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Original Research Paper

Numerical analysis of nanofluid flow inside a trapezoidal microchannel using different approaches

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ABSTRACT

In this study, developing laminar forced convection of Al_2O_3/water nanofluid flow inside a trapezoidal microchannel has been investigated. The numerical simulation is conducted using two different methods which consider the effect of non-uniform nanoparticle distribution: Buongiorno's Two-component non-homogeneous model, and Eulerian-Lagrangian two-phase method. The results are compared to experimental data and also single-phase and dispersion methods. It is shown that the Eulerian-Lagrangian method predicts microchannel Nusselt number more accurately than Buongiorno's model. Particle distribution is not uniform in the cross section of microchannel, and with increasing Reynolds number this nonuniformity is more. Moreover, the effect of different forces on heat transfer is discussed. It is found that the influence of Saffman's lift force is negligible while Brownian and thermophoretic forces affect the heat transfer coefficient slightly. Furthermore, it is shown that the use of experimental correlation for nanoparticle Nusselt number makes the numerical results more accurate, so it is important to take into account the scale effects and use the suitable correlations.

1. Introduction

The high increase of heat dissipation from electronic chips has led to seeking new methods of cooling, in order to achieve longer electronic device life. Single phase liquid cooling through microchannel heat sink was first introduced by Tuckerman and Pease [1]. In their pioneer work, they suggested that decreasing the hydraulic diameter of channel would result in higher heat transfer rate. Several studies have been conducted in recent years [2–5]. As the carrier fluid plays an important role in microchannel heat sink's heat removal, adding solid high-conductivity nanoparticles enhances the performance of conventional coolants such as water and ethylene glycol. For the first time, this suspension of nanoparticles inside a base fluid was called nanofluid by Choi [6]. Nanofluids, due to their promising features, such as stability, high performance and slight increase in pressure drop, seem to have suitable characteristics for heat transfer. Thus, a lot of researchers have studied the nanofluid flow and heat transfer. Not only forced convection, natural and mixed convection of nanofluids have been investigated so far [7–9], although in the present work forced convection has been considered.

Several experiments have been conducted in recent years for nanofluid flow inside microchannels. Chein and Chuang [10] performed an experiment with CuO/water nanofluid flow inside trapezoidal microchannel with volume fraction from 0.2% to 0.4%. The results showed that the pressure drop increases slightly with adding nanoparticles and nanofluid can absorb more heat than its base fluid.

Jung et al. [11] investigated laminar forced convective heat transfer of Al_2O_3/water nanofluid inside rectangular microchannel. They measured Nusselt number at different volume fractions and showed that Nusselt number increases with increasing Reynolds number. Also at a volume fraction of 1.8%, the convective heat transfer coefficient rises up to 32%.

Wu and Cheng [12] experimentally investigated flow and heat transfer of alumina/water nanofluid through trapezoidal microchannel. The hydraulic diameter was 194.5 µm, and it was shown that with the increase of particle concentration, Prandtl number and Reynolds number, the Nusselt number increases.

In order to model the heat transfer enhancement of nanofluids, several methods have been proposed. Most of the theoretical investigations so far for nanofluid flow and heat transfer were based on single-phase model. In this approach, the nanofluid is considered to be homogeneous and nanoparticles are in thermal equilibrium with surrounding fluid. The equations of motion and

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Nomenclature

F	force, N/m^2
V	velocity, m/s
A	area, m^2
a	short base of microchannel, m
b	long base of microchannel, m
C_c	Cunningham correction factor
C_p	specific heat, J/kg K
D_B	Brownian diffusion coefficient, m^2/s
D_h	hydraulic diameter of microchannel, m
d_p	particle diameter, m
D_T	thermal diffusion coefficient, m^2/s
f	friction factor
h	convective heat transfer coefficient, W/mK
h	height of microchannel, m
k	thermal conductivity, W/mK
k_b	Boltzmann constant, $1.3806 * 10^{-23}\ \frac{m^2\ kg}{s^2\ K}$
l	MCHS length, m
m	mass flow rate, kg/s
Nu	Nusselt number
P	pressure, Pa
q''	wall heat flux, W/m^2
Re	Reynolds number
$S_{p,e}$	energy source term
$S_{p,m}$	momentum source term
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	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

