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Effect of thermal buoyancy on flow and heat transfer around a permeable circular cylinder with internal heat generation

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ABSTRACT

Mixed convection heat transfer around a permeable circular cylinder with internal heat generation in steady flow was numerically investigated by applying the finite volume method for the coupled porous and pure fluid regions with collocated body-fitted and multi-block grids. Particular emphasis is given to the dual role of thermal buoyancy in flow pattern and heat transfer performance with regard to effects of the Reynolds number (Re), Darcy number (Da), and Richardson number (Ri). Details of flow and thermal characteristics are presented in terms of streamlines, isotherms, velocity distribution, wake length, drag coefficients, and Nusselt number around a permeable cylinder. Thermal buoyancy is found to have positive or negative impact on flow and heat transfer, depending on the orientation of the interaction between buoyancy force and incoming flow. Aiding buoyancy delays or completely suppresses the onset of the recirculating wake and enhances heat transfer, while opposing buoyancy has the opposite effect. For all cases studied here, heat transfer rate from a porous cylinder is higher than that from a solid one. Results also show that drag coefficients decrease with Re for the aiding buoyancy case, while present complex development for the opposing buoyancy case. All drag coefficients and average Nusselt number (Nu_{ave}) with opposing buoyancy are smaller than those with aiding buoyancy. Also, for a high $Ri \geq 1$, inverse flow appears at the rear of the cylinder due to the prominent influence of opposing buoyancy.

1. Introduction

Fluid flow around porous bluff bodies with heat transfer has attracted extensive attention for several decades due to its significant value and wide applications in nature and engineering industries, such as cooling and heating for food, nuclear biological chemical equipment, heat exchangers, metal melting and solidification, flow around bridges and buildings as well as electronic components. A relevant example is the nuclear reactor core [1], in which the system of arrangement of nuclear fuel and septum can be considered as the porous configuration, involving flow and heat transfer characteristics. Therefore, understanding the inherent characteristics of flow and heat transfer around a porous bluff body significantly contributes to the improvement of these applications.

Plenty of efforts in theoretical, numerical, and experimental aspects have been made to investigate flow pattern and wake structures of flow past an obstacle. The shape of standing vortices behind a solid body in the steady viscous flow was discussed by Takami and Keller [2]. They investigated flow patterns at different Reynolds numbers and pointed out that a pair of closed vortices appears at the rear cylinder surface when Reynolds number is above a certain value. An experiment on steady flow around a circular cylinder was conducted by Coutanceau and Bouard [3]. Their experimental results showed that the standing eddies or twin vortices attach to the rear surface of cylinder, and the length of vortices rises with an increase in Reynolds number. Similar results can be obtained in the numerical studies conducted by Catalano et al. [4], Ding et al. [5], and Rajani [6]. Attention was also paid to the mechanism of unsteady flow. For instance, the vortex shedding frequency behind a cylinder at low Reynolds number was studied by Nishioka and Sato [7].

Flow past a porous bluff body was investigated by many researchers. Noymer et al. [8] examined the drag coefficient for steady flow through a porous cylinder. The drag coefficient was found to be similar to that for a solid cylinder at very low permeability, and approximately approach to zero at very high permeability. Symmetric recirculating wake was also observed downstream behind the porous cylinder. Yu et al. [9,10] found that the recirculating wake either penetrates or completely detaches

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Nomenclature

Notations

B	buoyancy force, [N]
g	gravitational acceleration, [m/s^2]
d	diameter of cylinder, [m]
Re	Reynolds number, $v_\infty d/\nu$
Pr	Prandtl number, ν/α
Gr	Grashof number, $g\beta(T^* - T^*_\infty)d^3/\nu^2$
Ri	Richardson number, Gr/Re^2
Da	Darcy number, K/d^2
K	permeability of cylinder, [m^2]
q'''	heat source, [W/m^3]
C_d	coefficient of total drag, $2F_d/\rho v_\infty^2$
C_{dp}	coefficient of pressure drag, $2\triangle p/\rho v_\infty^2$
C_{dv}	coefficient of viscous drag, $2\tau_w/\rho v^2{}_\infty$
F_d	drag force, [N]
R_c	thermal conductivity ratio, k_e/k_f
Nu	Nusselt number, hd/k_f
h	heat transfer coefficient
A	surface area, [m^2]
k_f	thermal conductivity of fluid
k_e	effective thermal conductivity
n	normal direction
t	tangential direction
x	dimensional horizontal coordinate, [m]
y	dimensional vertical coordinate, [m]
u	dimensional x-component velocity, [m/s]
v	dimensional y-component velocity, [m/s]
p	pressure, [Pa]
T^*	temperature, [°C]
X	dimensionless horizontal coordinate, x/d
Y	dimensionless vertical coordinate, y/d
U	dimensionless x-component velocity, u/v_∞
V	dimensionless y-component velocity, v/v_∞
P	dimensionless pressure
T	dimensionless temperature

