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Temperature fluctuations in a nonisothermal mercury pipe flow affected by a strong transverse magnetic field

Ivan Belyaev [a,b,*], Peter Frick [a,c], Nikita Razuvanov [a], Evgeniy Sviridov [a], Valentin Sviridov [a]

[a] *Moscow Power Engineering Institute, Krasnokazarmennaya 14, Moscow 111250, Russia*
[b] *Joint Institute for High Temperature RAS, Izhorskaya st. 13 Bd. 2, Moscow 125412, Russia*
[c] *Institute of Continuous Media Mechanics, Academ. Korolyov, 1, Perm 614013, Russia*

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ABSTRACT

Liquid metal flows in rectangular ducts and circular pipes under high thermal loads and strong transverse magnetic fields are of great interest in context of developing cooling systems for fusion reactors. In this study, a downward flow of mercury in a uniformly heated pipe affected by a transverse magnetic field is studied experimentally. We show that moderate magnetic fields (0.2–1 T; Hartmann numbers 100–500) not only do not suppress the temperature fluctuations, but lead to the existence of significantly different regimes, characterized by strong temperature fluctuations. At least two different states of fluctuating flow exist. These states generate quantitatively different patterns of temperature fluctuation characteristics in the pipe cross-section. Domains of existence of both regimes are localized in the parameter plane Richardson versus Hartmann numbers. It is shown that these regimes are controlled by the Richardson number and disappear at high Hartmann numbers (above 500).

1. Introduction

Interest in heat and mass transfer in liquid metals under strong magnetic fields is largely stimulated by their application as a coolant and working fluid in fusion reactors [1,2]. The peculiarity of the flows in such systems is the combination of large flow rate, high temperature gradients and strong magnetic field.

Strong transverse magnetic field (MF) deeply affects the liquid metal flow, flattening the velocity profile and suppressing the turbulent fluctuations [3,4]. However, even in the simplified flow between two infinite parallel plates, numerical simulations reveal regimes characterized by long periods of nearly steady two-dimensional flow interrupted by violent three-dimensional bursts [5]. The transition to bounded flows (ducts) substantially alters the structure of both the mean flow and secondary flow motion. In rectangular ducts the strong transverse MF provides an almost flat core, while Hartmann layers develop near the walls transverse to the magnetic field. Jets can arise near the walls parallel to the MF, if the perpendicular to the field walls are electrically conducting [6]. Two types of instabilities of such flows have been found in numerical simulations. The first occurs in the form of small-scale vortices, while the second appears at higher Reynolds numbers and is associated with the formation of large-scale structures which involve bursts of fluid at the walls parallel to the MF [7].

High heat flux stimulates generation of specific secondary motions in MHD flows. Strong flow-opposing buoyancy force form reverse flows near the heated wall [8]. Experimental study downward flow of mercury in heated pipes affected by transverse MF revealed intense low-frequency temperature fluctuations [9]. It turned out that available magnetic field (up to about 1T) was insufficient to suppress these temperature fluctuations. Experimental [10] and numerical [11] studies of a downward flow in non-uniformly heated pipe confirmed the formation of anomalous high amplitude temperature fluctuations.

Experimental and numerical studies of heated liquid metal flows in rectangular ducts [12–14] were stimulated by modern fusion reactor concepts [2] and showed that high heat fluxes and magnetic field cause instabilities leading to several possible flow regimes. In the weak turbulent regime, the induced vortices are localized near the inflection point of the base velocity profile, while the boundary layer at the wall parallel to the magnetic field is slightly disturbed. In the strong turbulent regime, the bulk vortices interact with the boundary layer causing its destabilization and formation of secondary vortices that may travel across the flow, even reaching the opposite wall [15].

The phenomenon of high-amplitude temperature pulses is of strong engineering interest as it may produce additional thermal stresses and provoke corrosion in the wall material. The new HELM

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* Corresponding author at: Moscow Power Engineering Institute, Krasnokazarmennaya 14, Moscow 111250, Russia.

E-mail address: bia@ihed.ras.ru (I. Belyaev).

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Experimental Facility at the JIHT RAS extended the available range of magnetic fields [16,17] and allowed us to revisit the problem of temperature fluctuations in heated pipe flows under strong MF. The new experiments aimed to study in detail the structure of temperature fluctuations and its evolution in the parametric space, extending the analysis to very high Hartmann numbers. We show that different regimes of strong temperature fluctuations exist at moderate Hartmann numbers. These regimes are controlled by the Richardson number and disappear under at very high Hartmann numbers. Results of this study are presented in this paper.

2. Experimental setup and measured data

The experimental section is a vertical pipe of inner diameter $d = 19$ mm and a 0.5 mm wall located in the magnet pole gap and uniformly heated from outside by an electrical heater. The wall material is a stainless steel, 18% of Cr (analog of X10CrNiTi18-10, AISI 321). The magnet provides homogeneous transverse field in the area, which entirely covers and extends beyond the area of heating (see Fig. 1). Heat losses to the environment are less than 10% of applied heat, and were measured using three sensors based on differential thermocouples mounted on the outer surface of the experimental section. Heat losses are excluded in calculating of the actual heat flux in the following analysis. Mean bulk temperature is calculated using the actual heatflux, inlet and outlet temperatures.

