Swirling to improve heat transfer in the MHD flow of liquid metal in a duct

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Abstract. The subject of this study is the effect of the initial "swirling" of the flow by installing cylindrical elements in the initial flow region affected by strong magnetic field. In particular, various designs (longitudinal, transverse, and inclined arrangement with respect to the magnetic field) and the dimensions of the cylinders are considered. To create liquid metal systems that are more predictable and possibly more efficient from the point of view of thermal hydraulics, we experimentally studied the flow in a rectangular channel with dimensions of 56×16 mm. For the first time, it was found that the presence of an initial flow disturbance leads to significant changes in the flow at a significant length (700 mm).

1. Introduction

In several applications, the flow of liquid metal occurs under conditions of strong magnetic fields (MF) [1]. In this case, the traditional turbulence is quickly suppressed, the heat transfer coefficients are reduced, while in many cases, the development of magnetic-convective fluctuations (MCF) of velocity and temperature occurs. The boundaries of the existence of such regimes and the flow structures that generate them in various configurations are the subject of active research, both experimental and numerical [1], but it is already clear that from the technical side they represent rather a negative impact-complicating the design with their diversity.

In the framework of this research, an experimental study of the initial disturbance effect on the liquid metal downward flow in a heated duct under the influence of a transverse MF (i.e. coplanar field, when its induction is directed along the wide side of the duct) magnetic field is carried out. Both configurations with one-sided heating of the channel and with symmetrical two-sided heating at different values of the flowrate are considered.

Further, the effect on the flow by its swirling due to the flow elements will be called passive, as opposed to active methods of influencing the flow: electric charge, active change in the geometry of the channel or mixing of the liquid using movable mechanical devices [2]. Passive influence on the flow is of the greatest practical interest since active systems are more difficult to operate and coordinate with other systems.

As sources of initial perturbation, replaceable sections (components of the experimental working section) were used, in each of which swirlers devices ("swirlers") of various designs were mounted.
Using the probe technique, the temperature profiles, and the intensity of temperature fluctuations in a heated duct were measured. Based on the obtained data, dimensionless heat transfer parameters are calculated, such as the intensity of temperature fluctuations, the temperature in the flow and at the wall, and local heat transfer coefficients. The data are presented as a dependence of the heat transfer parameters on the magnitude of the influence of the MF (Hartmann number Ha).

2. Experimental conditions
The scheme of the experimental working section and the ratio of the heating zones, the area of influence of the MF and the cross-section under study are shown in Figure 1. As sources of the initial flow disturbance, flow swirling devices ("swirlers") were used in the study. In total, four versions of "swirlers" were manufactured and studied (Figure 2).

![Figure 1. The scheme of the experimental working section and the ratio of heating zone, MF distribution and the studied cross-section. a) general concept; b) the scheme of the studied cross-section.](image)

The physical and dimensionless parameters of the experiment, which presented in the graphs are calculated as follows:
- Duct inner section: \( 2a \times 2b = 16 \times 10^{-3} \, m \times 56 \times 10^{-3} \, m \);
- Characteristic size \( D = 4a \);
- Reynolds number \( Re = \frac{U \cdot D}{\nu} \), where \( U \) - average flow rate \( (m/s) \), \( \nu \) - kinematic viscosity coefficient of mercury \( (m^2/s) \) [3];
- Grashof number \( Gr = \frac{g \cdot \beta \cdot q \cdot D^4}{\lambda \cdot \nu^2} \), where \( g \) - acceleration of gravity (\( \approx 9.8 \, m/s^2 \)), \( \beta \) - thermal expansion coefficient \( (1/K) \), \( q \) - heat flux density \( (W/m^2) \), \( \lambda \) - thermal conductivity coefficient of mercury \( (W/m \cdot K) \) [3], \( \nu \) - kinematic viscosity coefficient of mercury \( (m^2/s) \) [3];
- Hartmann number \( Ha = B \cdot D \cdot \sqrt{\frac{\zeta}{\eta}} \), where \( B \) - magnetic induction \( (T) \), \( \zeta \) - electrical conductivity coefficient \( (S/m) \), \( \eta \) - dynamic viscosity coefficient of mercury \( (Pa \cdot s) \) [3].
3. Results

The results of the experiments are presented in Figure 3 - 5. The studies were carried out under modes with different flowrate (Re=(2.5; 5; 7.5)×10³) in a wide range of MF values (Ha=0-380). The experimental results are presented for two points of the cross-section under study: for the central point (0mm; 0mm) or for a point with a coordinate (0mm; 8mm) located near the heated wall. With symmetrical two-sided heating, the results obtained for points near the walls are almost identical (the tolerance of the measured temperature values within one mode is no more than 9 % with its average value of ≈ 1.8 %), therefore, the graphs are shown only for one of the sides.

