DNS OF MIXED CONVECTION IN A LIQUID METAL FLOW WITH IMPOSED TRANSVERSE MAGNETIC FIELD

LISTRATOV Ya.[1], OGNERUBOV D.[1], SVIRIDOV V.[1], ZIKANOV O.[2]
Affilation: [1]National Research University "Moscow Power Engineering Institute"– 111250, Russia, Moscow, Krasnokazarmennaya st, 14, [2]Department of Mechanical Engineering, University of Michigan, State of Michigan, USA
e-mail address of corresponding author: yaroslav.listratov@gmail.com

Abstract : We present the results of direct numerical simulation (DNS) of magnetohydrodynamic flow in circular horizontal pipe under strong transverse magnetic field with influence of natural convection. Under consideration flow modes which possible in liquid metal circuits of fusion reactor blanket cooling systems [1]. Sufficient amount of experimental data with MHD-flows of liquid mercury in long vertical and horizontal pipes under strong transverse and longitudinal magnetic fields [2-3] show that at high Hartmann numbers (Ha~300) appears strong temperature fluctuations. More of that thermal stresses that appears in pipe wall could be comparable with breaking point stresses of channel wall material.

1. Introduction

The main objective of this research is to find explanation and validation of the experimental data in case of the slow high-amplitude fluctuations of temperature that arise at strong magnetic fields. These data obtained at the Moscow Power Engineering Institute (MPEI) and the Joint Institute of High Temperatures (JIHT) of the Russian Academy of Science on the mercury facility. The configuration chosen for the analysis is that of a long horizontal pipe liquid metal flow with the lower half of the wall heated at a constant heat transfer rate *q* and a uniform magnetic field *B* imposed in the transverse horizontal direction (fig 1).

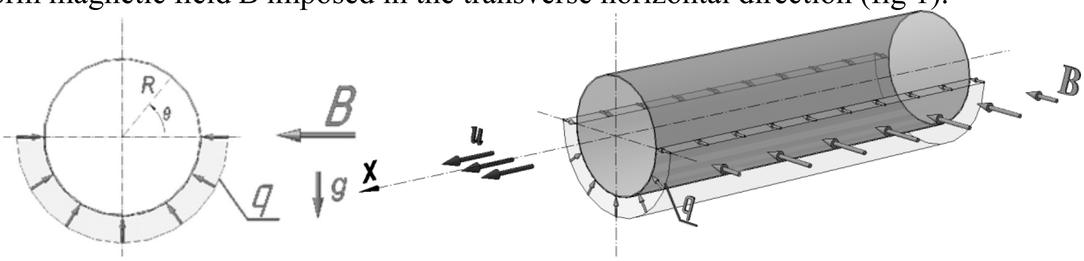


Figure 1: Flow configuration

The most interesting results of the experiment have been recently announced [4] are shown on the figure 2. Without the magnetic field (fig. 2a) fluctuations are irregular and typical for the turbulent flow as confirmed by the spectrum. A sufficiently strong magnetic field (Ha=100) should suppress the turbulence and lead to a flow without temperature fluctuations (fig. 2b). Stronger magnetic field (Ha=300), however, reappears fluctuations with significantly higher amplitude and low dominating frequency (fig. 2c). The fluctuations do not disappear up to highest value Ha = 500 reached in the experiments. The distributions of the temperature fluctuation intensity along the pipe are shown on the figure 3. After the flow enters the zone of uniform magnetic field, which starts at x/d=6, the intensity decreases, as result of turbulence suppression. The decrease continues until the end of the magnet at Ha=100. However at Ha=300 and 500 the decrease is replaced by growth at some distance. This growth is associated with fluctuations illustrated on the figure 2c. It is very important to analyze this phenomenon because similar fluctuations appeared in a liquid metal blanket of a fusion reactor can cause thermal stresses on the blanket wall.

