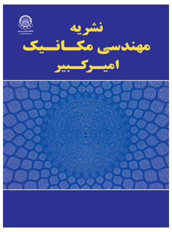

Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 53(special issue 3) (2021) 457-460
DOI: 10.22060/mej.2020.16065.6276

Numerical simulation of nanofluid flow in an annulus with porous baffles based on combination of Darcy-Brinkman-Forchheimer model and two-phase mixture model

H. Namadchain, I. Zahmatkesh, S. M. Abolhasan Alavi*

Department of Mechanical Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran

ABSTRACT: In this paper, forced convection heat transfer of a nanofluid in an annulus with porous baffles on the inner and outer walls is investigated numerically. The nanofluid is simulated based on the two-phase mixture model while the flow in the porous region is described by the Darcy-Brinkman-Forchheimer model. The fluid flow is considered laminar, steady, axisymmetric, and incompressible. The governing equations have been solved using the finite volume method. The effect of parameters such as the Darcy number, the height of the porous baffles, the thermal conductivity ratio, and the volume fraction, and the type of the nanoparticles on the flow field, heat transfer, and pressure drop have been investigated. The results show that the use of the porous baffles in the flow path leads to significant variations in the characteristics of the flow and heat transfer. Reducing the Darcy and Reynolds numbers leads to the formation of vortices behind the baffles that has a significant impact on the heat transfer. By decreasing the Darcy number, the heat transfer increases substantially. This also causes a severe pressure drop in the flow. Increasing the thermal conductivity ratio raises the local Nusslet number at the wall near the baffles, which is more remarkable in higher values of permeability. Increasing the height of the porous baffles reduces the thickness of the boundary layer and enhances heat transfer.

Review History:

Received: Apr. 14, 2019
Revised: Aug. 28, 2019
Accepted: Mar. 10, 2020
Available Online: Mar. 22, 2020

Keywords:

Heat Transfer
Nanofluid
Two-Phase Mixture Model
Porous Baffle
Darcy-Brinkman-Forchheimer Model

1- Introduction

Using nanofluid and porous media are two effective methods to enhance heat transfer in heat exchange systems. Nanofluid is a fluid containing solid nanoparticles with high thermal conductivity. The addition of these nanoparticles to a base fluid can cause significant variations in the thermophysical properties of the fluid. Porous media can also improve the heat transfer characteristics. When a fluid flows through porous media, the random motion of the fluid through the solid matrix increases the fluid mixing, which can enhance the heat transfer considerably.

In this study, the forced convection heat transfer of nanofluids in an annulus with staggered porous baffles is investigated numerically. For this purpose, the two-phase mixture model and the Darcy-Brinkman-Forchheimer model are employed simultaneously to simulate the nanofluid flow in the porous baffles. The implementation of these models in a configuration with porous baffles has been reported rarely in the literature. A numerical investigation of fluid flow and heat transfer in a channel with porous baffles was carried out by Davari and Maerefat [1] who studied the effects of geometric parameters of the baffles on the flow and heat transfer characteristics.

2- Problem Description

The schematic of the considered problem is shown in Fig. 1, which includes an annulus with a length of 28m, an internal radius of 0.4m, and an external radius of 1m, with four porous baffles on the walls. Geometric parameters of porous baffles are non-dimensionalized based on the hydraulic radius (R_H) of the annulus. The working fluid is Al_2O_3/water nanofluid and the porous matrix is made of aluminum foam with a porosity of 0.9, which is in local thermal equilibrium with the nanofluid. Moreover, a uniform velocity profile is specified at the inlet and the nanofluid enters the annulus at a constant temperature of 300 K. Besides, both walls are at a constant temperature of 400 K. It is assumed that the fluid flow is laminar, incompressible, and axisymmetric.

3- Governing Equations

Since our computational domain contains two regions including a clear domain and a porous domain, we need a set of equations for each region. The two-phase mixture model is used to describe the nanofluid behavior while the Darcy-Brinkman-Forchheimer model is added to it for the porous domain. The equations are solved using the finite volume method along with the SIMPLE algorithm. The continuity,

