ARTICLE IN PRESS

JID: HFF [m5G;July 23, 2016;12:21]

International Journal of Heat and Fluid Flow 000 (2016) 1–17

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Study of directional control of heat transfer and flow control in the magnetohydrodynamic flow in cylindrical geometry

Udhayakumar S.[a], Abin Reejesh A.D.[a], Sekhar T.V.S.[b], Sivakumar R.[a,*]

[a] Department of Physics, Pondicherry University, Puducherry–605 014, India
[b] School of Basic Sciences, Indian Institute of Technology Bhubaneswar, Bhubaneswar–751 013, India

ARTICLE INFO

Article history:
Received 23 December 2015
Revised 19 May 2016
Accepted 22 June 2016
Available online xxx

Keywords:
Heat transfer
Magnetic field orientation
Flow control
High accuracy numerical scheme
Directional dependence

ABSTRACT

Two-dimensional laminar electrically conducting flow and its heat transfer is considered and the control of heat transfer in different directions is analysed using a class of high accuracy numerical scheme in curvilinear coordinate system. Numerical flow solutions with temperature fields were obtained for range of Reynolds number $10 \leq Re \leq 40$, Prandtl number $0.065 \leq Pr \leq 7$ and Interaction parameter $0 \leq N \leq 5$. For weak magnetic fields, the drag coefficient increases by 37% when the field direction is aligned with that of flow, and when the field is directed perpendicular to flow direction, it drastically increases by 390% for $Re = 40$. For stronger magnetic field strengths, the drag coefficient increases like square root of interaction parameter. When no field is applied the heat transfer takes place in the entire region of downstream, but when the magnetic field is switched on, the direction of applied magnetic field influences the heat transfer to take place in the selected direction of the downstream by forming plumes in those directions. In contrast to a reduction in mean Nusselt number due to aligned magnetic field, the heat transfer increases due to transverse magnetic field.

1. Introduction

The study of thermo-MHD flow over on bluff bodies is a challenging area in research because of additional coupling of Maxwell's equation to the equations of hydrodynamics and hence due to the associated action of Lorentz forces. It has wide range of industrial and engineering applications not limited to casting of metals, metal working process, stirring, liquid metal flow, cooling circuit of fission reactors, fusion reactors, etc., wherein a general liquid metal flow and its control is of prime importance.

A few reports are available that investigate the effect of magnetic filed on the flow and heat transfer due to flow past obstacles. The steady, two-dimensional incompressible MHD flow past a circular cylinder with an applied magnetic field parallel to the main flow is theoretically studied by using series truncation method (Bramley, 1974; 1975) and found that an applied magnetic field keeps the flow to stay attached to the cylinder, and in some cases the flow does not separate until the rear stagnation point. An experimental investigation (Lahjomri et al., 1993) on the effect of aligned magnetic field show that field suppress the 2D flow instability and lead to the suppression of vortex shedding. Sooner after this experimental result, a few numerical computations (Mutschke et al., 1998; 1997; 2001; Shatrov et al., 1997) show that the flow instability in the wake in the presence of magnetic field for 2D and 3D flow. They reported that depending on the applied magnetic field strength, the vortex shedding can be suppressed or eliminated. The effect of magnetic field on the flow by immerse boundary method is studied with a view to establish the performance of the MIB method (Grigoriadis et al., 2010). The previous reports are pertaining to flow dynamics only and in the next paragraph, the reports on the heat transfer analysis due to flow and magnetic field are discussed.

