International Journal of Heat and Fluid Flow 000 (2017) 1–10

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

MHD liquid metal flow and heat transfer between vertical coaxial cylinders under horizontal magnetic field

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ARTICLE INFO

Article history:
Received 28 July 2016
Revised 14 December 2016
Accepted 2 January 2017
Available online xxx

Keywords:
Free convection
MHD
Aspect ratio
Liquid metals
Annuli
CFD

ABSTRACT

Direct numerical simulations are presented of MHD liquid metal flow and heat transfer in vertical annuli. Three annular gaps and four ratios of annular height to annular gap are considered. The walls of the external and internal cylinders are isothermal with the temperature of the outer cylinder being higher and, thus, buoyancy is the driving force. The results show that the fluid motion increases as the aspect ratio and the annular gap become larger. The presence of the magnetic field results to fluid deceleration and, thus, to flow stabilization. Additionally, non symmetric flow patterns develop, due to the magnetic field, resulting in differently sized normal and parallel wall layers, namely the Hartmann and the Roberts layers, respectively. For all annular gaps considered, the highest spatially averaged heat transfer rates are obtained for aspect ratios equal to 1.

1. Introduction

One of the challenges in the design of future fusion power plants is the confinement of the fusion plasma (Davidson, 2001). In the tokamak concept a strong magnetic field is used to maintain the plasma away from the reactor walls. In such a design the neutrons released by the fusion reaction will be captured by making use of a “blanket module” (Malang et al., 2009). Within the blanket, a flow of lithium-containing alloy $PbLi_{17}$ will be placed where neutrons will react with lithium to produce tritium. The blanket geometry has not yet been finalized (Abdou et al., 2015) and, thus, research is being carried out with respect to different geometries and operating conditions. However, most of the research, including the present study, has considered simpler geometries and operating conditions than those expected in real fusion blankets.

For instance, Li et al. (2005) investigated a geometry consisting of two coaxial cylinders where a liquid metal was placed in the annular gap while Helium was flowing inside the inner cylinder. They showed that the use of such a design could reduce significantly the MHD disadvantages, i.e. the non-conductive Helium can remove the heat without excessive pressure drop. Uda et al. (2000) studied experimentally and numerically a free convection liquid metal flow inside a vertical tube, in which a heater pin was placed at its bottom along its axis while an external uniform magnetic field was applied horizontally. It was shown that temperatures increased for stronger magnetic fields while, in contrast, fluid motion and heat transfer rates decreased. The comparison between the experimental and the numerical results was good. Smolentsev et al. (2010) presented various MHD geometries of the DCLL (Dual Cool Lead Lithium) breeding blankets. Special emphasis was given to the blanket design, consisting of two ducts: a) both rectancular, b) a rectagular and a circular, and c) both circular. In all cases the access ducts had two insulating flow inserts: one inside the internal duct and the other in the gap between the ducts. Results were presented, for case (a), in terms of velocity distribution and pressure drop.

In the present work a similar configuration is examined in which a liquid metal is placed in the gap between two coaxial vertical cylinders while a uniform magnetic field is applied horizontally with all walls electrically insulated. Internal heating due to the neutrons in real fusion blankets is neglected and the study focuses on investigating the influence on the flow of different annular gaps and aspect ratios (annular height to gap). This is in contrast to previous works of Kakarantzas et al. (2011, 2007) where only one aspect ratio of 3 and one annular gap of 1 were considered. The main goal is to identify the most efficient geometry and operating conditions in terms of flow stability and heat transfer enhancement.

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.01.001
0142-727X/

Nomenclature

A	aspect ratio, i.e. ratio of annular height to annular gap
B_0	magnitude of the external magnetic field (kg/(s^{2}A))
g	gravity acceleration (m/s^2)
$Ha = R_o B_0 \sqrt{\sigma/\rho\nu}$	Hartmann number
$\mathbf{J}$	electric current density (A/m^2)
L	height of the cylinders (m)
$Nu_{i,\,o}$	local Nusselt number along the inner/outer cylinder
$\overline{Nu}_{i,o}$	azimuthally averaged Nusselt number along the inner/outer cylinder
$\overline{Nu}_{i,o,tot}$	averaged Nusselt number on the inner/outer cylinder
p	fluid pressure (Pa)
$Pr = \nu/\alpha$	Prandtl number
Q	volumetric heating rate (W/m^3)
$R = R_o - R_i$	(m) annular gap
$Ra = g\beta\Delta T R^3/\nu\alpha$	Rayleigh number
R_i	radius of the inner cylinder (m)
R_o	radius of the outer cylinder (m)
$r,\ \theta,\ z$	radial, tangential and axial coordinates, respectively
t	time (s)
$T = (T^* - T_i)/\Delta T$	non-dimensional temperature
T^*	temperature of the fluid (K)
$T_{i,\,o}$	temperature of the inner/outer cylinder (K)
$\Delta T = QR_o^2/k$	characteristic temperature difference (K)
$u_r,\ u_\theta,\ u_z$	radial, tangential and axial velocities, respectively
$\mathbf{v}$	velocity vector

Greek letters

α	fluid thermal diffusivity (m^2/s)
β	fluid coefficient of thermal expansion (1/K)
η	Kolmogorov length scale
ν	fluid kinematic viscosity (m^2/s)
ρ	fluid density (kg/m^3)
σ	fluid electrical conductivity (s^3 A^2/m^{2}kg)
Φ	electrical potential (m^2 kg/s^3 A)

