International Journal of Thermal Sciences 123 (2018) 1–13

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Heat transfer enhancement by silver nanowire suspensions in microchannel heat sinks

Eylül Şimşek [a], Sahin Coskun [b, c], Tuba Okutucu-Özyurt [a, *], Husnu Emrah Unalan [b]

[a] Dept. of Mechanical Engineering, Middle East Technical University, Dumlupınar Blv. No 1, 06800, Ankara, Turkey
[b] Dept. of Metallurgical and Materials Engineering, Middle East Technical University, Dumlupınar Blv. No 1, 06800, Ankara, Turkey
[c] Department of Materials Science and Engineering, Northwestern University, Evanston, IL, 60208, USA

A R T I C L E I N F O

Article history:
Received 21 November 2016
Received in revised form
20 June 2017
Accepted 28 August 2017

Keywords:
Silver nanowires
Silver nanofluid
Microchannel heat sink
Surfactant
Stability

A B S T R A C T

Convection heat transfer and pressure drop characteristics of water based silver nanowire suspensions flowing through CMOS compatible monolithic microchannel heat sinks are investigated experimentally. Three different rectangular channels of 200 μm × 50 μm, 100 μm × 50 μm and 70 μm × 50 μm cross sectional area are used during the experiments. The stability of the silver nanofluids is established by the added polyvinylpyrrolidone (PVP) as the surfactant. To investigate the potential heat transfer enhancement by the silver nanofluids, the experiments are performed with deionized (DI) water, PVP-DI water solution, and the silver nanofluid with added PVP. It is observed that the silver nanofluid had higher heat transfer coefficient than both the PVP-DI water solution, and DI water only. Moreover, all fluids have similar hydrodynamic performance. The prepared silver nanofluid sample is a successful example of a stable nanofluid that has very little surfactant such that the existence of the surfactant does not cause a decrease in the heat transfer coefficient, while maintaining the stability. Upto 56% enhancement in the heat transfer coefficient is reached with practically no increase in the pumping power. The study is the first in using silver nanowire suspensions for heat transfer enhancement.

1. Introduction

The use of microchannel heat sinks was first suggested by Tuckerman and Pease to remove high heat fluxes from small volumes [1]. An extensive series of studies followed this initial work to validate the usage of microchannels for cooling applications [2–7]. Initially, conventional liquids such as water were used as coolants in microchannels, however, the low thermal conductivity of the liquids was a limitation for removing higher heat fluxes from the channels.

One proposed solution to this problem is nanofluids which are obtained by the addition of high thermal conductivity nanoparticles (1–100 nm in size) in base fluids to enhance their thermal conductivities [8]. Due to the nanometer-size of the particles involved, the nanofluid usage does not cause any operational problems such as clogging or corrosion in the channels as in the case of micro-sized particles [9].

The major problem with nanofluid usage is the difficulty in maintaining long term stability [10,11]. To have a stable nanofluid, different techniques are employed which can be classified as physical and chemical methods. The addition of a surfactant is one of the approaches used during the production of the nanofluid to eliminate particle agglomeration. Although the surfactant usage is common, the investigation of its effect on the thermal performance is rare. Several experimental and theoretical studies have been performed to comprehend the improved thermophysical properties of nanofluids, especially their thermal conductivities [12–15]. To date, only one theoretical study included the effect of a surfactant layer in the thermal conductivity model [16].

The nanofluid studies commonly indicate that the heat transfer performance of the nanofluid is superior to its base fluid. The heat transfer enhancement varies depending on the particle size, the concentration of the particles/surfactant, and also on the particle material. In forced convection heat transfer studies, mostly metal oxide nanoparticles were investigated rather than pure metallic nanoparticles [17]. Nitiapiruk et al. [18] performed experiments

* Corresponding author.
E-mail address: okutucu@metu.edu.tr (T. Okutucu-Özyurt).