An experimental study (Uda et al., 2001) of forced convection heat transfer of liquid lithium flowing in an annular channel and temperature fluctuations under transverse magnetic fields revealed a degradation of heat transfer due to applied field. Later, a two-step time-split scheme is used to study the fluid flow and forced convection heat transfer around a circular cylinder under the magnetic field for $Re = 100$ and 200, and concluded that the vortex shedding in the wake becomes weaker and further that if the magnetic field is greater than certain value, then the flow and thermal fields become steady (Yoon et al., 2004). The flow dynamics and heat transfer of a liquid metal past a circular cylinder inside a plane channel (bounded flow) under a transverse magnetic field is studied by (Cassells et al., 2016; Hussam and Sheard, 2013; Hussam et al., 2011) using spectral element method. Recently, the

* Corresponding author.
E-mail addresses: sekhartvs@iitbbs.ac.in (Sekhar T.V.S.), rs4670@gmail.com, rsk.phy@pondiuni.edu.in (Sivakumar R.).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.06.011
0142-727X/

Please cite this article as: Udhayakumar S. et al., Study of directional control of heat transfer and flow control in the magnetohydrodynamic flow in cylindrical geometry, International Journal of Heat and Fluid Flow (2016), http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.06.011

Nomenclature

a, d	Radius and diameter of cylinder.
c	Specific heat capacity of fluid.
C_D	Total drag coefficient.
H_∞	Magnetic field at far distance.
$\boldsymbol{J}$	Electric current density.
k	Thermal conductivity of the fluid.
l_s	Separation length
N	Magnetic interaction parameter $=\sigma H_\infty^2 a/\rho U_\infty$.
Nu	Local Nusselt number.
$\overline{Nu}$	Average Nusselt number.
p	Pressure.
Pr	Prandtl number $=\mu c/k$.
Re	Reynolds number $=2aU_\infty/\nu$.
T	Dimensionless temperature.
T_s	Surface temperature of the cylinder.
T_∞	Uniform free stream temperature.
V_r	Radial velocity $=(1/r)\cdot(\partial\psi/\partial\theta)$.
V_θ	Transverse velocity $=-\partial\psi/\partial r$.
U_∞	Uniform free stream velocity.
γ	Angle of inclination of magnetic field with respect to free stream flow.
μ	Dynamic viscosity of the fluid.
ν	Kinematic viscosity of the fluid.
ρ	Density of the fluid.
σ	Electrical conductivity of the fluid.
θ_s	Separation angle
(r, θ)	2D cylindrical polar coordinates.
(ξ, η)	Coordinates after $r=e^{\pi\xi}$, and $\theta=\pi\eta$ transformation.
(ψ, ω)	Stream function and vorticity of the fluid.

natural convection flow of an electrically conducting fluid in a rectangular cavity (bounded flow) under different directions of uniform magnetic field is numerically studied (Yu et al., 2013) and reported that the heat transfer is not only determined by the strength of the magnetic field, but also influenced by the inclination angle. The effect of inclination angle of the applied magnetic field on the natural convection heat transfer is studied for the case of square cavity (Sathiyamoorthy and Chamkha, 2010) and found that the mean Nusselt number decreases nonlinearly with magnetic field, which is also observed in a previous study (Teamah, 2008). Using the lattice Boltzmann method, the study of natural convection MHD flow revealed that a radial magnetic field affects the patterns of streamlines together with an increase in thermal boundary layer thickness (Ashorynejad et al., 2013). In a recent mixed convection study (Kefayati, 2015) in the lid-driven cavity, it is observed that the heat transfer degrades upon the application of magnetic field.

From the above literature survey, it is noted that most of the studies were focussed on the flow and wake dynamics around bluff bodies subjected a magnetic field aligned in a particular direction, which may be parallel or transverse. In addition, there are no reports on the heat transfer studies due to unbounded flow configuration in presence of magnetic field in different directions for the case of flow around cylinders. Based on these facts, the aim of the present work is to analyse the influence of the direction of applied magnetic field in the problem of laminar magnetohydrodynamic flow over on isothermal circular cylinder and its heat transfer properties. We use a class of high order finite difference technique to simulate the system and the results are presented for $10 \le Re \le 40$, $0.065 \le Pr \le 7$ in presence of different magnetic fields.

