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Numerical optimization of microchannel heat sink (MCHS) performance cooled by KKL based nanofluids in saturated porous medium

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ABSTRACT

This work presents a thermal and flow analysis of a fin shaped microchannel heat sink (MCHS) cooled by different nanofluids (Cu and Al_2O_3 in water) based on “saturated porous medium” and least square method then results are compared with numerical procedure. The Forchheimer–Brinkman-extended Darcy equation is used to describe the fluid flow and the two-equation model with thermal dispersion is utilized for heat transfer. The effect of nanoparticle size and volume fraction, volume flow rate, inertial force parameter and channel width investigated on total thermal resistance, friction factor and Nusselt number. The effective thermal conductivity and viscosity of nanofluid are calculated by KKL correlation. Central composite design (CCD) is applied to obtain the desirability of the optimum value of the nanofluid flow characteristics. Results show that Cu–water nanofluid is more lucrative thermally *versus* Al_2O_3–water nanofluid. It is found that total thermal resistance, friction factor and Nusselt number are not sensitive to inertial effect while they change significantly due to other parameters such as nanoparticle size and volume fraction, volume flow rate and channel width. We obtained that Nusselt number enhancement has direct relationship with inertial force parameter and volume flow rate.

1. Introduction

Nanofluids are widely used in many engineering and industrial applications, for example, biological solutions, melts of polymers, paints, asphalts and glues etc. Nanofluid consists of a base fluid usually water, ethylene glycol, oil or engine oil and nanopowders such as Cu, CuO, Al_2O_3, TiO_2 or nanodiamond and usually a dispersant or surfactant to keep the nanoparticles' suspension stable.

The main features of using nanofluids in such systems are enhancing the heat transfer and viscosity improvement. Nanoparticles that are suspended in the base fluid will transfer heat with their Brownian motion and interactions. Considering these advantages, nanofluids attract more and more interests theoretically and experimentally. Researchers have been perplexed by the thermal phenomena behind the recently discovered nanofluids. One fascinating feature of nanofluids is that they have anomalously high thermal conductivities at very low nanoparticle concentrations. The term nanofluid was first proposed by Choi [1] to indicate engineered colloids composed of nanoparticles dispersed in a base fluid. Khanafer et al. [2] first conducted a numerical investigation on the heat transfer enhancement due to adding nanoparticles in a differentially heated enclosure. They found that the suspended nanoparticles substantially increase the heat transfer rate at any given Grashof number. Several studies have been performed on prediction of thermal conductivity of nanofluids [3–6]. Various studies to predict the effect of nanofluid on heat transfer rate have been presented by [7–10].

Das et al. [11] have found that the properties of a nanofluid cannot be predicted as weighted average of the fluid and solid nanoparticle components using simple mixture rules. Wang et al. [12] concluded that a combination of several factors such as surface action, particle motion and electro-kinetic effects caused the increased heat transfer in nanofluids. Xuan and Li [13] proposed increased surface area of particles per unit volume, collision between particles, and the dispersion of particles as the reason for enhanced heat transport. The reasons suggested by Keblinski et al. [14] include Brownian motion of the particles, molecular-level layering of the liquid at the liquid/particle interface, the nature of heat transport in the nanoparticles, and the effects of nanoparticle clustering. Buongiorno [15] considered seven possible fluid–particle interaction effects in nanofluid convection (diffusion, inertia, thermophoresis, diffusiophoresis, Magnus effect, fluid drainage, and gravity). Mahalingam [16] and Kishimoto and Ohsaki [17] have been dedicated on modeling and optimization of MCHS

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Nomenclature

a	wetted area per volume
Bi	equivalent Biot number (haH^2/k_{se})
c_p	specific heat
C	inertial force coefficient
f	friction factor
Da	Darcy number (K/H^2)
D_h	hydraulic diameter
h	interstitial heat transfer coefficient
$\bar{h}$	overall heat transfer coefficient
H	channel height
k_0	stagnant thermal conductivity
k_{bf}	thermal conductivity of base fluid
k_{nf}	effective thermal conductivity of nanofluid
K_p	particle thermal conductivity
K_s	solid thermal conductivity
k_{se}	effective thermal conductivity of solid
K	permeability
L_h	length of heat sink
$\overline{Nu}$	overall Nusselt number
p	pressure
P	dimensionless pressure gradient
Pe	Peclet number
q_w	heat flux over the bottom surface
Q	volume flow rate
R_{fin}	fin thermal resistance
R_{flow}	thermal resistance of MCHS
R_{total}	total thermal resistance of MCHS
T	temperature
u	velocity
U	dimensionless velocity
W_{ch}	width of channel
W_{hs}	width of the heat sink
Y	dimensionless vertical coordinate
t	thickness of the channel plate
A_1	kinematic viscosity parameter
A_2	porosity ratio
A_3	thermal conductivity ratio
Re_{nf}	Reynolds number of nanofluid flow

