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Numerical configuration design and investigation of heat transfer enhancement in pipes filled with gradient porous materials

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ABSTRACT

A novel design of a GPM-filled pipe structure was proposed to improve the heat transfer and reduce pressure drop of fluid flowing through the pipes filled with gradient porous materials. The pore-size gradient and porosity gradient were studied for both partially and fully filled configurations. The effects of GPMs on the fluid flow and heat transfer in the pipes were investigated and compared with the those under the conditions of non-porous materials and homogeneous porous materials (HPMs) serving as controls. Some typical GPM configurations were studied with $Rp = 0.6$ and $Rp = 1.0$, showing an enhanced heat transfer and a relatively low friction factor can be reached in comparison with the controls. An attempt was made to illustrate the mechanism of heat transfer enhancement with the field synergy theory. Velocity-based average pore-size was introduced to explain the reduction in friction factors in GPM configurations. A tradeoff analysis between pressure drop and heat transfer enhancement was made based on performance evaluation criteria (PEC).

1. Introduction

The enhancement of heat transfer has been extensively studied because it plays a critical role in the design of many devices applied in the power and energy fields [1–8]. Among many techniques available, porous material filling has become one of the most effective methods to enhance the heat transfer in many applications, including but being not limited to heat exchangers [1,2], combustion equipment [3], microchannel heat sinks [4], solar thermochemical reactors [5] and heat pipes [6]. Using porous materials to enhance the heat transfer in energy systems has many advantages. For example, the Nusselt number in porous material-filled pipes with laminar flows is approximately 50% higher than that in channels without porous materials. The heat transfer coefficient is higher for systems filled with porous materials than that in systems without porous materials [7].

Current studies on the heat transfer enhancement with porous materials almost exclusively focus on the use of homogenous porous materials with uniform distribution of pore size and porosity. Early work reported by Mohamad [7] and Pavel and Mohamad [8] showed that the enhancement of heat transfer can be achieved by increasing the pressure drop in a pipe partially filled with porous materials. Later investigations covered the effects of porous structure and processing parameters, such as Darcy numbers [9], thermal conductivity ratio [10], configuration of porous structure [11], and geometry of channel [12–14]. Heat transfer efficiency and pressure drop are the two most important properties that need to be addressed. However, based on the current studies, it is inevitable to increase the flowing resistance while improving the heat transfer. Although an enhanced heat transfer with a reduced pressure drop are desired, it is usually difficult to improve both aspects simultaneously using HPM.

In contrast with HPM that possesses homogeneous porous structure, GPM is one class of functionally graded materials with a gradual change of either porosity or pore size along a defined axis [15]. The gradient porous structure has unique properties, especially the ability to integrate different functions, even contradictory ones, and achieve an optimized configuration [16]. A number of GPMs can be found in nature [16,17]. Currently, a number of techniques are available to produce GPMs, such as powder metallurgy [18], melt processing [19] and graded polymer processing [20–23]. GPMs have been used for different applications,

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Nomenclature

c_p	specific heat, J/(kg K)
dp	pore size of the porous material, m
D	pipe diameter, m
Da	Darcy number, K/r_o^2
F	inertia coefficient
h_m	average heat-transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
k_e	effective thermal conductivity, W/(m K)
k_f	thermal conductivity of the fluid, W/(m K)
k_s	thermal conductivity of the porous solid, W/(m K)
K	permeability of the porous medium, m^2
L	pipe length, m
Nu_m	average Nusselt number
p	actual pressure, Pa
P	dimensionless pressure
Pr	Prandtl number
r	radial coordinate, m
r_0	pipe radius, m
r_p	radius of the porous material, m
R	dimensionless radial coordinate
Re	Reynolds number
Rp	dimensionless radius of the porous material
T	temperature, K
T_{in}	inlet temperature, K
u	axial velocity component, m/s
u_{in}	inlet velocity, m/s
$\|u\|$	velocity magnitude
$\|U\|$	dimensionless velocity magnitude
v	velocity component in the r-direction, m/s
z	axial coordinate, m

