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International Journal of Heat and Mass Transfer 48 (2005) 2571–2581
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

# MHD effect on flow structures and heat transfer characteristics of liquid metal–gas annular flow in a vertical pipe

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Received 22 May 2003; received in revised form 19 January 2004
Available online 13 March 2005

## Abstract

The magnetohydrodynamic (MHD) effect on the flow structures and heat transfer characteristics was studied numerically for a liquid metal–gas annular flow under a transverse magnetic field. The side layers, in which the velocity was increased, appeared near the eastern and western sidewalls in an annular MHD flow as in a single-phase liquid metal MHD flow. Temperature distribution in the liquid film, and the Nusselt number distribution in the angular direction were influenced by the flow structures with the side layers. Consequently heat transfer rate was higher at the eastern/western sidewalls than that at the southern/northern walls. The pressure drop in the MHD annular flow is of the same order of magnitude as in the single-phase MHD pipe flow under similar liquid metal flow condition.


*Keywords:* Liquid metal–gas annular flow; MHD effects; Flow structures; Heat transfer; Pressure drop

## 1. Introduction

The flow of liquid metals in the presence of a magnetic field has been a topic of great interest for several decades. Experimental and mostly analytical studies were performed for the development of magnetohydrodynamic (MHD) devices of electromagnetic flow meters, MHD generators, electromagnetic pumps and accelerators [1–9]. Steady, incompressible rectilinear flow under transverse magnetic field has received most attention of all the areas of MHD flows mentioned above [4,7]. MHD duct flows have been systematically analyzed particularly for the flow in the rectangular duct with both conducting and non-conducting walls.

In recent decades, researches of MHD liquid metal flow have been performed mainly for the development of fusion technology, particularly for the conceptual design of the self-cooled liquid metal blanket of magnetically confined fusion reactor [10], and further for the exploration of innovative concepts for fusion chamber technology, namely, first wall, blanket, divertor and vacuum vessel [11]. A number of experimental and analytical studies have been carried out so far to investigate the hydrodynamic and heat transfer characteristics of the liquid metal flows in a duct and those with free surfaces subjected to MHD forces. Previous studies in this research field have been reviewed by Lielausis [12] and recent understandings have been summarized by Kirillov et al. [13], Morley et al. [14] and Abdou et al. [11].

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0017-9310/$ - see front matter 
doi:10.1016/j.ijheatmasstransfer.2004.12.041

**Nomenclature**

| | |
|---|---|
| $B_0$ | magnetic flux density of the uniform field (T) |
| $C_f$ | friction factor |
| $c_p$ | specific heat (J/kg K) |
| $g$ | gravitational acceleration (m/s$^2$) |
| $Ha$ | Hartmann number ($Ha = 2B_0R_i\sqrt{\sigma/\mu}$) |
| $h$ | heat transfer coefficient (W/m$^2$ K) |
| $j$ | electric current density (A/m$^2$) |
| $j_x$ | electric current density component in the $x$ direction (A/m$^2$) |
| $j_y$ | electric current density component in the $y$ direction (A/m$^2$) |
| $Nu$ | Nusselt number ($Nu = hR_i/\lambda$) |
| $Nu_{an}$ | Nusselt number in annular two-phase flow |
| $Nu_{sn}$ | Nusselt number in single-phase flow |
| $p$ | pressure (Pa) |
| $q$ | heat flux (W/m$^2$) |
| $r$ | radial coordinate in cylindrical coordinate system |
| $R_0$ | outer radius of circular pipe (m) |
| $Re$ | Reynolds number for single-phase flow ($Re = 2\rho V_0R_i/\mu$) |
| $Re_g$ | gas Reynolds number for annular flow ($Re_g = 2\rho_g V_{0g}R_g/\mu_g$) |
| $Re_L$ | liquid Reynolds number for annular flow ($Re_L = 2\rho V_{zm}(R_i - R_g)/\mu$) |
| $R_g$ | radius of gas core (m) |
| $R_i$ | inner radius of circular pipe (m) |
| $T$ | temperature (°C) |
| $T_b$ | bulk temperature (°C) |
| $V$ | velocity (m/s) |
| $V_0$ | initial velocity for single-phase flow (m/s) |
| $V_{0g}$ | average velocity in gas core of annular flow (m/s) |
| $V_z$ | velocity component in the axial direction (m/s) |
| $V_{zm}$ | average liquid velocity of annular flow (m/s) |
| $x$ | $x$ coordinate in Cartesian coordinates (m) |
| $y$ | $y$ coordinate in Cartesian coordinates (m) |
| $z$ | axial coordinate in cylindrical coordinate system (m) |

*Greek symbols*

| | |
|---|---|
| $\Theta$ | dimensionless temperature |
| $\Theta_b$ | dimensionless bulk temperature |
| $\delta$ | liquid film thickness of annular flow (m) |
| $\phi$ | electric potential (V) |
| $\lambda$ | thermal conductivity of liquid (W/m °C) |
| $\mu$ | dynamic viscosity of liquid (Pa s) |
| $\mu_g$ | dynamic viscosity of gas (Pa s) |
| $\theta$ | polar angular coordinate in cylindrical coordinate system |
| $\rho$ | liquid density (kg/m$^3$) |
| $\rho_g$ | gas density (kg/m$^3$) |
| $\sigma$ | electric conductivity of liquid (mho/m) |
| $\sigma_w$ | electric conductivity of wall (mho/m) |
| $\tau$ | shear stress (N/m$^2$). |

In the cases of liquid wall concepts for the chamber technology of magnetically confined fusion reactor, the problems emerging from two contradictions have attracted much more attentions. One contradiction is between the efforts to enhance heat transfer rate and to decrease the MHD pressure drop along the flow channel. To enhance heat transfer rate, liquid metals are the best candidates for the working fluids but meanwhile liquid metal flowing in a strong magnetic field inevitably results in excess and actually very serious MHD pressure drop. The other contradiction is between the effort to decrease the MHD pressure drop along the flow channel and the constraints of materials under the operating conditions of a fusion reactor. The non-conducting non-metallic structural devices are the best choice to mitigate magnetic pressure drop due to MHD effects, but non-metallic materials are generally not compatible with liquid metals at high temperature of several hundreds degree centigrade. An idea has been therefore proposed by Bender and Hoffman [15], which uses a gas–liquid metal two-phase flow for the purpose of increasing heat transfer coefficient meanwhile mitigating pressure losses of the flow (since mass flow rate of two-phase flow is less than that of single-phase liquid to remove the same heat flux) and using insulator coatings to degrade the pressure drop. This issue has been intensively investigated [16–20]. Nonetheless, the details of the two-phase MHD flow structure are still worthy to be explored and can be treated preferably by numerical approaches as will be shown later.

It is well known that the MHD flow in a duct can be divided into three regions (as shown in Fig. 2), i.e., core region, the Hartmann layer and side layer [21,22]. The viscous and inertia forces are negligible in the core region where velocity is nearly constant. The shear is so strong that viscous forces can compete with magnetic forces in the Hartmann layer adjoining a solid wall normal to the applied magnetic field. The flow structure in the side layer is strongly dependent on the wall conductance ratio and consequently on the current density distribution. The flow speed in the side layers is higher than