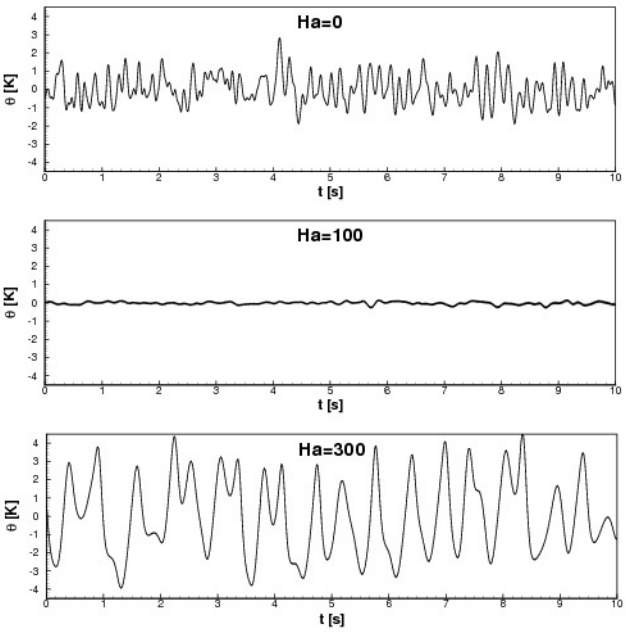
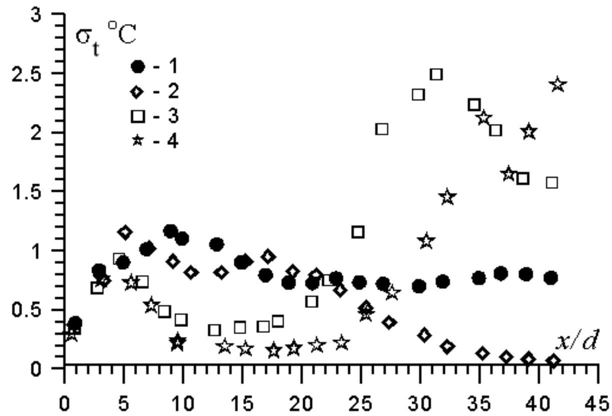


Figure 2: Time signals of temperature fluctuations measured at the point with coordinates $r/d=0.35$, $\theta=3\pi/2$ (bottom of the pipe), $x/d=37$ after beginning of the heating.
Flow parameters: $Re=ud/\nu=10^4$, $Gr=gbqd^4/\nu^2\lambda=8.5\cdot10^7$, $Ha=Bd(\sigma/\rho\nu)^{1/2}$.



1 – Ha=0, 2 – Ha=100, 3 – Ha=300, 4 – Ha=500

Figure 3: The temperature fluctuation intensity distributions (time averaged) measured along the pipe at the point with coordinates $r/d=0.35$, $\theta=3\pi/2$ (bottom of the pipe).
$Re =10^4$, $Gr =8.5\cdot10^7$.

For the start the linear stability analysis and direct numerical simulations are conducted to analyse this case [5]. It is found at the magnetic field strength far exceeding the laminarization threshold, the natural convection develops in the form of coherent quasi-two-dimensional rolls aligned with the magnetic field. Transport of the rolls by the mean flow causes high-amplitude, low-frequency fluctuations of temperature. Given work is an extension of the research of this phenomenon. Direct numerical simulations are performed to determine flow patterns in the range of the non-dimensional flow parameters achievable in the experiments: $Re=5000\text{-}11000$, $Gr=0\text{-}1.3\cdot10^8$, $Ha=0\text{-}300$, $Pr=0.022$.

2. Presentation of the problem

The numerical model is designed to be possibly close to the conditions of the experiment [5]. In particular, as illustrated in figure 4, the computational domain includes the entire experimental test section. The segment with wall heating and the segment with nearly uniform magnetic field have the same lengths as in the experiment.

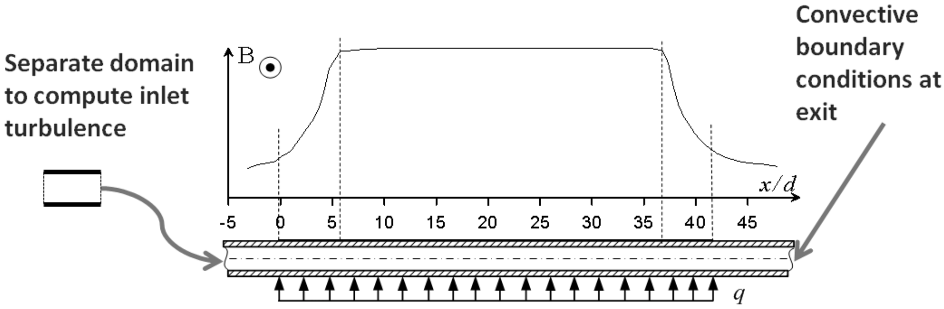


Figure 4: The computational domain. Distribution of magnetic field obtained in experiment.

