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Original Research Paper

Numerical investigation of nanofluid heat transfer inside trapezoidal microchannels using a novel dispersion model

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ABSTRACT

In the present work, steady state, laminar, hydrodynamically and thermally developing flow in a trapezoidal microchannel heat sink (MCHS) is investigated. Navier–Stokes equations are solved using finite volume method. A new correlation for the dispersion model is suggested to explain the heat transfer enhancement of nanofluids. Two kinds of nanofluids, Al_2O_3–water and CuO–water were considered and the results were validated using open literature data. It is shown that the proposed correlation gives the best result among other models. Furthermore, the effects of nanoparticle size and volume fraction on heat transfer are evaluated. The results show that the average Nusselt number increases rapidly with decrease of diameter of nanoparticles, but increasing nanoparticle size more than 60 nm does not affect heat transfer considerably. Moreover, when the Reynolds number is low, adding more nanoparticles increases heat transfer slightly, so using nanofluid in applications where the Reynolds number is not commonly high (e.g. in microchannel fluid flow) sounds ineffective.

1. Introduction

After the pioneer work of Tuckerman and Pease [1], microchannels have been studied by many researchers due to their promising heat transfer features [2–5]. The large amount of heat dissipation from electronic devices has led to improvement in new techniques of cooling. As surface to volume ratio of microchannels is very high, they provide heat removal advantages. Although impressive amount of work about cooling features of microchannels has been done, the literature still is open for further investigations.

On the other hand, the performance of conventional coolants such as water is limited due to their low thermal properties. One method to enhance heat transfer is to add high conductivity solid particles [6]. Nanofluids are colloidal suspensions of nanoparticles in base fluids, and unlike microscale and miniscale particles, they do not cause sedimentation, clogging or pipeline erosion. Moreover, the increase of nanofluids pressure drop is not considerable [7], thus their use in electronic cooling devices sounds promising. Numerous studies have been performed to investigate nanofluid flow in microchannel heat sinks.

Chein and Huang [8] showed that using nanofluids as coolants in silicon microchannels can considerably increase the heat performance. Using theoretical models and experimental correlations, they investigated Cu–water flow through two specific silicon microchannel heat sink (MCHS) geometries. Furthermore, it was shown that there is no significant pressure drop difference between nanofluid and its base fluid.

Koo and Kleinstreuer [9] simulated conjugated heat transfer for water-based and ethylene glycol-based nanofluid flow inside rectangular MCHS. Thermal conductivity and dynamic viscosity were suggested to be the sum of static and Brownian parts. High-Prandtl number liquids were found to have greater heat transfer performance.

Jang and Choi [10] numerically studied thermal resistance and heat transfer of nanofluid flow in a rectangular microchannel. They concluded that the thermal resistance and also the temperature difference between microchannel wall and the coolant reduces, thus using nanofluids in microchannel heat sinks is an efficient way to remove heat from high flux devices.

Chein and Chuang [11] experimentally investigated the performance of CuO–water nanofluid inside a trapezoidal microchannel heat sink. The presence of nanoparticles resulted in more energy absorption from microchannel compared to the base fluid when the flow rate was low.

Nguyen et al. [12] conducted an experiment with turbulent flow of alumina–water inside a cooling system of microprocessors. It was shown that smaller particles produce higher convective heat transfer coefficient.

Li and Kleinstreuer [13] numerically solved CuO–water flow and thermal field through a trapezoidal microchannel. They used

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Nomenclature

A	area (m^2)
a	short base of microchannel (m)
b	long base of microchannel (m)
C	empirical constant
C_p	specific heat (J/kg K)
D_h	hydraulic diameter of microchannel (m)
d_p	particle diameter (m)
h	convection coefficient (W/mK)
h	height of microchannel (m)
k	thermal conductivity (W/mK)
l	MCHS length (m)
m	mass flow rate (kg/s)
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
q''	wall heat flux (W/m^2)
Re	Reynolds number
T	temperature (K)
t	height of MCHS (m)
u, v, w	velocity components in x, y and z directions respectively (m/s)
Q	wall heat flux (W)
R	radius of microchannel (m)