*Corresponding author's email: m-a-alavi@mshdiau.ac.ir

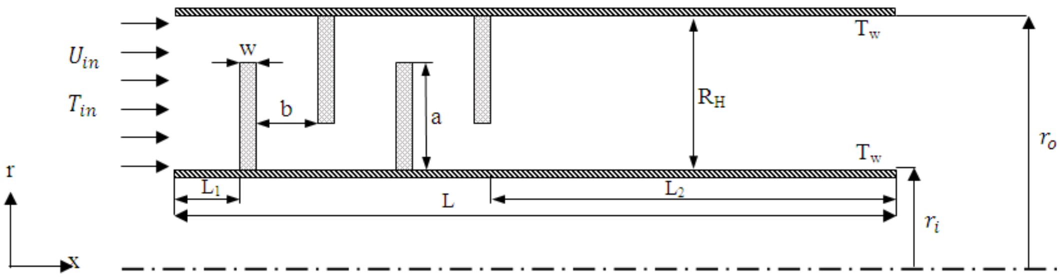

Fig. 1. Schematic of fluid flow in the channel having porous baffles

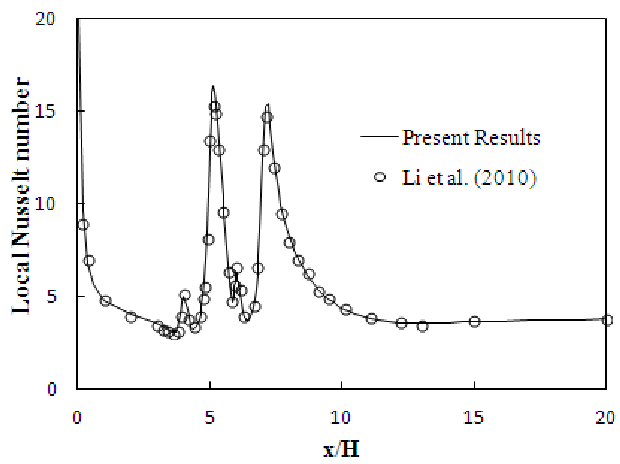

Fig. 2. The bracket must be closed at the end of "Comparison of the local Nusselt number obtained from the current research with the results of Li et al. [2]

momentum, energy, and the nanoparticles concentration equations for the clear domain are as follows [2]:

$$\vec{\nabla}.(\rho_m \vec{v}_m) = 0 \tag{1}$$

$$\vec{\nabla}.(\rho_m \vec{v}_m \vec{v}_m) = \vec{\nabla}.\left[\mu_m\left(\vec{\nabla}\vec{v}_m + \vec{\nabla}\vec{v}_m^{\,T}\right)\right] \tag{2}$$

$$\vec{\nabla}.\sum_{k=1}^{2}(\varphi_k \vec{v}_k \rho_k C_{pk} T) = \vec{\nabla}.(\lambda_{eff}\vec{\nabla}T) \tag{3}$$

$$\vec{\nabla}.(\varphi_{np}\rho_{np}\vec{v}_m) = -\vec{\nabla}.(\varphi_{np}\rho_{np}\vec{v}_{dr,np}) \tag{4}$$

For the porous domain, however, the momentum and energy equations take the following form:

$$\frac{\rho_m}{\varepsilon^2}\left[\vec{v}_m.\vec{\nabla}\vec{v}_m\right] = -\vec{\nabla}p + \frac{\mu_m}{\varepsilon}\nabla^2\vec{v}_m - \frac{\mu_m\vec{v}_m}{K} - \frac{\rho_m \varepsilon C_d}{\sqrt{K}}\vec{v}_m\left|\vec{v}_m\right| + \vec{\nabla}.\left(\sum_{k=1}^{2}\varphi_k\rho_k\vec{v}_{dr,k}\vec{v}_{dr,k}\right) \tag{5}$$

$$\vec{\nabla}.\sum_{k=1}^{2}(\varphi_k \vec{v}_k \rho_k C_{pk} T) = \vec{\nabla}.(\lambda_{eff}\vec{\nabla}T) \tag{6}$$

4- Results and Discussion

The present simulation is validated against the results of Li et al. [3]. For this purpose, a laminar water flow through a channel with staggered porous blocks at a Reynolds number of 100 is simulated and the results are compared with those of that work. The comparison is shown in Fig. 2, which indicates an excellent agreement.

To study the effect of the Darcy number on the heat transfer performance, the distributions of the local Nusselt number at both the inner and outer walls for different Darcy numbers are depicted in Fig. 3. It can be seen that the Darcy number affects the heat transfer rate considerably in such a way that decreasing the Darcy number enhances the heat transfer significantly. In the low values of the Darcy number, the permeability of porous baffles is not significant. As a result, the flow field is more distorted and the variations in the Nusselt number are sharper. In $Da=10^{-6}$, however, the peaks in the Nusselt number occur near the porous baffles, while its minimums appear in the space between the baffles. It is evident that in high values of the Darcy number, the variations in the Nusselt number are similar to that of an annulus without porous baffles due to the lower blockage effect. It is also obvious that heat transfer on the inner wall is higher than the outer wall, which goes back to due to the smaller radius and the higher velocity magnitudes.