The numerical model included the procedure used to generate the isothermal turbulent flow at the inlet. The computational grid has Nr=90 (clustered) and N□=96. In the axial direction, the grid has 1696 uniform distributed points, which corresponds to 32 points per unit length.
The entire computed flow in its fully developed state for various Ha is illustrated in figure 5.
(a)

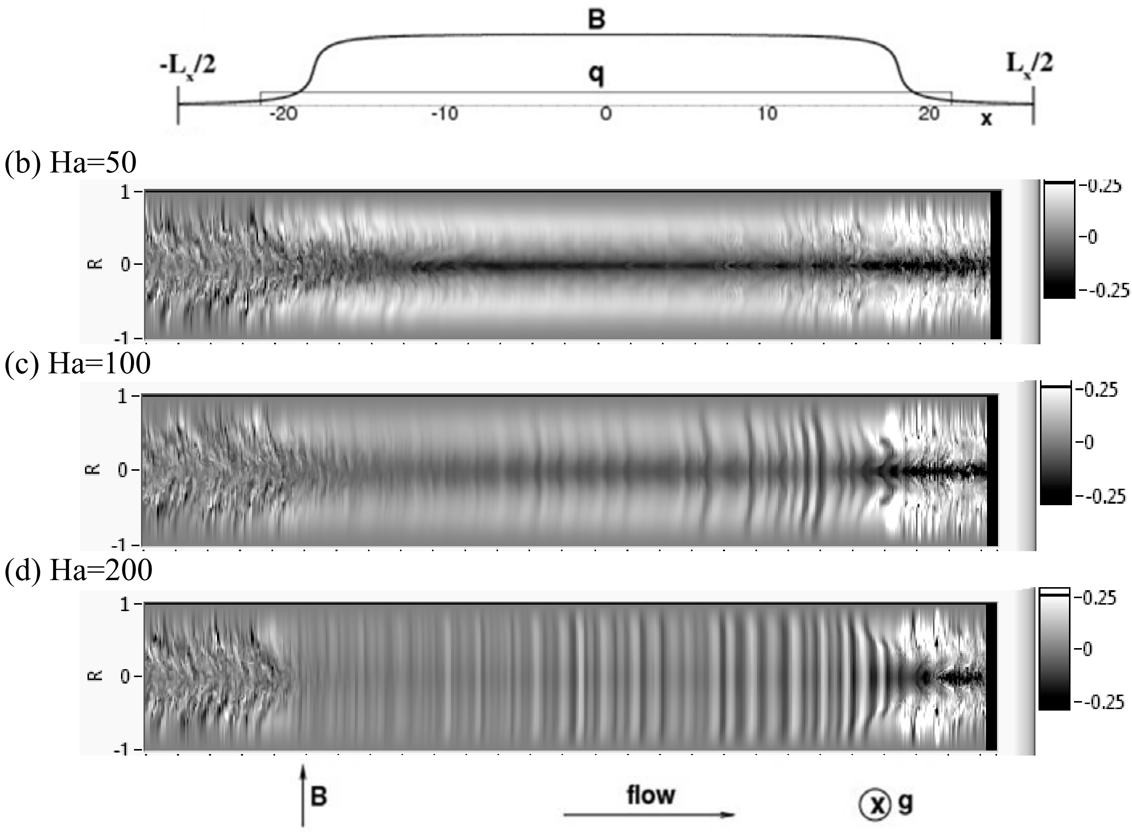


Figure 5: DNS results. (a) distributions of the transverse magnetic field *B*
and wall heating *q* along the computational domain; (b-d) fully developed flow shown using snapshots vertical velocity u_z in the horizontal cross-section through the pipe axis.
Re = 9000, Gr = $6{\cdot}10^7$.

