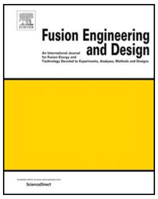
Fusion Engineering and Design 127 (2018) 226–233

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes



Buoyancy effects in vertical rectangular duct with coplanar magnetic field and single sided heat load – Downward and upward flow

I.R. Kirillov[a], D.M. Obukhov[a,*], V.G. Sviridov[b], N.G. Razuvanov[c], I.A. Belyaev[c], I.I. Poddubnyi[b], P.I. Kostichev[b]

[a] JSC «NIIEFA» (D.V. Efremov Institute of Electrophysical Apparatus), St. Petersburg, 196641, Russian Federation
[b] National Research University "Moscow Power Engineering Institute" (MPEI), 14 Krasnokazarmennaya str., Moscow, Russian Federation
[c] Joint Institute of High Temperatures of the Russian Academy of Science (JIHT), 13/19 Izhorskaya str., Moscow, Russian Federation

ARTICLE INFO

Keywords:
Liquid metal
Magnetic field
Heat transfer
Buoyancy
Temperature fluctuation

ABSTRACT

The effects specific for downward and upward flows of liquid metal (LM) in a vertical rectangular duct in a coplanar magnetic field (MF) are investigated. The experiments were performed in the JIHT's test facility with a closed magnetohydrodynamic (MHD) mercury loop. The temperature and velocity fields were measured in the duct with single-side heating in a coplanar magnetic field. The averaged temperature fields, wall temperature distributions, statistical characteristics of temperature fluctuation and longitudinal velocity profiles were obtained. The results for the downward and the upward flow under different flow conditions are compared.

1. Introduction

There are liquid metal-cooled fusion blankets proposed and designed for DEMO and experimental fusion reactors where liquid metal flows in vertical rectangular ducts between ceramic breeder units providing their cooling [1,2]. Heat transfer under these conditions is governed by a magnetic field parallel to the duct side wall (i.e., by the coplanar magnetic field) and the effect of natural convection (buoyancy) manifesting itself depending on the flow direction relative to the gravity vector direction (downward or upward flow). The experimental investigation and numerical simulation of these flows in round pipes was performed in [3–6], and certain results for rectangular ducts are presented in [7,8]. These results demonstrate that heat transfer increases and large temperature fluctuations appear in the downward flow in a certain range of characteristic parameters. This is likely to be caused by secondary large-scale vortexes formed in the flow.

The experimental study of natural convection effects in a downward flow in the rectangular duct with one-side heating exposed to a coplanar magnetic field was presented in [7]. The one-side heating is the limit case of the heating non-uniformity caused by different heat fluxes from ceramic breeder units on opposite walls of the duct due to exponential decay of radiation in the blanket [2]. The results are presented in this paper for the Reynolds numbers different from those used in [7] and are compared for the downward and the upward flow at the same characteristic parameters to reveal the differences between these flows.

2. Experimental facility

The test facility is a mercury loop with a vertical test section mounted in the magnet gap. For test facility characteristics, see Table 1.

The test section was a rectangular duct with an aspect ratio of $a/b = 56/17$ (mm) and a 2.5 mm thick wall. The duct was manufactured from 18%Cr stainless steel (Russian equivalent of AISI 321 steel). A schematic diagram of the flow is shown in Fig. 1. The magnetic field (MF) induction vector $\mathbf{B}$ is parallel to the larger duct wall. The heat flux q from electric heaters was applied to one wall of the duct to simulate the limit case of heat load non-uniformity. Under these conditions, the downward and the upward flow (where the mercury velocity vector $\mathbf{V}$ had the same or opposite direction with respect to the gravity vector $\mathbf{g}$) was studied. Using the double width of the duct, $d = 2b$,as the characteristic dimension yields the following characteristic parameters: the Hartman number $Ha \leq 800$, the Reynolds number $Re = (12–50)·10^3$, the Grashof number $Gr \leq 6·10^8$, the heat flux $q = 35\ kW/m^2$. The same parameters of the Test Blanket Module for ITER [7] are: $Ha = 2500–10\,000$, $Re = (1–20)·10^3$, $Gr = (0.4–8.0)·10^8$, $q = (10–40)\ kW/m^2$.

