Buoyancy effects in vertical rectangular duct with coplanar magnetic field and single sided heat load

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Abstract. In some DEMO blanket designs liquid metal flows in vertical ducts of rectangular cross-section between ceramic breeder units providing their cooling. Heat exchange in these conditions is governed by the influence of magnetic field (coplanar) and by buoyancy effects that depend on the flow orientation to the gravity vector (downward and upward flow). Magnetohydrodynamic and heat transfer of liquid metal in vertical rectangular ducts is not well researched. Experimental study of buoyancy effects in rectangular duct with coplanar magnetic field for one-sided heat load and downward and upward flows is presented in this paper. The detail research with has been done on mercury MHD close loop with using of the probe technique allow to discover several advantageous and disadvantageous effects. The intensive impact of buoyancy force has been observed in a few regime of downward flow which has been laminarized by magnetic field. Due to the development in the flow of the secondary large-scale vortices heat transfer improved and the temperature fluctuations of the abnormally high intensity have been fixed. On the contrary, in the upward flow the buoyancy force stabilized the flow which lead to decreasing of the turbulence heat transfer ratio and, consequently, deterioration of heat transfer.

1. Introduction

In some of the liquid metal fusion blankets being proposed and developed for DEMO and experimental fusion reactors liquid metal flows in vertical ducts of rectangular cross-section between ceramic breeder units providing their cooling [1]. Heat exchange in these conditions is governed by the influence of magnetic field oriented along the side wall (coplanar magnetic field) and by buoyancy effects that depend on the flow orientation to the gravity vector (downward and upward flow). Experimental study and numerical simulation of such flows in cylindrical tubes may be found in [2-3], some results for rectangular ducts – in [4]. They show that for downward flow in a certain range of characteristic parameters heat transfer increases and high temperature fluctuations appear. This is believed to be due to the secondary large-scale vortexes in the flow.

Experimental study of buoyancy effects in rectangular duct with coplanar magnetic field for one-sided heat load and downward flow was presented in [4]. One-sided heat load is the limiting case of heat load non-uniformity caused by different heat fluxes from ceramic breeder units on duct’s opposite side walls due to exponential decay of radiation in blanket [1]. The results are presented here for Reynolds numbers different from those in [4] and compared for downward and upward flow at the same characteristic parameters to reveal the differences for both cases.
2. Experimental facility

The experimental facility is a mercury loop with test section mounted vertically in magnet gap. The length of experimental section is 2.0 m and the length of uniform magnetic field - 0.6 m. Maximum value of the magnetic field equal 1 T.

The test section represented the duct of rectangular cross section with sides dimensions 56 and 17 mm and walls thickness - 2.5 mm. The duct walls are made from stainless steel X10CrNiTi18-10. Magnetic field (MF) \( B \) is directed along the large side of the duct cross section. Heat flux \( q \) produced with electric heaters was applied from one side of the duct representing the limiting case of heat load non-uniformity. Downward and upward flow (mercury velocity \( V \) coincides or acts opposite gravity vector \( g \)) were studied. Double width of duct \( d=2b \) as a characteristic size were used for calculation of the dimensionless characteristic parameters (Table 1).

In the design of Test Blanket Module for ITER [4] the same parameters level are reached: \( Ha=2500–10\,000, Re=(1-20)\cdot10^3, Gr=(0.4–8.0)\cdot10^8, q=(10-40)\,\text{kW/m}^2 \).

### Table 1. Characteristic dimensionless parameters

| Parameters         | Definition                                      | Value         |
|--------------------|-------------------------------------------------|---------------|
| Hartmann number    | \( Ha=B_0d(\sigma/\mu)^{0.5} \)                 | 0-800         |
| Reynolds number    | \( Re=V_0d/\nu \)                               | (12-50)\cdot10^3 |
| Grashof number     | \( Gr=q_1qd/\lambda N^2 \)                      | 0 - 6\cdot10^8 |

![Figure 1. Investigated flow scheme \( q_1=0; q_2\neq0 \) and photo of the experimental facility.](image)

There is a zone of hydrodynamic stabilization with a length \( Z_0=10d \) which is located before heating zone. A zone of magnetic field coincides with the heating zone. Measurements of temperature field were obtained in a cross-section located at a distance \( 21d \) from the duct input using a special swivel-type probe, which is installed from the exit of experimental section. A copper – constantan (T-type) micro thermocouple with junction size \( \delta =0.25 \) mm is installed at the tip of the rod. The thermocouples accuracy is 0.2 °C. The MF measurement accuracy is equal 2 %. The flow rate and average velocity measurement accuracy is 0.5+3 % depending on regime specifics. The pressure drop measurement accuracy is about 5%.