The flow visibly changes about midway through the magnet zone. A pattern of upward and downward motions and associated variations of temperature appear and increases in amplitude as we move downstream. In the absence of turbulence, the natural thermogravitational convection becomes a dominant mechanism that determines the temperature and velocity field. At Ha=50 or less the geometrically preferable form of the laminar convection is that of streamwise rolls with upward flow along the walls and downward flow in the middle (fig. 6a). However, at Ha = 200 and higher the convection structures developing in the flow change their type and become aligned with the magnetic field (fig. 6b). At Ha = 100, an intermediate mode of convection rolls with unstable states moving downstream is observed.

(a) Ha=50 (b) Ha=200

Figure 6: Structure of convection rolls at moderate (a) and strong (b) magnetic field. Isosurfaces of three-dimensional vertical velocity u_z in the pipe segment 35 < x/d < 38. Re =9000, Gr =$6\cdot10^7$.

The DNS results will now be compared with the experiment. The distributions of the temperature fluctuation intensity along the pipe at Ha=300 are shown on the figure 7.

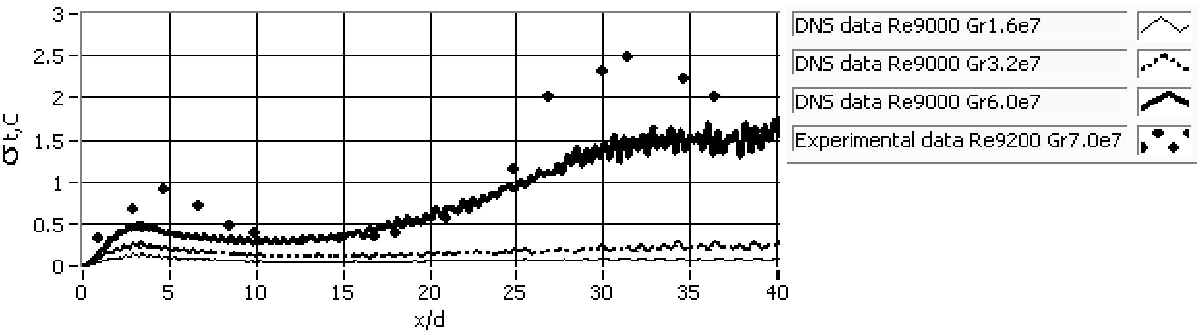


Figure 7: The temperature fluctuation intensity distributions (time averaged) computed along the pipe at the point with coordinates r/d=0.35, θ=3π/2 (bottom of the pipe). Ha=300

As in the experiment intensity decreases after the entering uniform magnetic field. At some distance we observe a growth due to re-oriented rolls aligned with the magnetic field. However, if we reduce the heating that is the Grashof number, it lead to return the mode of streamwise rolls with low level of temperature fluctuations.

Figure 8 show the distribution of time-averaged dimensionless wall temperature along the pipe perimeter in middle section.

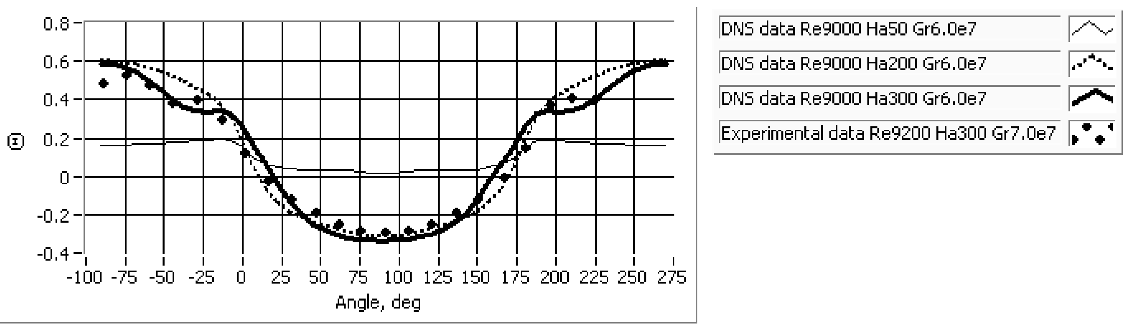


Figure 8: Comparison between DNS and experiment. Lines correspond to the time-averaged dimensionless wall temperature distribution in the pipe section x/d=30 after beginning for various Ha in DNS, while symbols show the data measured in the experiment.