Here, the Reynolds number ($Re = V_0 d/\nu$) based on the characteristic velocity of fluid gives the ratio of inertial to viscous force in the flow, V_0 is the characteristic fluid velocity, ν is the kinematic viscosity. The squared Hartmann number ($Ha = B_0 d(\sigma/\mu)^{0.5}$) is the ratio of electromagnetic force to viscous force, where B_0 is the external magnetic field, σ is the electrical conductivity, μ is the dynamic viscosity. The parameter Ha^2/Re is a ratio of electromagnetic force to inertial

---

[*] Corresponding author.
E-mail address: obukhov@sintez.niiefa.spb.su (D.M. Obukhov).

https://doi.org/10.1016/j.fusengdes.2018.01.006
Received 4 August 2017; Received in revised form 22 November 2017; Accepted 2 January 2018

Table 1
Parameters of the test facility.

Test section length, m	2.0
Heat flux, kW/m^2	0–45
Heated section length, m	0.81
Magnetic field, T	0–1.0
Length of electromagnet, m	0.7
Length of uniform magnetic field zone, m	0.6

force. The Grashof number was determined using the heat flux instead of the temperature difference ($Gr_q = g\beta q_c d^4/\lambda\nu^2$), where g is the gravity acceleration, β is the volumetric thermal expansion coefficient, $q_c = 0.5(q_1 + q_2)$ is the average heat flux on the walls; λ is the thermal conductivity. The parameter Gr_q/Re^2 is the ratio of the buoyancy to the viscous forces acting on a fluid. The Peclet number is Pe = Re·Pr, where Pr is the Prandtl number.

There is a hydrodynamic entrance region with a length of $Z_0 = 10d$ which is upstream of the heated section. The section exposed to the magnetic field coincides with the heated zone. The temperature field was measured in a cross-section at a distance of 20*d* from the duct inlet using a special rotary probe which was inserted into the duct via the test section outlet. The velocity profiles were measured by the temperature correlation velocimetry (TCV) method [9] with two thermocouples using temperature fluctuation in the main flow. A copper – constantan (T-type) microthermocouple with a junction size of $\delta = 0.25$ mm was installed at the tip of the rod. The thermocouples accuracy is 0.2 °C. The rod coordinates were controlled with an accuracy of 0.03 mm. The MF measurement accuracy was 2%. The flow rate and the average velocity were measured with an accuracy of 0.5–3% depending on the test conditions. The pressure drop measurement accuracy was about 5%.

For more information about the experiment, see Refs. [7,8].

3. Experimental results

The hydrodynamics and heat transfer of a liquid metal flow in a transverse (coplanar) magnetic field is governed primarily by the electromagnetic interaction. MF suppresses the flow turbulence and generates electric currents in flowing electrically conducting liquid, which change the velocity profile.

The buoyancy forces additionally affect the nonisothermal turbulent flow. Their influence is determined by the parameter Gr/Re^2. The buoyancy forces are the highest near the heated duct wall and accelerate the upward flow in this zone but decelerate the downward flow. Consequently, in case of the upward flow the buoyancy force acts in a direction opposite to the friction force thereby enhancing the stability and decreasing the turbulence intensity. In case of the downward flow, the buoyancy force acts in a direction opposite to the main flow and, hence, becomes a source of flow instability generating additional turbulence and augmenting heat transfer.

Prior to discussing the experimental results, note that the electric contact between mercury and the walls was not perfect. The pressure drop measured across a duct length of 986 mm for different Re and Ha numbers corresponded to the electrical resistance of duct walls which was about 27 times greater than the stainless steel resistance (see Ref. [7]). This means that there is an electroinsulating layer between the duct wall and mercury which should be considered in interpreting the results.