http://dx.doi.org/10.1016/j.ijthermalsci.2017.08.021
1290-0729/

Nomenclature

Symbols		**Subscripts**	
A	Area [μm^2, m^2]	avg	Average
C	Constant	Bf	Base fluid
c	Coverage factor	e	Electrical
c_p	Specific heat [kj/kgK]	f	Fluid
D_h	Hydraulic diameter [μm]	fd,h	Hydrodynamic
f	Friction factor	fd,t	Thermal
$\overline{h}$	Convective heat transfer coefficient [W/m^{2}K]	i	Inlet
k	Thermal conductivity [W/mK]	max	Maximum
l	Axial distance [m]	measured	Experimentally measured value
L	Length [mm, cm]	minor	Minor losses
M	Sample number	nf	Nanofluid
$\dot{m}$	Mass flow rate [kg/s]	np	Nanoparticle
n	Empirical shape factor	o	Outlet
Nu	Nusselt number	th	Thermal
P	Pressure [Pa]	w	Wall
$\dot{P}$	Pumping power [W]	**Abbreviations**	
Pe	Peclet number	CMOS	Complementary metal oxide semiconductors
q	Heat [W]	DAQ	Data acquisition system
q''	Heat flux [W/m^2]	EG	Ethylene glycol
r_h	Hydraulic radius [μm]	FM	Figure of merit
Re	Reynolds number	LMTD	Log mean temperature difference
s	Standard deviation	PCB	Printed circuit board
T	Temperature [°C]	PVP	Polyvinylpyrrolidone
u	Mean velocity [m/s]	SEM	Scanning electron microscope
U	Uncertainty	**Greek Symbols**	
$\dot{V}$	Volumetric flow rate [m^3/s]	γ	Aspect ratio (height/width)
x	Entrance length [cm]	μ	Dynamic viscosity [N.s/m^2]
y	Relative uncertainty	ρ	Density [kg/m^3]
		χ	Particle volume fraction
		ψ	Sphericity

with TiO_2 − water nanofluid in microchannels and used different thermophysical models in the calculation of Nusselt number and friction factor. Volumetric concentrations of the TiO_2 nanofluid samples were changed between 0.5% and 2%. Constant heat fluxes were applied to microchannels of 40 channels with 500 μm width, 800 μm height and 40 mm length. After the experiments, three different models were used to calculate the thermal conductivity and viscosities of the TiO_2 nanofluids. It was observed that Nusselt numbers calculated by different models were very close to each other so that different models can conveniently be used to estimate the thermal conductivity of the nanofluids. Moreover, the TiO_2 nanofluids yielded higher heat transfer coefficients compared to water for all volumetric concentrations.

Peyghambarzadeh et al. [19] examined the performance of two different nanofluids (water based CuO and Al_2O_3) in a heat sink that consists of 17 rectangular microchannels with a cross-sectional area of 400 μm × 560 μm. A constant heat flux was applied to the system and the average heat transfer coefficient with respect to Reynolds number was plotted to compare the performances of the two nanofluids. It was observed that both nanofluids had better thermal performances compared to pure water. Up to a critical Reynolds number, the ratio of the Nusselt number with the nanofluid to that with the base fluid (Nu ratio) increased with Reynolds number. However, Reynolds numbers higher than a limiting value caused a decrease in the Nu ratio. This limiting Reynolds number value should not be exceed so that the use of nanofluids could be justified at high heat removal rates.

Singh et al. [20] carried out experiments with alumina nanoparticles in water and ethylene glycol flowing through microchannels of 218 μm and 303 μm hydraulic diameters. The effects of base fluid type and nanoparticle concentration on the heat transfer performance in microchannels were investigated. Results of this study showed that the nanofluid yielded higher heat transfer coefficient than the base fluid and Nusselt number increased with an increase in the nanofluid concentration as expected.

Only a single study [21] has been encountered in the literature which investigated the effect of pure metallic nanoparticles such as gold and silver, and the effect of surfactant on heat transfer. In this study, the performance of spherical silver nanoparticles suspended in DI water in micro-pin fin heat sinks was studied. A relatively low volumetric concentration (0.00197%–0.0121%) of the silver nanoparticles was employed in the experiments. In addition, a solution with the surfactant only was prepared to compare its thermal and hydrodynamic performance relative to pure DI water, and to the silver nanofluid. It was observed that the nanofluid yielded higher heat transfer coefficient, but higher pressure drop relative to the surfactant-DI water solution.

In an earlier study, the authors of the present work performed experiments on pure gold nanoparticles in DI water with PVP added as the surfactant [22]. The nanofluid concentrations ranged from 0.125 to 1 mg/mL (0.00064–0.005% volume). It was shown that the PVP added gold nanofluid always exceeded the heat transfer performance of the PVP-DI water solution, however it occasionally yielded higher heat transfer coefficients compared to that by pure DI water depending on the nanoparticle size and the nanofluid mass flow rate. No detectable change was observed in the pressure drop.

In the present study, for the first time in the literature, the thermal and hydrodynamic performances of silver nanowires are investigated. The nanowires are suspended in PVP added DI water, and passed through microchannels. For this aim, three different MEMS-fabricated copper microchannels having cross sectional areas of 200 μm × 50 μm, 100 μm × 50 μm and 70 μm × 50 μm have been used. To differentiate the effect of the surfactant, three different coolants have been prepared: pure DI-water, a PVP-DI water solution, and a suspension of silver nanowires in DI-water with PVP added as the surfactant (referred to as silver nanofluid from this point on). The convection heat transfer coefficient and pumping powers have been compared for the flow of each coolant through the microchannels. The stability of the silver nanofluids