Greek symbols

α	thermal diffusivity (m^2/s)
μ	dynamic viscosity (kg/ms)
ϕ	volume concentration of nanoparticles
ρ	density (kg/m^3)

Subscripts

bot	bottom
d	dispersion
eff	effective
f	fluid
in	inlet
m	mean
nf	nanofluid
out	outlet
p	particle

a new temperature-dependent model for the thermal conductivity of nanofluid. It was found that the thermal performance increases with volume fraction. Wu et al. [14] performed an experiment in trapezoidal MCHS using alumina–water nanofluid as a coolant. The effect of Reynolds number, Prandtl number and volume fraction was investigated. They proposed dimensionless correlations for the flow friction and the Nusselt number.

The experimental study of Jung et al. [15] on nanofluid flow through a rectangular microchannel showed that the Nusselt number rises with increasing Reynolds number in laminar flow. Base fluids were water and a mixture of water and ethylene glycol.

Mohammed et al. [16] numerically investigated conjugate heat transfer of alumina–water in rectangular MCHS. It was observed that MCHS wall temperature reduces with increasing volume fraction of particles in high heat flux. With the optimum value of nanoparticle volume fraction, the cooling of MCHS increases. Mohammed et al. [17] also studied heat transfer of nanofluid flow through trapezoidal MCHS numerically. Different base fluids and substrate materials have been considered with 2% volume fraction of diamond. It was shown that the higher Prandtl number base fluids exhibit the greater heat transfer coefficient. For low Prandtl number base fluids like water, it was suggested that the substrate material of high thermal diffusivity should be used.

Kalteh et al. [18] numerically studied Cu–water nanofluid heat transfer inside a parallel plate microchannel using Eulerian–Eulerian two-phase model. They concluded that the relative velocity and temperature between two phases was negligible. Kalteh et al. [19] also experimentally investigated heat transfer of alumina–water through wide rectangular MCHS. They compared the experimental data with numerical results of the Eulerian–Eulerian two-phase model and concluded that the two-phase method has better agreement with experiment than the homogeneous single-phase analysis. Using the Eulerian–Eulerian method, Fani et al. [20] studied CuO–water nanofluid flow inside a trapezoidal MCHS. The effect of Brownian motion and viscous dissipation on thermal performance of MCHS were investigated.

As single-phase homogeneous model shows discrepancies with experimental results, and two-phase analysis seems time-consuming, several models have been proposed to explain substantial thermal enhancement of nanofluids. One of these models is thermal dispersion. Using mathematical expression of the dispersion model in porous media, Xuan and Roetzel [21] proposed this model for heat transfer enhancement in nanofluids. They suggested that the irregular movement of nanoparticles leads to thermal dispersion, so the increase of convective heat transfer of nanofluid over its base fluid is due to two factors: higher nanofluid thermal conductivity and thermal dispersion phenomena.

Wen and Ding [22] considered the effect of Brownian motion, as well as shear-induced and viscosity-gradient-induced particle migration on heat transfer of nanofluid inside a minichannel. They implied that the non-uniformity of concentration plays an important role in heat transfer enhancement.

Several studies have been conducted to take into account the effect of particle migration and dispersion phenomena together [23–26]. Bahiraei and Hosseinalipour [23] studied particle migration effect on convective heat transfer coefficient of TiO_2–water nanofluid using dispersion model. They showed that thermophoresis has a dominant effect in particle migration. They also conducted an experiment and compared the numerical results, which were in a good agreement. In another investigation [24], they used the same method along with homogeneous method and discrete phase modeling for Al_2O_3–water nanofluid flow inside a tube. Comparing with experimental data, they concluded that their thermal dispersion model gives the best results considering calculation time.

As mentioned, some researchers have studied nanofluid flow through a microchannel, but there are a few studies which focus on dispersion model. Also, using the dispersion model to investigate heat transfer in trapezoidal MCHS is not considered yet. As a matter of fact, the cross section of microchannels made by a common, inexpensive fabrication technique (anisotropic etching) in silicon substrate is either trapezoidal or rectangular, so it is important to broaden our studies for such important, useful microchannels. In the present work, the forced laminar convection