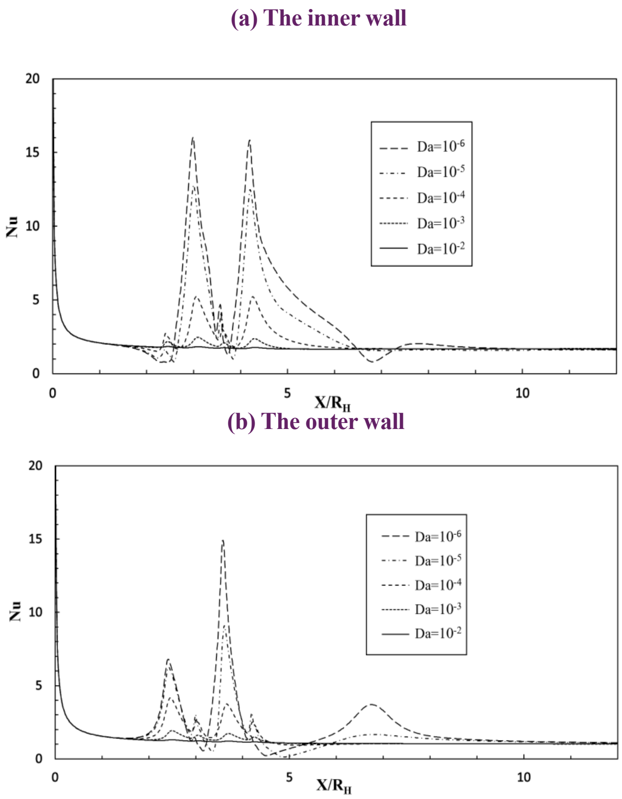

Fig. 3. The local Nusselt number for different Darcy numbers at (a) The inner wall (b) The outer wallFig. 3. The local Nusselt number for different Darcy numbers

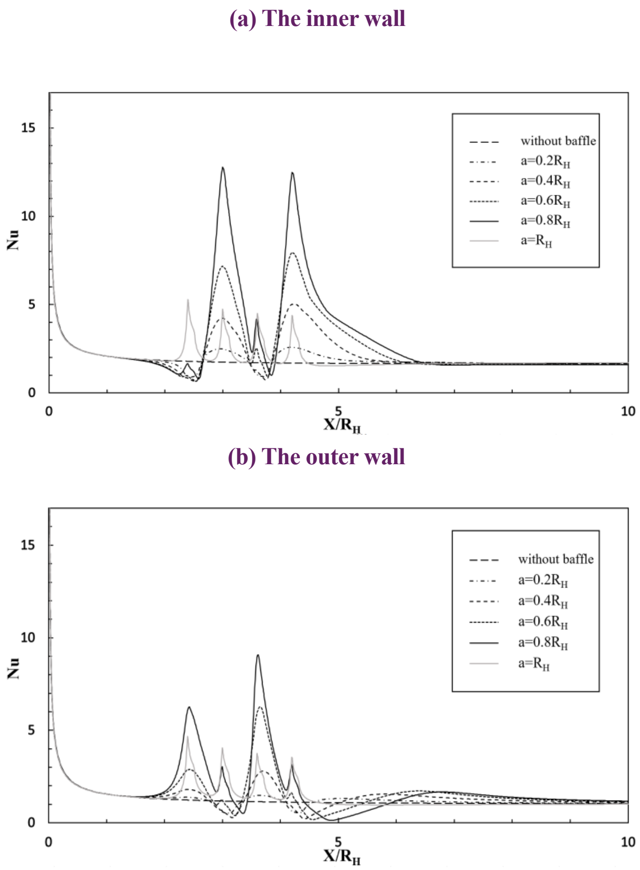

Fig. 4. The local Nusselt number for different baffle heights at (a) The inner wall (b) The outer wall

The effect of the height of the baffle on the variations of the local Nusselt number at both the inner and outer walls is shown in Fig. 4. Here, a rise in the height of the baffle leads to a velocity elevation. This decreases the boundary layer thickness and improves the heat transfer rate. However, this effect remains true until $a = 0.8R_H$. When the porous baffles occupy the whole radius, the clear gap disappears and the velocity acceleration due to the rise in the height of the baffle may not occur.

5- Conclusions

Based on the presented study we reached the conclusion that the use of the porous baffles resulted in improvement of the heat transfer but it was accompanied by a rise in the pressure drop. It was found that the vortices generated by the porous baffles changed the fluid flow and heat transfer characteristics considerably. Moreover, it was observed that increasing the height of porous baffles up to $a = 0.8R_H$ elevates the heat transfer. A reduction in the Darcy number also contributed to the heat transfer elevation.

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HOW TO CITE THIS ARTICLE

H. Namadchain, I. Zahmatkesh, S. M. Abolhasan Alavi, Numerical simulation of nanofluid flow in an annulus with porous baffles based on combination of Darcy-Brinkman-Forchheimer model and two-phase mixture model. Amirkabir J. Mech Eng., 53(special issue 3) (2021). 457-460

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