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Two-phase numerical simulation of hybrid nanofluid heat transfer in minichannel heat sink and experimental validation

Vivek Kumar, Jahar Sarkar*

Department of Mechanical Engineering, Indian Institute of Technology (B.H.U.), Varanasi, UP 221005, India

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ABSTRACT

Nanofluid cooled mini-micro channel heat sink has become a pleasant alternative for electronics and thermal applications recently due to its compactness and enhanced heat transfer characteristics. In the present study, a numerical simulation on laminar forced convection flow of DI water based Al_2O_3 nanofluid and Al_2O_3-MWCNT hybrid nanofluid in minichannel heat sink has been performed using two-phase mixture model to investigate the heat transfer and pressure drop characteristics. The experimental study on hybrid nanofluid flow in minichannel heat sink has also been conducted and validated the numerical model. Effect of some important parameters, such as, hydraulic diameter, channel aspect ratio, composition of Al_2O_3 and MWCNT in hybrid nanofluid and Reynold number has been investigated as well. Two-phase (heterogeneous) model has good agreement with the experiment result as compared to single phase (homogenous) approach. Maximum heat transfer coefficient has been found for 0.01 vol% (Al_2O_3 + MWCNT) (7:3) hybrid nanofluid for minichannel depth of 0.5 mm. Pressure drop has been found maximum for minichannel of 0.5 mm channel depth. The developing length can increase by using nanofluid. Maximum heat transfer coefficient improvement of 15.6% has been observed with no appreciable increment in pressure drop by using hybrid nanofluids.

Nomenclatures

A	effective heat transfer area (m^2)
Ar	channel aspect ratio
c_p	specific heat ($J{\cdot}kg^{-1} K^{-1}$)
d_h	hydraulic diameter (mm)
f	friction factor
h	heat transfer coefficient ($W{\cdot}m^{-2} K^{-1}$)
h_{ch}	channel height (mm)
k	thermal conductivity ($W{\cdot}m^{-1} K^{-1}$)
$\dot{m}$	mass flow rate ($kg{\cdot}s^{-1}$)
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
Q	heat transfer rate (W)
Re	Reynolds number
t	fin width (mm)
t_1	thickness of asbestos plate (mm)
t_2	distance from channel base to minichannel base (mm)
T	temperature (°C)
u,v,w,V	velocity ($m{\cdot}s^{-1}$)
vof	volume fraction
w_{ch}	channel width (mm)

Greek symbols

μ	dynamic viscosity (Pa·s)
ρ	density ($kg{\cdot}m^{-3}$)
φ	volume concentration

Subscripts

bf	base fluid
ch	channel
eff	effective
f	fluid
in	inlet
l	channel length
m	mixture
nf	nanofluid
np,p	nanoparticle
out	outlet

Abbreviation: MWCNT, multi walled carbon nanotube; MCHS, mini/micro channel heat sink

* Corresponding author.
E-mail address: jsarkar.mec@itbhu.ac.in (J. Sarkar).

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s surface

1. Introduction

Use of liquid-cooled Mini/Micro Channel Heat Sink (MCHS) is the effective way to tackle high heat dissipation in space constraint electronic devices and keep them in their desired designation for good functionality. Due to increasing demand of energy density, the further improvement in term of higher heat dissipation capability can be obtained by using liquid of better thermophysical properties and nanofluids [1] as well as hybrid nanofluids [2] have emerged as a viable candidate for their better heat transfer characteristics. In much practical application, it is required to adjust between different properties because a single material does not hold all the favorable characteristics required for a particular purpose, so hybrid terms come here [2]. Alumina nanoparticle is widely used in nanofluids due to low cost, availability, chemical stability and higher heat transfer improvement to pumping power increase ratio [3]. On the other hand, multi-walled carbon nanotube (MWCNT) has attracted many researchers due to their higher thermal conductivity and very high aspect ratio for application in nanofluids [4]. Hence, alumina and MWCNT can be the best combination in hybrid nanofluid for MCHS applications. Although, the experimental studies on heat transfer and fluid flow characteristics of nanofluid in MCHS have been conducted by many investigators [5–12], whereas, investigations on hybrid nanofluids flow in MCHS are very limited in the open literature [2,13].