3.1. Moderate low effect of the buoyancy force: $Re = 40{\cdot}10^3$, $Gr/Re^2 = 0.25$

The dimensionless longitudinal velocity profiles in two orthogonal planes along axes $X = x/b$ and $Y = y/b$ measured by the TCV method in the upward flow are shown in Fig. 2. The average flow velocity V_0 was chosen as a scale in calculating of the dimentionless velocity. It is evident that the profiles along the X axis are uniform (filled) both without magnetic field and in the coplanar MF. The profiles along the Y axis are nonsymmetrical and have a maximum near the heated wall (Y = 1). This behavior of the velocity profiles is caused by the effect of natural or thermo-gravitational convection (TGC) in a magnetic field: the buoyancy force is directed upwards as the main flow does and accelerates the flow near the heated duct wall.

Similar data for the profiles of dimensionless longitudinal velocity in the downward flow are shown in Fig. 3. The velocity profiles as those in the upward flow are relatevely uniform along the axis X both without MF and in the presence of MF. A considerable difference in the velocity profiles along the Y axis is evident: the minimum velocity is observed near the heated wall, and the maximum is at the “cold” duct wall where $q_1 = 0$. In the downward flow, the buoyancy force decelerates the flow near the heated wall displacing the flow to the “cold” duct wall.

The time-averaged temperature profiles are presented below with the dimensionless temperature Θ determined as$\Theta = \frac{\lambda}{d}\frac{T - T_f}{q_w}$, where T is the local temperature, T_f is the average temperature of the fluid in a chosen cross section, q_w is the average heat flux for two duct walls, $q_w = 0.5(q_1 + q_2)$.

The measured two-dimensional temperature field demonstrated that isotherms were almost parallel to the wider duct wall. The dimensionless temperature distributions for upward flow in two perpendicular planes, along $X = x/b$ and $Y = y/b$ axes are shown in Fig. 4.

The temperature profiles are almost uniform along X axis parallel to the wider duct wall, which is parallel to the MF induction vector, while profiles along axis Y (along the shorter duct wall) are strongly nonuniform and have the greatest gradient at the heated wall. The profiles depend weakly on the Hartmann number.

It is interesting to note that the wall temperature in this case does

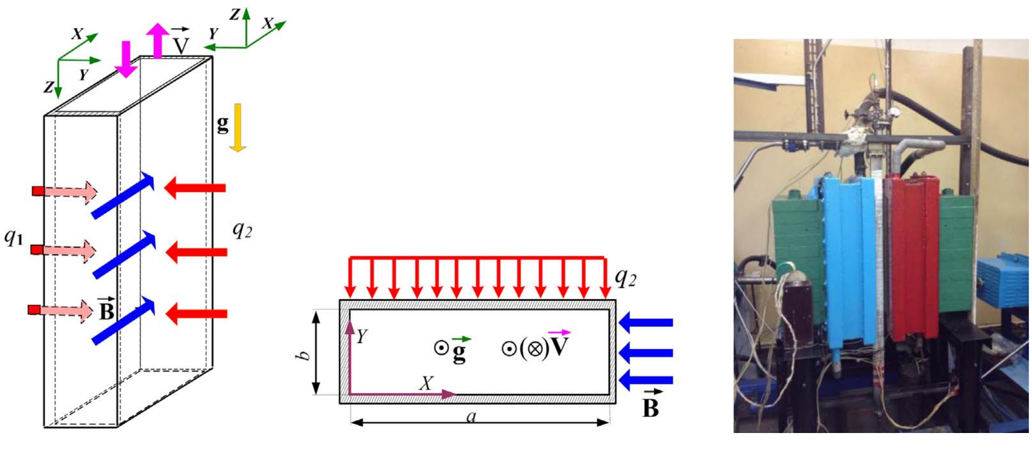


Fig. 1. Schematic of the flow ($q_1 = 0$; $q_2 \neq 0$) and a view of the experimental facility.