Applied Thermal Engineering 140 (2018) 86–94

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Forced convection in bidisperse porous media incorporating viscous dissipation

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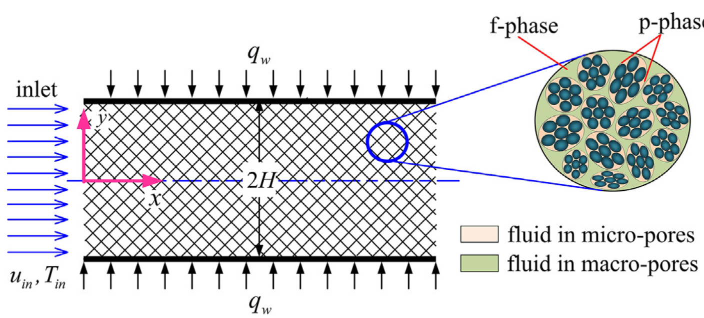
HIGHLIGHTS

- Forced convection in a bidisperse parallel-plate channel is studied incorporating viscous dissipation.
- The analysis emphasizes on the effects of bidispersivity and viscous dissipation on the thermal performance.
- Critical Brinkman numbers arising from the cold wall cases lead to the singularity in Nusselt numbers.
- The bidispersivity plays a significant role in balancing the wall heat flux and the heat generated by viscous dissipation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Bidisperse porous medium
Forced convection
Local thermal equilibrium
Viscous dissipation

ABSTRACT

Forced convective heat transfer in a parallel-plate channel filled with a bidisperse porous medium (BDPM) is studied analytically incorporating viscous dissipation, in which the constant wall heat flux condition is taken into account. The flow is assumed to be hydrodynamically and thermally fully developed and is described by a two-velocity one-temperature formulation. Exact solutions are obtained for the temperature distributions of both f- and p-phases and the Nusselt number. The analysis emphasizes on the effects of bidispersivity and viscous dissipation on the thermal performance. It is found that the existing critical Brinkman numbers, which arise from the cold wall case only, lead to the singularity in Nusselt numbers. More importantly, the bidispersivity plays a significant role in balancing the heat flux at the wall and the heat generated by viscous dissipation. For both cases with and without viscous dissipation, the Nusselt numbers become independent of the bidispersivity when the Darcy number ratio increases.

1. Introduction

Abundant studies focused on the thermal convection in a monodisperse (regular) porous medium (MDPM) [1–5]. In the analysis of forced convective heat transfer in porous media, the viscous dissipation usually acts as a source term which leads to dramatic change of flow and temperature fields. Viscous dissipation is more significant in the laminar regime due to the steep gradients as compared to the turbulent flow. For forced convection in porous media, the effect of viscous dissipation is essentially important due to the presence of the frictional heating arising from increasing contact of the fluid with the solid phase and the wall together with internal heating associated with the mechanical power required to extrude the fluid through a porous medium [6–8]. However, there are relative few analytical studies on forced convection through porous media considering the effects of viscous dissipation. Hung and Tso [9] conducted an analytical study on fully developed forced convection in a homogeneous porous medium. It was found that the heat generation due to frictional heating is confined in

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https://doi.org/10.1016/j.applthermaleng.2018.05.036
Received 28 March 2018; Received in revised form 5 May 2018; Accepted 9 May 2018
Available online 16 May 2018
1359-4311/

the vicinity of the wall while the heat generation due to internal heating occupies a large portion of the porous medium originated from the center of the channel. Repaka and Satyamurty [10] examined the dependence of limiting Nusselt numbers on the viscous dissipation and the degree of asymmetry when the parallel plates are kept at unequal temperatures. Yi et al. [11] analytically studied the effect of thermal asymmetrical boundaries on entropy generation of viscous dissipative flow of forced convection in thermal non-equilibrium porous media. From the second-law point of view, an optimum condition with a high Nusselt number and a low entropy generation was identified at a Darcy number of 10^{-4}. In recent years, Hung and his coworkers [8,12–14] focused on the viscous dissipative forced convection in nanofluid-saturated porous media. Ting et al. [12] emphasized on the disparities induced by the viscous dissipation between the two models with and without the viscous dissipation. When the viscous dissipation is neglected, the thermal performance of nanofluid is overrated as much as 60%, sufficiently serious to trigger an attention in the performance analysis. Ting et al. [8] investigated the thermal performance and entropy generation of water-alumina nanofluid flows in porous media embedded in a microchannel under local thermal non-equilibrium condition. It was found that the viscous dissipation effect is magnified significantly due to the embedment of the porous medium and the suspension of the nanoparticle in the working fluid. This alters thermal characteristics and entropy generation of the system. Subsequently, they investigated the entropy generation of nanofluid flow in asymmetrically heated porous microchannels with solid-phase heat generation [13].

