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Effect of a rotating cylinder in forced convection of ferrofluid over a backward facing step

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ABSTRACT

In this study, numerical analysis of the heat transfer enhancement and fluid flow characteristics of a rotating cylinder under the influence of magnetic dipole in the backward facing step geometry is conducted. The governing equations are solved with a finite element based commercial solver. The effects of Reynolds number ($10 \leqslant Re \leqslant 200$), cylinder rotation angle ($-75 \leqslant \Omega \leqslant 75$) and strength of the magnetic dipole ($0 \leqslant \gamma \leqslant 16$) on the heat transfer characteristics are studied for backward facing step flow. It is observed that the length and size of the recirculation zones can be controlled with magnetic dipole strength and cylinder rotation angles. As the Reynolds number increases, local Nusselt number increases and number of peaks in the presence of the magnetic field decreases. The effect of cylinder rotation on the local Nusselt number distribution is more pronounced at low Reynolds number.

1. Introduction

Flow separation and its subsequent reattachment have many practical engineering applications such as flow around buildings, airfoils, combustors and collectors of power systems. A benchmark problem where flow separation and reattachment occur is the flow over a backward facing or forward facing step where a vast amount of research is dedicated in this field using numerical [1–7] and experimental methods [8–12]. A comprehensive review is presented in [13] for laminar mixed convection over vertical, horizontal and inclined backward- and forward-facing steps studied in the open literature. Heat transfer and fluid flow characteristics over a backward or forward facing step in a channel with the insertion of obstacles has received some attention in the literature [14–16].

The effects of magnetic field on the fluid flow and heat transfer have received much attention during the recent years due to its importance in many technological applications such as coolers of nuclear reactors, micro-electronic devices, purification of molten metals many others [17–21]. A review of heat transfer enhancement using ferrofluids is given in Ref. [22]. Due to the effect of the magnetic field, the fluid flow experiences a Lorentz force. Employing an external magnetic field can be used as a control method since magnetic field can suppress the convective flow field. Oztop and Pop [23] have studied the mixed convection with a magnetic field in a top sided lid-driven cavity heated by a corner heater. They showed that heat transfer decreases with increasing the Hartmann number and magnetic field plays an important role to control heat transfer and fluid flow. Strek and Jopek [24] have simulated the channel flow under the influence of magnetic dipole using a finite element code.They reported that inhomogeneous magnetic body force due to temperature gradient can prompt or inhibit convection similar to buoyancy force. Finlayson [25] have studied stability of ferromagnetic fluid for a fluid layer heated from below and subjected to a uniform vertical magnetic field. A temperature gradient was established across the fluid layer which causes a spatial variation in magnetization and hence convection. Jafari et al. [26] have studied the heat transfer and fluid flow characteristics for a kerosene based ferrofluid in two cylinders with different dimensions using computational fluid dynamics. They studied the effects of temperature gradients and uniform magnetic fields on the heat transfer and observed that magnetic field enhances the transport processes. They also showed that heat transfer increases when the magnetic field is perpendicular to the temperature gradient. In the present study, the effects of a rotating cylinder under the influence of magnetic dipole on the heat transfer enhancement and fluid flow characteristics are numerically studied. The effects of various parameters such as Reynolds number, cylinder rotation angle and strength of the magnetic dipole are examined for convective heat transfer enhancement over a backward facing step flow. To the best of authors' knowledge and based on above literature survey such a study has not been seen in the published literature.

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Nomenclature

a, b	location of the cylinder center (m)
$\mathbf{B}$	magnetic induction, (T)
c, d	location of the magnetic dipole (m)
h	local heat transfer coefficient (W m^{-2} K^{-1})
$\mathbf{H}$	magnetic field (A m^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	length of the bottom wall (m)
Mn	magnetic number, $\frac{\mu_0 H_r^2}{\rho_0 v_r^2}$ (–)
n	unit normal vector
Nu	local Nusselt number, hS/k (–)
p	pressure, (Pa)
Re	Reynolds number, $u_0 S/\nu$ (—)
S	step size (m)
T	temperature (K)
$u,\ v$	x-y velocity components (m s^{-1})
$x,\ y$	Cartesian coordinates

Greek characters

α	thermal expansion coefficient (K^{-1})
θ	non-dimensional temperature, $\frac{T-T_c}{T_h-T_c}$ (–)
μ_0	magnetic permeability of vacuum (N A^{-2})
ν	kinematic viscosity (m^2 s^{-1})
χ	magnetic susceptibility (–)
γ	strength of the magnetic dipole (Am)
ρ	density of the fluid (kg m^{-3})
Ω	nondimensional rotation velocity of cylinder, $\frac{\omega S}{2u_0}$ (–)

