



Correlations of heat transfer effectiveness in a minichannel heat sink with water-based suspensions of Al_2O_3 nanoparticles and/or MEPCM particles

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ABSTRACT

In this work, an experimental study is carried out to examine the cooling performance of a minichannel heat sink using water-based suspensions of alumina nanoparticles (nanofluid), and/or microencapsulated phase change material (MEPCM) particles in terms of the averaged Nusselt number $\overline{Nu}_{ind}$, the wall temperature control effectiveness ε_{Tw} , and the averaged thermal resistance control effectiveness $\varepsilon_{R_{avg}}$ for the relevant parameters in the following ranges: the Reynolds number, $Re = 133$ – 1515 ; the mass fractions of the nanoparticles and/or MEPCM particles dispersed in the water-based suspensions, ω_{np} or $\omega_{mepcm} = 0$ – 10 wt.%; and the heating power. The heat sink was fabricated from copper with 10 rectangular minichannels which were maintained at a uniform base heat flux. The resulting experimental data for the various effectivenesses of using the water-based suspensions formulated in the minichannel sink were found well correlated with the relevant dimensionless parameters in general forms.

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1. Introduction

Along with the fast development of microelectronics, the cooling of electronic device plays a very important role on its performance and life because the drastically increased density of chips and current–voltage handling capability would lead to high heat accumulation within the electronic devices. Minichannel or micro-channel heat sinks become one of the best methods to improve the high heat accumulation due to its higher heat transfer performance, smaller geometric size and volume per heat load, lower coolant requirement and lower operational cost, etc. However, the thermal performance of minichannel heat sink is limited due to the thermal conductivity and specific heat of the coolants. Hence, to improve thermal performance, the use of functional thermal fluids [1] by compounding different substances or different phases of matter (solid, liquid, or gas) has raised increasing interest in view of their potential applications in technologies. The nanofluids and the solid–liquid phase change material suspensions (PCM suspensions), in which the solid particles (in nanometer size) and the micro-encapsulated phase change material (MEPCM) particles are, respectively, incorporated as the dispersed phase in the suspensions, have attracted vast attentions due to their perspective

potentials as high-performance coolants in various applications [1–3].

The reviews of the progress in exploring the heat transfer characteristics of various formulations of nanofluids are available in Refs. [4–8]. To improve thermal performance of the liquid-cooled mini or micro channel heat sinks, the water-based nanofluids in heat sinks have been studied [9–18]. As for the heat transfer correlations of nanofluids, some studies have been presented in Refs. [19–21]. On the other hand, some studies [22–32] have focused on the forced convection heat transfer characteristics of the suspensions dispersed with particles containing various solid–liquid phase change materials in ducts. The feasibility of utilizing MEPCM suspensions for the heat transfer enhancement in a forced flow has been demonstrated experimentally and numerically.

The thermophysical properties and convective heat transfer effectiveness of the hybrid Al_2O_3 nanoparticles and MEPCM particles were investigated experimentally by Ho and his colleagues [33,34]. The results showed that the dispersion of increasing fraction of Al_2O_3 nanoparticles can effectively improve the intrinsic characteristics of low thermal conductivity of the pure MEPCM suspensions, resulting even in significantly enhanced thermal conductivity with respect to the pure water. The effects of hybrid water-based suspensions of Al_2O_3 nanoparticles and MEPCM particles on forced convection heat transfer in circular tube have been experimentally studied by Ho et al. [35]. They concluded that significant enhancement in cooling effectiveness of the hybrid