Greek symbols

α_s	aspect ratio of microchannel (H/w_c)
μ	viscosity
ε	porosity
ρ	density
ϕ	nanoparticles volume fraction
θ	dimensionless temperature
Γ	inertial force parameter (Cu$_m$)

Subscripts

bf	base fluid
f	fluid
m	mean value
nf	nanofluid
p	particle
s	solid
w	wall

through using "fin approach" which is based upon the assumption that fluid temperature is uniform in the direction perpendicular to coolant flow. Many of these researches reviewed by Philips [18]. Zhao and Lu [19] and Kim [20] compared two major MCHS model, fin approach and porous medium model and deduced that the fin approach has limited range of validity and on the other hand the "porous medium model" is more appropriate. Ghazvini and Shokouhmand [21] focused on two common analytical approaches, the Fin model and the porous media approach. And they investigated channel aspect ratio effect on heat transfer rate.

Recently electronic components are needed to work at a faster rate, and so high-powered integrated circuits have been produced in order to meet this this need. These high-speed circuits are expected to produce heat fluxes that will cause the circuit to exceed its permissible temperature. In order to solve this problem, microchannel heat sinks were introduced in 1981 by Tuckerman and Pease [22]; this heat sink is simply a substrate with many small channels and fins arranged in parallel, such that heat is efficiently carried from the substrate into the coolant. Their study was conducted for water flowing under laminar conditions through microchannels machined in a silicon wafer. Today, many cooling technologies have been carried out to meet the high heat dissipation rate requirements and maintain a low junction temperature. Among these efforts, the microchannel heat sink (MCHS) has received much attention because of its ability to make high heat transfer coefficient, small size and volume per heat load, and small coolant requirements. Recent progress in MCHS development was provided by Kandlikar et al. [23].

Recent developments in nanotechnology show that the nanofluid is an efficient coolant for electronic devices in this case some researches have done recently in the field of micro channel heat sink [24–28]. In order to enhance the thermal conductivity of working liquids and thereby further improve performance of the liquid-cooled microchannel heat sinks, the use of nanofluid has reported by many studies in literature, a summary of which is presented in recent review works [29–37]. Wang's group optimized the geometric structure of water-cooled and nanofluids-cooled MCHS using a three-dimensional heat sink model with the simplified conjugate-gradient method [38–40]. Recently some analytical investigation of microchannel heat sink have studied [41,42]. In this study we considered an analytical solution in order to solve the governed equation too. We used least square method (LSM) to solve the governing equations.

Least square method, collocation method (CM) and Galerkin method (GM) called the weighted residuals methods (WRMs). Lately, more attention has been dedicated to these analytical methods for using in the heat transfer problems [43–46]. Recently least square method is introduced by Bouaziz and Aziz [47] and is applied for prediction of the performance of a longitudinal fin [48]. They found that least squares method is simple compared with other analytical methods. Shaoqin and Huoyuan [49] developed and analyzed least squares approximations for the incompressible magnetohydrodynamic (MHD) equations. Recently Hatami and Ganji [50] and Sheikholeslami et al. [51] applied LSM and CM on fin performance and nanofluid in porous channel respectively. Hatami and Ganji [52] investigated heat transfer and flow analysis for a non-Newtonian nanofluid flow in the porous medium between two coaxial cylinders by LSM and CM.

Hatami and Ganji [52] investigated the heat transfer of a fin shaped microchannel heat sink (MCHS) cooled by Cu–water nanofluid and obtained temperature distribution in solid section (fin) and fluid section (Cu–water) by porous media approach and least square method and compared the results with numerical procedure. This work is continuing Hatami and Ganji's work [52]. He just investigated the heat transfer analysis of a microchannel heat sink cooled by Cu–water nanofluid considering the Brinkman nanofluid model for nanofluid viscosity and considered two parts of k_{nf} for nanofluid thermal conductivity containing two constant parameters obtained by an experimental study by Prasher et al. The model he used causes a limitation in usage of different nanofluid and extending the range of nanofluid volume fraction. Also he neglected the inertial force parameter for governing the equations. In this work, the viscosity of nanofluid and effective thermal conductivity are calculated by KKL (Koo–Kleinstreuer–Li) correlation. Also in the present paper, least square method (LSM) and

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