A bidisperse porous medium (BDPM) is composed of clusters of large particles that are agglomerations of small particles. In the light of this structure, a BDPM is usually looked at as a regular porous medium in which the solid phase is replaced by another porous medium. Since the first definition of BDPM by Chen et al. [14,15] in 2000, some researchers have investigated the natural and forced heat transfer in bidisperse porous media. The BDPM has been applied to absorbents for enhancing absorption performance or heat pipes for augmenting heat transfer rate [16–18]. The forced convection in a BDPM has emerged as an important research field in recent years. This has been motivated by its high area to volume ratio and consequently interesting thermal behavior. Unlike the MDPM, a BDPM has two scales of porosity denoted by macro-pores between the clusters and micro-pores within them. Usually, the macro-pores are denoted by the f-phase and the remainder of the structure is done by the p-phase. The working fluid occupies all of the f-phase and a fraction of the p-phase. Nield and Kuznetsov [19] proposed a two-velocity two-temperature model for investigating forced convection in a BDPM filled parallel-plate channel. Later, Nield and Kuznetsov [20] investigated analytically the thermally developing forced convection in a parallel-plate channel with walls held at constant temperature. Further, Nield and Kuznetsov [21,22] studied symmetric and asymmetric heating configurations for a parallel-plate channel partially filled with a BDPM. For the case of asymmetric heating, a singular behavior of the Nusselt number was found and explained. Straughan [23] revisited the problem of thermal convection in a BDPM. The possibility of oscillatory convection was studied by using a highly accurate Chebyshev tau numerical method. Narasimhan and Reddy [24] utilized the bidisperse porous medium approach to analyze the thermal management of heat generating electronics which are modeled as micro-porous blocks separated by macro-gaps in a channel. It was reported that the geometry and distribution of such a BDPM channel can be suitably tuned through the bidispersion parameters to augment the heat transfer and reduce the pressure drop. Later, Narasimhan et al. [25] extended the BDPM approach to treat the thermal management of data centers densely packed with heat generating electronic equipments. Ajay et al. [26] numerically studied the forced convection cooling of electronic chip with and without a porous medium. Their study revealed that the average surface temperature of the electronic chip was reduced by 4.21 K using the bidisperse porous medium heat sink instead of the conventional one. Wang et al. [27] investigated the forced convection in a circular BDPM pipe. They found that the BDPM pipe with higher Darcy numbers gives rise to higher heat transfer performance than the MDPM one. In the case with lower Darcy numbers, however, the BDPM pipe does not display any superiority to the MDPM one although the former yields higher Nusselt number than the latter.

In the literature, however, the effects of viscous dissipation on the heat transfer in ducts filled with bidisperse porous media have not been elucidated yet. Motivated by the significance of viscous dissipation and the bidisperse porous insertion on the thermal behavior, the objective of the present study is to investigate the forced convective heat transport through a parallel-plate channel filled with a BDPM. The viscous dissipation terms are incorporated in the energy equation under the local thermal equilibrium condition. The effects of viscous dissipation and bidispersivity on the heat transfer are discussed in detail.

2. Heat transfer model for bidisperse porous media

2.1. Problem statement

The physical model and the coordinate system are shown in Fig. 1. The fluid flows through a parallel-plate channel fully filled with a BDPM subject to a constant heat flux boundary condition. The distance between plates is $2H$ and the constant heat flux at the walls is q_w. Only the upper half of the structure is considered due to the symmetry. The following assumptions are invoked in the present study:

- The steady forced convection flow is laminar and incompressible.
- The hydrodynamically and thermally fully developed conditions are

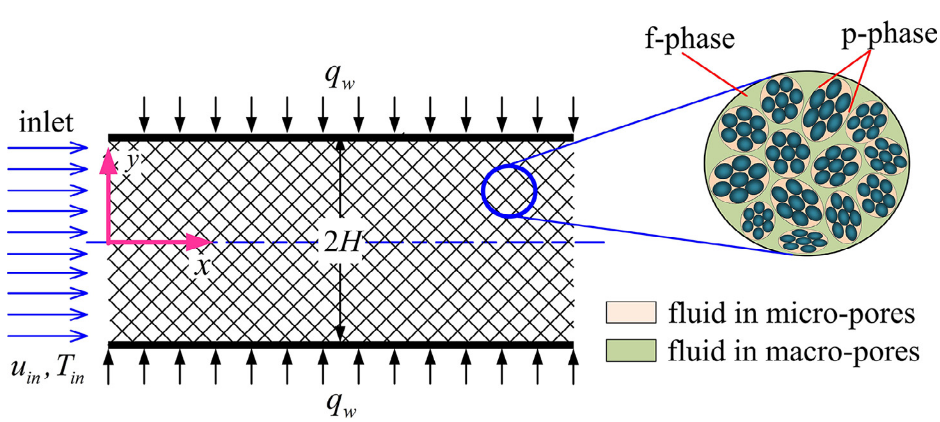

Fig. 1. Viscous dissipation flow through a parallel-plate channel filled with a BDPM.