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Laminar nanofluid flow in microheat-sinks

J. Koo, C. Kleinstreuer *

Department of Mechanical and Aerospace Engineering, North Carolina State University, Campus Box 7910, Raleigh, NC 27695-7910, USA

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Abstract

In response to the ever increasing demand for smaller and lighter high-performance cooling devices, steady laminar liquid nanofluid flow in microchannels is simulated and analyzed. Considering two types of nanofluids, i.e., copper-oxide nanospheres at low volume concentrations in water or ethylene glycol, the conjugated heat transfer problem for microheat-sinks has been numerically solved. Employing new models for the effective thermal conductivity and dynamic viscosity of nanofluids, the impact of nanoparticle concentrations in these two mixture flows on the microchannel pressure gradients, temperature profiles and Nusselt numbers are computed, in light of aspect ratio, viscous dissipation, and enhanced temperature effects. Based on these results, the following can be recommended for microheat-sink performance improvements: Use of large high-Prandtl number carrier fluids, nanoparticles at high volume concentrations of about 4% with elevated thermal conductivities and dielectric constants very close to that of the carrier fluid, microchannels with high aspect ratios, and treated channel walls to avoid nanoparticle accumulation.

Keywords: Nanofluid; Brownian motion; Particle interaction; Effective thermal conductivity; Effective dynamic viscosity; Microheat-sink; Viscous dissipation

1. Introduction

In order to cope with ever increasing demands from the electronic, automotive and aerospace industries, cooling devices have to be small in size, light-weight and of high performance. The level and reliability of heat rejection efficiency largely determine the optimal design of cooling devices. Inspired by the microchannel heat-sink idea proposed by Tuckerman and Pease [1], several new designs and modeling approaches of high performance cooling devices have been proposed, including the fin model and the "porous medium" model. For example, Koh and Colony [2] introduced the porous medium model, which Tien and Kuo [3] expanded by adopting a modified Darcy's law for the momentum equation and volume-averaging for the energy equation. Kim et al. [4] compared analytically the one-equation and two-equation models for heat transfer in microchannel heat sinks. They reported that the one-equation model is valid only when the fluid phase is in local thermal equilibrium with the solid phase. They investigated parameters such as the Darcy number and conductivity ratio, which influence the validity of local thermal equilibrium, and concluded that the one-equation model is adequate for channels with high aspect ratios as well as for flows of highly conductive fluids. Zhao

* Corresponding author. Tel.: +1 919 5155261; fax: +1 919 5157968.
E-mail address: ck@eos.ncsu.edu (C. Kleinstreuer).

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Nomenclature

A	Hamaker constant [J]
c	specific heat [J/kg K]
d	surface distance [m]
D	particle diameter [m]
f	modeling function [–]
k	thermal conductivity [W/m K]
n	refractivity [–]
n	particle number density [m^{-3}]
Nu	Nusselt number [–]
p	pressure [N/m^2]
Pr	the Prandtl number [–]
q	heat flux [W/m^2]
Re	Reynolds number [–]
T	temperature [K]
U_0	inlet velocity [m/s]
w	interparticle potential [J]
x	axial coordinate [m]
y	surface distance [m]
y,z	coordinates [m]

Greek symbols

α	volume fraction [–]
β	modeling parameter [–]
δ	boundary layer thickness [%]
κ	Boltzmann constant [J/K]
μ	dynamic viscosity [N s/m^2]
ρ	density [kg/m^3]
Φ	viscous dissipation function [s^{-2}]
θ	dimensionless temperature [–]

Superscripts/subscripts

m, n	exponents
c	continuous phase
d	discrete phase
f	fluid
l	liquid phase
m	mass flux mean value for liquid phase
*	dimensionless quantities
n	normal component
p	particle phase
s	solid (wall) phase
w	wall ($y = 0$)

and Lu [5] and Kim [6] compared the fin model and porous medium model. They suggested that the porous medium model is more accurate and more suitable for optimizing microchannels with high aspect ratios.

In order to further enhance microheat-sink performance, the use of nanofluids is proposed. Nanofluids, as coined by Choi [7], represent a new class of engineered heat transfer fluids which contain metallic or carbon-based particles with an average size of about 10 nm. Specifically, aluminum- and copper-oxide spheres as well as carbon-nanotubes of an average diameter of 30 nm were employed with volume concentrations of 0.001–6%. They generated, under static conditions, elevated thermal conductivities where $k_{\text{nanofluid}} < 3k_{\text{carrier fluid}}$ [8–10]. Thus, the use of nanofluids, for example in heat exchangers, may result in energy and cost savings and should facilitate the trend of device miniaturization.

Traditional theories, such as Maxwell [11] or Hamilton and Crosser [12], cannot explain this thermal phenomenon. Thus, new assessments and mathematical models of the new apparent (or effective) thermal conductivity have been proposed. For example, Xuan and Li [13] summarized previous experimental observations and concluded that $k_{\text{eff}} \equiv k_{\text{nanofluid}}$ was a function of both the thermal conductivities of the nanomaterial and carrier fluid, in terms of particle volume fraction, distribution, surface area, and shape. Yu and Choi [14,15] modified the Maxwell equation and Hamilton–Crosser relation for k_{eff} of solid-liquid suspensions to include the effect of ordered nanolayers around the particles. They also matched the model with observed conductivities by adjusting the nanolayer thickness and conductivity. Jang and Choi [16] suggested an effective thermal conductivity model considering the particles Brownian motion. They focused on the heat transfer between particles and carrier fluid, which is not directly related to the heat transfer phenomena in the fixed reference frame. Furthermore, the validity of their thermal boundary layer thickness, which they defined as $3\delta_{BF}/Pr$, where $Pr \sim \mathcal{O}(10)$ and δ_{BF} is the diameter of the fluid molecule, is questionable when applying the continuum approach together with their Nusselt number correlation. Kumar et al. [17] developed a new expression for the thermal conductivity, considering the increase of effective heat transfer area and particle motion. However, increasing the particle surface area is merely an indirect mechanism for heat transfer enhancement of the whole system. To consider the impact of particle Brownian motion, they replaced the particle-phase heat conductivity with $c \cdot \bar{u}_p$, which is problematic because the thermal conductivity is a property of the particle material. Koo and Kleinstreuer [18] developed a new, experimentally validated thermal conductivity model which takes the effects of particle Brownian motion and induced surrounding fluid motion into account (see Section 2.2).