We see that the DNS results have a good agreements with the experimental data. Moreover, figure 8 show overly inhomogeneous distribution of the wall temperature in case of strong magnetic field (Ha = 200 and higher) unlike at Ha = 50. This is confirmed if we consider the temperature perturbations at the topmost and bottommost wall points (figure 9). Such inhomogeneity can lead to the dangerous thermal stresses on the wall.

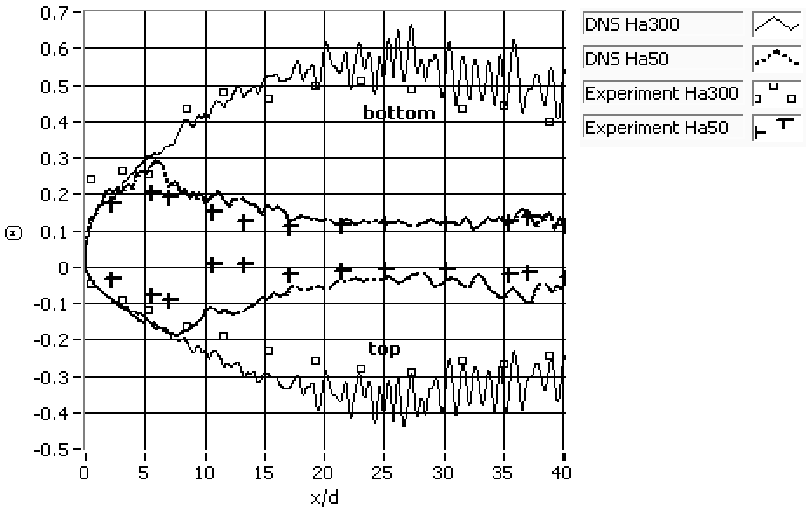


Figure 9: Comparison between the DNS and the experiment. Lines correspond to the instantaneous temperature distribution, while symbols show the time-averaged data measured in the experiment. (a) Temperature perturbations at the topmost ($\nabla = \pi/2$) and bottommost ($\nabla = 3\pi/2$) wall points. Re = 9000, Gr = $6\cdot10^7$.

3. Conclusion

We have conducted the DNS analysis of the flow in a horizontal pipe with the lower half of the wall heated and an imposed transverse magnetic field. The main results are the detection and detailed study of the convection structures having the form of rolls aligned with the field. Existence of such structures was suspected on the basis of the experimental results, but could not be proven because of the limitations of flow visualization in liquid metals. Our computations leave no reasonable doubt that such convection structures appear at high Hartmann numbers and are responsible for the anomalous temperature fluctuations detected in the experiments.

Financial support of this research was provided by the Ministry of Education and Science of the Russian Federation, Russian Fund for Basic Research.

4. References

[1] Smoletsev, S.; Moreau, R. & Abdou, M.: Characterization of key magnetohydrodynamic phenomena for PbLi flows for the US DCLL blanket. Fusion Eng. Design, 83 771-783 (2008).

[2] Sviridov, V. G.; Razuvanov, N. G.; Ivochkin, Yu. P.; Listratov, Ya. I.; Sviridov, E. V.; Genin, L.G.; V.G.; Belyaev, I. A.: Liquid Metal Heat Transfer Investigations Applied to Tokamak Reactor. Proc. the International Heat Transfer Conference IHTC14, USA, pp.1-8 (2010).

[3] Sviridov, V. G.; Razuvanov, N. G.; Ivochkin, Yu. P.; Listratov, Ya. I.; Sviridov, E. V.: The experimental liquid metal heat transfer investigations applied to fusion reactors. Fundamental and Applied MHD, Proc. 7th PAMIR Conf., Giens, France, pp. 885-890 (2008).

[4] Genin, L. G., Zhilin, V. G., Ivochkin, Y. P., Razuvanov, N. G., Belyaev, I. A., Listratov, Y. I., Sviridov, V. G. Temperature fluctuations in a heated horizontal tube affected by transverse magnetic field. Fundamental and Applied MHD, Proc.the 8th International Pamir Conference, Borgo, Corsica, pp. 37–41 (2011).

[5] O. Zikanov, Ya.I.Listratov, and V.G.Sviridov. Natural convection in horizontal pipe flow with strong transverse magnetic field. J. Fluid Mech., vol. 720, pp. 486–516 (2013).