Fusion Engineering and Design 104 (2016) 1–8

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

I.R. Kirillov[a], D.M. Obukhov[a,*], L.G. Genin[b], V.G. Sviridov[c], N.G. Razuvanov[c], V.M. Batenin[c], I.A. Belyaev[c], I.I. Poddubnyi[b], N.Yu. Pyatnitskaya[c]

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

HIGHLIGHTS

- Heat transfer in vertical duct mercury flow in coplanar magnetic field is studied.
- Mean velocity, temperature and temperature pulsations are measured.
- Buoyancy influence on heat transfer is found.

ARTICLE INFO

Article history:
Received 20 March 2015
Received in revised form 12 October 2015
Accepted 11 January 2016
Available online 1 February 2016

Keywords:
Liquid metal
Magnetic field
Heat transfer
Buoyancy
Temperature fluctuation

ABSTRACT

This article investigates an effect which was found out in downward flow of liquid metal (LM) in vertical rectangular duct in coplanar magnetic field (MF).

The experiments have been performed on facility which located in JIHT. This facility is magneto hydrodynamic (MHD) mercury close-loop. The temperature field measurements have been performed at one side heating conditions in coplanar magnetic field. The averaged temperature fields, wall temperature distributions and statistical characteristics of temperature fluctuation have been obtained.

The strong influence of counter thermo-gravitational convection (TGC) on average and fluctuation parameters has been observed. The influence of TGC in magnetic field leads to developing of temperature low-frequency fluctuations with high magnitude. The temperature fluctuation amplitude in a wide range of operating conditions is higher than turbulence level.

1. Introduction

Liquid metal (LM) fusion blankets constitute a large group of proposed and being developed fusion blankets [1]. The primary purpose of LM in such blankets is tritium breeding, and LM blankets provide unique opportunity to keep on-line (without blanket replacement) the required enrichment with ^{6}Li isotope to provide the reactor tritium self-sufficiency over long enough service life time. In self-cooled/single cooled blanket options LM (lithium, lead–lithium) is the only coolant at the same time. In dual coolant blankets first wall and blanket structure is cooled with another heat transfer agent (gas–helium or water), while breeding zone is cooled with LM.

Among important issues studied for such blankets, such as structural materials development and characterization, tritium extraction, safety issues due to LM chemical activity, MHD issues find large attention. Since LMs are electrically conductive, reactor magnetic field (MF) influences their flow in many aspects. Electric currents are induced during LM motion in magnetic field and are closed through electroconducting walls, nearby ducts, LM itself (primarily in ducts with electroinsulating walls or in regions of changing magnetic field intensity/ducts geometry). This leads to MHD pressure drop, change of velocity distribution, multichannel effect (influence of electric currents generated in one duct on pressure drop and flow distribution in the neighboring ducts). MHD pressure drop in self-cooled blankets may be too large, thus needing electroinsulating barriers on the interface LM/structure wall. Velocity profile change with appearing of jets near electroconducting walls causes MHD instabilities and leads to corrosion increase. Magnetic field influences turbulent pulsations and affects buoyancy

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

http://dx.doi.org/10.1016/j.fusengdes.2016.01.010
0920-3796/

as well. Review of these phenomena study and results obtained may be found for example in [2–4].

Experimental study and numerical simulation of buoyancy effects in tubes with different inclination to gravity force and in longitudinal and coplanar magnetic field were performed MPEI and JIHT on a previous stage of work [5]. Experiments were conducted on mercury-convenient modeling working fluid for studying heat transfer in heavy metals, such as eutectic lead–lithium alloy (LL). It was shown that magnetic field affects temperature distribution in the flow and on the duct walls making it non-uniform with zones of degraded heat transfer (local Nusselt number is below that for laminar flow), leads to abnormally intensive low frequency temperature pulsations.

Experimental results for vertically oriented rectangular duct in coplanar magnetic field with one-sided heat load are presented in the paper. The work is done in support of ITER LLCB TBM (Lead–Lithium Ceramic Breeder Test Blanket Module), where LL flows in a number of parallel poloidal rectangular ducts between ceramic breeder (CB) layers [6,7]. Radiation heat generated in two adjacent CB layers facing two sides of one LL duct differs due to radiation energy decay.

In a very similar to our case configuration Direct Numerical Simulation (DNS) was performed [8], a hypothesis of elevator mode convection gives a strong physical background to issues observed in this work experimentally.

Analytical [9] and numerical [9,10] investigations of possible types of instabilities in a vertical blanket channels in case of upward flow shows that upward flow configuration faces similar issues. Classification of instabilities and stability curves should be taken as a first approach to analysis of problem presented in our work.

