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Rotating metal foam structures for performance enhancement of double-pipe heat exchangers

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ABSTRACT

In order to enhance the amount of heat transported in a double-pipe heat exchanger, a compound enhancement is proposed incorporating both active and passive methods. The first one is through introducing secondary flows in the vicinity of the conducting surface using metal foam guiding vanes, which are fixed obliquely and rotating coaxially to trap fluid particles while rotation and then force them to flow over the conducting surface. The other is via covering the conducting surface between the two pipes with a metal foam layer to improve the heat conductance across it. This proposal is examined numerically by studying the three-dimensional, steady, incompressible, and laminar convective fluid flow in a counter-flow double-pipe heat exchanger partially filled with high porosity metal foam and rotating coaxially. With regards to the influence of rotation, both the centrifugal buoyancy and Coriolis forces are considered in the current study. The generalised model is used to mathematically simulate the momentum equations in the porous regions. Moreover, thermal dispersion has been taken into account while considering that fluid and solid phases are in a local thermal non-equilibrium. Computations are performed for a wide range of design parameters influencing the performance achieved such as the operating conditions, the configuration of the guiding vanes utilised, and the geometrical and thermal characteristics of the metal foam utilised. The results are presented by means of the heat exchanger effectiveness, pressure drop, and the overall system performance. The current proposed design has effectively proved its potential to enhance the heat transported considerably in view of the significant savings in the pumping power required compared to the heat exchangers fully filled with metal foams. Furthermore, the data obtained reveal an obvious impact of the design parameters inspected on both the heat exchanged and the pressure loss; and hence, the overall performance obtained. Although the heat exchanger effectiveness can be improved considerably by manipulating the design factors, care must be taken to avoid unnecessary expenses resulted from potential increases in pressure drop.

1. Introduction

Improving the performance of power generation plants while minimising the environmental damage caused by the excessive use of fossil fuels has become a crucial concern recently. To achieve a high thermal efficiency in power generation systems, heat recirculation is applied between the cold intake and hot exhausts to recover a part of its thermal energy instead of releasing it directly to the environment (Alhusseny and Turan [1]). Heat recirculation is usually accomplished by means of two options. Either a recuperative or regenerative heat exchanger is used, depending respectively on whether the heat exchange takes place directly via a thermally conductive surface separating the two streams or through an intermediate storage medium exposed to them alternately (Hewitt et al. [2]).

Enhancing the heat transported in recuperative heat exchangers has acquired increasing attention due to their crucial role in many practical applications found in industry, power plants, and space exploration, as well as many others. Heat transfer enhancement techniques can be classified into active, in which an external power is required; passive, which does not require an external power input; or compound, where two or more of the aforementioned techniques may be employed simultaneously to achieve a larger enhancement than what can be produced using the individual techniques separately (Bergles [3]).

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Nomenclature

a_{sf} solid-to-fluid interfacial specific surface area
c_p specific heat of fluid phase
C_c cold stream heat-capacity rate $C_c = \dot{m}_c\, c_{p,c}$
C_h cold stream heat-capacity rate $C_h = \dot{m}_h\, c_{p,h}$
C_{min} the smaller of the hot (C_h) and the cold (C_c) fluid-phase heat-capacity rates
d_f fibre diameter
d_p pore diameter
Da Darcy number, $Da = K/D_h^2$
D_h hydraulic diameter of the channel
D_{i1}, D_{i2} internal and external diameters of the inner annular tube
D_{o1}, D_{o2} internal and external diameters of the outer annular tube
F inertial coefficient
h_{sf} solid-to-fluid interfacial specific heat transfer coefficient
H_{sf} dimensionless solid-to-fluid interfacial specific heat transfer coefficient
k thermal conductivity
K permeability of the porous medium
$\dot{m}$ fluid mass flow rate
OSP overall system performance, $OSP = 0.5(Q_c + Q_h)/PP$
p dimensional pressure
p_r dimensional reduced pressure
PP pumping power
Pr Prandtl Number, $Pr = \nu_f/\alpha_e$
Q_c heat rate gained by the colder stream, $Q_c = C_c\,(T_{c,2} - T_{c,1})$
Q_h heat rate given by the hotter stream, $Q_h = C_h\,(T_{h,1} - T_{h,2})$
Q_{max} optimum heat transported from hot to cold stream, $Q_{max} = C_{min}\,(T_{h,1} - T_{c,1})$
R_Ω radial distance to the centreline of the double-pipe heat exchanger
Ra_Ω rotational Rayleigh number, $Ra_\Omega = \Omega^2 R_\Omega\, \beta\, \Delta T_c\, D_h^3/\nu_f\, \alpha_e$
Re Reynolds number, $Re = u_{in}\, a/\nu_f$
Re_d Reynolds number based on the fluid velocity near the fibre, $Re_d = u\, d_f/\phi\, \nu_f$
Ro rotation number, $Ro = \Omega\, D_h/u_{in}$
S hollow ratio
T dimensional temperature
ΔT_c dimensional characteristic temperature difference, $\Delta T_c = T_{h1} - T_{c1}$
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
ϕ metal foam porosity
ε heat exchanger effectiveness
κ solid to fluid-phase thermal conductivity ratio
Ω angular velocity
β coefficient of thermal expansion
ω pore density
γ distinguishing parameter between the hollow and porous region

Subscripts
c, h cold, hot stream
d dispersive
e effective
f, s fluid, solid phase
H hollow region
in inlet
int interface surface between the hollow and porous region
1, 2 inlet to/out from the heat exchange section
Ω rotation

Superscripts
n Normal to the interface between the hollow and porous region

One of the simplest arrangements of recuperators available in industry and practical applications is the double-pipe heat exchanger. It is widely utilised in practical applications, and hence, has been the focus of plenty of studies recently. In the light of economic considerations, many efforts have been made to construct cheaper and smaller but more effective heat exchangers.

Among these investigations, some have been dedicated to renew the boundary layer developing over the heat exchange surface, and hence, enhance the amount of heat transported. For example, it was found that placing propellers inside the inner tube leads to enhance the heat exchanged by up to 250% and a further enhancement can be achieved through increasing Reynolds number and/or the number of propellers used [4]. Another passive way is to place a strip turbulator twisted in certain angles to touch the inside wall of the inner pipe [5], where heat transfer rate can be improved by 100% or more through increasing the pitch length. Also, it was found that covering the conducting surface with a porous layer [6–8] or attaching porous structures to this surface [9,10] can considerably improve the effectiveness achieved.

Convective flows in porous materials have been widely investigated for over the last decades and various aspects were considered for different applications, where their state of art has been summarised extensively by Nield and Bejan [11] as well as Ingham and Pop [12]. However, most studies have been limited to media having a porosity range of **0.3–0.6** and there are relatively few studies on convective flow phenomena in materials with very high porosity like open-cell metal foams.

High porosity metal foams are usually porous media with low density and novel structural and thermal properties (Tianjian [13]). They offer light weight, high rigidity and strength, and high surface area, which make them able to recycle heat efficiently. 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. Therefore and due to their ability to meet the highly thermal demands with no excessive loss in pressure, open-cell metal foams have been utilised in heat exchangers [14,15] besides internal cooling of both turbine blades [16] and the rotor windings of high-capacity electrical generators [17–19]. Thus, it is not surprising to use them recently in double-pipe heat exchangers [20,21], where a substantial enhancement in the heat transfer performance has been acquired.

With regards to combined fluid flow and heat transfer in rotating porous media, relevant studies have been motivated by its