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Effects of centrifugal buoyancy on developing convective laminar flow in a square channel occupied with a high porosity fibrous medium

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ABSTRACT

The development of three-dimensional heat transfer and fluid flow in a square channel rotating in a parallel-mode has been investigated numerically. The duct is occupied by a foam material of high porosity ($\varepsilon \geqslant 0.9$) and subjected to a uniform wall heat flux. In regards to the influence of rotation, both the centrifugal buoyancy effect and Coriolis forces are considered in the current study. The generalised model is used to mathematically simulate the momentum equations employing the Boussinesq approximation for the density variation. Moreover, both the fluid and solid phases are considered to be in local thermal non-equilibrium. The governing equations are discretised according to the finite volume method employing the hybrid differencing scheme to calculate the fluxes across the faces of each control volume in the transverse plane. Computations are performed for a wide range of dimensionless parameters including the medium porosity ($0.9 \leqslant \varepsilon \leqslant 0.97$), rotation number ($0 \leqslant \mathrm{Ro} \leqslant 1.0$), Darcy–Rayleigh rotational number ($1.1 \times 10^3 \leqslant Ra^*_\Omega \leqslant 6.2 \times 10^5$), and solid to fluid-phase thermal conductivity ratio ($10^2 \leqslant \kappa \leqslant 10^3$), while the values of Reynolds and Prandtl numbers are maintained constant at Re = 2000 and Pr = 0.7, respectively. The results reveal that the rotation seems to have a dominant role in enhancing heat transfer at high levels of porosity and low conductivity ratios. However, this role is reduced gradually with decreasing the medium porosity or increasing thermal conductivity ratio, but does not completely vanish. Eventually, the worth of using high porosity fibrous media in enhancing the heat transported through rotating channels has been inspected. An overall enhancement parameter was compared for the current study with a previous work regarding turbulent flow in a rotating clear channel, where it has been confirmed that the current proposal is practically justified and efficient.

1. Introduction

Rotating machinery operating at extreme temperature conditions usually need to be cooled internally by involving cooling channels inside them. Flow passages parallel to the axis of rotation are involved in some cooling aspects such as the rotor windings of high-capacity electrical generators, which allow to the increased magnetic and electrical loadings safely. In non-isothermal flows, the effects of rotation including centrifugal buoyancy can influence the characteristics of coolant flow by creating a secondary flow that changes the longitudinal velocity contours in addition to the temperature profiles, and in turn, the heat transfer performance will be altered. The phenomena of fluid flow and heat transfer in stationary channels are considerably different from those in the rotating case due to the existence of Coriolis and centrifugal forces. This is why it is unlikely to apply their empirical correlations and theoretical solutions to the rotating ones Yang et al. [1]. According to its orientation, the rotation of channels can be classified into axial, parallel, radial or slant mode Soong [2].

The isothermal flow development in radially rotating channels was investigated by Jen et al. [3] and Fann and Yang [4], where the effect of centrifugal buoyancy was not considered. The influences of buoyancy induced by rotation on the convective fluid flow in radially rotating passages were studied later by Fann et al. [5], Fann and Yang [6], and Yan and Soong [7].

Regarding to the rotating channels in parallel-mode, Morris [8] presented an extensive review of the convective fluid flow in rotating ducts including reported results of analytical and experimental studies for fully developed and developing, laminar and turbulent fluid flow and heat transfer in circular or rectangular channels. Neti et al. [9] studied numerically the effect of centrifugal buoyancy on the developing laminar flow and heat transfer in a rectangular

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Nomenclature

a	side length of the channel
a_{sf}	solid-to-fluid interfacial specific surface area
c_p	specific heat of fluid phase
d_f	fiber diameter
d_p	pore diameter
Da	Darcy number, $Da = K/a^2$
D_h	hydraulic diameter of the channel
E	dimensionless eccentricity of the rotating channel $E = H/D_h$
F	inertial coefficient
h_{sf}	solid-to-fluid interfacial specific heat transfer coefficient
H	radial distance from the axis of rotation to the lower wall of the duct
H_{sf}	dimensionless solid-to-fluid interfacial specific heat transfer coefficient
K	permeability of the porous medium
k_f	thermal conductivity of fluid phase
k_s	thermal conductivity of solid phase
Nu	average Nusselt number
p	dimensional pressure
P	dimensionless reduced pressure
Pe	Peclet number $\mathrm{Pe} = \mathrm{Re}\ \mathrm{Pr}$
p_r	dimensional reduced pressure
Pr	Prandtl number, $Pr = \nu_f/\alpha_e$
Ra_Ω	rotational Rayleigh number, $Ra_\Omega = \Omega^2 H\ \beta\ \Delta T_c a^3/\nu_f\ \alpha$
Ra^*_Ω	rotational Darcy–Rayleigh number, $Ra^*_\Omega = Da\ Ra_\Omega$
Re	Reynolds number, $\mathrm{Re} = u_{in}\ a/\nu_f$
Re_d	Reynolds number based on the fluid velocity near the fiber, $Re_d = u\ d_f/\varepsilon\ \nu_f$
Re_Ω	rotational Reynolds number, $Re_\Omega = \Omega\ \boldsymbol{D_h^2}/\nu$
Ro	rotation number, $\mathrm{Ro} = \Omega\ D_h/u_{in}$
T_f	dimensional fluid-phase temperature
T_s	dimensional solid-phase temperature
u, v, w	dimensional velocity components
U, V, W	dimensionless velocity components
v	dimensional velocity vector
x	dimensional position vector
x, y, z	dimensional coordinates
X, Y, Z	dimensionless coordinates