2. Experimental conditions

The test configuration of LM flow in a field of mass forces is shown in Fig. 1. It is a flow of mercury in vertical heated rectangular duct in a coplanar MF (a vector of magnetic field B is directed along large side of the duct cross section $B_x \neq 0$). A sides ratio in the duct cross section is $a/b = 56/17$ (mm). The duct walls are made from RF stainless steel, 18% of Cr (EU analog X10CrNiTi18-10, AISI 321). A dimensionless wall thickness is $d_w/b = 2.5/17$ (mm). Liquid metal flows along a gravity vector facing counter flow thermo gravitational force.

A double width of duct $d = 2b$ is taken as a characteristic length in estimating the characteristic parameters instead of usually used $a/2$ in MHD. The reason is that measured values of the wall temperature correlated best with laminar and turbulent values for 2D duct flow with such choice. There is a zone of hydrodynamic stabilization with a length $Z_0 = 10d$ which is located before heating zone. After that, there is a heating zone itself with a heat flux density possible on both sides of duct q_1 and q_2. A zone of MF coincides with heating zone ($0 < z < 30$). The duct walls are electrically conducting. The ratio between steel electrical conductivity and mercury electrical conductivity is 9.8/7.5.

Non-inductive approach can be used in the most applications of magneto hydrodynamics as for fusion typical applications usually Ha and Ha^2/Re are in order 10^2 to 10^5 and the magnetic Reynolds number $R_m = \mu_m \sigma V_0 d \ll 1$: in the expression μ_m is the fluid magnetic permeability, σ is the fluid electrical conductivity, V_0 is the fluid characteristic velocity and d is the characteristic size [11]. Other non-dimensional parameters which describe a character of MHD flow are determined in the following way. The Reynolds ($Re = V_0 d/\upsilon$) number based on the characteristic velocity of fluid gives the ratio of inertial to viscous force in the flow, where υ – kinematic viscosity. The Hartmann number is determined as ($Ha = B_0 d(\sigma/\mu)^{0.5}$), where B_0 – external magnetic field, μ – dynamic viscosity. The parameter Ha^2/Re is a ratio of electromagnetic force to inertial force. The Grashof number was build using heat flux instead of the temperature difference – $Gr_q = g\beta q_c d^4/\lambda \upsilon^2$, where β – volumetric thermal expansion coefficient; $q_c = 0.5(q_1 + q_2)$ – average heat flux on the walls; λ – thermal conductivity, g – gravitational acceleration. The parameter Gr_q/Re^2 is a ratio of buoyancy and viscous forces acting on a fluid. Dimensionless temperature is determined as $\Theta = \frac{1}{Nu} = \frac{\lambda \Delta T}{dq_c}$.

The typical system of governing equations consists of the mass, momentum, energy and additional Maxwell's equations. A detail description of the system of governing equations can be found in

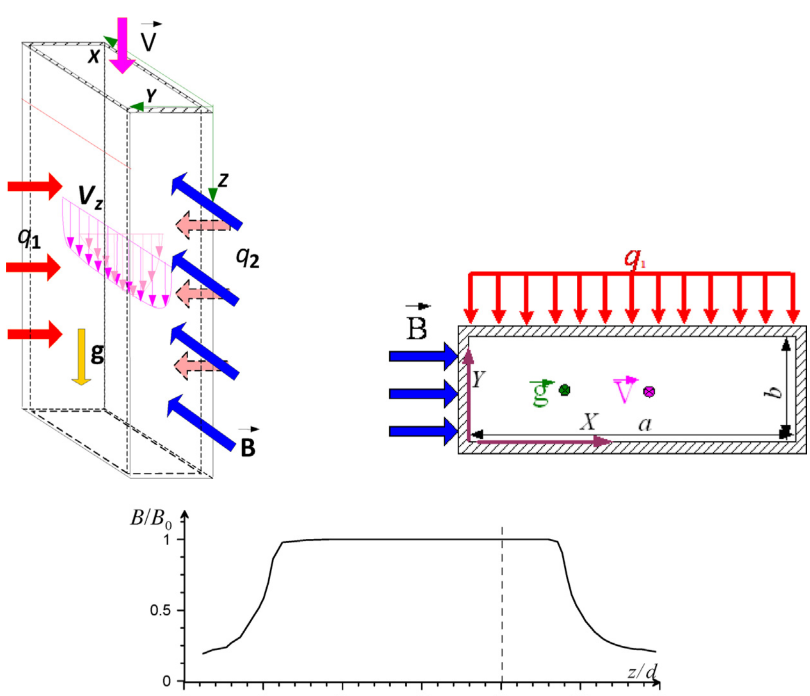

Fig. 1. Investigated flow scheme ($q_1 \neq 0$; $q_2 = 0$), MF distribution.