Validation of Local Thermal Equilibrium (LTE) in Porous Media for Variation in Flow Rate and Permeability: Transient Analysis

Gudekota Rudresh, Surendra Singh Rathore and
Balkrishna Mehta

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Gudekota Rudresh, Surendra Singh Rathore and **Balkrishna Mehta**

Department of Mechanical Engineering, Indian Institute of Technology Bhilai
Raipur - 492015 (Chhattisgarh India)

Presenting authors' email: surendrar@iitbhilai.ac.in
Other Author's Email(s): krishnab@iitbhilai.ac.in

Abstract

The problem of local thermal equilibrium (LTE) between solid and fluid phases in a porous medium is dealt in the present transient numerical study, and, the validity of the LTE is performed for Reynolds no. ($10 < Re < 1000$) and Darcy no. ($10^{-6} < Da < 10^{0}$). Observed result shows that, for $100 < Re < 1000$, the LTE is valid for all ranges of Da, however, for $10 < Re < 100$, the LTE deviates towards non-equilibrium, and the deviation tend to decrease for the lower Da. Time plays a vital role over both the Re and Da.

Keywords: Mini-channel, Porous media, Darcy-Forchheimer-Brinkman equation, Local Thermal Equilibrium (LTE).

1. Introduction

The cooling of electronic devices with high heat flux dissipation at a mini scale opened the doors to adopt passive cooling devices like heat pipes (Moosavi et al. [1]). Porous media are an essential part of the evaporator section in the heat pipes, through which heat transfer takes place. The mathematical modeling of heat transfer process in a porous medium critically depend on the extent of thermal equilibrium between the solid and fluid phases (Vafai and Sozen [2]). Therefore, in the present work, a transient study is performed for flow rate (Reynolds no., $Re = \rho U H/\mu$) and the porous media characteristics (Darcy no., $Da = K/H^2$) to identify the regimes for the validity of the LTE, or else deviation from it.

2. General Specifications

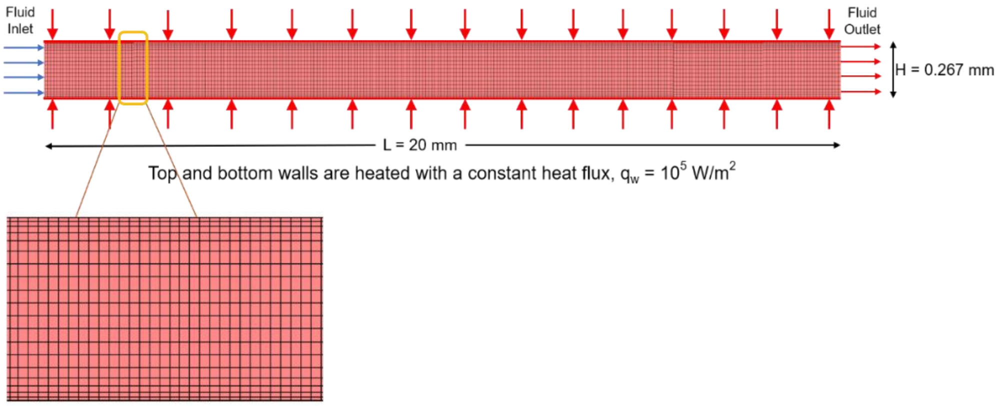

Figure 1. The physical model of the microchannel with the structured mesh, biased at walls with higher mesh density.

Forced convective flow through a microchannel, filled with homogenous and isotropic porous media (Hetsroni et al. [3]) is studied in the present work. Transient numerical investigation on 2D microchannel of dimensions (L × H) of 20 mm × 0.267 mm (refer to Figure 1) are performed for parameters such as Reynolds number (Re) and the Darcy number (Da) with an objective to characterise the regimes for the validity of Local Thermal Equilibrium (LTE).

The validity of local thermal equilibrium is verified for different flow rates (10 < Re < 1000) and porous media conductance (10^{-6} < Da < 10^{0}). In each parametric study, transient simulations are performed from the initial condition and ran till the steady state condition is reached. ANSYS ICEM-CFD software is used for creating the geometry and grid (refer to Figure 1), whereas, numerical simulations are performed on the commercial CFD solver ANSYS Fluent (Version 18.1). SIMPLE (Semi Implicit Method for Pressure Linked Equations) algorithm is used for pressure-velocity coupling. Spatial discretization of pressure is done using second order scheme and second order upwind is used for the momentum and energy equations discretization. Convergence criteria for continuity, momentum and energy equations are 10^{-6}, 10^{-6}, and 10^{-12} respectively.