Greek symbols

μ	viscosity, kg s/m
ρ	Density, kg/m^3
ε	porosity
θ	dimensionless temperature
φ	field synergy angle

Subscripts

f	fluid
s	solid

including thermal barrier coatings, scaffolds for tissue engineering, medical implants and separation [15–17,24]. As the structure of GPM can easily be tailored by varying the gradients of pore size or porosity, GPM has shown a high potential for adjusting the thermal and viscous profiles of the fluids flowing through its porous architecture [15–20]. Therefore, it is expected that a balance between heat transfer efficiency and pressure drop can be obtained in the GPM-filled pipes when a proper configuration is used. However, such studies are still missing in the literature [7–10].

To address these emerging issues mentioned above, a novel configuration of pipes filled with GPM was proposed in this work. The effects of GPMs on the enhancement of thermal and fluid flow performances were studied. The numerical analysis was performed using a commercial Computational Fluid Dynamics (CFD) software (Fluent, ANSYS 14.5) [25]. The simulation was run under different porosity gradients and pore-size gradients in both GPM- and HPM-filled configurations. Profiles of heat transfer and flowing resistance were sequentially analyzed and discussed. An attempt to explain the mechanism of heat transfer enhancement and pressure drop reduction was then made using a synergy field theory with velocity-based average pore size (dp). Finally, an optimization of the GPM configuration was obtained based on PEC.

2. Model descriptions

2.1. Physical model

A 2-D model with an axisymmetric configuration is illustrated in Fig. 1. The fluid enters a GPM-filled pipe with a uniform temperature T_{in} and a uniform velocity u_{in}. The wall is set to have a constant temperature T_w which is higher than the initial temperature of the fluid.

Air is used as the model fluid in this study which is assumed to be Newtonian with a pressure-dependent density. AISI304 serves as the porous material in this model. Details on this material can be found in the reference [26]. GPM is assumed to be completely saturated by the fluid [7–10]. The thermo-physical properties of the fluid and solid phases can be found in Table 1. In this work, four different GPM-filled pipe configurations are considered:

(1) The GPM has a porosity (ε) gradient along the axial direction of the pipe.
(2) The GPM has a porosity (ε) gradient along the radial direction of the pipe.
(3) The GPM has a pore-size (dp) gradient along the axial direction of the pipe.
(4) The GPM has a pore-size (dp) gradient along the radial direction of the pipe.

2.2. Governing equations

In the modeling of heat transfer, local thermal equilibrium (LTE) is usually assumed to exist between the solid and fluid phases, especially when the volumetric heat transfer coefficient is very high and no heat is released in either the solid phase or the fluid phase [27]. Mohammad [7] and Pavel and Mohamad [8] assumed the LTE condition to investigate the effect of porous materials on heat transfer in their study. Alkam et al. [28] and Maerefat et al. [27] also simulated the forced convection in a channel/pipe filled with porous material with the assumption of LTE. Therefore, LTE is assumed in our work. Moreover, the Forchheimer–Brinkman Darcy model is adopted assuming laminar, boundary layer flow with no internal heat generation and neglecting viscous dissipation [7,8]. Then the mass, momentum and energy conservation equations can be written as follows:

Mass conservation:

$$\frac{\partial}{\partial z}(\rho u) + \frac{1}{r}\frac{\partial}{\partial r}(r\,\rho v) = 0, \tag{1}$$

Axial-direction momentum conservation:

$$\frac{\partial}{\partial z}(\rho u u) + \frac{1}{r}\frac{\partial}{\partial r}(r\,\rho v u) = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial z}\left(u_e\frac{\partial u}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r u_e\frac{\partial u}{\partial r}\right) - f\frac{\mu u}{K} - f\frac{\rho F}{\sqrt{K}}|u|u, \tag{2}$$