Subscripts

c	cold wall
max	maximum
mean	average
h	hot wall

2. Physical model and numerical study

A schematic description of the physical problem considered in this study is shown in Fig. 1. A channel with a backward facing step is considered. The step size of backward facing step is S and channel height is $2S$. At the inlet of the channel, a parabolic velocity and a uniform temperature are imposed. The downstream length starting from the edge of the step to the exit of the channel is $35S$ to ensure that the recirculation length downstream of the step is independent of the computational domain. The downstream bottom surface of the backward facing step is maintained at constant temperature higher that the inlet temperature, while the other walls of the channel are assumed to be adiabatic. An adiabatic rotating cylinder with diameter ($D = S$) is mounted at the location $(x_c, y_c) = (S, S)$ where the coordinate system is positioned at the step on the bottom wall of the channel. A magnetic dipole is located below the channel and the fluid is electrically non-conducting (ferrofluid does not induce electromagnetic current). The momentum equation for an incompressible fluid and constant viscosity is modified by adding a term related to magnetic field as

$$\rho\mathbf{u}.\bigtriangledown\mathbf{u} = -\bigtriangledown p + \bigtriangledown.(\mathbf{HB}) + \mu\bigtriangledown^2\mathbf{u} \tag{1}$$

where $\mathbf{H}, \mathbf{B}$ denote the magnetic field and magnetic induction. The energy equation for an incompressible fluid can be stated as

$$\rho c\mathbf{u}.\bigtriangledown T = k\bigtriangledown^2 T + \Phi - \mu_0 T\frac{\partial\mathbf{M}}{\partial T}((\mathbf{u}.\bigtriangledown)\mathbf{H}) \tag{2}$$

where $\mathbf{M}$ denotes the magnetization. Maxwell's equation for a non-conducting fluid can be written as

$$\bigtriangledown.\mathbf{B} = 0, \qquad \bigtriangledown\times\mathbf{H} = 0 \tag{3}$$

The constitutive relation between $\mathbf{B}, \mathbf{M}$ and $\mathbf{H}$ can be stated as

$$\mathbf{B} = \mu_0(\mathbf{M} + \mathbf{H}) \tag{4}$$

The magnetic field is induced with a magnetic dipole located below the channel downstream of the step. For the magnetostatic case, a magnetic scalar potential can be defined $\mathbf{H} = -\bigtriangledown V_m$

$$V_m(x) = \frac{\gamma}{2\pi}\frac{x-c}{(x-c)^2 + (y-d)^2} \tag{5}$$

where γ, c and d denote the magnetic field strength, and position where the dipole is placed. The term in the momentum equation is the force per unit volume when the spatially non-uniform magnetic field is employed to the magnetic fluid. The relation between the magnetization vector $\mathbf{M}$ and magnetic field vector $\mathbf{H}$ can be written as

$$\mathbf{M} = \chi_m\mathbf{H} \tag{6}$$

where χ_m is the total magnetic susceptibility

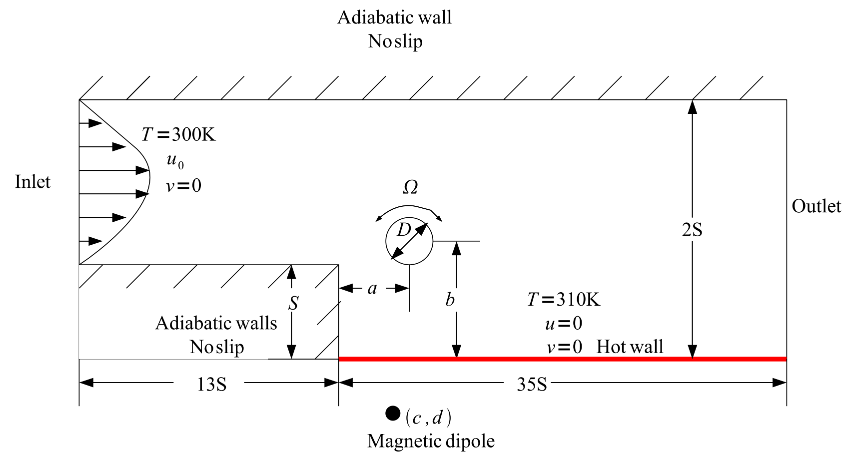

Fig. 1. Geometry and boundary conditions of backward facing step.