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Numerical modeling of convective heat transfer of thermally developing nanofluid flows in a horizontal microtube

Abdolali Khalili Sadaghiani [a], Mehmet Yildiz [b], Ali Koşar [c,*]

[a] Faculty of Engineering and Natural Sciences, Sabanci University, Tuzla, Istanbul 34956, Turkey
[b] Faculty of Engineering and Natural Sciences, Integrated Manufacturing Technologies Research and Application Center, Sabanci University, Tuzla, Istanbul 34956, Turkey
[c] Center of Excellence for Functional Surfaces and Interfaces for Nano Diagnostics, Faculty of Engineering and Natural Sciences, Sabanci University, Tuzla, Istanbul 34956, Turkey

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In this study, forced convection heat transfer of alumina-water nanofluid (1–3 vol%) flows was investigated inside a microtube for Reynolds numbers ranging from 500 to 2000 using the Eulerian multiphase model. In the Eulerian model, the Brownian motion, thermophoresis effect and particle-particle interactions were taken into account. The single phase (homogeneous) model was also congruently implemented to compare with the implemented two-phase (suspended particle) model. In the single phase model, four sets of the most used correlations (viscosity, conductivity) were utilized to study the effect of different correlations on convective heat transfer. Convective heat transfer in a microtube with a length of 12 cm and inner and outer diameters of 500 and 700 μm, respectively, was modeled with relevant boundary conditions. The inlet temperature was set as 293 K, the atmospheric pressure was maintained at the outlet, and constant heat flux ranging from 25 to 300 kW/m^2 was imposed on the channel walls. Having validated the model, the effects of volume fraction on heat transfer and flow characteristics were discussed in detail. The velocity and temperature profiles of two phase model were obtained. The results of numerical modeling indicated that adding nanoparticles to the base fluid significantly changed velocity profiles and enhanced heat transfer. While the addition of 3 vol% alumina nanoparticle to the base fluid at Reynolds number of 2000 led to an enhancement in convective heat transfer up to 50%, the single phase model resulted in an enhancement of about 15%. It was observed that the homogeneous (single-phase) model underestimated thermal and hydrodynamic results of nanofluid flows.

1. Introduction

With fast advancements in microsystem technologies, it becomes a challenge to cool microelectromechanical systems (MEMS). As a result, many researchers have directed their efforts towards liquid coolants to improve heat transfer in micro devices. Consequently, research on heat and fluid flow in micro scale devices has rapidly progressed during this decade. Conventional fluids such as water have rather poor thermal properties. Therefore, many researchers have recently considered dispersing small particles in a base fluid to enhance cooling performances of micro and nano systems and studied thermophysical and hydrodynamic properties of such fluids [1–12]. The dispersion (consisting of discrete nanosized particles and a conventional base fluid) with improved thermal properties was named as nanofluid by Choi et al. [13,14], who showed that the thermal conductivity of the base fluid could be increased up to 100% upon adding nano-particles with a volume fraction of 1% to the base fluid.

There are many experimental studies on nanofluids in the literature [15–25]. Hwang et al. [6] conducted an experimental study in order to investigate pressure drop and convective heat transfer for laminar alumina-water nanofluid flows in a uniformly heated tube. They discussed the effects of nanoparticles' migration due to the viscosity gradient, Brownian diffusion, and thermophoresis on the enhancement of convective heat transfer of nanofluids and stated that the enhancement in convective heat transfer cannot be explained only by the increase in the thermal

* Corresponding author.
E-mail address: kosara@sabanciuniv.edu (A. Koşar).

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Nomenclature

C_p	specific heat capacity ($J/kg\ K$)
C_D	drag coefficient (−)
d_p	nanoparticles diameter (m)
D_B	Brownian diffusivity, (m/s)
D_h	hydraulic diameter of microchannel (m)
D_T	thermophoresis coefficient (m/s)
f	friction factor (−)
G	particle−particle interaction modulus (Pa)
G_p	viscosity coefficient ($Pa.s$)
h	convective heat transfer coefficient ($W/m^2\ K$)
h_v	volumetric heat transfer coefficient ($W/m^2\ K$)
h_p	fluid-particle heat transfer coefficient, ($W/m^2\ K$)
k	thermal conductivity ($W/m\ K$)
k_B	Boltzmann constant (J/K)
L	length (m)
Nu	Nusselt number (−)
P	pressure (Pa)
PP	pumping power (W)
Pr	Prandtl number (−)
Q	volumetric flow rate (m^3/s)
$\dot{q}$	heat flux (W/m^2)
R_{col}	particle−particle interaction force (N/m^3)
R_d	drag force (N/m^3)
R_{vm}	virtual mass force (N/m^3)
R_{pq}	interaction force (N/m^3)
Re	Reynolds number (−)
S	source term (unit varies)
T	temperature (K)
$\vec{v}$	velocity vector (m/s)
V	volume (m^3)
u,v	velocity components in the x and y directions respectively (m/s)
U	non-dimensional velocity in the x direction (−)
x,y,z	axial, vertical and normal coordinates, respectively (m), location (m)

