International Journal of Thermal Sciences 50 (2011) 61–72

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Numerical investigation of cooling performance with the use of Al_2O_3/water nanofluids in a radial flow system

Yue-Tzu Yang*, Feng-Hsiang Lai

Department of Mechanical Engineering, National Cheng Kung University, Tainan 70101, Taiwan

ARTICLE INFO

Article history:
Received 8 March 2010
Received in revised form
26 August 2010
Accepted 30 August 2010
Available online 2 October 2010

Keywords:
Nanofluids
Radial flow
Laminar forced convection
Heat transfer enhancement
Heat flux

ABSTRACT

Simulation is conducted to investigate the forced convection flow of Al_2O_3/water nanofluid in a radial flow cooling system using a single phase approach. Computations are validated with experimental data available in the literature. Results show the same trend as revealed in some of the published works that the Nusselt number increases with the increase of Reynolds number and nanoparticle volume fraction, though the increase in pressure drop is more significant with the increase of particle concentration. Temperature-dependent thermophysical properties of nanofluids are found to have a marked bearing on the simulation. Under a fixed pumping power the nanofluid shows no higher heat transfer rate than water at heat flux $q'' \leq 3900\ \mathrm{W/m^2}$, while as the heat flux increases the enhancement using a nanofluid becomes more remarkable. Considerable improvements in the average Nusselt number and significant reductions in the thermal resistance under a given pumping power are revealed compared to that of pure water at some supplied heat fluxes. For 4% Al_2O_3/water mixture at $PP_{rel} = 0.5$, the average Nusselt number increases by about 4% and 10% respectively as the heat flux $q'' = 16,000\ \mathrm{W/m^2}$ and $q'' = 34,000\ \mathrm{W/m^2}$ is applied, while the thermal resistance can be reduced by 2.3% and 7%.

1. Introduction

Nanotechnology is considered by many researchers to be one of the significant forces that drive the next major industrial revolution of this century. A significant research effort has been committed to exploring the thermal transport properties of colloidal suspensions of nanosized solid particles (nanofluids). The presence of the nanoparticles in the fluids increased appreciably the effective thermal conductivity of the fluid and consequently enhanced the heat transfer characteristics. Nanofluids have a distinctive characteristic which is quite different from those of traditional solid-liquid mixtures in which milli-meter or micro-meter sized particles are involved. Thus, nanofluids are best for applications in which fluid flows through small passages because nanoparticles are small enough to behave similar to liquid molecules.

Experimental works [1,2] reported that with low nanoparticles concentrations (1–5 vol%), the effective thermal conductivity of the suspensions can increase by more than 20% for various mixtures. Xuan and Li [3] studied turbulent flow in a straight tube using a Cu/water nanofluid and revealed a 40% heat transfer enhancement. The forced convection flows of CNT (carbon nanotube) nanofluids through a horizontal tube were investigated by Ding et al. [4]. The results showed remarkable enhancement of the convective heat transfer and the enhancement depends on the flow conditions (Reynolds number), CNT concentration and the pH value, with the smallest effect of pH. Furthermore, for nanofluids containing 0.5 wt.% CNTs, the maximum enhancement was found to reach over 350% at Re = 800, which could not be attributed purely to the enhanced thermal conduction. Turbulent flow and heat transfer of three different nanofluids (CuO, Al_2O_3 and SiO_2) in an ethylene glycol and water mixture flowing through a circular tube under constant heat flux condition were numerically analyzed [5]. It was noted that at a constant Reynolds number, Nusselt number increases by 35% for 6% CuO nanofluids over the base fluid. The application of 6 nm copper-in-water and 2 nm diamond-in-water nanofluids in the micro-channel heat sinks was numerically discussed [6], and the Brownian motion was accounted in the mathematical model. Chakraborty and Roy [7] theoretically analyzed the influence of nanofluids on thermally developing and hydrodynamically developed electroosmotic transport in parallel plate microchannels. It was revealed that the influences of the nanofluids are much more conspicuous in the thermal entrance region, as compared to the thermally fully developed region. Moreover, appreciable effects of nanofluids are only observed for higher values of Peclet numbers, whereas their influences are virtually imperceptible for a lower Peclet number. Ho et al. [8] conducted experiments to investigate the cooling performance of

* Corresponding author. Tel.: +886 6 2757575x62172; fax: +886 6 2352973.
E-mail address: ytyang@mail.ncku.edu.tw (Y.-T. Yang).