Greek symbols

α	thermal diffusivity, [m^2/s]
β	thermal expansion coefficient, [°C^{-1}]
β_1	viscous stress jump coefficient
β_2	inertial stress jump coefficient
ν	fluid kinematic viscosity, [m^2/s]
ε	porosity
ρ	fluid density, [kg/m^3]
θ	position on the surface of cylinder (measured from the front stagnation point), [°]

Subscripts

∞	free stream
1	fluid region
2	porous region
ave	average

from the cylinder surface, and its size and location mainly depend on Reynolds number and Darcy number. The main difference between the porous cylinder and its solid counterpart is that the porous medium can partially divert fluid. At large Darcy number ($Da \geq 10^{-2}$), the deviation of flow is small, and more fluid flows through the cylinder without an initiation of wake [11]. As Darcy number decreases to 10^{-6}, the recirculation length is almost the same as that of a solid one. Additionally, the critical Reynolds number for the occurrence of recirculating wake is smaller than that of a solid cylinder in a given range of Darcy number [10,12].

Dennis et al. [13] examined steady laminar forced convection around a circular cylinder with constant wall temperature. They found that both local and average Nusselt numbers experience a growing trend with increasing Reynolds number, which indicates that heat transfer rate can be accelerated as Reynolds number rises. Lecordier et al. [14] pointed out that heating is able to strengthen the stability of the wake, and can suppress the vortex shedding in air while the opposite phenomenon is observed in water for forced convection. They found that Nusselt number increases with Re and approaches a constant when $Re > 20$. Chen et al. [15] applied the continuity of temperature and heat flux to address the thermal boundary condition at the porous-fluid interface, and pointed out that optimal heat transfer effect can be achieved at medium Darcy number and large Reynolds number without excessive frictional loss. Valipour and Ghadi [16] presented comprehensive simulations on forced convective flow around a porous circular cylinder with internal heat generation. They found that local and average Nusselt numbers increase with an increment in Reynolds and Darcy numbers, similar to the results obtained for other shape porous cylinders [17,18]. The maximum heat transfer rate occurs close to the front surface while the minimum value occurs at the rear side owing to the development of the thermal boundary layer.

Study on heat transfer from a bluff body under the influence of aiding and opposing buoyancy has also attracted much attention. For the aiding buoyancy case, Ahmad and Qureshi [19] analyzed the mixed convection heat transfer from a horizontal circular cylinder with a uniform heat flux in the range of $1 \leq Re \leq 60$. Both Nusselt number and drag coefficient increase with the buoyancy parameter. They also found that the cylinder with a uniform heat flux has higher Nusselt number than the one with constant wall temperature. The local and average heat transfer for steady air flow around a circular cylinder with a constant heat flux has been experimentally studied by Mohammed and Salman [20]. They revealed that Nusselt number increases with an increase in heat flux. Also, free convection was discovered to diminish heat transfer at low Re and intensify heat transfer at high Re. Srinivas et al. [21] numerically investigated the effect of aiding buoyancy on heat transfer from an isothermally heated cylinder immersed in steady power-law fluid. Buoyancy impact is found to be stronger in shear-thinning fluids and/or at low Re than that in shear-thickening fluids and/or at high Re. Chatterjee and Mondal [22] revealed that flow separation is suppressed gradually by thermal buoyancy, and completely disappears at a certain critical value of buoyancy parameter. Chatterjee and Sinha [23] found that flow becomes unsteady as the buoyancy parameter increases when rotating a circular cylinder, and vortex shedding occurs beyond some critical values of Richardson number. As for opposing buoyancy, Chang and Sa [24] reported that the shedding frequency is increased and the roll-up process is more activated as opposing buoyancy increases. Patnaik et al. [25] numerically demonstrated that opposing buoyancy could trigger vortex shedding at low Reynolds number of $20 \leq Re \leq 40$, and a wider wake due to greater entrainment from free stream is observed. Gandikota et al. [26] studied the effect of opposing buoyancy on flow and heat transfer from a circular cylinder. They found that the variation of average Nusselt number is