Numerical simulation of nanofluid flow in MCHS is still challenging issue and many models can be applied to capture the complex mechanisms for heat transfer enhancement. Single-phase (homogeneous) model has been adopted in many investigations on MCHS with various nanofluids and hybrid nanofluids [14–18]. However, as the homogeneous model is unable to capture the heat transfer mechanism of nanofluids accurately, two-phase mixture model has been adopted recently for numerical simulation of nanofluids in MCHS. Kalteh et al. [19] simulated steady state, laminar flow and constant wall temperature conditions for Cu-water nanofluids in microchannels using Eulerian-Eulerian two phase flow approach. Their result reveals that mixture model is in good agreement with experimental data and mixture model theory is possibly applied to nanofluids flow in microchannels for laminar flow. Kalteh et al. [20] also studied the laminar convective heat transfer characteristics of an Al_2O_3-water nanofluid studied inside a wide rectangular microchannel heat sink both numerically by adopting two-phase Eulerian-Eulerian method using the finite volume approach and experimentally. Their study reveals that the two-phase Eulerian- Eulerian method results are in better agreement with experimental results than the homogeneous (single-phase) model. Moraveji and Ardehali [21] did a CFD modeling of laminar forced convection on Al_2O_3 nanofluid in mini-channel heat sink using four models (single phase, VOF, mixture, Eulerian). It found that two-phase models were more precise than single phase model when compared with experimental reference data. Single and two phase model has been used by Naphon and Nakharintr [22] to study laminar convective heat transfer of TiO_2 nanofluids in a minichannel heat sink. Two phase model results are closer to experimental result when comparing to single phase model. Esmaeilnejad et al. [23] numerically investigated the convection heat transfer and laminar flow of nanofluids in microchannel using two-phase mixture model. The result showed that the thermal resistance reduces about 27.2% and pressure drop increases approximately 50.7% with Peclet number (*Pe*) of 700 and 4 vol% concentration of nanoparticles with using shear thinning non-Newtonian base fluid. Recently, Ambreen and Kim [24] compared various numerical models (Homogeneous, discrete phase and Eulerian-Eulerian (Mixture, Volume of Fluid, Eulerian)) to investigate laminar forced convection of Al_2O_3 + water and TiO_2 + water nanofluids in the mini/micro channels and found Eulerian-Eulerian models is better as compared to homogenous model. Hence, the two phase model study carried the numerical calculations at least one step forward in terms of simulating the physics of nanofluids. The mixture model has been successfully used in numerical simulation of nanofluids in other heat transfer application also [25–29]. Hence, two phase mixture model has been employed in this study to simulate the hybrid nanofluids in MCHS.

However, the studies on numerical simulation of hybrid nanofluids flow in MCHS using mixture model is very limited. Nimmagadda & Venkatasubbaiah [30] employed two-phase mixture model to analyzed the heat transfer characteristics of (Al_2O_3 + Ag) hybrid nanofluid at different Reynold number and particle volume concentrations in a wide rectangular micro-channel. Two-phase mixture model has been used by Nimmagadda & Venkatasubbaiah [31] also for the numerical investigation to analyze the performance of microchannel under forced convection laminar flow using hybrid nanofluid (Cu + Al, water + methanol). However, a single geometry and single nanoparticles composition were considered in their study. Hence, with best of the authors' knowledge, no numerical simulation of hybrid nanofluids in MCHS using mixture model to consider geometric and nanoparticle composition (ratio of different nanoparticles) effects is not available in open literature.

The objective of present study is to numerically analyze the performance of minichannel heat sink of different geometries using Al_2O_3-MWCNT/DI water hybrid nanofluids using the mixture model. The experimental study has been conducted on minichannel heat sink to validate the numerical model. Uniform and constant heat fluxes have been applied from the bottom and all other surfaces are adiabatic for no heat losses. Effects of aspect ratio, hydraulic diameter, flow rate, temperature and nanoparticle composition have been discussed. Velocity and temperature profile along the channel length has also been studied as well using mixture model.

2. Formulation of the problem

Water, Al_2O_3/water nanofluids and Al_2O_3-MWCNT/water hybrid nanofluids have been used as a coolant in a minichannel heat sink (MCHS). The volume fraction of alumina used in Al_2O_3/water nanofluid is 0.01%. In hybrid nanofluid, Al_2O_3 and MWCNT have been mixed in three different ratios (9:1, 8:2 and 7:3) with the total volume fraction of 0.01%. The numerical analysis has been performed at the constant heat flux of 8.3 W/cm^2 and at the laminar flow regime $50 < Re < 500$.

The minichannel heat sink is made of aluminum, covered by an adiabatic acrylic plate on top. A schematic of the structure of a rectangular minichannel heat sink is shown in Fig. 1. The bottom surface of the heat sink is uniformly heated using heater supplied with AC current. Three different geometries are considered for numerical study based on the channel height taking 3 mm, 1 mm and 0.5 mm (aspect ratio 3, 1 and 2, respectively). Minichannel heat sink consists of 9 parallel rectangular shaped minichannels having length 30 mm, having channel width and fin width of 1 mm each. It may be noted that the minichannels are supposed to be identical in terms of both heat transfer and hydrodynamics.

3. CFD methodology

3.1. Governing equations for single phase model

Assuming incompressible, Newtonian and laminar flow thorough MCHS, the dimensional governing equations for steady state condition (continuity, momentum, and energy) using the single phase model are as follows:

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

x momentum equation: