Magneto-convective fluctuation during downward flow of liquid metal in a heated pipe in a transverse magnetic field

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Abstract. An imposed strong magnetic field suppresses turbulence and profoundly changes the nature of the flow of an electrically conducting fluid. We consider this effect for the case of mixed convection flows in pipes and ducts, in which unique regimes characterized by extreme temperature gradients and high-amplitude fluctuations (the so-called magnetoconvective fluctuations) have been recently discovered. The configuration is directly relevant to the design of the liquid-metal components of future nuclear fusion reactors. This work presents the general picture of the flow transformation emerging from the recent numerical studies (DNS - Direct Numerical Simulation), illustrates the key known facts, and outlines the remaining open questions. Implications for fusion reactor technology and novel experimental and numerical methods are also discussed.

1. Introduction
One possible coolant for TOKAMAK-type fusion reactors is a liquid metal. Liquid metal will have to circulate in the heat exchange ducts under the influence of high temperature gradients and a strong transverse magnetic field. Such conditions are difficult for experimental reproduction of high heat fluxes and magnetic fields. In most modes, a strong transverse magnetic field stabilizes a flow, flattening velocity profile and suppressing turbulence [1]; however, buoyancy forces created by temperature gradients generate specific structures in a magnetic field, which manifest themselves in the form of large-scale magneto-convective fluctuations (MCF) of velocity and, as a consequence, temperature. Appearance of magneto-convective fluctuations depends on a thermophysical properties of coolant, geometry of a channel and its orientation with respect to force of gravity and magnetic field, as well as on operating parameters. It is found that even strong magnetic fields (up to 1 T in experiment) cannot always suppress high-amplitude temperature fluctuations [2]. The nature of fluctuations during the downward flow of liquid metal in pipes [2] and ducts [3] is significantly different [4].

The assumed magnetohydrodynamic (MHD) configurations close to conditions of thermonuclear and hybrid reactors [5] are experimentally and numerically studied by a joint research group of NRU MPEI and IJHT RAS [6], using mercury as a model coolant. Within the framework of this work a complex research is carried out using the method of DNS and results are compared with the data.
obtained experimentally. DNS code described in detail in [7] provides a solution of the system of equations of MHD using a computational scheme based on finite difference method.

A configuration that may be used in a liquid-metal blanket is considered to be the downward flow of liquid metal in a non-uniformly heated pipe under the influence of a transverse magnetic field (figure 1). High heat loads allow evaluating the effect of buoyancy forces on a liquid metal flow.

![Figure 1](image)

**Figure 1.** Problem configuration: cross-section, length distribution of heating, magnetic field for simulation (a, c) and experiment (b, c). Schematic illustration of the effect of buoyancy forces on mixed convection in vertical channels. Laminar velocity profiles in the cases of downward (d, e) mean flow and with asymmetric (d) and symmetric (e) constant-rate heating of the walls are shown.

The liquid metals have high thermal conductivity and, accordingly, a role of buoyancy forces in mixed convection increases significantly [8]. Due to the growth of temperature gradient, an influence of buoyancy forces extends beyond a wall region and penetrates into a core of flow. In vertical channels, this influence may be different and is determined by the direction of forced flow and heating configuration (figures 1, d and e). In the downward flow, the influence of buoyancy forces provokes a decrease in velocity and can also lead to the formation of return flows near a heated wall (figures 1, d-e), that is, in this configuration, formation of jets near the wall, which move in opposite direction to the flow core. Based on the results of experiments [9], a numerical simulation by DNS is performed for the downward flow in a vertical non-uniformly heated pipe (figure 1, d) under the influence of a strong transverse magnetic field. A more detailed description of various flow configurations and mechanisms of natural convection effects are given in [10].

2. Numerical methods
The magnetic field and heating were simulated as close as possible to configuration of experiment [9]. Prandtl number (Pr) was assumed to be 0.025, Reynolds number (Re) was $10^4$, Grashof numbers (Gr) were taken in the range from $10^7$ to $10^8$, and Hartmann numbers (Ha) ranged from 50 to 900.
Richardson number ($Ri = Gr/Re^2$), which characterizes the ratio between buoyancy and inertia forces, Stuart number ($N = Ha^2/Re$), which characterizes the ratio between Lorentz and inertia forces, and Reynolds number ($Rh = Re/Ha = (u\delta H)/\nu$) calculated from Hartmann layer thickness are also useful in characterizing the flow regime.

Figure 2. Results of simulations of downward flow in a pipe with heating half of the wall (see the diagram at the left) at $Re = 10^5$; $Gr = 6 \times 10^7$ and $Ha = 50$ – (a, f); $Ha = 300$ – (b, g); $Ha = 500$ – (c, h); $Ha = 700$ – (d, i); $Ha = 900$ – (e, j). Snapshots of distributions of streamwise velocity $u_{str}$ (a)-(e) and temperature $\theta = (T - T_m)/(q\cdot d/\lambda)$, where $T_m$ is the mean-mixed temperature, °C; $q$ is the wall-averaged heat flux, W/m² (f)-(j) in the vertical plane across of magnetic induction.