More information on experiment description may be found in [4].

3. Experimental results

The experimental results have been obtained for range of Reynolds number 12000-50000 and all results can be divided on two groups: mode with low impact of the thermo-gravitational convection (TGC) and mode with relatively high influence of the TGC. The first group of results characterized by
the fact that magnetic field suppress the turbulent fluctuation and for investigated configuration this type of interaction is observed with Reynolds number Re > 40 000. In this paper the experimental results from the second group with with relatively high influence of the TGC are presented more detail.

3.1. Relatively low impact of the buoyancy force: Re=40·10³, Gr/Re²=0.25

The averaged over time temperature profiles are presented below with dimensionless temperature Θ calculated as $\Theta = \frac{\lambda}{d} \frac{T - T_f}{q}$, where $T$ – local temperature, $T_f$ – average temperature of fluid in a chosen cross section, $q$ – heat flux density which is averaged for both sides of the duct $q = 0.5(q_1 + q_2)$. The dimensionless temperature distributions for upward flow and downward flow along axis $Y = y/b$ are shown in figure 2. Profiles along axis $Y$ (along short duct side) are strongly non-uniform with maximum gradient on the heated wall. The profiles depend weakly on Hartmann number for upward flow (figure 2a).

The different behavior of the experimental points is observed for downward flow (figure 2b). The temperature of the heated wall significantly changes in MF - it is steadily growing with Hartmann number increasing up to Ha=500. Following magnetic field increase up to Ha=800 leads to the temperature decrease (this fact needs confirmation at larger Ha values). Thus we observe a significant delamination of the temperature profiles near heated wall on Hartmann number.

For comparison a reciprocal variables of Nusselt number (Θ=1/Nu) for a flat duct are shown in the figures: for the developed turbulent flow with the use of Lyon’s integral equation $Nu_T = 10 + 0.025Pe^{0.8}$ [5] and for the stabilized laminar flow $Nu_L = 8.24$ in case of single side heating.

![Figure 2](image)

Figure 2. Dimensionless temperature profiles along axis $Y (X=1.6)$ in section 21d: a - upward flow; b - downward flow, $q_1/q_2=0/35$ kW/m² $(Gr_q=4.0·10^8)$, $Re = 40·10^3$: 1) Ha=0; 2) 120; 3) 300; 4) 500; 5) 800.

Dimensionless wall temperature $\Theta_w = \frac{\lambda}{d} \frac{T_w - T_f}{q_w}$, where $T_w$ – wall temperature, distribution along duct perimeter are shown in figure 3 for upward flow. It is seen that wall temperature distribution is significantly non-uniform due to the fact that three sides of the duct are non-heated. The heated wall temperature in coplanar MF depends slightly on Hartmann number.

The swivel probe gives the information only in one cross-section but for obtain results along channel the ”comb” probe should be used. The distribution of the dimensionless wall temperature $\Theta_w$ obtained for two walls: heated and adiabatic walls along duct length for Hartman numbers 0÷800 in case of upward flow is shown in figure 4. These temperatures are maximum and minimum temperatures in each cross section of the duct. The filled markers are used for heated wall and empty – for adiabatic wall. The measured temperatures are far from theoretical values $Nu_L$ and $Nu_t$ obtained for
parallel-plate duct. A difference between wall temperatures is high and increase with increasing of magnetic field.

![Figure 3. Distribution of dimensionless wall temperature $\Theta_w$ over duct perimeter in section 21d (upward flow), $q_1/q_2= 0/35$ kW/m$^2$, Re = 40·10$^3$: 1) Ha=0; 2) 120; 3) 300; 4) 500; 5) 800.](image)

Now let us consider experimental results for temperature fluctuations. The distribution of dimensionless temperature fluctuations $\sigma/(q_d/\lambda)$ into flow core along duct length is shown in figure 5 in case of upward flow. The character of the distribution is extremely heterogeneous.

