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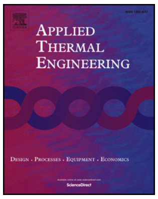

Research Paper

Thermal performance analysis of a microchannel heat sink cooling with copper oxide-indium (CuO/In) nano-suspensions at high-temperatures

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HIGHLIGHTS

- Thermal performance of CuO/liquid indium nanofluid was experimentally investigated.
- A rectangular microchannel was used as a heat exchanging medium.
- ~900% enhancement in Heat transfer coefficient compared to water was achieved.
- Liquid indium nanofluid was more suitable for high temperature applications.
- Penalty for pressure drop in peristaltic flow of CuO/indium was registered.

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ABSTRACT

An experimental investigation was conducted on the thermal performance and pressure drop of a microchannel heat sink under the low heat flux condition. Copper oxide nanoparticles (with the mean particle size of 50 nm) was dispersed in the liquid indium and experiments were conducted at 170 °C to avoid from solidification. The heat transfer coefficient, pressure drop and friction factor of the microchannel heat sink were experimentally measured at different mass concentrations of the liquid metal nanofluid and at different caloric temperatures. Results showed that with an increase in the applied heat flux to the microchannel, the higher heat transfer coefficient was achieved. In addition, with an increase in the peristaltic mass flow, higher heat transfer coefficient was registered. For the nanoparticle concentrations of up to 1%, no significant enhancement in the heat transfer coefficient was seen, however, for higher mass concentrations of up to 8%, the heat transfer coefficient increased and for the mass concentrations > 8%, the heat transfer coefficient decreased. The correlations available in the literature have failed to estimate the Nusselt number for the CuO/In nanofluid, thereby using the regression analysis, a new correlation was proposed for the Nusselt number with a deviation of ± 20%. A massive penalty in pressure drop was also registered for the liquid indium nanofluid at the mass concentration of 8% and higher.

1. Introduction

Process intensification (PI) in high-temperature systems such as solar thermal receivers and has received a great attention in recent years. PI in heat transfer phenomena not only results in the efficient design of the equipment but also reduces the space required for the process. Solar thermal receivers are heat exchanging tools which are widely used in concentrated solar thermal energy. The heat transfer fluid in a solar receiver reaches to temperatures as a high as 700 °C. considering the fact that state-of-the-art receiver can work at ~900 °C, most of conventional heat transfer fluid cannot be used in this temperature range. Moreover, such high temperature can cause some problems such as thermal shock and disintegration of fabrication material of the solar receiver. This is because thermal conductivity together with overall heat transfer coefficient in current solar thermal receiver is limited to the material and pool thermal conductivity of heat transfer fluid. Therefore, there is a need for further investigation to design a new generation of solar thermal receiver and to use a new thermal engineering fluid with superior thermal performance [1].

Microchannel heat exchanging systems are relatively new instrument with wide applications which have been targeted by PI and enable one to transfer significant amount of heat in a small space with the help of high surface area exposed to convective heat transfer domain. To achieve this, air, water or ethylene glycol has been recognized to be a

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Nomenclature

A	area, m^2
C_p	kJ/kg·°C
d	hydraulic diameter, m
H	height of microchannel, m
I	current, A
k	thermal conductivity, W/m·°C
l	length, m
m	a constant, see data reduction section
$\dot{m}$	mass flow rate, kg/m^2·s
N	number of channels
Q	heat, W
Q”	heat flux, kW/m^2
R_f	fouling thermal resistance of microchannel (m^2·°C/kW)
R_{th}	thermal resistance of microchannel (°C/W)
s	distance between thermocouple and wall of microchannel, m
T	temperature, °C
V	voltage, volt
W	width of microchannel, m
z	axial distance, m

Subscriptions

av.	average
b	bulk
in	inlet
Conv.	convection
out	outlet
th	thermocouple
w	wall
z	axial

Greek letters

η	fin efficiency
ρ	density, kg/m^3
ν	fluid flow rate, m/s
μ	viscosity, cP

suitable coolant for microchannel heat sinks. However, due to the demands for designing the high-temperature processes with superior heat dissipation, these coolants have reached their limitations as their thermal conductivity is limited (e.g. 0.65 W/m·°C) and their operating temperature is also limited to 200 °C (for ethylene glycol). Therefore, nanofluids as a new thermal engineering fluid was considered as a potential option for enhancing the physical properties of conventional fluids. Nanofluids have wide applications in different engineering and non-engineering sectors [2–5]. Interestingly, the heat transfer coefficient for a microchannel is ten times higher than conventional heat exchangers [6]. Likewise, for a same operating condition, the thermo-hydraulic performance of a microchannel is 50% larger than a conventional heat exchanger. Thereby, this is a driver for further investigations on the plausible application of microchannel in solar thermal receiver systems.

