Comparison of Numerical Models of Flow and Heat Transfer Through Porous Medium in a Vertical Channel

Trilok G\textsuperscript{1} and N Gnanasekaran\textsuperscript{1,2}
\textsuperscript{1}National Institute of Technology Karnataka, Surathkal
\textsuperscript{2}Corresponding author

E-mail: gnanasekaran@nitk.edu.in (N Gnanasekaran)

Abstract. Porous medium modelling technique has opened up ways for number of numerical studies to investigate the performance of many devices that involve heat exchanging process. Such modelling technique not only avoids huge cost and time as compared to experimental analysis but also makes computationally less time-consuming as in case of numerical simulation by exact geometry modelling of porous materials. In this regard the present paper analyses two different thermal models namely local thermal equilibrium model and local thermal non-equilibrium model along with two different flow models namely Darcy flow model and Darcy extended Forchheimer model. Suitability of the mentioned models in predicting heat transfer through metal foam and wire mesh porous medium is examined subjected to variations in structural aspects of the porous medium that could be primarily represented by variation in porosity and pore density. For this purpose, a vertical channel subjected to constant heat flux capable of housing porous medium reported in literature is numerically modelled and air flow is numerically simulated through the channel. A variety of structural configuration (combination of different porosity and pore density) of the mentioned porous media are considered and among the mentioned flow and thermal models, best suited models for predicting flow and heat transfer through such medium are identified with appropriate justifications. It is revealed from the present study that, Darcy-Forchheimer and LTNE models are best suited to predict flow and heat transfer through porous media than the basic Darcy and LTE models.

1. Introduction

Metal based porous media such as metal foams, packed wire-mesh structures, packed perforated sheets etc., have been conventionally used as heat transfer enhancing media in many heat exchanging devices. High specific surface area, low density and higher thermal conductivity of these kinds of porous media favors heat transfer process for a great extent, however with a penalty of increased pressure drop due to increased resistance to the fluid flow as a result of the complicated restricted path through such medium. For the benefit of heat transfer enhancement, such metal based porous medium have been used in many heat transfer applications such as fuel cell [1], [2] micro channel heat sinks [3], [4], solar receivers [5], [6] etc., Numerical analysis extensively helps to analyze such kinds of porous media in many engineering applications with limited time and easy modifications unlike experimental procedure that involve more time and huge experimental cost accompanied by experimental errors. However, numerical modeling of the exact geometry of porous medium can be very difficult as well equally time consuming for both modeling and simulations. Therefore, flow and thermal models that represent and depict flow and heat transfer through such medium are necessary to model such kind of porous medium.
in many engineering devices. In this regard, Darcy proposed a model to depict flow through porous media which is popularly known as Darcy flow model that considers pressure drop due to additional viscous effects in the Navier-Stokes equation. Later Forchheimer extended Darcy’s model by adding extra inertial term to the Darcy equation to account for the inertial losses during flow through porous medium. In terms of heat transfer local thermal equilibrium model (LTE) and local thermal non-equilibrium model (LTNE) are well known thermal models to depict heat transfer through porous medium. Local thermal equilibrium (LTE) model assumes thermal equilibrium between the fluid phase and the porous solid phase. Thus, solves a single energy equation containing effective thermal conductivity of the fluid saturated porous medium. On the other hand, local thermal non-equilibrium (LTNE) model considers heat exchange between the solid and the fluid phases separately and accounts it for the total heat transfer through the porous medium. Therefore, LTNE model considers two energy equations solved individually for fluid and solid phases of the fluid saturated porous medium. In the present work comparison of these distinguished flow and energy models is made highlighting the suitability of these models to predict flow and heat transfer phenomenon through metal foam porous media filled in a vertical channel.

2. Computational domain.
A vertical channel experimental analysis by Kamath et al. [7] studying heat transfer in porous media is chosen as the reference work and the same experimental domain is modeled as numerical domain in the present work. Sketch of experimental and numerical domain is shown in Fig. 1 consisting a vertical channel with dimension of 27 × 250 × 390 (mm), that constitutes a heater attached to aluminum plate of thickness 3mm in order to supply 20 W of constant heat input. Aluminum foam samples are placed within the channel as shown in Figure 1. Numerical results are validated against results of experimental work of Kamath et al. [7].