Greek symbols

θ	the dimensionless temperature
α_e	the effective thermal diffusivity
ρ_f	fluid density
μ_f	dynamic viscosity
ν_f	kinematic viscosity
ε	porosity of the fibrous medium
κ	solid to fluid-phase thermal conductivity ratio
κ_e	solid to fluid-phase effective thermal conductivity ratio
Ω	angular velocity
β	coefficient of thermal expansion

Subscripts

0	reference point
b	bulk
e	effective
f	fluid phase
in	inlet
m	mean
s	solid phase
w	wall
w, avg	peripherally wall averaged
Ω	rotation

channel of 2/1 aspect ratio and rotating in parallel mode. However, the effects of buoyancy induced by rotation on the characteristics of fluid flow and heat transfer were not indicated in detail. A quite similar problem to that analysed by Neti et al. [9] was re-examined experimentally later by Levy et al. [10]. It was found that both pressure drop and heat transfer rate are enhanced noticeably with increasing the rotation rate. The development of secondary flow due to centrifugal buoyancy in channels rotating about parallel axis was examined numerically by Soong and Yan [11] for both iso-flux and isothermal conditions. It was noticed that rotational effects in the case of constant heat flux are more important than those in the isothermal case, where it is noticed that at the fully developed region secondary flow retains its vortices in the iso-flux channels unlike the isothermal ducts where they almost vanish. Recently, a numerical study of the developing turbulent flow and heat transfer in a square channel rotating in parallel mode was conducted by Sleiti and Kapat [12]. The problem was examined for high levels of both rotation and applied heat flux. This study reveals that increasing the rate of rotation reduces the heat transfer rate at the closest wall to the axis of rotation while enhances it at the remaining walls, but in general it increases the overall heat transfer rate.

Forced convective flow and flow induced by buoyancy effects in porous materials have been investigated widely for over the last decades and various aspects have been considered for different applications, where their state of art has been summarised extensively by Kaviany [13], and Nield and Bejan [14]. However, most of these studies have been limited to granular materials and packed beds due to their wide applications in natural and industrial porous media, where their porosity have a range of 0.3–0.6. Therefore, there are relatively few studies on convective flow phenomena in materials that have very high porosity ($\varepsilon \geqslant 0.9$) like metal foams.

In regards to combined fluid flow and heat transfer in rotating porous media, relevant studies have been motivated by the wide range of practical and fundamental applications in engineering and geophysics. Chemical processing, materials, and food processing industries, in addition to rotating machinery are just a few examples of its engineering applications cited by Vadasz [15]. A three-dimensional isothermal fluid flow in a rotating square channel occupied by a heterogeneous porous medium was studied analytically Vadasz [16] and numerically Havstad and Vadasz [17] using the Darcy formulation. The data has confirmed the ability of inducing a mainstream flow along the channel by means of the secondary circulation resulting from the locally varying permeability. The natural convection induced by the centrifugal acceleration in a narrow porous layer subjected to rotation was examined analytically by Vadasz [18], Vadasz [19], and Vadasz [20] for an axis of rotation attached to the porous layer, distant from the porous layer, and located within the porous layer, respectively. The results indicated that displacing the porous layer away from the axis of rotation has a destabilizing effect, while placing the rotation axis within the porous layer produces a stabilising influence in the part of the layer located to the left of the axis of rotation and conversely a destabilising effect to the right part of it. Recently, the mutual effect of the centrifugal buoyancy and Coriolis force on the natural convection within a rotating cubical cavity in the presence of a constant magnetic field is investigated numerically by Jena et al. [21]. The centrifugal buoyancy was found to have a