



# Developing convective flow in a square channel partially filled with a high porosity metal foam and rotating in a parallel-mode



Ahmed Alhusseny<sup>a,b,\*</sup>, Ali Turan<sup>a</sup>, Adel Nasser<sup>a</sup>

<sup>a</sup> School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK

<sup>b</sup> Mechanical Engineering Department, College of Engineering, University of Kufa, Najaf, Iraq

## ARTICLE INFO

### Article history:

Received 7 April 2015

Received in revised form 6 May 2015

Accepted 25 June 2015

Available online 14 July 2015

### Keywords:

High porosity foam

Rotation

Channel

Thermal dispersion

Partial occupation

Interface

## 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 partially occupied by a foam material of high porosity  $\varepsilon \geq 0.89$  and subjected to a uniform wall heat flux. In regards to the influence of rotation, both the centrifugal buoyancy and Coriolis forces are considered in the current study. 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. The governing equations are discretized according to the finite volume method with employing a hybrid differencing scheme. Computations are performed for a wide range of parameters including the hollow ratio ( $0 \leq S \leq 1$ ), foam porosity ( $0.89 \leq \varepsilon \leq 0.97$ ), pore density ( $5\text{PPI} \leq \omega \leq 40\text{PPI}$ ), solid to fluid thermal conductivity ratio ( $250 \leq \kappa \leq 4000$ ), Reynolds number ( $250 \leq \text{Re} \leq 2000$ ), and rotation number ( $0 \leq \text{Ro} \leq 1$ ), while the values of characteristic temperature difference and Prandtl numbers are maintained constant at  $\Delta T_c = 1000^\circ\text{C}$  and  $\text{Pr} = 0.7$ , respectively. Results reveal that flow resistance and heat transport are augmented with either decreasing the hollow ratio and foam porosity or increasing Reynolds and rotation numbers, while two contradictory trends are found for the impact of increasing pore density on heat transfer; either enhancing or suppressing depending on the size of hollow zone. In addition, both rotation and thermal dispersion have dominant roles in enhancing heat transfer at the higher levels of porosity or the lower values of conductivity ratios. However, these roles are reduced gradually with decreasing the foam porosity or increasing thermal conductivity ratio, but do 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 is 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.

© 2015 Elsevier Ltd. All rights reserved.

## 1. Introduction

Rotating machinery operating at extreme temperature conditions usually need to be cooled internally by involving cooling channels inside them. Flow via passages parallel to the axis of rotation, or what is usually called “rotating in a parallel mode”, 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

\* Corresponding author at: School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK.

E-mail address: [Ahmed.Alhusseny@postgrad.manchester.ac.uk](mailto:Ahmed.Alhusseny@postgrad.manchester.ac.uk) (A. Alhusseny).

**Nomenclature**

$a$	side length of the channel	$\mathbf{x}$	dimensional position vector
$a_{sf}$	solid-to-fluid interfacial specific surface area	$x, y, z$	dimensional coordinates
$c_p$	specific heat of fluid phase	$X, Y, Z$	dimensionless coordinates
$d_f$	fiber diameter	<i>Greek symbols</i>	
$d_p$	pore diameter	$\theta$	dimensionless temperature
$Da$	Darcy number, $Da = K/D_h^2$	$\rho_f$	fluid density
$D_h$	hydraulic diameter of the channel	$\mu_f$	dynamic viscosity
$E$	dimensionless eccentricity of the rotating channel $E = H/D_h$	$\nu_f$	kinematic viscosity
$F$	inertial coefficient	$\varepsilon$	porosity of the fibrous medium
$h_{sf}$	solid-to-fluid interfacial specific heat transfer coefficient	$\kappa$	solid to fluid-phase thermal conductivity ratio
$H$	radial distance from the axis of rotation to the lower wall of the duct	$\kappa_d$	dispersive to fluid-phase effective thermal conductivity ratio
$H_{sf}$	dimensionless solid-to-fluid interfacial specific heat transfer coefficient	$\Omega$	angular velocity
$k$	thermal conductivity	$\beta$	coefficient of thermal expansion
$K$	permeability of the porous medium	$\omega$	pore density
$Nu$	Nusselt number	$\xi$	mass flow fraction, $\xi = m_p/(m_p + m_H)$
$p$	dimensional pressure	$\gamma$	distinguishing parameter between the hollow and porous region
$p_r$	dimensional reduced pressure	<i>Subscripts</i>	
$P$	dimensionless reduced pressure	$b$	bulk
$Pr$	Prandtl Number, $Pr = \nu_f/\alpha_e$	$d$	dispersive
$Ra_\Omega$	rotational Rayleigh number, $Ra_\Omega = \Omega^2 H \beta \Delta T_c a^3 / \nu_f \alpha$	$e$	effective
$Re$	Reynolds number, $Re = u_{in} a / \nu_f$	$f$	fluid phase
$Re_d$	Reynolds number based on the fluid velocity near the fiber, $Re_d = u_d / \nu_f$	$H$	hollow region
$Re_\Omega$	rotational Reynolds number, $Re_\Omega = \Omega D_h^2 / \nu$	$in$	inlet
$Ro$	rotation number, $Ro = \Omega D_h / u_{in}$	$int$	interface surface between the hollow and porous region
$s$	hollow region size	$P$	porous region
$S$	hollow ratio, $S = s/D_h$	$s$	solid phase
$T$	dimensional temperature	$w, avg$	peripherally wall averaged
$\Delta T_c$	dimensional characteristic temperature difference, $\Delta T_c = q_w a / k_{fe}$	$\Omega$	rotation
$u, v, w$	dimensional velocity components	<i>Superscripts</i>	
$U, V, W$	dimensionless velocity components	$n$	normal to the interface between the hollow and porous region
$\mathbf{v}$	dimensional velocity vector		

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 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 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.

Convective flows in porous materials have been investigated widely for over the last decades and various aspects were considered for different applications, where their state of art has been summarized extensively by Nield and Bejan [8]. However, most studies have been limited to granular materials and packed beds, which have a porosity 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.

High porosity metal foams are usually porous media with low density and novel structural and thermal properties Tianjian [9]. 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, 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 [10] with taking into account the effect of thermal dispersion on the heat transport performance. 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. [11]. 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 [12] 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 the fiber and pore diameters in addition to the porosity. Due to the significant difference existed between thermal conductivities of metal foams and fluid flowing across them, using the

Download English Version:

<https://daneshyari.com/en/article/7056503>

Download Persian Version:

<https://daneshyari.com/article/7056503>

[Daneshyari.com](https://daneshyari.com)