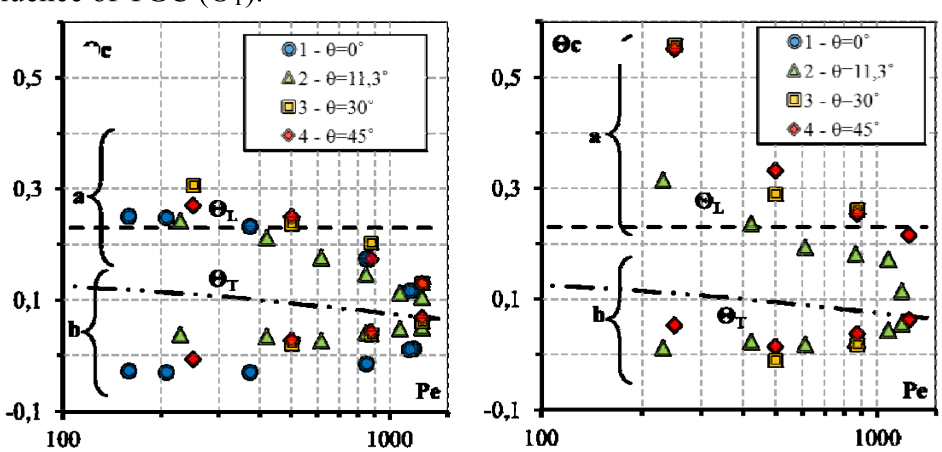


a) Ha = 0 b) Ha = 480

Figure 5: Θ distribution along tube perimeter $z/d = 37$, $\mathrm{Re} = 10\cdot10^3$, $\mathrm{Gr} = 0.8\cdot10^8$, for various inclinations.

Without MF experimental points with different inclinations lie close enough to each other. Natural convection causes a significant temperature difference between upper (φ = 180˚) and lower (φ = 0˚, 360˚) generatrix. Imposition of the longitudinal magnetic field MF (Fig. 5(b)) at an inclination of 11 ˚ changes picture slightly [4]. A different result is observed at inclination angles of 30˚, 45 ˚ as there development of reverse flow is happening. In this case, local temperature increases throughout the cross section, especially near the upper generatrix where significant overheating occur. What is more, "bell-shaped" form of temperature distribution along the perimeter is saved. As we can see from fig.5, lowest temperature is at lower generatrix and highest at upper in regimes with reverse flow and without. As for the horizontal tube configuration, we found degraded heat transfer zone in case of uniform heating even without MF. This is important, because of the additional thermal stress risk for heat exchanger design [1].

The results of heat transfer studies at different inclination angles are generalized in the form of distributions of local dimensionless wall temperature Θ at upper and lower generatrix from various Peclet numbers (Pe = Re•Pr) (Fig. 6). This difference for such a configuration means total difference of temperatures at tube perimeter. In horizontal and inclined tubes (up to 45 ˚) without magnetic field, (Fig. 6(a)) we observe a similar pattern: difference between Θ in cross section decreases with Pe growth, and values of Θ tend to characteristics of purely turbulent heat transfer without influence of TGC (Θ_T).



a) Ha = 0 b) Ha = 480

Figure 6: Local Θ at upper φ = 180° (a) and lower φ = 0° generatrix (b), $\mathrm{Gr}_q = 0.8\cdot10^8$.

When applying the MF (Ha = 480) (Fig. 6(b)) in inclined tubes difference in the values of Θ in a cross section increases as the angle grows despite the fact that configuration is changing to vertical one. It is known, that in vertical configuration with uniform heating we have uniform temperature distribution. Significant heterogeneity in the temperature distribution over the cross section is observed up to the maximum available number Pe. This happens due to counter TGC forces, which slow down flow near the upper generatrix and even provide development of stable reverse flow at low Pe numbers.

3. Conclusion

In summary for downflow in tubes with inclination up to $\theta=45^{\circ}$ to the horizon characteristics of heat transfer are much closer to a horizontal tube than to a vertical one. As in horizontal tubes, heterogeneity of wall temperature along the section perimeter is significant. The temperature difference at the top and bottom of the tube exceeds the values obtained in the equivalent modes for horizontal tubes, especially in the presence of a longitudinal MF.

The role of thermogravitational convection in the entire range of regime parameters is essential. Specificity of inclined tubes is inhibited region near the upper generatrix. It was observed that in the presence of a strong longitudinal MF reverse flow may develop from these inhibited regions. This phenomenon was first discovered and investigated experimentally by direct measurement of the longitudinal velocity component using thermocouple correlation technic. In the region near the upper generatrix a reverse flow was observed while lower part of the flow was accelerated by performing the contrary law of continuity. Reverse flow lead to extremely high heterogeneity in the distribution of the wall temperature over the tube section and extremely low Nusselt number: Nu<1 for local values on top of the tube. Transition to regimes with reverse flow were obtained smoothly, without crisis. Observed in regimes with longitudinal magnetic field reverse flow is quite stable, as increase of temperature gradient across the section were not accompanied with any growth of temperature fluctuations amplitude.

Work is supported by RF president award СП-2363.2012.2 and RF president grant MK-4882.2012.8.

4. References

[1] Belyaev, I.A., Genin, L.G., Listratov, Ya.I., Melnikov, I.A., Sviridov, V.G., Sviridov, E.V., Ivochkin, Yu.P., Razuvanov, N.G., Shpanskiy, Yu.S.: Liquid metal heat transfer specific in a tokamak reactor. Magnetohydrodynamics vol. 49 (2013),, no. 1-2, pp. 177-190.

[2] ITER Design Description Document. Part 1.6. Blanket. Part 1.7. Divertor. ITER Joint Central Team – San-Diego, USA – 1994.

[3] Kuteev, B.V., Lukash, Y., Petrov, V.S., Shpanskiy, Yu.S.: Magnetic system of a compact spherical tokamak FNS-ST. VANT 2010(4): p. 40-47, (in Russ.).

[4] Belyaev, I.A., Listratov, Ya. I., Razuvanov, G.N., .Sviridov, V.G.: Liquid metal heat transfer in an inclined tube affected by a longitudinal magnetic field. Proc. the 8th International PAMIR Conference on Fundamental and Applied MHD, France, 2011, p.43-49.