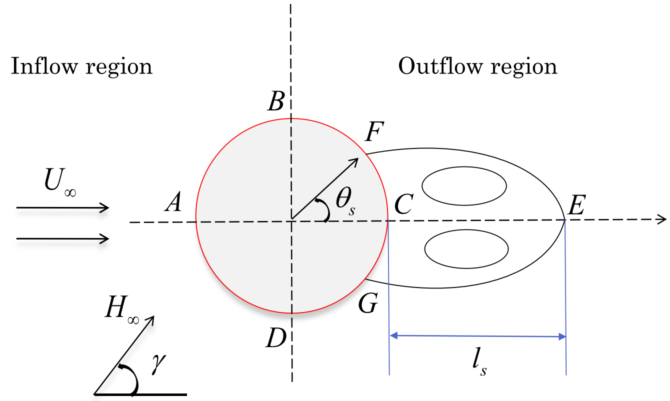

Fig. 1. Schematic diagram showing the flow configuration with magnetic field making an angle γ with the flow direction.

2. Mathematical formulation

The radius of the cylinder is a (and d is diameter) and isothermal surface temperature of the cylinder is T_s. It is placed in an uniform flow of an incompressible fluid with free stream velocity U_∞ and magnetic field $H_\infty(\gamma)$ whose direction γ will be a variable. The fluid is assumed to satisfy the Boussinesq approximation and the free stream fluid temperature is T_∞. The flow considered here is from left to right and $(\theta, a)=(\pi, 1)$ is taken as front stagnation point and $(\theta, a)=(0, 1)$ is taken as rear stagnation point. The flow is assumed to be steady and cylindrical coordinates are used with the angle measured from downstream axis, $\theta=0$. The schematic sketch of the flow configuration is shown in Fig. 1, where A, C are front and rear stagnation points respectively, E is reattachment point, F and G are separation points, θ is cylindrical polar coordinate angle and γ is the direction of magnetic field with respect to $\theta=0$ horizontal axis. The fluid properties are the density ρ, the kinematic viscosity ν, the thermal conductivity k, the electrical conductivity σ and specific heat capacity c. The steady state governing equations are non-dimensionalized and the dimensionless parameters are Reynolds number Re, Prandtl number Pr, and the interaction parameter N which are defined by:

$$Re=\frac{2aU_\infty}{\nu},\quad Pr=\frac{\mu c}{k},\quad N=\frac{\sigma H_\infty^2 a}{\rho U_\infty} \tag{1}$$

By assuming that the induced magnetic field is very small in comparison to the external uniform magnetic field, we adopt the low magnetic Reynolds number or the quasi-static approximation. The constant magnetic field $\boldsymbol{H}(\gamma)$ is applied in different directions γ and is taken to be:

$$\boldsymbol{H}=(h_r, h_\theta, h_z)=[-\cos(\theta+\gamma),\quad \sin(\theta+\gamma),\ 0] \tag{2}$$

where θ is the angle in the cylindrical polar system. Here, $\gamma=0$ is taken as streamline or aligned magnetic field, and $\gamma=90^\circ$ shall be treated as transverse magnetic filed. The other magnetic field directions taken for present numerical experiments are $-75\le\gamma\le 75$. The non-dimensionalized steady state governing equations are:

$$\nabla\cdot\boldsymbol{V}=\boldsymbol{0} \tag{3}$$

$$(\boldsymbol{V}\cdot\nabla)\boldsymbol{V}=-\nabla p+\frac{2}{Re}\nabla^2\boldsymbol{V}+N(\boldsymbol{J}\times\boldsymbol{H}) \tag{4}$$

$$(\boldsymbol{V}\cdot\nabla)T=\frac{2}{RePr}\nabla^2 T \tag{5}$$

$$\boldsymbol{J}=\boldsymbol{E}+(\boldsymbol{V}\times\boldsymbol{H}) \tag{6}$$

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