Applied Thermal Engineering 145 (2018) 735–742

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Heat transfer performance evaluation based on local thermal non-equilibrium for air forced convection in channels filled with metal foam and spherical particles

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HIGHLIGHTS

- Local thermal equilibrium model seriously overestimates heat transfer in porous media.
- Neither inertial nor thermal dispersion is negligible under high pumping power.
- Metal foam with lower porosity results in higher performance under low pumping power.
- Packed bed with larger particles results in higher performance under high pumping power.

ARTICLE INFO

Keywords:
Forced convection
Metal foam
Packed bed
Heat transfer performance

ABSTRACT

A local thermal non-equilibrium heat transfer analysis was conducted for air forced convection in channels filled with metal foam and particles. A general analytical expression was obtained for evaluating Nusselt numbers for the hydro-dynamically and thermal fully developed channel flows subject to constant heat flux, which can be used to investigate heat transfer performances of various porous media under equal pumping power. Such performance evaluations were made for aluminum metal foams of the porosity ranging from 0.85 to 0.95 and the pore diameter to channel half height ratio ranging from 0.01 to 0.20, and also for various packed aluminum particles of the diameter to channel half height ranging from 0.01 to 0.20. It has been found that the conventional local thermal equilibrium model leads to substantial overestimation of Nusselt number in the range of moderate pumping power, especially when the metal foam with large pore diameter is used to fill the channel. The analysis also revealed that in the moderate range of pumping power, the metal foam of comparatively low porosity performs better, while, in the high range of pumping power, the packed bed with large particle diameter gives higher heat transfer performance due to enhanced thermal dispersion.

1. Introduction

Heat transfer in porous media has been extensively investigated both theoretically and experimentally for some years because of its possible heat transfer augmentation due to substantially high specific surface area within a porous matrix [1,2]. The high specific surface area leads to interstitial convective heat transfer between the solid structure and the fluid passing through the porous matrix core. For the interstitial heat transfer to be active, heat must be spread from the heated end walls throughout to the porous matrix in the channel core. Thus, the solid structure of sufficiently high thermal conductivity should be constructed in such a way that heat conduction takes place within the solid structure with an acceptable level of fin efficiency.

In this respect, porous media having consolidated structures possess an advantage over unconsolidated porous media [3]. Metal foam is a typical consolidated porous medium of high solid thermal conductivity. In reality, however, the solidity of the metal foam (typically 5% to 25%) cannot be made so high due to its manufacturing constraints that the

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https://doi.org/10.1016/j.applthermaleng.2018.09.097
Received 24 July 2018; Received in revised form 4 September 2018; Accepted 22 September 2018
Available online 24 September 2018
1359-4311/

Nomenclature

b	inertial coefficient (1/m)
c_{pf}	specific heat of fluid at constant pressure (J/kg K)
Da	Darcy number (–)
d_m	pore diameter of metal foam (m)
d_p	particle diameter of packed sphere (m)
h	heat transfer coefficient (W/m^2 K)
H	half channel height (m)
h_v	interstitial volumetric heat transfer coefficient (W/m^3 K)
k	thermal conductivity (W/m K)
k_{dis}	dispersion thermal conductivity $k_{dis} = \zeta \rho_f c_{pf} l u$ (W/m K)
k_{stag}	stagnant thermal conductivity (W/m K)
K	permeability (m^2)
l	reference scale for thermal dispersion (m)
Nu_H	Nusselt number $Nu_H = \frac{hH}{k_f}$ (–)
Nu_v	dimensionless interstitial volumetric heat transfer coefficient $Nu_v \equiv \dfrac{h_v H^2}{k_f}$ (–)
p	pressure (Pa)
P	dimensionless pressure drop per unit length $P \equiv \left(\dfrac{\rho_f{}^2 H^4}{\mu_f{}^3}\right)\left(-\dfrac{dp}{dx}u\right)$ (–)
Pr	Prandtl number (–)
q_w	wall heat flux (W/m^2)
Re_H	Reynolds number, dimensionless velocity $Re_H = uH/\nu_f$ (–)
T	temperature (K)
T^*	dimensionless temperature $T^* = (T - T_w)k_f/Hq_w$ (–)
u	Darcian velocity (apparent velocity) in x direction (m/s)
x	coordinate in the flow direction (m)
y	coordinate normal to the channel wall with its origin on the center (m)
y^*	dimensionless vertical coordinate $y^* = \frac{y}{H}$ (–)