2. Flow configuration and model description

A vertical annular container with height L is considered as shown in Fig. 1. The annular gap is $R = R_o - R_i$ where R_o, R_i are the radius of the outer and inner cylinders, respectively with $R_o = 1$ in all cases. Four aspect ratios $A = 0.5, 1, 2$ and 3 and three gaps $R = 0.4, 0.6$ and 0.8 are examined. A highly electrically conducting fluid is used with Prandtl number $Pr = 0.0321$, corresponding to the $PbLi_{17}$ alloy which is one of the most serious candidates for fusion blankets. A uniform magnetic field $\mathbf{B}_o$ is applied horizontally in the direction $\theta = 0$, $\mathbf{g}$ is the gravity acceleration and $T_i < T_o$ are the temperature of the inner and the outer cylinders, respectively. The top and bottom walls are considered adiabatic while the outer and inner cylindrical walls are isothermal. Thus, free convection is the driving force of the fluid motion.

The magnetohydrodynamic equations are non-dimensionlized by the following quantities: the outer radius R_o, the free fall velocity $u_{ref} = \sqrt{g\beta\Delta T R_o}$, the pressure $p_{ref} = \rho u_{ref}^2$, the time $t_{ref} = R_o/u_{ref}$, and the electric potential $\Phi_{ref} = R_o B_0 u_{ref}$, where ρ is the density of the fluid and β its thermal expansion coefficient.

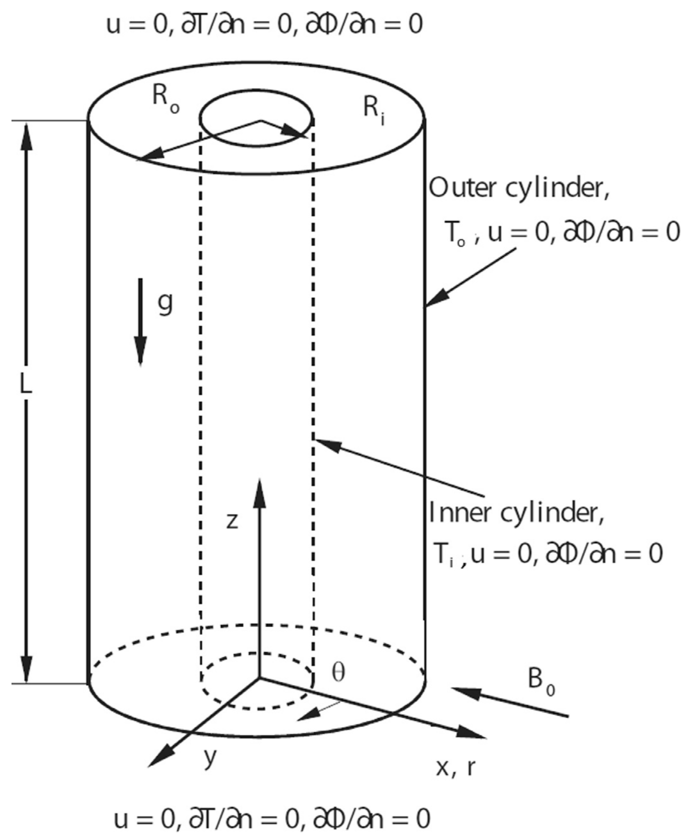

Fig. 1. Flow configuration and boundary conditions.

The non-dimensional temperature T is defined as $T = (T^* - T_i)/\Delta T$, where T^* is the fluid temperature and $\Delta T = (T_o - T_i)$. Thus, the dimensionless equations governing this flow and heat transfer problem read:

$$\nabla \cdot \mathbf{v} = 0 \tag{1}$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla p + T\mathbf{k} + \left(\frac{Pr}{Ra}\right)^{\frac{1}{2}} \nabla^2 \mathbf{v} + Ha^2 \left(\frac{Pr}{Ra}\right)^{\frac{1}{2}} (\mathbf{J} \times \mathbf{B_0}) \tag{2}$$

$$\frac{\partial T}{\partial t} + (\mathbf{v}\cdot\nabla)T = \left(\frac{1}{PrRa}\right)^{\frac{1}{2}} \nabla^2 T \tag{3}$$

where, $\mathbf{k}$ is the unit vector in the axial z-direction.

The electric current is based on Ohm's law (Davidson, 2001):

$$\mathbf{J} = -\nabla\Phi + \mathbf{v} \times \mathbf{B_0} \tag{4}$$

Using the electric current conservation:

$$\nabla \cdot \mathbf{J} = 0. \tag{5}$$

the electric potential is given by:

$$\nabla^2 \Phi = \nabla \cdot (\mathbf{v} \times \mathbf{B_0}) \tag{6}$$

For the flows considered here, the low magnetic Reynolds number approximation is used since the induced magnetic field remains very small compared to the external one. As a consequence the magnetic induction equation need not be solved, see Sarris et al. (2006). The dimensionless parameters characterizing this flow are: the Rayleigh number, $Ra = g\beta\Delta T R_0^3/\nu\alpha$, representing the ratio of buoyancy to viscous forces, the Hartmann number, $Ha = B_0 R_o \sqrt{\frac{\sigma}{\rho\nu}}$, expressing the ratio of electromagnetic to viscous forces, and the Prandtl number $Pr = \frac{\nu}{\alpha}$, representing the ratio of

Please cite this article as: S.C. Kakarantzas et al., MHD liquid metal flow and heat transfer between vertical coaxial cylinders under horizontal magnetic field, International Journal of Heat and Fluid Flow (2017), http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.01.001