For the first time, Tuckerman and Pease [7] introduced a microchannel heat sink for cooling process of a processor, in which microchannel offered higher surface area for the heat transfer. They demonstrated that higher thermal performance in comparison with conventional processor coolers at the cost of pressure drop can be achieved, if a microchannel is used for the cooling process. The coolant was deionized water. Since Choi et al. [8] introduced the application of nanofluid in cooling systems, especial attention has been paid to the nanofluid flowing inside a microchannel heat sink. For example, Choi et al. [9] conducted a numerical study to investigate the cooling performance of a microchannel heat sink with nanofluids. Using a theoretical model of thermal conductivity of nanofluids that accounts for the fundamental role of Brownian motion, they showed that temperature contours and thermal resistance of a microchannel heat sink with nanofluids such as 6 nm copper/water and 2 nm diamond/water is decreased and the cooling performance of a microchannel heat sink with water-based nanofluids containing diamond (1 vol%, 2 nm) at the fixed pumping power of 2.25 W is enhanced by about 10% compared with that of a microchannel heat sink with water. However, a comparison between the amount of pumping power and heat dissipation, the enhancement was not plausible. More importantly, the operating temperature of the cooling system was limited to 100 °C and such systems cannot be used for high-temperature systems such as solar thermal receiver. Similar results was also reported in another work conducted by Chein et al. [10]. A theoretical analysis, followed by an experimental investigation were conducted to demonstrate that more energy and lower wall temperature can be obtained under the assumption that heat transfer is enhanced by the presence of nanoparticles. Experiments were then performed to verify the theoretical predictions. CuO/water was used at volume fractions of 0.2–0.4%. It was found that nanofluid-cooled heat sink can absorb more energy than water-cooled one when the flow rate was low. However, the limitation in operating temperature of 100 °C limited the application of microchannel for high-temperature systems. Another challenge with their experiments was the flow inconsistency and the issue due to the deposition of nanoparticles within the system over the extended time. Thus, they demonstrated that water is not a plausible coolant for the particulate system as it cannot retain the stability of coolant within the microchannel.

Shape of microchannel was also subject of some investigations such as the work reported by Xie et al. [11,12]. They performed a numerical study to investigate the thermal performance of a rectangular minichannel heat sink under a constant heat flux. They showed that the effect of dimension of channels, wall and bottom thicknesses of channel played a critical role on pressure drop and also the thermal performance. However, concentration changes in nanofluids were considered in the simulations. They also did not report any penalty or rise in pressure drop and friction factor. The study was limited to low-temperature conditions and conventional coolants e.g. water was considered in the work. The influence of type of working fluid on the thermal performance of microchannels have also been studied in the literature. For example, Ijam et al. [13] conducted a comparative investigation on thermal performance of a microchannel working with silicon/water and titanium/water nanofluids. They found out that silicon/water nanofluids presented a higher thermal conductivity, but titanium–water nanofluid could provide a more improvement on heat flux at 12.77%. Chai et al. [14–16] investigated the potential effect of the structure of design on of microchannel heat sinks and showed that an increase in heat interchanging area and redeveloping of thermal boundary layers were interacted on the fluid flow and heat transfer mechanism. However, There are studies such as [17] in which, deterioration of heat transfer rate and thermal performance is reported due to the over dispersion of the particles in the base fluid. A similar investigation conducted by Abu-Nada et al. [18] showed that the average Nusselt number reduced when the nanoparticles volume fraction was more than 5%. The results showed that there is an optimal concentration for nanoparticles adding into working fluids to ameliorate the heat transfer performance. Small particles might agglomerate and deposit inside the microchannel. Later, this results were confirmed by Sarafraz et al. [19–22].

According to the above-mentioned literature, in spite of the extensive researches conducted on the potential application of different