avg	average
bot	bottom
f	fluid
in	inlet
m	mean
nf	nanofluid
out	outlet
p	particle
w	wall

heat transfer are solved using the modified thermophysical properties to take into account the addition of nanoparticles to the base fluid. One of the drawbacks of using single-phase homogeneous method, is that it is dependent on the proposed thermophysical properties, and there are so many ways of modeling these properties. The other approach in numerical simulation is two-phase method, which considers velocity and temperature difference between base fluid and nanoparticles and there is no need to consider a model for overall thermophysical properties of nanofluid. Eulerian-Eulerian and Eulerian-Lagrangian methods are two-phase methods which have been considered recently by the researchers of nanofluid field, although they have been implemented for many other applications other than nanofluids [13,14].

Using the Eulerian-Eulerian method, Kalteh et al. [15,16] studied Copper/water nanofluid flow inside an isothermally heated microchannel. It was concluded that the particle distribution is uniform and the relative velocity and temperature between solid and liquid phases are negligible.

Bianco et al. [17] numerically investigated developing laminar flow of alumina/water inside a tube using single and two-phase discrete particles model. The maximum difference of average Nusselt number between two-phase and single-phase models were 11% at $\phi = 4\%$.

Singh et al. [18] numerically and experimentally studied nanofluid hydrodynamics. The trapezoidal microchannels were fabricated in three different hydraulic diameters. Water and Ethylene Glycole were used as base fluid and alumina was added with 0.25%, 0.5% and 1% volume concentration. The theoretical investigation was made using Eulerian-Lagrangian two-phase method. The influence of volume fraction, hydraulic diameter, base fluid and particle diameter were discussed.

Fani et al. [19] found that the viscous dissipation and Brownian motion have influence on heat transfer of nanofluids. They investigated CuO/water nanofluid inside a trapezoidal microchannel heat sink with Eulerian-Eulerian method.

In addition to single and two-phase methods, There are some other models proposed to explain enhanced heat transfer of nanofluids, one of them is particle migration. Wen and Ding [20] showed that the non-uniform particle distribution over the tube cross section leads to the higher Nusselt numbers. They suggested that the Brownian motion, shear-induced and viscosity-gradient-induced particle migration in nanofluids can enhance heat transfer. The other method is porous medium approach. Pourmehran et al. [21] studied nanofluid flow inside microchannel heat sink and by using least square and numerical simulation based on saturated porous medium, optimized the nano particle size, volume fraction, flow rate and inertial force. Rahimi-Gorji et al. [22] presented analytical investigation based on the porous media approach and the Galerkin method and optimized the channel geometry.

Buongiorno [23] proposed a model in which the effective slip mechanisms in nanofluid flow is Brownian motion and thermophoresis. According to his work, by using order-of-magnitude analysis, energy transfer due to nanoparticle dispersion is insignificant, and Brownian motion and thermophoresis just cause the nanoparticles' slip. As the concentration of nanoparticles plays an important role in thermophysical properties of nanofluid, these properties influence the heat transfer characteristics of nanofluids. His proposed model for nanofluid modeling consists of four equations, 2 mass (nanoparticles and nanofluid), one momentum and one energy equation. In the other words, his model is nonhomogeneous and nanoparticle/fluid slip velocity is allowed, while there is thermal equilibrium and nanoparticle/fluid temperature differences doesn't exist.

Using Buongiorno's model, Heyhat and Kowsari [24] studied laminar alumina/water flow through a constant wall temperature circular pipe. They showed that particle migration has an important effect on heat transfer enhancement of nanofluids.

The other method known as dispersion model suggests that the increase of heat transfer of nanofluids is related to perturbation of velocity and temperature due to the presence of nanoparticles. This model was first introduced by Xuan and Roetzel for nanofluids [25] and was employed by several researchers [26–29].

Bahiraei and Hosseinalipour [30] studied the effect of thermophoresis on particle migration. In their model, they combined

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