Figure 3- 5 shows the dependences of the dimensionless intensity of temperature fluctuations σ* on the Ha for the case of homogeneous and symmetrical two-sided heating (Gr=1.25×10^8) at different values of flowrate (Re numbers): Re=2.5×10^3 (Figure 3), Re=5×10^3 (Figure 4), Re=7.5×10^3 (Figure 5).

In the case of one-sided heating, the values of σ* are significantly higher than in the configuration with symmetrical two-sided heating. The highest values of σ* are observed in the center of the studied section (Figure 3a, 4a, 5a), decreasing when approaching the wall (Figure 3b, 4b; 5b). Here and further in the text, when analyzing experimental data of configurations with one-sided heating, when mentioning a point on the wall, we mean a point on the heated wall, since the values of the characteristics of interest in this area are most important, and the values of the parameters under consideration are higher than on the non-heated (adiabatic) wall.

It should be noted that in all the experiments conducted for the case of unilateral heating, the following is observed: in the entire studied range of the acting MF (numbers Ha) - at first (Ha=0), the change in the values of σ* is insignificant, after which, with an increase in the influence of MF (Ha>25), there is a sharp intensive increase in the values of σ*, which has a peak in the region at Ha ≈ (50-80), followed later by a monotonous decrease in the values of σ*, passing at Ha (100-150) either into growth (Figure 3, 4), or (at high values; for example: Re=7.5×10^3-Figure 5) to some stable level.

Since the structural formation of velocity perturbations in the duct behind the "swirlers" is determined by the ratio of inertial and electromagnetic forces, it is reasonable to consider the behavior of the intensity σ* in dependence on the parameter of the MHD interaction N = Ha^2/Re. At Re = 2.5·10^3, 5·10^3 and 7.5·10^3 (Figs. 3a, 4a and 5a), the intensity maxima for all "swirlers" are accordingly achieved at Ha = 50, 70, and 85, that corresponds to N = 1, 1 and 0.96. We suppose that at Ha <50, the sensor registers the ordinary duct turbulence. Upon reaching the said above the numbers Ha, for which the parameter N ~ 1, large-scale anisotropic vortical structures elongated along the field, are formed and detached behind the "swirlers", persisting up to the measuring section and give the observed jumps in...
the intensity $\sigma^*$ [4]. A further increase in $Ha$ gives decreasing the intensity of the perturbations, associated with growing their Hartmann friction on the walls perpendicular to the magnetic field.

In general, an increase in the flow rate in the case of symmetrical two-sided heating is accompanied by a decrease in the values of $\sigma^*$ (Figure 3-5), while a similar effect is not observed for configurations with one-sided heating. The nature of the dependence $\sigma^*(Ha)$ for the case of symmetrical two-sided heating (at the same values of the applied heat load) is as follows: first, in the region of $Ha \approx (25-50)$, there is (in general) a preservation of the values of $\sigma^*$ at the level of the values for experiments without MF ($Ha=0$), after which the increase in the influence of MF in different areas of the studied section differs significantly at observed flowrates. At a low flowrate ($Re=2.5\times10^3$-Figure 3), an increase in the Hartmann number is accompanied in the center of the flow (Figure 3a) a sharp increase in $\sigma^*$ at $Ha \sim 50$ (in the growth of $\sigma^*$ at the same time, at the point of the flow located further from the center, and at the points on the wall (Figure 3b) - a decrease in the values of $\sigma^*$; further, with an increase in MF ($Ha>100$), the values of $\sigma^*$ stabilize on the wall, and increase in the center of the flow. With an increase in the flow rate ($Re=5\times10^3$ – Figure 4), the stable values of $\sigma^*$ in the region at $Ha \approx (0-50)$ begin to increase first (more sharply in the center of the flow – Figure 5a; most smoothly-Figure 4b), and then decrease in different areas of the cross-section with different intensity. At the maximum realized flow rate ($Re=7.5\times10^3$-Figure 5), in the general case, despite some difference in the nature of the dependence $\sigma^*(Ha)$ at different points of the section, the absolute values of the change $\sigma^*$ are insignificant.

![Figure 3](image_url)

**Figure.** 3 Dependence of the dimensionless intensity of temperature fluctuations on the Hartmann number in the mode ($Re=2.5\times10^3$, $Gr=1.25\times10^8$) for configurations with two-sided heating (open symbols) and one-sided heating (filled symbols). a) central point (0; 0); b) point at the heated wall (0; 8).