The process of velocity field deformation, as well as the development of vortex structures under the influence of magnetic field can be traced in figure 2. Three characteristic flow patterns can be distinguished here. At $Ha = 50$ (figure 2, a), the influence of magnetic field is insignificant and the flow structure corresponds to turbulent one. At the values of $Ha$ from 300 to 500 (figures 2, b and c), the large-scale vortex structures are formed in the flow, characterizing high-amplitude low-frequency MCF. Further increase of magnetic induction up to the range from $Ha = 700$ to 900 (figure 2, d and e)
forms stable vortex structures in the flow, however, their kinetic energy is lower and generation frequency is higher, which allows fully forming the wall layer of heated liquid.

Figure 3 significantly extends understanding of a flow structure in MCF mode. Once in the region of magnetic field influence, instabilities are immediately formed in a flow, which generates MCF (figure 3, b). Further along the flow (figure 3, c), a systematized region of large-scale vortex structures is formed. However, as soon as a flow leaves magnetic field, the ordered structures collapse (figure 3, d) and flow turbulization occurs.

**Figure 3.** Isosurfaces of a transverse velocity for Re=$10^4$; Gr=$10^8$; Ha=300.
Figure 4. Waveforms of transverse dimensionless velocity component (left) and temperature (right) from pipe center ($R=0, z/d=37.4$) obtained by direct numerical simulation for $Re=10^4$, $Gr=10^7$ – (a), (c), (f); $Gr=10^8$ – (b), (d), (g); $Ha=300$ – (a, b); $Ha=700$ – (c, d); $Ha=900$ – (f, g).

The characteristic changes in the flow structure may be recorded from a waveform obtained from the center of the investigated pipe section (corresponding to experimental $z/d=37.4$ [9]) in figure 4. The magnetic field in modes with lower thermal load (figures 4, a, c and f), generates stable harmonic MCF. Frequency of fluctuation of both velocity and temperature is much higher (figure 4, f) than in high thermal load modes, and amplitude of fluctuations is much lower. This is due to the fact that a buildup of a near-wall layer of heated fluid occurs gradually and it retains its shape, and its partial entrainment occurs from the front (similar to figure 2, j). In modes with high thermal load (figures 4, b, d and g), frequency of MCF is lower and amplitude is much higher (figure 4, g). A significant difference is also that MCF generation occurs at significantly lower $Ha$ numbers (figure 4, b). Moreover, there are $Gr$ and $Ha$ ratios, where a magnetic field generates the low-frequency high-amplitude MCF (figure 4, d). This effect arises due to an increase in velocity of natural-convective jets near the wall, accompanied by an increase in a near-wall layer of heated fluid. Counter-directional movement in the region of near-wall layer of a heated liquid and a flow core, together with large-scale vortex structures formed by a transverse magnetic field, entrains part of the near-wall layer of a heated liquid downward the flow (similar to figure 2, h).

In [9] it was possible to describe the MCF existence regions in detail. The detected and described boundaries are shown in figure 5. Dimensionless intensity of temperature fluctuations $\sigma^*$ normalized to a turbulent level was used for the analysis. Numbers denote the regimes in which a numerical simulation by DNS method mentioned in this paper were performed. Results correlate well and the mode with low-frequency high-amplitude MCF are within the limits described in [9].

Conclusions
The research findings presented in this review demonstrate the unique nature of the channel flows with strong combined effects of thermal convection and magnetic field. Behavior of such flows is profoundly different from anything observed previously in hydrodynamics. It is also surprising and counter-intuitive in the sense that it cannot be anticipated on the basis of our understanding of the
effects of thermal convection and magnetic fields taken separately. The key features of the flow transformation are the high-amplitude low-frequency magnetoconvective fluctuations (MCFs) and exceptionally strong variations of temperature.

![Figure 5. Domain of existence of MCFs in the (N, Ri) and (Rh⁻¹, Ri) planes. Each point is an experimental measurement of the maximal temperature STD in the pipe cross-section (data from [9]. Numbers indicate the regimes from present work: Re=10⁴; Gr=6·10⁷ – (1-5); Gr=10⁷ – (6-8); Gr=10⁸ – (9-11); Ha=50 – 1; Ha=300 – (2, 6, 9); Ha=500 – 3; Ha=700 – (4, 7, 10); Ha=900 – (5, 8, 11).

The properties of the transformed flows vary depending on many factors, such as the orientation of the channel with respect to gravity, flow direction, orientation and spatial shape of the imposed magnetic field, heating arrangements, the length of the channel’s segments with applied heating and magnetic field, the shape of the channel’s cross-section, and, of course, the values of the governing parameters: Gr, Ha, and Re.

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