1290-0729/$ – see front matter © 2010 Elsevier Masson SAS. All rights reserved.
doi:10.1016/j.ijthermalsci.2010.08.017

Nomenclature

A_w	heating area (m^2)
b	wafer thickness (m)
c_P	specific heat capacity (J/kg K)
D	inlet tube diameter (m)
D_h	hydraulic diameter (m) $D_h = 2\delta$
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
k_r	relative thermal conductivity $k_r = k_{nf}/k_{bf}$
L	inlet tube length (m)
Nu	Nusselt number $Nu = \frac{hD_h}{k_{nf}}$
$\overline{Nu}$	average Nusselt number
p	pressure (Pa)
PP	pumping power (W)
PP_{ref}	reference pumping power (W)
PP_{rel}	relative pumping power $PP_{rel} = PP/PP_{ref}$
Q	heat rate (W)
q''	heat flux (W/m^2)
r	radial coordinate
R_{ext}	radius of heated wafer (m)
R_i	radius of confinement disk (m)
R_{th}	thermal resistance (K/W)
Re	Reynolds number $Re = \frac{\rho_{nf} v_0 D_h}{\mu_{nf}}$
T	temperature (K)
T_{cr}	critical temperature (K)
T_0	inlet temperature (K)
$\overline{T}_w$	average wall temperature (K)
v	velocity (m/s)
v_0	inlet velocity (m/s)
v_r	radial velocity (m/s)
v_θ	circumferential velocity (m/s)
v_z	axial velocity (m/s)
z	axial coordinate

Greek symbols

δ	disks gap (m)
ϕ	particle volume fraction
μ	dynamic viscosity (kg/m s)
μ_r	relative dynamic viscosity $\mu_r = \mu_{nf}/\mu_{bf}$
θ	circumferential coordinate
ρ	density (kg/m^3)

Subscripts

b	bulk
bf	base fluid
f	fluid
nf	nanofluid
p	particle
rel	relative
s	solid
w	wall

a microchannel with Al_2O_3/water nanofluid, and the results revealed that the nanofluid-cooled heat sink outperformed the water-cooled one by examining the heat transfer rate and the pressure drop.

The results of Das et al. [9] indicated an increase of enhancement characteristics with temperature, which makes the nanofluids even more attractive for applications with high energy density. Nguyen et al. [10] investigated the viscosity of Al_2O_3/water nanofluid with two different particle diameters, 36 nm and 47 nm. It revealed that for higher particle fractions, viscosities of 47 nm particle-size are clearly higher than those of 36 nm size. The applications of Einstein's formula and those derived from the linear fluid theory not appropriate for nanofluids were also reported in the study. A comprehensive model for predicting the effective viscosity of dilute suspensions of nanoscale colloidal particles was presented in the work [11]. The results showed a profound influence of the combined particle agglomeration and breakup features as well as the interparticle interaction potentials on the rheological characteristics of the nanofluid. Angue Mintsa et al. [12] examined the effective thermal conductivity of alumina/water and copper oxide/water nanofluids, and the relative increase in thermal conductivity was observed to be more important at higher temperatures. Thermal conductivity characteristics of CNT nanorefrigerants were tested in the paper [13], and the experimental results showed that the thermal conductivities of CNT nanorefrigerants are much higher than those of CNT/water nanofluids or spherical-nanoparticle-R113 nanorefrigerants. Vadasz and Govender [14] theoretically investigated the heat transfer features, and found that the thermal wave effects via hyperbolic heat conduction could explain the excessively improved effective thermal conductivity of the suspension.

Moreover, the relative increase of the viscosity was found more than four times larger than that of the conductivity [15]. Yu et al. [16] studied the rheological behavior of ethylene glycol based nanofluids containing ZnO nanoparticles and the shear-thinning activity was found in high volume fraction. Experimental investigations have been carried out by Sahoo et al. [17] to study the rheological behavior of aluminum oxide nanofluid at temperature between -35 °C and 90 °C. In the work [18], the aggregation of particles was observed, and both Newtonian and non-Newtonian behaviors of the fluids were discussed.

Xuan and Roetzel [19] analyzed nanofluids with the dispersion model and derived correlations for predicting the Nusselt number. Buongiorno [20] discussed the possible mechanisms that can produce a relative velocity between the nanoparticles and the base fluid, and concluded that only Brownian diffusion and thermophoresis are important slip mechanisms in nanofluids. The heat transfer and viscous pressure loss characteristics of alumina–water and zirconia–water nanofluids in laminar flow regime were studied experimentally [21]. The heat transfer coefficients in the entrance region and in the fully developed region were found to increase by 17% and 27%, respectively, for alumina–water nanofluid at 6 vol % with respect to pure water. The zirconia–water nanofluid heat transfer coefficient increases by approximately 2% in the entrance region and 3% in the fully developed region at 1.32 vol %. The results showed that both the measured nanofluid heat transfer coefficient and pressure loss agree with the traditional model predictions for laminar flow. This suggested that the nanofluids behave as homogeneous mixtures.

To simulate the heat transfer and flow features of nanofluids, two approaches, a single-phase model and a two-phase model, have been adopted in the literature. Izadi et al. [22] numerically studied the laminar forced convection of Al_2O_3/water nanofluids in an annulus using a single phase approach, and found that temperature profiles are affected by the particle concentration. Simulations were carried out by Kumar et al. [23] with various thermo-physical models of the nanofluid which showed a significant influence of models on the performance. The periodic natural convection in an enclosure filled with nanofluids was examined [24]. A periodic behavior was found for the flow and thermal fields as a result of the oscillating heat flux, and the utilization of nanoparticles, in particular Cu, enhances the heat transfer especially at low Rayleigh numbers. Kuznetsov and Nield [25] studied the natural convective boundary-layer flow of