3. Mathematical Modeling

For the flow in porous media, Darcy-Forchheimer-Brinkman equation is used which accounts for the additional pressure drop due to viscous and inertial resistances, along with the wall effect (Zeng and Grigg [4]). The energy equation has two distinct forms based upon the thermal equilibrium between the solid and fluid phases in the porous media. In case of thermal non-equilibrium (LTNE), two energy equations are solved separately for each phase, whereas, in case of thermal equilibrium (LTE), a single energy equation is solved (Vafai and Amiri [5]). For the present study, both LTNE and LTE energy equations are solved to compare the deviation in the resulting temperature fields and thus to identify the regimes in which LTE assumption holds valid.

(a) LTNE ($T_s \neq T_f$)

for fluid phase $$\varepsilon(\rho_f c_{pf})\frac{\partial T_f}{\partial t} + (\rho_f c_{pf})\,\vec{v}.\nabla(T_f) = \varepsilon\nabla.(k_f \nabla T_f) + h_{sf}a_{sf}(T_s - T_f) \quad (1)$$

for solid phase $$(1-\varepsilon)(\rho_s c_{ps})\frac{\partial Ts}{\partial t} = (1-\varepsilon)\nabla.(k_s \nabla T_S) + h_{sf}a_{sf}(T_f - T_s) \quad (2)$$

(b) LTE ($T_s = T_f = T$)

$$(\rho c_P)_e\frac{\partial T}{\partial t} + (\rho_f c_{pf})\,\vec{v}.(\nabla T) = \nabla.(k_e \nabla T) \quad (3)$$

Where, ρ_s and ρ_f are solid and fluid density, c_{ps} and c_{pf} are solid and fluid specific heat capacities, k_s and k_f are solid and fluid thermal conductivities. $\vec{v}$ is the superficial velocity of fluid, T_s and T_f are solid and fluid temperature obtained from the LTNE equation. Subscript 'e' represents the effective properties of porous medium which are obtained using the volume weighted average of the solid and fluid properties. T is the temperature obtained from the solution of LTE equation. Moreover, ε, a_{sf} and h_{sf} represents respectively the porosity, specific area density of solid fluid interface wall, and pore-level heat transfer coefficient.

4. Results

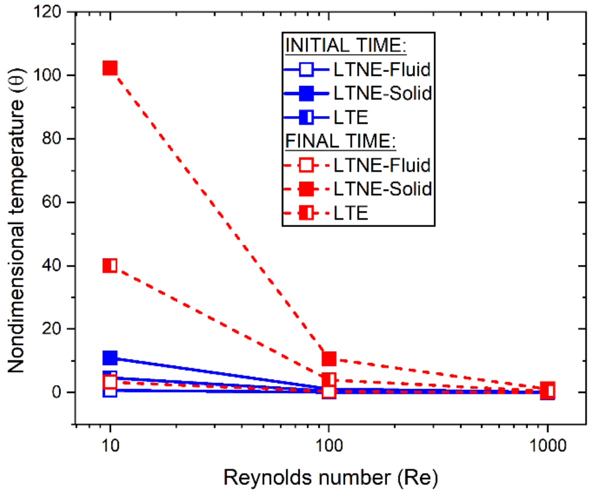

Figure 2. Variation of nondimensional average temperature for the range of Reynolds number.

Figure 2 shows the nondimensional temperatures ($\theta = \frac{(T-T_{ref})k}{q''H}$) for LTNE (fluid and solid), and LTE (equilibrium) cases, averaged at the outlet boundary at the beginning and end of the transient simulation. At low Re (Re = 10), dispersion of thermal energy is weaker due to lower advection, resulting in a thermal non-equilibrium, whereas, this situation is reversed for higher Re (Re = 1000). In addition to that, at the initial time, there is a sudden imparting of inertial effects (transient term in the governing equations), whereas, at the final time (when steady state condition is reached), the flow stabilizes, and thermal non-equilibrium is attained at low Re (Re = 10) and thermal equilibrium at high Re (Re = 1000).

5. Summary

In the numerical analysis of the microchannel filled with porous media, the observations made are: (a) At the initial stage, the insignificant difference between solid and fluid temperature follow the LTE condition. At the later stage, however, significant difference in temperature between solid and fluid tending towards LTNE condition. (b) Variation of Reynolds number (Re) shows the LTE assumption is applicable for higher flow rates (Re > 100). (c) Effect of Darcy number (Da) is that at low Re (Re < 100), the LTE condition is difficult to achieve, however at low Da (Da = 10^{-6}), this deviation is observed to be getting reduced. Interestingly, the LTE condition is observed in the whole range of Da values at higher Re (Re = 1000).

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