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Analytical interpretation of the local thermal non-equilibrium condition of porous media imbedded in tube heat exchangers

Maziar Dehghan *, Milad Tajik Jamal-Abad, Saman Rashidi

Mechanical Engineering Department, Semnan University, Semnan, Iran

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A B S T R A C T

Local thermal non-equilibrium (LTNE) effects in the developed region of the forced convection in a circular tube filled with saturated porous medium are analytically studied at the constant wall-temperature boundary condition, as well as at the iso-flux boundary condition. The flow in the pipe is described by the Brinkman-Forchheimer-extended Darcy equation. A two-equation model is used for the energy balance. Profiles describing the velocity field obtained by perturbation techniques are used to find the temperature distributions using the successive approximation method. Moreover, the velocity and temperature fields are simulated numerically to validate the results of the analytical part. A fundamental relation and a new dimensionless number, ΔNE, for the temperature difference between the fluid and solid phases (LTNE intensity) are established based on a perturbation analysis. It is found that the LTNE intensity (ΔNE) is proportional to the product of the normalized velocity and the dimensionless temperature at LTE condition and depends on the conductivity ratio, Darcy number, and the porosity of the medium. Finally, the proposed relation for the LTNE intensity is simple and fundamental for estimation of the importance of LTNE condition.

1. Introduction

Flow of fluids in porous media not only presents a theoretically challenging problem but also has a wide range of scientific, technological and engineering applications like packed bed chemical reactors and geothermal energy reservoirs. There are several industrial applications where high heat flux or high boundary temperature compared to the fluid temperature, and chemical reactions lead to a significant degree of local thermal non-equilibrium condition. Theoretical consideration of fluid flow in porous media has received great attention in recent years, and the interest is motivated by its engineering applications. The fluid flow and heat transfer in porous saturated channels with various cross sections have important applications in many fields of engineering such as filtration, purification processes, underground water resources, geological studies, petroleum industries, solar collectors, packed beds storing the solar heat, and solar rooms of green houses. Consequently, thermal and flow characteristics inside tube filled with porous media was investigated by several researcher in recent years [1–5]. Porous medium insertion is a way to increase the heat transfer ability of the thermal systems. Today, other ways of thermal enhancement together with the use of porous media could be pioneering in the thermal performance optimizations [6–9].

Kuznetsov [10] proposed a relation for the intensity of the local thermal non-equilibrium for flow between parallel-plates at constant heat flux condition. It was the first time that the LTNE phenomenon was treated analytically based on the Brinkman-Forchheimer-extended Darcy model. Heat transfer performance for forced convection in a heated tube with a porous medium core and a tube with a wall covered with a porous medium layer were investigated by Yanga et al. [11]. Both local thermal and non-thermal equilibrium analyses were carried out in their work and results showed that the local thermal non-equilibrium analysis is essential for the case of forced convection in a tube with a heated wall surface covered with a porous medium layer, whilst the local thermal equilibrium analysis suffices to capture transport phenomena for the case of forced convection in a tube with a porous medium core. Haji-Sheikh et al. [12] studied determination of the heat transfer to a fluid passing through a porous passage with impermeable walls. They showed that the Green's function solution can produce accurate information related to heat transfer to fluids passing through ducts. The thermal performance of a tubeless conventional collector which is improved by inserting porous substrates at the inner side of the collector absorber plate

* Corresponding author. Address: PO 35196-45399, Semnan, Iran. Tel.: +98 911 3120673; fax: +98 231 3354122.

E-mail addresses: m-dehghan@aut.ac.ir, dehghan.maziar@gmail.com (M. Dehghan), miladtajik6@gmail.com (M.T. Jamal-Abad), samanrashidi3983@gmail.com (S. Rashidi).

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Nomenclature

a_{sf}	specific surface area (m^{-1})
c_p	specific heat at constant pressure ($J kg^{-1} K^{-1}$)
C_F	inertial constant
d_p	particle diameter (m)
Da	Darcy number, K/R^2
F	Forchheimer number
G	negative of the applied pressure gradient in the flow direction ($Pa\ m^{-1}$)
h_{sf}	fluid-solid heat transfer coefficient ($Wm^{-2} K^{-1}$)
K	permeability of the medium (m^2)
k	conductivity ratio
k_f	conductivity of fluid phase ($Wm^{-1} K^{-1}$)
$k_{f,eff}$	effective conductivity of fluid phase ($Wm^{-1} K^{-1}$)
k_m	effective conductivity of the medium ($k_{f,eff} + k_{s,eff}$) ($Wm^{-1} K^{-1}$)
k_s	conductivity of solid phase ($Wm^{-1} K^{-1}$)
$k_{s,eff}$	effective conductivity of solid phase ($Wm^{-1} K^{-1}$)
M	viscosity ratio
n	number of iterations
Nu	Nusselt number
O	order of magnitude
Pe	Peclet number
Pr	Prandtl number
q''_w	heat flux at the wall (Wm^{-2})
R	tube radius (m)
s	porous medium shape parameter
T	temperature (K)
T_m	bulk mean temperature (K)
T_w	wall temperature (K)
u	dimensionless velocity
u^*	velocity (ms^{-1})
$\widehat{u}$	normalized velocity
U^*	mean velocity (ms^{-1})
x, r	dimensionless coordinates
x^*, r^*	dimensional coordinates (m)