Greek symbols

α	thermal diffusivity(m^2/s)
β	interphase drag coefficient (Pa/m), proportionality factor
θ,θ^*	non-dimensional temperatures (−)
λ	mean free path (m)
μ	dynamic viscosity ($Pa.s$)
ρ	density (kg/m^3)
τ	shear stress (Pa)
$\underline{\underline{\tau}}_q$	deviatoric stress tensor (Pa)
φ	volume fraction (−)

Subscripts

B	Brownian
col	collision of particles
eff	effective
f	base fluid
i	phase index (fluid, particle)
in	inlet
m	mean
nf	nanofluid
p	particle
q	phase (particle or liquid)
T	Thermophoresis
w	wall

conductivity of nanofluids, and can also be attributed to the flattening of the velocity profile. Singh et al. [24] investigated the effects of alumina nanoparticles' volume fraction and diameter on convective heat transfer of nanofluid flows in microchannels. They stated that the main reason behind different behavior of nanofluids may be due to shear induced migration of nanoparticles, which leads to nonuniform distribution of particles in nanofluid flows. Xuan and Lee [18] investigated the effect of volume fraction and Reynolds number on convective heat transfer of turbulent copper-water nanofluid flows. They concluded that dispersed nanoparticles provided remarkable enhancements in heat transfer. They proposed a new convective heat transfer correlation for nanofluid flows in a tube. Jung et al. [19] experimentally studied convective heat transfer of nanofluids in a rectangular microchannel and showed that Nusselt number obtained from nanofluid with 1.8% nanoparticle volume fraction was up to 32% higher compared to the pure water case. Wu et al. [20] investigated convective heat transfer characteristics of alumina-water laminar nanofluid flows in trapezoidal microchannels. They observed that pressure drop and friction factor in nanofluids slightly increased when compared to those of pure water, while Nusselt number considerably increased. They found that the alumina nanoparticles deposited on the inner wall of microchannels more easily with increased wall temperature.

Although the majority of the studies in the literature show that adding nanoparticles to base fluid enhances heat transfer, there are also investigations stating otherwise. Liu and Yu [21] conducted an experimental study to investigate single phase forced convection of alumina-water nanofluid flows. They concluded that, rather than enhancing convective heat transfer, the presence of nanoparticles caused deterioration of heat transfer in the transition and at the early stage of fully developed turbulent flows. Narvaez et al. [22] investigated heat transfer characteristics of alumina nanofluid flows by designing a coolant loop apparatus to model a typical aircraft avionics cooling loop. Their results showed no evidence for heat transfer enhancement with the addition of alumina nanoparticles.

From the numerical point of view, two major approaches, namely, homogeneous (single phase) [26] and suspended particle (two-phase) approaches have been employed to numerically investigate heat transfer characteristics of nanofluid flows [27]. Most of the studies have been performed using the single phase (homogeneous) model [11,28–36], where a homogeneous mixture of nanoparticles and base fluid is considered as the nanofluid, whereas nanoparticles and base fluid are considered as separate phases in the suspended particle (two-phase model) [37–39].

Khanafer et al. [28] numerically studied the effect of nanoparticle volume fraction on heat transfer. They presented an analysis based on thermophysical properties of nanofluids and proposed a heat transfer correlation for nanofluids. Kim et al. [29] studied convective instabilities driven by buoyancy and heat transfer characteristics of nanofluids. They showed that heat transfer was enhanced with the increase in volume fraction of nanoparticles. Roy et al. [30] investigated hydrodynamic and thermal fields of alumina-water nanofluids in a radial laminar flow cooling system. They observed that an addition of nanoparticles even with small volume fractions in a traditional coolant could