Main characteristics of the experimental setup are summarized in Table 1, where V is the average velocity; ν – the kinematic viscosity, σ, σ_w – the electric conductivities of the mercury and wall, ρ – the density, α – the coefficient of thermal expansion, λ – the thermal conductivity, and d_w is the wall thickness.

A swivel-type probe is attached to the pipe outlet and allows us to measure temperature at any point (x, y) in a fixed cross-section at $z/d = 37$ (the origin of coordinate z coincides with the beginning of the heating zone), which is close to the downstream end of uniform magnetic field, where flow development effects are expected to vanish. Up to the heating zone, there is an additional straight stabilization section of length about $60d$.

The cross-section can be scanned by the probe following any prescribed trajectory. After each probe displacement the control systems takes a pause of 5 s to eliminate possible distortion of the flow by probe motion. Each waveform is saved for further post-processing. Final images are plotted using polynomial triangulation and display distribution of temperature characteristics over the cross-section. The standard experimental data post-processing provides maps of the mean dimensionless temperature $\theta = (T - T_b)\lambda/(q \times d)$, the dimensionless standard deviation (STD) of temperature fluctuations $\sigma_\theta = \sigma_T\lambda/(q \times d)$, the skewness $b_1 =< (\theta - \overline{\theta})^3 > /\sigma_\theta^3$ and the kurtosis $g_2 =< (\theta - \overline{\theta})^4 > /\sigma_\theta^4$.

Table 1
Experiment parameters.

Parameter	Quantity	Value
Inner pipe diameter	d, mm	19
Pipe length	L_{pipe}, m	2.005 (106d)
Heat flux density	q, kW/m^2	0–55
Magnetic induction	B, T	0–2.7
Length of uniform MF	L_B, m	$\approx 0.9\ (43d)$
Reynolds number	$\mathrm{Re} = \frac{Vd}{\nu}$	$(5-35) \times 10^3$
Hartmann number	$\mathrm{Ha} = Bd\sqrt{\frac{\sigma}{\rho\nu}}$	0–1350
Grashof number	$\mathrm{Gr} = \frac{g\alpha q_w d^4}{\lambda\nu^2}$	$(0-1.2) \times 10^8$
Wall conductance ratio	$C = \frac{\sigma_w d_w}{\sigma d}$	< 0.04
Richardson number	$\mathrm{Ri} = \mathrm{Gr}/\mathrm{Re}^2$	0–1

3. Results

To illustrate the variability of observed the temperature fields, we present in Fig. 2 the distribution of temperature field characteristics for three specific regimes. Black dots in all maps show the points, in which the temperature signal has been acquired during at least 100 s.

The regime, shown in the upper row of Fig. 2 and marked by (0), serves as reference experiment and demonstrates the structure of temperature field under moderate Reynolds and Grashof numbers ($\mathrm{Re} = 1.1 \times 10^4$, $\mathrm{Gr} = 8 \times 10^7$) in absence of magnetic field. All maps are approximately axially symmetric. The temperature fluctuations (Fig. 2-0-b) agree well with the known distribution for heated pipe flow [18–20]. The distribution of skewness (Fig. 2-0-c) reveals negative values near the wall and positive values in the flow bulk. Such a picture is typical for the heated pipe flow, where the heat is transferred from walls into the bulk. The turbulence is fully developed, the kurtosis is distributed homogeneously (Fig. 2-0-d) and its values are close to 3, corresponding to Gaussian probability distribution and showing weak contribution of rare strong events.

The regime I (Fig. 2-I) is recorded under the same Reynolds and Grashof numbers, but in the presence of moderate transverse magnetic field ($B = 0.7$T, $\mathrm{Ha} = 350$). In this case the temperature field (Fig. 2-I-a) loses axial symmetry due to the Hartmann effect, and the wall temperature becomes non-uniform around the perimeter of the pipe cross section. Hartmann layers with strong velocity gradients and enhanced drag force are more pronounced in the domains where the magnetic field is perpendicular to the wall, i.e. in vicinity of points ($x = \pm R, y = 0$). Here, the temperature boundary layers become thinner as well. Domains close to ($x = 0, y = \pm R$), where the electric ring current provided by Hartmann effect is parallel to the magnetic field, and, therefore, does not interact with the applied field, will be hereinafter referred as

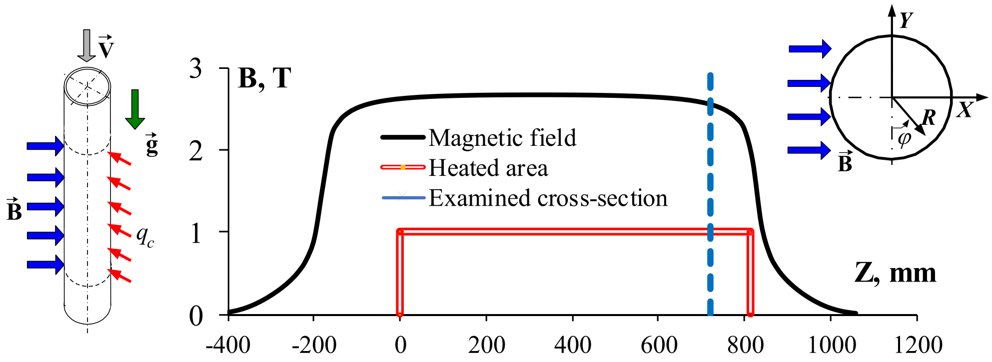

Fig. 1. Problem configuration.