Greek letters

ε	porosity (–)
ε^*	effective porosity (–)
ζ	empirical coefficient for thermal dispersion conductivity (–)
μ	viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ξ	dimensionless parameter associated with interstitial heat transfer coefficient (–)
ρ	density (kg/m^3)

Subscripts

B	bulk mean
f	fluid phase
s	solid phase
w	wall

heat conduction from the heated end walls to cold core region is rather limited despite of its high thermal conductivity of the metal phase [4]. The unconsolidated packed bed filled with metal particles, on the other hand, possess comparatively high solidity (more than 60%) and solid phase conductivity, but, the thermal resistance among the packed spherical particles is comparatively high such that its effective thermal conductivity is limited to a low level for even for closely packed particles. Thus, both packed beds and metal foams have certain drawbacks in views of effective interstitial heat transfer. A rational heat transfer performance evaluation is needed to judge which porous medium is more effective for each particular case of heat transfer application using such porous media.

The pressure drops in a channel filled with a porous medium depend on various geometrical factors such as porosity, pore scale and particle diameter. The pressure drop in a metal foam is said to be much less than that in a packed bed. The pressure drop in a metal foam of high porosity with small pore scale, however, can be much higher than that in a packed bed of comparatively large particle diameter, under equal pumping power. The pumping power (i.e. the product of the pressure drop and volume flow rate) available in a specific application is usually limited to a certain level. Hence, the heat transfer performance evaluation under the constraint of equal pumping power, namely, the volume goodness factor evaluation (i.e. evaluation on the basis of heat transfer coefficient under equal pumping power), is preferred in most practical heat transfer applications.

In this study, a general analytical procedure for heat transfer performance evaluation which allows local thermal non-equilibrium will be presented, since the local thermal equilibrium between the solid and fluid often fails in practical heat transfer applications especially when associated with air as a working fluid. Furthermore, both inertial and thermal dispersions, which are often neglected in the cases of air-metal combination, will be fully taken into consideration. It will be shown that neither of inertial and thermal dispersion is negligibly small under the range of comparatively high pumping power.

There are some elaborate mathematical models available, including those for heat conduction in porous media [5], two-phase flow in porous media [6], dual porosity continua [7], bidisperse porous media [8], nanofluid saturated porous media [9], functionally graded porous media [10] and volumetric solar receiver with double-layer ceramic foam [11]. However, no general theoretical procedure has been proposed so far for local thermal non-equilibrium heat transfer performance evaluation on the basis of equal pumping power, which makes it possible to compare the heat transfer performances of the channels filled with different porous matrices including both consolidated and unconsolidated porous media. In order to establish such a general evaluation procedure, we shall basically follow the analytical procedure based on the two-energy equation model proposed by Zhang et al. [12] for nanofluid saturated porous media. Forced convective flow in a channel filled with a porous medium, with given permeability, inertial coefficient, interstitial heat transfer and thermal dispersion coefficients, is considered to derive a general expression for the Nusselt number valid for all porous media. Then, the values of the Nusselt number obtained under equal pumping power for various channels filled with metal foams and closely packed particles will be compared with one another, so as to evaluate their performances on the basis of equal pumping power.

2. Governing equations

A substantial number of theoretical investigations based on the volume averaging theory [13–15] were carried out to elucidate heat transfer characteristics associated with convection in porous media. Thermal dispersion resulting from fluid mixing due to complex porous structure has been investigated by a number of researches including Cheng and Zhu [16] and Yang and Nakayama [17]. Local thermal non-equilibrium models (i.e. two energy equation models) were introduced by Quintard and Whitaker [14], Nakayama et al. [18] and many others. Direct numerical simulations for determination of thermal dispersion have been first proposed by Kuwahara et al. [19] and Kuwahara and Nakayama [20] while a similar numerical procedure was adopted to determine the interstitial heat transfer coefficient by Kuwahara et al. [21] for unconsolidated porous media and Nakayama et al. [3] for consolidated porous media. The effect of tortuosity on the effective thermal conductivity of porous medium was elegantly taken into