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Hydrodynamically and thermally developing flow in a rectangular channel filled with a high porosity fiber and rotating about a parallel axis☆

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ABSTRACT

Rotating machineries operating at extreme temperature conditions usually need to be cooled internally by involving cooling passages inside them. A potential way to improve heat dissipated by these channels is by filling them with high porosity metal foams $\varepsilon \geq 0.89$. This proposal is examined numerically by studying developing convective flow across a porous rectangular channel subjected to a uniform wall heat flux and rotating in a parallel mode. In regards to the influence of rotation, both centrifugal buoyancy and Coriolis forces are considered. The generalized model is used to mathematically simulate the momentum equations employing the Boussinesq approximation for the density variation. Moreover, thermal dispersion has been taken into account with considering that fluid and solid phases are in a local thermal non-equilibrium. Computations are performed for a wide range of dimensionless parameters including the aspect ratio, medium porosity, fiber size, rotation number, and solid- to fluid-phase thermal conductivity ratio, while the values of Reynolds and Prandtl numbers are maintained constant. The results reveal that both rotation and thermal dispersion have significant roles in enhancing heat transfer at high levels of porosity and low conductivity ratios. However, these roles are reduced gradually with decreasing the medium porosity or increasing thermal conductivity ratio, but do not completely vanish. In addition, overall performance is improved with either decreasing the aspect ratio for $A_r < 1$ or increasing it for $A_r > 1$. Eventually, the worth of using high porosity fibers in enhancing the heat transported through rotating channels has been inspected. An overall enhancement parameter was compared for the current study with a previous study 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 of the cooling aspects such as the rotor windings of high-capacity electrical generators, which allows for increased magnetic and electrical loadings. 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, rotation of channels can be classified into axial, parallel, radial, or slant mode (Soong [2]).

Regarding to convective fluid flow in channels rotating in parallel mode, Morris [3] presented an extensive review 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. Centrifugal buoyancy effect on developing convective laminar flow via a rectangular channel rotating in parallel mode was studied numerically by Neti et al. [4] and then experimentally by Levy et al. [5], where 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 a parallel axis was examined numerically by Soong and Yan [6] 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 secondary flow at the fully developed region retains its vortices in the iso-flux channels unlike the isothermal ducts where

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Nomenclature

a	Width of the channel
A_c	Channel cross-sectional area $A_c = a\,b$
A_r	Channel aspect ratio $A_r = b/a$
a_{sf}	Solid-to-fluid interfacial specific surface area
b	Height of the channel
c_p	Specific heat of fluid phase
d_f	Fiber diameter
d_p	Pore diameter
Da	Darcy number, $Da = K/{D_h}^2$
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	Thermal conductivity
Nu	Average Nusselt number
p	Dimensional pressure
P	Dimensionless reduced pressure
p_r	Dimensional reduced pressure
Pr	Prandtl Number, $Pr = \nu_f/\alpha_e$
Ra_Ω	Rotational Rayleigh number, $Ra_\Omega = \Omega^2 H\,\beta\,\Delta T_c\,a^3/\nu_f\,\alpha$
Re	Reynolds number, $Re = u_{in}\,a/\nu_f$
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, $Re_\Omega = \Omega\,D_h^2/\nu$
Ro	Rotation number, $Ro = \Omega\,D_h/u_{in}$
T	Dimensional temperature
u, v, w	Dimensional velocity components
U, V, W	Dimensionless velocity components
$\mathbf{v}$	Dimensional velocity vector
$\mathbf{x}$	Dimensional position vector
x, y, z	Dimensional coordinates
X, Y, Z	Dimensionless coordinates

Greek symbols

θ	Dimensionless temperature
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_d	Dispersive to fluid-phase effective thermal conductivity ratio
Ω	Angular velocity
β	Coefficient of thermal expansion

Subscripts

b	Bulk
d	Dispersive
e	Effective
f	Fluid phase
in	Inlet
s	Solid phase
w, avg	Peripherally wall averaged
Ω	Rotation

they almost vanish. Recently, a numerical study of developing turbulent flow and heat transfer in a square channel rotating in parallel mode was conducted by Sleiti and Kapat [7]. The problem was examined for high levels of both rotation and applied heat flux. This study reveals that the total heat transfer rate is, in general, enhanced with increasing the rotation rate although it is reduced at the wall closest to the axis of rotation.

Natural and forced convective flows 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 summarized extensively by Nield and Bejan [8]. 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 has a range of 0.3–0.6. Therefore, there are relatively few studies on convective flow phenomena in materials that have very high porosity ($\varepsilon \geq 0.89$) 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 [9]. A three-dimensional isothermal fluid flow in a rotating square channel occupied by a heterogeneous porous medium was studied analytically (Vadasz [10]) and numerically (Havstad and Vadasz [11]) using Darcy formulation. The data have confirmed the ability to induce a mainstream flow along the channel by means of the secondary circulation resulting from a locally varying permeability. Natural convection induced by centrifugal acceleration in a narrow porous layer subjected to rotation was examined analytically by Vadasz [12–14] for an axis of rotation attached to, distant from, 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 that enhances the centrifugal buoyancy. More recently, Alhusseny and Turan [15] presented a numerical study for Coriolis' effect on combined heat and mass transfer in a radially rotating porous channel. It was found that rotation has a negative impact on heat and mass transport, where this role is gradually reduced with decreasing the medium permeability but does not completely vanish.

High porosity metal foams are usually porous media with low density and novel structural and thermal properties (Tianjian [16]). They offer light weight, high rigidity and strength, and high surface area, which make them able to recycle energy efficiently. Therefore and due to their ability to meet the high rates of thermal dissipation required in electronic industry applications, they have received more attention recently. Also, their open-cell structure makes them less resistant to the fluids flowing through them, and hence, pressure drop across them is much less than it in the case of flow via packed beds or granular porous media. Forced convection in high porosity metal foams was studied analytically and experimentally by Hunt and Tien [17] with taking into account the effect of thermal dispersion on the heat transport performance, where it was found that dispersive transport becomes more significant with increasing the flow rate or the medium permeability. Metal foams are often classified as high porosity materials that consist of irregular shaped and tortuous flow passages. However, some aspects regarding to granular porous media and packed beds need to be adjusted for metal foams (Boomsma et al. [18]). Pressure drop and heat transfer through the fibrous medium are significantly affected by its geometrical characteristics such as fiber size, pore size, pore density, and cell shape. A model for the fiber to pore diameter ratio (d_f/d_p) was developed by Calmidi [19] as a function of the foam porosity. Furthermore, this experimental and analytical study proposed mathematical models for both permeability and inertial coefficient as functions of