ARTICLE IN PRESS

Progress in Natural Science: Materials International xxx (xxxx) xxx–xxx

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Progress in Natural Science: Materials International

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

Original Research

Flow and heat transfer behaviour of nanofluids in microchannels☆

James Bowers[a], Hui Cao[b], Geng Qiao[c], Qi Li[b], Gan Zhang[b], Ernesto Mura[c], Yulong Ding[b,*]

[a] SSE Engineering Centre, Knottingley WF11 8SQ, UK
[b] Birmingham Centre for Energy Storage & School of Chemical Engineering, University of Birmingham, B15 2TT, UK
[c] Global Energy Interconnection Research Institute Europe GmbH, 10117, Germany

ARTICLE INFO

Keywords:
Nanofluid
Microchannel
Heat transfer
Pressure drop
Friction factor
Thermal conductivity
Viscosity

ABSTRACT

Flow and heat transfer of aqueous based silica and alumina nanofluids in microchannels were experimentally investigated. The measured friction factors were higher than conventional model predictions at low Reynolds numbers particularly with high nanoparticle concentrations. A decrease in the friction factor was observed with increasing Reynolds number, possibly due to the augmentation of nanoparticle aggregate shape arising from fluid shear and alteration of local nanoparticle concentration and nanofluid viscosity. Augmentation of the silica nanoparticle morphology by fluid shear may also have affected the friction factor due to possible formation of a core/shell structure of the particles. Measured thermal conductivities of the silica nanofluids were in approximate agreement with the Maxwell-Crosser model, whereas the alumina nanofluids only showed slight enhancements. Enhanced convective heat transfer was observed for both nanofluids, relative to their base fluids (water), at low particle concentrations. Heat transfer enhancement increased with increasing Reynolds number and microchannel hydraulic diameter. However, the majority of experiments showed a larger increase in pumping power requirements relative to heat transfer enhancements, which may hinder the industrial uptake of the nanofluids, particularly in confined environments, such as Micro Electro-Mechanical Systems (MEMS).

1. Introduction

The increasing miniaturization and modes of operation of electronic and optical devices requires an ability to remove larger amounts of excess heat per unit surface area from their components. Improved cooling performance can be achieved by increasing the available heat transfer surface area by utilizing, for example, fins and microchannels; however, the extent to which further cost-effective improvements can be made with this approach may be limited. Alternatively, improvements on the heat transfer properties of heat transfer fluids may offer further scope for improving the cooling performance. Liquids containing suspended nanoparticles, or the so called nanofluids, Choi [1], have been shown in various studies to exhibit higher thermal conductivities than that of their base liquids; see for example Sarviya and Fuskele [2] for a recent review. Nanofluids may therefore enable the operation of smaller and lighter cooling systems for use in applications, such as MEMS and NEMS (Micro and Nano Electro-Mechanical Systems), devices using lasers and optical fibres, fuel cells, etc. In order to take advantage of the heat transfer enhancements seen with nanofluids, the nanoparticles need to be as stable as possible to avoid clogging and sedimentation within heat transfer equipment. Only recently has the technology existed to cost effectively produce stable nanofluids with appreciable concentration and in large quantities.

1.1. Thermal conductivity enhancements of nanofluids

Thermal conductivity enhancement of a base liquid with the addition of suspended particles arises due to the larger thermal conductivity of particles compared with the base liquid. In the literature, there exist theoretical models for the thermal conductivity of particle suspensions, such as the Maxwell and Hamilton-Crosser models, which many researchers have successfully applied to a variety of particle suspensions. According to these models thermal conductivity enhancement of particle suspensions compared to their base liquids arises solely due to the larger thermal conductivity of particles compared to the base liquid. However, in the literature many researchers have observed thermal conductivity enhancements of nanofluids far in excess of these theoretical models. Moghadassi et al. [3] reported a 52% thermal conductivity enhancement of 30 nm CuO in paraffin with 5 vol%. The authors stated that nanoparticle – liquid suspensions generate a shell of organized liquid molecules on the particle surface. These organized molecules more efficiently transmit energy, via phonons, to the bulk of

☆ Peer review under responsibility of Chinese Materials Research Society.

* Corresponding author.
E-mail address: y.ding@bham.ac.uk (Y. Ding).

https://doi.org/10.1016/j.pnsc.2018.03.005
Received 13 November 2017; Accepted 22 February 2018

Nomenclatures

a	Microchannel height (m)
A	Cross sectional area of microchannel flow geometry (m^2)
α	Microchannel aspect ratio (-)
b	Microchannel width (m)
C^*	A measure of the agreement between experimental and theoretical fluid friction factors (-)
C_p	nanofluid specific heat capacity (J/kg K)
d	particle diameter (m)
d_a	particle aggregate diameter (m)
D_h	Microchannel hydraulic diameter (m)
f	Fluid friction factor (-)
f^*	Geometric constant (-)
F	fluid volumetric flowrate (m^3/s)
k	Thermal conductivity (W/m K)
k_B	Boltzmann constant (1.38×10^{-23} J/K)
L	Microchannel length (m)
P	Pressure (Pa)
P_P	Pumping power (W)
Pe	Peclet number (-)
Q_h	Heat flux (W)
Re	Reynolds number (-)
u	Fluid velocity (m/s)
x	Distance along microchannel cross section (m)
y	Empirical constant (-)
z	Empirical constant (-)

