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The characteristics of convective heat transfer in microchannel heat sinks using Al_2O_3 and TiO_2 nanofluids☆

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ABSTRACT

The present study aims to provide an overall analysis about nanofluids flowing through microchannel heat sinks. Al_2O_3 and TiO_2 nanofluids based on deionized water with particle volume fractions of 0%, 0.1%, 0.5%, 1.0% were prepared by the two-step dispersion method. Nonionic surfactant polyvinylpyrrolidone (PVP) was added into the nanofluids to avoid particle aggregation and enhance stability. An ImageIR 3350 was used to get the temperature distribution on the substrate of microchannel heat sinks. The results reveal that the thermal conductivity and dynamic viscosity of Al_2O_3 and TiO_2 nanofluids are both improved with the increase of particle volume fraction. Compared with a rectangular microchannel heat sink, the performance of heat transfer in fan-shaped microchannel heat sink is more strengthened using Al_2O_3 nanofluids. The thermal motion of nanoparticles could promote the interruption of laminar flow and intensify the heat transfer between fluids and channel walls. The cyclical change with a fixed period on equivalent diameter could also help destroy the boundary layers.

1. Introduction

With the rapid development of science and technology, problems of heat dissipation in micro-device are becoming increasingly serious. Despite of the remarkable progress of strengthening heat transfer on technique, novel views are still expected to solve the troubles on heavy-duty apparatus or compact radiators. Nanofluids, proposed by Choi [1], represent a new type of heat transferring medium which can enhance the thermal conductivity of working fluids effectively by dispersing metallic or metallic oxide nanoparticles into the base fluids, such as water, ethylene glycol, etc. As the traditional air-cooled has almost reach its limitation, nanofluids are becoming one of the most potential liquid cooling working mediums.

Numerous studies have been carried out to investigate the property on heat conduction of nanofluids. It is found that the solid particles have distinct features apart from conventional dimension when its size is diminished to the radius of micron or nanometer. The drastic Brownian motion gives rise to the collision among particles and fluids, and the capability both on heat conduction and on heat transfer could be intensified. Murshed et al. [2] prepared nanofluids by dispersing spherical shape TiO_2 nanoparticles into deionized water with a diameter of 15 nm. The thermal conductivity with a volume fraction of 5% was nearly increased by 30% compared with deionized water. Hwang et al. [3] found that the thermal conductivity of nanofluids increased with the increase of particles volume fraction, but fullerene nanofluid based on water had a lower thermal conductivity due to its poor thermal conductivity of 0.4 W/(m·K). There are still many researchers who held contrary opinions according to their published works. Eapen et al. [4] and Shima et al. [5] discussed the effect of microconvection on the heat conduction of nanofluids. The findings confirmed that the microconvection induced by Brownian motion of nanoparticles is not the major mechanism on the thermal conductivity enhancement. Putnam et al. [6] measured the thermal conductivity of 4 nm Au-ethanol nanofluids; only 1.3% enhancement came out at the volume fraction of 0.018%. Utomo et al. [7] had also observed that titanic and alumina nanofluids did not show unusual enhancement on thermal conductivity. Buongiorno et al. [8] also performed a study of nanofluids worldwide using a variety of experimental approaches. The results suggested that nanoparticles could not help to enhance the thermal conductivity substantially. Those studies were disagreeable with the anomalous promotion frequently reported in the literature [9–11].

The van der Waals forces can hold nanoparticles together and lead to clusters in the end, while the stability gets worse with the evident appearance of two-layer effect. Xia et al. [12,13] added surfactants into the nanofluids as stabilizing agent to resist particle aggregation. The results revealed that the surfactants had an important effect on improving stability of nanofluids especially at an optimal concentration versus the nanoparticle volume fraction. However, it could also affect the physical characteristics as the zero-shear viscosity of nanofluids with 4.0 wt.% PVP was two times than that of water. Gu et al. [14] pointed out that high thermal conductivity of materials was not the decisive factor, because the particle shape could also have substantial effects on the heat

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Nomenclature

c_p	Specific heat, kJ/(kg·K)
D_h	Hydrodynamic diameter, mm
W	Width of the microchannel, mm
H	Height of the microchannel, mm
L	Length of the microchannel, mm
u_m	Mean velocity, m/s
Q_v	Volumetric flow rate, m^3/s
A_c	Channel heat transfer surface, mm^2
N	Channel number
Re	Reynolds number
ΔT	Temperature difference, °C
T	Temperature, °C
Δp	Pressure drop, kPa
f	Friction factor
h	Heat transfer coefficient, kW/(m^2·K)
Nu	Nusselt number
Q	Heat flow, W
q	Heat flux, W/cm^2
Greek symbols	
ρ	Density, 10^3kg/m^3
μ	Dynamic viscosity, mPa·s
ψ_v	Volume fraction, %
ψ_m	Mass fraction, %
λ	Thermal conductivity, W/(m·K)
Subscripts	
f	Base fluid
nf	Nanofluids
p	Nanoparticles
out	Outlet
in	Inlet
w	Wall
ave.	Average
m	Mean
max	Maximum
min	Minimum

conduction. Moreover, the effect of PH, zeta-potential and temperature on nanofluids is also obvious. As a great deal of studies has been performed to explore the heat conduction mechanism of nanofluids, the results could vary much from different experimental approaches. At the same time, researchers are paying more attention to the application in actual thermal devices using various kinds of nanofluids.

