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Investigation of permeability and porosity effects on the slip velocity and convection heat transfer rate of Fe_3O_4/water nanofluid flow in a microchannel while its lower half filled by a porous medium

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ABSTRACT

In this study, we numerically investigated the forced heat-transfer and laminar flow in a two-dimensional microchannel whose lower half was filled with a porous medium. The nanoparticles used were Fe_3O_4 and a water-based fluid. The nanoparticles were considered in the form of a completely stable suspension in a water-based fluid. The nanofluid flow in this microchannel was modeled employing the Darcy–Forchheimer equation. We also hypothesized that there was a thermal equilibrium between the solid phase and nanofluid for energy transfer. And the walls of the microchannels were assumed at a constant temperature higher than the inlet fluid temperature. Also, the slip boundary condition was assumed along the walls. The effects of Darcy number, porosity and slip coefficients, and Reynolds number on the velocity and temperature profiles, and local Nusselt number were studied in both porous and non-porous regions in this research. In this study, the Darcy number was assumed to be Da = 0.1 and 0.01, Reynolds number Re = 25, 50, and 100, slip coefficient B = 0.1, 0.01, and 0.001, the porosity of the porous medium ε = 0.5 and 0.9, and the volume percentage of the nanoparticles φ = 0%, 2%, and 4%. With the Darcy number decreasing, the local Nusselt number increased in the non-porous region, and decreased in the porous region. And this phenomenon was observed for the first time. The increase in the Reynolds number increased the heat transfer in both regions. For instance, the local Nusselt number increased 4 times with the Reynolds number changing from 25 to 100 under the same conditions. The decreased Darcy number in the porous medium increased the amount of slip velocity near the walls in the non-porous region, and on the other hand, the decreased Darcy number in the porous medium reduced the slip velocity in the porous region. Also, the jump observed in the slip velocity, was due to the presence of the fluid velocity in the microchannel width.

1. Introduction

Nowadays, heat transfer is faced with two major challenges: on the one hand, cooling equipment with high thermal flux, and on the other hand, the issue of reducing the size of equipment. Air cooling is the most common method of cooling, while this method does not work in transferring high heat fluxes. Therefore, engineers have become interested in liquid cooling methods. Cooling liquids usually have poor heat transfer properties, and they definitely will not be used much in the future to transfer ultra-high heats [1–6]. In the last one hundred years, scientists and engineers have made many efforts to enhance the low thermal conductivity of the liquids through the addition of nano-sized solid particles. Since metal solids have higher thermal conductivity coefficients than the fluids have, it is expected that the suspension of metal solid nanoparticles in the fluid, increases its thermal conductivity as well as other properties [7–23]. Masoud Hosseini et al. [24] examined a dimensionless model is discussed to forecast effective thermal conductivity of nanofluids regarding the dimensionless groups. .Their finding non-linear correlation for thermal conductivity which demonstrates a good compatibility between present model and experimental data of Al_2O_3/H_2O nanofluids compared to other models. Abdollahzadeh Jamalabadiand et al. [25] studied Thermal loading by radiant heaters is used in building heating and hot structure

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Nomenclature

B	non-dimensional slip coefficient (/h)
Da	darcy number ($=K/H^2$)
d_p	diameter of nanoparticles (= 15 nm)
F	inertia coefficient
K	permeability (m^2)
Pr	Prandtl number ($= \upsilon_{nf}\ \alpha_{nf}$)
q''	heat flux, (W/m^2)
Re	Reynolds number ($=u_c h/\upsilon_{nf}$)
U	non-dimensional horizontal velocity
U_s	non-dimensional slip velocity
X	non-dimensional horizontal Cartesian coordinate
Y	non-dimensional vertical Cartesian coordinate

Greek symbols

α	thermal diffusivity ($=k/\rho c_p\ m^2\ s^{-1}$)
β	slip coefficient (m)
ϕ	volume fraction of nanoparticles
θ	non-dimensional temperature ($= (T - T_c)/(T_H - T_c)$)
λ	convection heat transfer coefficient ($W/m^2\ K$)