Greek symbols

ϕ	Particle volume fraction (-)
μ	Viscosity (Pa s)
ρ	Density (kg/m^3)

Subscripts

bf	Base fluid
max	Maximum
nf	Nanofluid
s	Solid

the fluid, hence the high thermal conductivity enhancement. Yasinskiy et al. [4] observed up to 53% enhancement in thermal conductivity of eutectic mixture of diphenyl oxide and biphenyl based nanofluids containing 2.44 vol% TiO_2 nanoparticles with 1-octadecanethiol as dispersant, aimed for concentrated solar power applications. Parsian and Akbari [5] investigated ethylene glycol containing 2 vol% Al_2O_3-Cu composite nanoparticles and observed 23–28% enhancement in thermal conductivity. Li et al. [6] found that the thermal conductivity enhancement of aqueous based silver (10–20 nm) nanofluids increased with increasing temperature from 25 °C to 50 °C. Karimi et al. [7] showed thermal conductivity enhancement up to 39% and 175% respectively for water-based magnetite and hematite nanofluids subject to a magnetic field.

A number of factors have been reported to affect the thermal conductivity of nanofluids. Two most important factors are nanoparticle size and temperature. Examples of the work on the particle size effect include Darvanjooghi and Esfahany [8] and Beck et al. [9] who showed that the thermal conductivity enhancement increased with increasing particle size, and Anoop et al. [10] who observed an opposite effect of particle size. Like the particle size effect, the work on temperature effect has also been controversial. Studies by Esfahani and Toghraie [11], Mahian et al. [12] and Koo and Kleinstreuer [13,14] showed an increased enhancement of thermal conductivity with an increase in temperature. Keblinski et al. [15], however, suggested little additional temperature effect on the thermal conductivity of nanofluids apart from that on the base liquid.

To interpret these experimentally observed larger enhancements than the theoretical predictions, various possible mechanisms were proposed by Keblinski et al. [15], Eastman et al. [16] and Chen et al., [17], including Brownian motion of nanoparticles, high thermally conductive liquid layers around nanoparticles, ballistic phonon transport, and nanoparticle clustering. Li and Xuan [18] also outlined other mechanisms such as interactions and collisions between particles, increased specific surface area due to suspended nanoparticles, and increased mixing and turbulence of the fluid. However, the exact mechanisms are still under debate.

1.2. Forced convective heat transfer with nanofluids in confined channels

Very fewer studies have been performed on the convective heat transfer of nanofluids, particularly in small channels. Lee and Mudawar [19] investigated forced convective heat transfer of aqueous suspensions of 36 nm Al_2O_3 nanoparticles (up to 2 vol% concentration) flowing through 21 parallel rectangular microchannels with 215 µm width, 821 µm depth and 4.48 cm length. An enhanced heat transfer coefficient was observed for laminar flows due to the addition of nanoparticles, specifically in the entrance region. They attributed this behaviour to nanoparticles having an appreciable effect on boundary layer development. Wen and Ding [20] came to similar conclusions from their experiments with Al_2O_3 nanoparticle suspensions in a much larger tube of 4.5 mm diameter. Lee and Mudawar [19] also concluded that due to the altered dependence on thermal conductivity of the Nusselt number with turbulent flow there was a much smaller enhancement compared to laminar flows. Chein and Chuang [21] investigated heat transfer of suspensions containing needle shaped CuO nanoparticles flowing through silicon microchannel heat sinks and found that the addition of nanoparticles resulted in higher heat transfer rates and lower wall temperatures at a flow rate lower than ~ > 10 ml/min, beyond which the benefits were not apparent. Koo and Kleinstreuer [13,14] investigated numerically the forced convective heat transport of suspensions of 20 nm CuO particles in water and ethylene glycol flowing through 300 µm by 100 µm channels. They suggested the use of nanofluids with a high-Prandtl number carrier fluid, a high particle volume concentration (~ 4%), and a highly thermally conductive particle with a dielectric constant close to that of the carrier fluid would give a good heat transfer performance. Maghrebi et al. [22] studied numerically the effects of flow and migration of nanoparticles under fully developed regime on heat transfer in a straight channel filled with a porous medium. The steady Darcy–Brinkman–Forchheimer equation was employed and nanoparticles were assumed to distribute non-uniformly inside the channel. It was shown that the local Nusselt number decreased with increasing Lewis number and the wall temperature gradient decreased as the Schmidt number increased due to the decreasing local Nusselt number. More recently, Nield and Kuznetsov [23] analysed numerically the forced convection of nanofluids flowing through a parallel-plate channel or a porous medium under laminar flow regime, taking into account of the effects of Brownian motion and thermophoresis. They showed that the combined effect of these two processes is to reduce the Nusselt number.

The modelling results of Koo and Kleinstreuer [13,14], Maghrebi et al. [22] and Nield and Kuznetsov [23] and the experimental data of Chein and Chuang [21] suggested that a low volume fraction of nanoparticles in nanofluids give a relatively small increase in the friction factor, and hence a small effect on the pressure drop and the pumping power. However, the small number of studies may not be representative as solution chemistry can have significant effects on nanoparticle