Greek letters

ΔNE	dimensionless number representing the intensity of LTNE condition
ε	small parameter ($1/h_{sf}\, a_{sf}$) ($W^{-1} m^3 K$)
θ	dimensionless temperature
μ	fluid viscosity ($Kg\ m^{-1} s^{-1}$)
μ_{eff}	effective viscosity in the Brinkman term ($Kg\ m^{-1} s^{-1}$)
ρ	fluid density ($kg\ m^{-3}$)
ϕ	porosity of the medium

Subscripts

i	index
f	fluid phase
s	solid phase

was considered numerically by Al-Nimr and Alkam [13]. They also, introduced a novel method by emplacing porous substrates at both sides of the inner tube wall in order to improve the thermal performance of a conventional concentric tube heat exchanger [14]. Mahmoudi and Karimi [15] investigated numerically heat transfer in a pipe partially filled with a porous medium under the LTNE condition. Effects of the Darcy number, the Forchheimer number as well as the porous medium thickness on the flow and heat transfer were studied in their work. Hooman and Ranjbar-kani [16] studied fully developed laminar forced convection inside a circular tube filled by saturated porous medium with uniform heat flux at the wall based on the Brinkman momentum equation. They applied the WKB and matched asymptotic expansion method for small and large values of the Darcy number, respectively. Hashemi et al. [17] proposed analytical solution for flow and heat transfer through a micro-annulus filled with porous media at velocity-slip and temperature-jump conditions. Rassoulinejad-Mousavi and Abbasbandy [18] solved the momentum and energy equations of the fluid flow in saturated porous media imbedded in a tube based on the spectral homotopy analysis method. They assumed a constant heat flux thermal boundary condition at the tube wall and provided dimensionless velocity and temperature graphs in some cases. Dehghan et al. [19] investigated the LTNE condition in the fluid saturated porous medium bounded by iso-thermal parallel-plates. They used the perturbation method to solve the momentum and energy equations. Also, they introduced a new dimensionless number to investigate the intensity of the LTNE condition in the channel flows. The simultaneous effect of LTNE, vertical heterogeneity of permeability, and non-uniform basic temperature gradient on the criterion for the onset of Darcy–Benard convection was studied numerically using the Galerkin method by Shivakumara et al. [20]. Straughan [21] proposed a novel system of partial differential equations involving Darcy's law, a parabolic fluid temperature equation and effectively a hyperbolic solid skeleton temperature equation. This system leads to novel physics, and oscillatory convection is found, whereas for the standard LTNE Darcy model, this does not exist. To see more about LTNE phenomena, one can refer to Ref. [22] which is devoted to the LTNE introduction.

In this study, the local thermal nonequilibrium condition in fully developed laminar flows inside circular tubes filled with saturated porous media at the constant wall-temperature boundary condition has been investigated based on a perturbation analysis. Also, an analysis for the case of iso-flux boundary condition has been presented in the appendix of the article. The Brinkman-Forchheimer-extended Darcy momentum equation has been applied and has been solved by the straight-forward and matched asymptotic expansion perturbation methods. The energy equation has been solved by the successive approximation method. To show the analytical results' accuracy, a numerical simulation of the momentum and energy equations has been done. Expressions for the dimensionless temperature and the Nusselt number at the situation of the constant wall temperature have been proposed. Also, a fundamental relation for the temperature difference between the

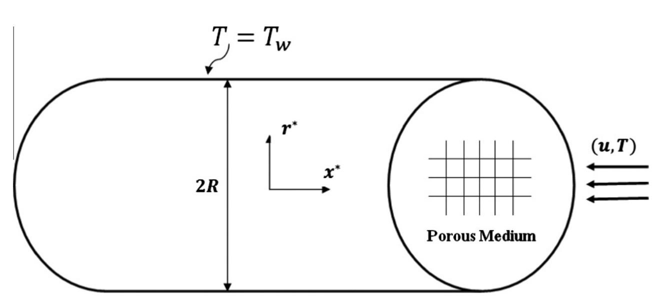

Fig. 1. Schematic diagram of the porous saturated tube.