![Figure 4. Distribution of the dimensionless temperature along duct length $Y=0$, $q_1/q_2= 0/35$ kW/m$^2$, Re = 40000: 1) Ha=0; 2) 300; 3) 500; 4) 800.](image)

A distributions of the temperature fluctuation intensity ($I$) for upward and downward flows are shown in figure 6 for different Hartmann numbers. An interesting feature is the fact that MF in the studied range doesn’t suppress turbulence completely in case of upward flow (figure 6a). For downward flow there is significant difference - unlike the previous case we observe here a strong influence of the MF on temperature fluctuation intensity (figure 6b). With Hartmann number increasing starting approximately with Ha=300 the fluctuation intensity strongly increases and this is not observed for upward flow.

The characteristic waveforms of the temperature fluctuation for upward and downward flows are shown in figure 7. In the region with maximum fluctuation intensity for different values of Hartmann number there is characteristic turbulent waveform for Ha=0. The character of the waveform almost doesn’t change and stay turbulent with Hartmann number increasing up to 300. But further increase of MF leads to changing of the waveform character. In these conditions (Re=40·10$^3$, Gr/Re$^2$=0.25) a
suppressing of the turbulence is not observed under both flow orientations. On the contrary the fluctuation intensity of the downward flow increases. Amplitude of fluctuation is increased more than several times in comparison with natural turbulence fluctuation intensity without MF.

![Figure 6](image_url)

**Figure 6.** Temperature fluctuations intensity profiles along axis Y/X=1.6 in section 21d for upward flow (a) and for downward flow (b), q/q2 = 0/35 kW/m², Re = 40·10³: 1) Ha=0; 2) 120; 3) 300; 4) 500; 5) 800.

As it was noted, earlier [4] this low-frequency surges can be explained by the generation of secondary vortices, which are induced by TGC in MF and lead to generation of large-scale vortex structures.

It is worth mentioning that for Re=50·10³, Gr/Re^3=0.16 the suppression of fluctuation intensity for downward flow was observed in the whole range of Ha numbers [4].

![Figure 7](image_url)

**Figure 7.** Temperature waveforms in the upward (left) and downward (right) flow core, Y=0.8, Re= 40·10³: a) Ha = 0; b) 800.

### 3.2. Summary of experimental results

Dependences of the perimeter averaged Nusselt number for heated wall on Peclet number for upward and downward flows are shown in figure 8. Experimental points are located below the dependence NuT1=4.9+0.0175Pe^0.8 [5] which was obtained for parallel-plane duct with one side heating. There is a dependence of averaged Nusselt number on MF (Ha number) for downward flow and practically no dependence on MF for upward flow.
Figure 8. The dependence of averaged Nusselt number from Peclet number for upward (a) and downward (b) flows: 1) Ha=0; 2) 300; 3) 500; 4) 800; \( \text{Nu}_1=10+0.025\text{Pe}^{0.8} \); \( \text{Nu}_{11}=4.9+0.0175\text{Pe}^{0.8} \) [5].

Conclusions

Heat transfer for duct flow in coplanar MF depends significantly on flow orientation: upward or downward. In both cases, we observed certain influence of the TGC on heat transfer.

For upward flow, the heated wall temperature does not change practically with increasing of MF. At the same time temperature in the flow core decrease more or less significantly (depending on Re numbers) with MF increasing. Judging from temperature fluctuations measurements, MF suppresses the turbulence (higher for small Re numbers), low-frequency fluctuations not higher than that for turbulence flow appear for \( 20\cdot10^3<\text{Re}<50\cdot10^3 \) and may be attributed to 2-D turbulence not suppressed with MF.

For downward flow, temperatures near the heated wall or all over the flow (for small Re) increase first with MF increasing and decrease with further increase of MF, thus enhancing heat transfer. There is a distinct difference in intensity of temperature fluctuations at small and large Re numbers. For \( 12\cdot10^3<\text{Re}<40\cdot10^3 \) low frequency temperature fluctuations of high amplitude (around 5 times higher than turbulent level) were detected due as believed to formation of large scale vortexes.

Acknowledgments

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