2.1. Numerical details and boundary conditions
In the present work 2D numerical simulations are carried out using ANSYS FLUENT software. Boundary conditions imposed on the 2D computational domain is shown in Figure 2. Dissimilar regions are established with appropriate interfaces.

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1:** Sketch of the experimental domain that is numerically modelled in the present study. Channel wall (1), porous medium (2), aluminum plate (3), heater (4).

**Figure 2:** Sketch of numerical domain depicting respective boundary conditions.
Using symmetry boundary condition available in the used computational software, the actual symmetric domain is simplified for reducing computational effort. Heat flux boundary condition is provided on the face of aluminium plate on to which actual heater is placed. Velocity inlet and pressure outlet conditions are specified at inlet and outlet of the channel. Side walls enclosing the channel are assigned with adiabatic boundary condition. Air is considered as the working fluid.

3. Governing equations pertaining to various models

Appropriate governing equations can also be found in [8], [9] and [10]. Equations 1 to 6 depicts the fundamental governing equation solved in the present numerical methodology pertaining to numerical modelling of flow and heat transfer in foam-free as well as foam filled region.

Governing equations for non-porous region:

**Continuity equation:**
\[
\frac{\partial \rho \phi u_i}{\partial x_i} = 0
\]  
(1)

**Momentum equation:**
\[
\frac{\partial (\rho \phi u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu_j \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right) - \frac{\partial \rho C_p T_f}{\partial x_j} \frac{\partial T_f}{\partial x_j}
\]  
(2)

**Energy equation:**
\[
\frac{\partial (\rho \phi C_p T_f)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \lambda_f \frac{\partial T_f}{\partial x_j} \right)
\]  
(3)

Governing equations for porous region:

**Continuity equation:**
\[
\frac{\partial \varepsilon u_i}{\partial x_i} = 0
\]  
(4)

**Momentum equation:**

a) Darcy equation
\[
\frac{\partial (\rho \phi u_i u_j)}{\partial x_j} = -\varepsilon \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu_j \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right) - \frac{\partial \rho \phi C_p T_f}{\partial x_j} \frac{\partial T_f}{\partial x_j} + \varepsilon \frac{\rho \phi C P I u_i u_j}{K}
\]  
(5a)

b) Darcy extended Forchheimer equation
\[
\frac{\partial (\rho \phi u_i u_j)}{\partial x_j} = -\varepsilon \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu_j \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right) - \frac{\partial \rho \phi C P I u_i u_j}{K} + \varepsilon \frac{\rho \phi C P I u_i u_j}{K} + \varepsilon \frac{\rho \phi C P I u_i u_j}{K}
\]  
(5b)

**Energy equation:**

a) LTE
\[
\frac{\partial (\rho \phi C_p T_f)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \lambda_f \frac{\partial T_f}{\partial x_j} \right)
\]  
(6a)

b) LTNE

For fluid: \( \varepsilon \frac{\partial (\rho \phi C_p T_f)}{\partial x_j} = \lambda_f \varepsilon \frac{\partial}{\partial x_j} \left( \frac{\partial T_f}{\partial x_j} \right) + h_s f a_{sf} (T_s - T_f) \)

For solid: \( \lambda_{se} (1 - \varepsilon) \frac{\partial T_s}{\partial x_j} = h_s f a_{sf} (T_s - T_f) \)

Where,
\[
\lambda_f = \lambda_f \varepsilon
\]
\[
\lambda_{se} = \lambda_s (1 - \varepsilon)
\]  
(6b)

4. Results and discussion

4.1. Comparison of flow models (Darcy and Darcy extended Forchheimer models)

Darcy model that considers additional viscous effects in the conventional Navier-Stokes equation and Darcy-extended Forchheimer model that considers both viscous as well as inertial losses in the conventional Navier-stokes momentum equation depict flow phenomenon through porous medium.
differently depending on the velocity range. These formulations can be seen in equation 5a and 5b. It can be observed from Figure 3 to 6 that flow phenomenon marked by pressure drop across the foam samples is almost predicted closely by both Darcy and Darcy-Forchheimer model at very low velocity. However, at higher velocity inertial effects are much more significant than at lower velocities, which is the reason Darcy-Forchheimer model predicts pressure drop closer to the experimental values even at higher velocity range.