design applications. the effect of thermal and geometrical parameters on entropy generation and the distribution field. Abbasian Arani et al. [26] studied laminar flow and heat transfer of nanofluid water/single-wall carbon nanotubes have been investigated in a novel design of double layered microchannel heat sink (MCHS). Goshayeshi et al. [27] examined effect of γ (gamma) and α (alpha) Fe_2O_3/Kerosene nanofluids for a closed loop pulsating heat pipe under the magnetic field. The results indicated that both heat transfer coefficient and thermal performance of the pulsating heat pipe are enhanced by the addition of Fe_2O_3 nanoparticles and. The increased input heat flux rises the heat transfer coefficient of the condenser and the evaporator. This study was to investigate the effect of a porous medium on a non-porous medium as well as heat transfer. But, if gravity is taken into account, it will be possible that the results change with changes in the position of the porous medium. Recently, some studies have been conducted on the effect of gravity on the heat transfer and kinematics of nanofluids, among which we can refer to the study conducted by Karimipour et al. [28]. They studied heat transfer in an oblique cavity at different angles while taking into account the gravitational force, the results show Nusselt numbers can be achieved at larger values of the inclination angle and nanoparticles volume fraction at free convection domination. Results imply the appropriate ability of LBM to simulate the mixed convection of nanofluid in a shallow inclined cavity. Manca et al. [29] studied the flow of water-aluminum oxide nanofluid in a two-dimensional channel with the uniform flux boundary condition on the external walls. The assumptions of this research included the stable properties of the nanofluid and use of a single-phase model for the nanofluid. They investigated the effects of the presence of ribs with different shapes, and changes in the Reynolds number and volume percentage of the nanoparticles on the heat transfer of the nanoparticles, and showed that increases in the Reynolds number and volume percentage of the nanoparticles will increase the heat transfer of the nanofluid. Mangrulkar et al. [30] investigated the heat transfer of nanofluids with changes in parameters such as: the flow geometry, boundary conditions, and the increased thermal conductivity of the fluid. They also investigated the effects of Reynolds number, mass concentration, and particle size on the heat transfer rate. The results of their work showed that increases in the Reynolds and Prandtl numbers increase the heat transfer coefficient, thus increasing the heat transfer rate. On the other hand, the addition of nanoparticles to the base fluid increases the thermal conductivity in the fluid. Ahmed et al. [31] numerically investigated a water-copper nanofluid in a channel using the finite difference method. The results of their work showed that increases in the Reynolds number and volume percentage of nanoparticles will increase the heat transfer of the nanofluid, while the pressure drop will be negligible. Akbarinia et al. [32] investigated the forced convection of a water-aluminum oxide nanofluid in a two-dimensional rectangular microchannel, and showed an increase in the heat transfer due to the increased volume percentage of the nanoparticles. Their results showed that the Reynolds number in the microchannel, was under the influence of the inlet velocity and kinetic viscosity of the nanofluid, and that the viscosity increased with the increased volume percentage of the nanoparticles. Li et al. [33] studied the flow of water-copper nanofluid and pure water in a trapezoidal microchannel. The results showed that the presence of copper nanoparticles in the water-based fluid, would increase the thermal performance. Jung et al. [34] investigated the flow of water-aluminum oxide nanofluid in a rectangular microchannel. In their work, they showed an increase in the heat transfer due to the increase in the Reynolds number and volume percentage of the nanoparticles. They also found out that an increase in the Reynolds number would cause an increase in the Nusselt number. Maiga et al. [35] numerically investigated the heat transfer of a nanofluids inside a pipe in both laminar and turbulent regimes. The result of their work showed that the heat transfer of Al_2O_3-ethylene glycol nanofluid was higher than that of Al_2O_3 water nanofluid. Kalteh et al. [36] numerically investigated the forced convective heat transfer of water-copper nanofluid in a laminar regime using a two-phase model. In this work, they investigated the difference of velocity and temperature between the liquid phase and nanoparticles phase, and the results showed that the relative velocity and temperature in the phases were very small and could be ignored. They showed that the volume percentage distribution of the nanoparticles was uniform, and the increase in the heat transfer was higher in the two-phase model than in the homogeneous model. Use of porous material in increasing the heat transfer, is considered as one of the important issues. Nowadays, scientists and researchers have conducted a lot of research on how to use porous media. By investigating the effective parameters in heat transfer enhancement, including: different arrangements to reduce pressure drop due to spaces blocked by porous media, changes in the permeability, and the effect of the porosity of different materials, they have been trying to enhance heat transfer using this method [37–42]. Pavel and Mohamad [43] numerically and experimentally investigated heat transfer in a channel with constant and uniform flux boundary condition on the walls and a net-shaped metal porous material placed in the center of the channel. The study was conducted for both the laminar and turbulent regimes in the range of Reynolds numbers from 40 to 1000, and the effects of porosity, the diameter of the porous material, the conductive heat transfer coefficient, and the Reynolds number on the heat transfer was investigated. Their results showed that in the case that the diameter of the porous material was close to