Microchannel heat sinks with different structure or dimension are designed to meet the requirements of the considerable heat dissipation in microelectromechanical systems. The geometry design plays an important role on the thermal and hydrodynamic performance. Zhang et al. [15] presented an experiment on circular microchannel heat sink with an inner diameter of 0.5 mm using Al_2O_3–water nanofluids as working fluid. The results showed that Nusselt number of Al_2O_3–water nanofluids increased remarkably by 10.6% with the increase of Reynolds number and particle volume fraction. Sohel et al. [16] also analyzed the thermal performance of a circular microchannel heat sink using more nanofluids at laminar flow. With the hydraulic diameter reduced to 0.4 mm, CuO–water nanofluid performed higher improvement of heat flux about 13.15% compared with water. And, the pressure drop increased linearly by adding more nanoparticles. Small reduction on equivalent diameter of microchannel will cause comparatively increase of velocity, and as a result, the process of heat convection could be accelerated.

The shape of microchannel could be manufactured to any reasonable structure, if it can help ameliorate the capability of heat transfer and is not difficult to achieve. Xie et al. [17] analyzed a rectangular minichannel heat sink numerically at a constant heat flux; the results indicated that the effect of dimensions, wall thickness and bottom thickness of channel played an important role on pressure drop or temperature. Based on the same minichannel, Ijam et al. [18] compared SiC–water with TiO_2–water nanofluid at turbulent flow. It was found that SiC–water nanofluids presented a higher thermal conductivity, but TiO_2–water nanofluid could provide a more improvement on heat flux at 12.77%. Mohammed et al. [19] compared three types of channel shapes (zigzag, curvy, and step) with a traditional straight microchannel using the finite-volume method (FVM). As a result, zigzag microchannel heat sink showed the more satisfied behavior with a lower temperature and a higher heat transfer coefficient. Chai et al. [20–22] focused on the structural design of microchannel heat sinks, in which it could be concluded that the increasing heat interchanging area and redeveloping of thermal boundary layers were interacted on the fluid flow and heat transfer mechanism.

The novel microchannel heat sink combined with the high thermodynamics capability nanofluids has provided a new thinking toward the high power capacity and heat loss in integrated circuit (IC) chips. However, Sommers et al. [23] found that the thermal performance deteriorated at a high particle mass fraction of 3%. The homologous consequence was gained by Abu-Nada et al. [24]. It is clear that the average Nusselt number reduced when the nanoparticles volume fraction was more than 5%. The results show that there is an optimal concentration for nanoparticles adding into working fluids to ameliorate the heat transfer performance. Small particles might agglomerate and abrasion in channel walls is unavoidable.

As it has been reviewed above, many researchers have investigated the characteristics of heat transfer in microchannel heat sinks with nanofluids, and different results were obtained. The comprehensive investigation of nanofluids flowing through microchannel heat sinks is necessary. As the microchannel heat sinks using nanofluids are feasible and effective approaches for strengthening convective heat transfer, Al_2O_3 and TiO_2 nanofluids are used as working fluids in the present work. Compared with the traditional rectangular microchannel heat sink, an optimized fan-shaped microchannel heat sink with the same dimension [25] is employed. What is more innovative is the use of an Infrared Thermal Camera, thus the temperature distribution on the substrate of microchannel heat sink will be watched clearly. Besides, the diameter of nanoparticles is chosen at 5 nm owing to the high specific surface area and the active thermal motion. The thermal conductivity, dynamic viscosity, pressure drop and heat transfer coefficient are all considered in this work. An overall analysis will be helpful to explore the physical mechanism during the process of fluids flow and heat transfer.

2. Experiment system

2.1. Description of the microchannel heat sinks

The rectangular and fan-shaped microchannel heat sinks are proposed by Xia et al. [25]. The number of microchannels is 30, and the size described in Fig. 1(a) [25] is designed with a dimension of 4 mm in length, which is 0.33 in aspect ratio. The whole width along the thirty microchannels is 6 mm. The hydraulic diameter is 0.15 mm. I-type inlet/outlet configuration of heat sink is chosen to fit the uniformity of fluids flow with a size of 10 mm in length, 10 mm in width, and 0.9 mm in thickness, respectively. The microchannel heat sink is inserted into an encapsulated part as shown in Fig. 1(b). The pressure taps are installed into inlet and outlet using for pressure drop collected.

The hydraulic diameter D_h is given as Eq. (1).

$$D_h = \frac{4W'H'}{2(W'+H')} \tag{1}$$