![Figure 3](image1.png)  
**Figure 3**: Comparing variation of experimental pressure drop with simulated results using different models for 10 PPI 0.95 porosity foam sample.

![Figure 4](image2.png)  
**Figure 4**: Comparing variation of experimental pressure drop with simulated results using different models for 20 PPI 0.90 porosity foam sample.

![Figure 5](image3.png)  
**Figure 5**: Comparing variation of experimental pressure drop with simulated results using different models for 30 PPI 0.92 porosity foam sample.

![Figure 6](image4.png)  
**Figure 6**: Comparing variation of experimental pressure drop with simulated results using different models for 40 PPI 0.90 porosity foam sample.

4.2. Comparison of thermal models (LTE and LTNE).

As depicted in equation 6a and 6b local thermal equilibrium model establishes thermal equilibrium between solid and fluid phases of the fluid saturated porous medium thereby has a single energy equation by considering effective thermal conductivity of the whole fluid saturated porous medium. On the contrary, local thermal non equilibrium model considers no thermal equilibrium between solid and fluid phases of the fluid saturated porous medium, instead considers substantial heat transfer between solid and fluid phases. Meaning, LTE model considers heat transfer coefficient between the fluid and solid
phases to be zero and LTNE considers quantifiable heat transfer coefficient between the solid and fluid phases of the fluid saturated porous medium.

A clear distinguishable variation of numerically predicted heat transfer coefficient value can be observed from Figure 7 to 8 when used different thermal models namely LTE and LTNE. It is quite evident in the obtained results that, at very lower velocities both the models predict the thermal behaviour almost same and accurate when compared with the experimental thermal behaviour. However, with increase in velocity, LTE model is observed to be over predicting the experimental results and results from LTNE model is closer to experimental results. The deviation of heat transfer coefficient predicted by LTE model gets farther away from the experimental results in a greater magnitude at higher velocities. It is also worthwhile to note that LTNE model rightly considers the changes in pore density measured as pores per inch (i.e., PPI) by accounting the changed surface area density ($a_{sf}$) appearing in equation 6b. Whereas LTE model doesn’t account for change in PPI through terms like ‘$a_{sf}$’ (surface area density) which alters with changes in pore density (PPI).

Figure 7: Comparing variation of experimental wall heat transfer coefficient with simulated results using different models for 10 PPI 0.95 porosity foam sample.

Figure 8: Comparing variation of experimental wall heat transfer coefficient with simulated results using different models for 20 PPI 0.90 porosity foam sample.

Figure 9: Comparing variation of experimental wall heat transfer coefficient with simulated results using different models for 30 PPI 0.92 porosity foam sample.

Figure 10: Comparing variation of experimental wall heat transfer coefficient with simulated results using different models for 40 PPI 0.90 porosity foam sample.
5. Conclusions
In the present work a detailed comparison is made among Darcy, Darcy-Forchheimer flow model and LTE (local thermal equilibrium), LTNE (local thermal non-equilibrium) thermal model to predict flow and heat transfer through metal foam porous medium filled in a vertical channel. The numerically predicted models suggests that, flow through porous medium of various porosity and pore density can be appropriately modelled with both Darcy and Darcy-Forchheimer model at lower velocities, however, at higher velocity range Darcy model under predicts flow phenomenon (pressure drop) whereas Darcy-Forchheimer model predicts closer pressure drop as that of experimental data even at higher velocities. In terms of predicting heat transfer through porous medium (metal foam in this study), LTNE model is observed to predict closer heat transfer behaviour at all velocity ranges whereas LTE model is observed to predict closer heat transfer behaviour only at extremely lower velocities.

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