It is established that with a low fluid flow rate ($Re=2.5\times10^3$-Figure 3) in all heating configurations, the presence of an initial flow disturbance in the form of a "swirl" of any design does not affect the flow structure – the values of $\sigma^*$ in the entire studied range of MF values for all "swirlers" (and for the experiment without a "swirl") are in a narrow range of values, the nature of the dependence of $\sigma^*(Ha)$ for all "swirlers" is the same.
Figure 4. Dependence of the dimensionless intensity of temperature fluctuations on the Hartmann number in the mode (Re=5×10³, Gr=1.25×10⁸) for configurations with two-sided heating (open symbols) and one-sided heating (filled symbols). a) central point (0;0); b) point at the heated wall (0;8).

An increase in the flow rate (Re=5×10³ - Figure 4) shows differences in the nature of the effect Ha the flow of different versions of the "swirlers" – with symmetrical two-sided heating in experiments with the "swirler" of version No. 2, a decrease in σ* in the cross section is observed much earlier than in experiments with "swirlers" of other versions (and in their absence), the difference between other "swirlers" is insignificant. However, a further increase in the flow rate (Re=7.5×10³-Figure 5) shows the following differences in experiments with different versions of "swirlers": against the background of a general decrease in the values of σ* with symmetrical two-sided heating in experiments with a "swirler" of execution No. 2, after the suppression of σ* observed at≈100, an increase in the influence of MF is accompanied by an increase in the values of σ*, a similar character of influence is less pronounced when using a "swirler" of versions No. 1 and No. 3, while both in the experiment without a "swirler" and with a "swirler" No. 4, the values of σ* take near-zero values (temperature fluctuations are suppressed).

Figure 5 Dependence of the dimensionless intensity of temperature fluctuations on the Hartmann number in the mode (Re=7.5×10³, Gr=1.25×10⁸) for configurations with two-sided heating (open symbols) and one-sided heating (filled symbols). a) central point (0; 0); b) point at the heated wall (0; 8).
At the same time, in the general case, with one-sided heating against the background of higher values of $\sigma^*$ (compared with the case of symmetrical two-sided heating), the differences in experiments using "swirlers" of different designs with an increase in flow are more obvious. So, if at low flow rates ($Re=2.5\times10^3$ – Figure 3) the values of $\sigma^*$ are in a narrow corridor, then already with an increased flow rate ($Re=5\times10^3$ – Figure 4) the corridor of values expands, however, differences in the nature of the dependence of $\sigma^*(Ha)$ are clearly visible when using "swirlers" of different versions at large flow values ($Re=7.5\times10^3$ – Figure 5) – also (as with symmetrical two-sided heating) in experiments with the "swirler" of version No. 2, the values of $\sigma^*$ are significantly lower (Figure 5 a, b), than in other experiments (including in experiments without the use of "swirlers"). Analyzing the dependences of $\sigma^*(Ha)$ at the cross-section point located on the heated wall (Figure 3b, 4b, 5b), for all the studied flow values, it should be noted that the influence of "swirlers" of versions No. 1 and No. 2 is identical not only in nature (qualitatively), but often quantitatively-the values of $\sigma^*(Ha)$ are very close (Figs. 3b, 4b, 5b).

4. Conclusions
Liquid metal downflow in a duct with two-sided and one-sided heating have been studied experimentally. The configuration with one-sided heating is of greater interest from a practical point of view. Also, experiments with this configuration, have shown significantly higher values of temperature fluctuations intensity comparing with symmetrical two-sided heating.

In both variants of heating at a low flow rate ($Re=2.5\times10^3$), the use of different configuration "swirlers" does not demonstrate a significant change in the duct flow characteristics measured in the exit-section. With an increase in the flow rate ($Re=5\times10^3$), the influence of the swirler No. 2 was manifested in the form of suppression of temperature fluctuations at a value of MF significantly lower than for "swirlers" of other versions, thereby reducing the area of existence of the phenomenon of magneto-convective fluctuations. In all the studied regimes "swirlers" in a form of rods with axis alined with magnetic field (No 1 and 2) have shown greater impact on the flow.

In general, "swirlers" have shown positive impact in terms of flow parameters prediction and additional thermal stress on the duct wall in all considered flow regimes. They led to decrease of generation of naturally evolving magneto-convective fluctuations (MCF) and have not produced any additional flow complexity.

Acknowledgments
The work is supported by the grants RFBR NNIOa 18-508-12005 and DFG KR 4445/2-1 research projects within a joint Russian-German collaboration program.

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