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Nomenclature

A	base area of the heat sink (m^2)	T_w	wall temperature of the heat sink (K)
A_{base}	total base area of the heat sink (m^2)	$\bar{T}_w$	average wall temperature of the heat sink (K)
c_p	specific heat of the water ($\text{J kg}^{-1} \text{K}^{-1}$)	Y	correlated variables in Eqs. (7) and (8)
D_h	hydraulic diameter of channel (m)	ΔT_{ref}	reference temperature difference
$\bar{h}_{\text{itd}}$	average heat transfer coefficient based on inlet temperature difference ($\text{W m}^{-2} \text{K}^{-1}$)	$\varepsilon_{R_{\text{avg}}}$	average thermal resistance effectiveness
k	thermal conductivity of the coolant ($\text{W m}^{-1} \text{K}^{-1}$)	ε_{T_w}	wall temperature control effectiveness
k_s	thermal conductivity of the substrate material ($\text{W m}^{-1} \text{K}^{-1}$)	ω	mass fraction
L	channel length (m)	μ	dynamic viscosity ($\text{kg m}^{-1} \text{s}^{-1}$)
$\bar{Nu}_{\text{itd}}$	average Nusselt number base on inlet temperature difference	ρ	coolant density (kg m^{-3})
Pe	Peclet number	Subscripts	
R_{avg}	average thermal resistance (K W^{-1})	bf	based fluid
Re	Reynolds number	in	inlet
Sb_{in}^*	modified inlet subcooling parameter, $(T_M - T_{\text{in}})/\Delta T_{\text{ref}}$	itd	inlet temperature difference
Ste^*	Stefan number	m	hybrid water-based suspensions and based fluid
T_{in}	inlet temperature of coolant (K)	np	nanoparticles
T_{out}	outlet temperature of coolant (K)	out	outlet
T_{tc}	temperatures measured in the base block of the heat sink (K)	pcm	phase change material
		w	wall

suspension over the pure PCM suspension, nanofluid, or water. However, the convection efficacy of utilizing the hybrid suspension appears severely outweighed by pressure drop penalty from its drastically increased viscosity relative to the pure nanofluid or pure MEPCM suspension.

Although the above investigations examined the characteristics of cooling performance in heat sinks or ducts, to the best of the authors' knowledge, no detailed correlations about the heat transfer effectiveness in the literature have been described for the cooling performance using the water-based suspensions of alumina nanoparticles and/or MEPCM particles in minichannel heat sinks. This motivates the present study which the detailed correlations of heat transfer effectiveness in minichannel heat sinks cooled by using water-based suspensions of alumina nanoparticles, and/or MEPCM particles were examined and presented experimentally.

2. Experimental study

To measure the heat transfer effectiveness of minichannel heat sinks with water-based suspensions of Al_2O_3 nanoparticles and/or MEPCM particles, the schematic of the experimental setup was built and shown in Fig. 1. The experimental setup contains a water-based suspension reservoir, a centrifugal pump, heat exchangers, a test section, a data acquisition system and a DC power supply. The working water with Al_2O_3 nanoparticles and/or MEPCM particles enters the loop from a reservoir through a filter and is pumped by a centrifugal pump. Two constant temperature bathes installed upstream and downstream of the test section were used to control the inlet and outlet fluid temperatures. The minichannel heat sink was fabricated from copper and contains 10 rectangular minichannels. Each rectangular channel has a width of 1 mm, a depth of 1.5 mm, and a length of 50 mm with corresponding hydraulic diameter being 1.2 mm. For the test section, it consists of a minichannel heat sink, housing, a cover plate, and two plate heaters. To obtain relatively uniform flow distribution through each channel, the inlet and outlet pendulums were designed, where two resistance temperature detectors (RTDs) were installed to measure the temperature rise across the heat sink. In addition, seven T-type thermocouples installed along the

centerline of the heat sink base were used to measure the temperature at 3 mm beneath the base surfaces of the heat sink. The heat flux to the test section was provided by means of a main heater powered by a DC power supply and was determined using the measured voltage and current. To minimize the heat loss, a compensative heater is installed parallel to the rear surface of the main heater to ensure negligible temperature gradient between the two heaters. Experimental runs for a given condition generally reached steady state about 30–60 min. In this work, all the measured quantities were logged by a data acquisition system.

Preparation of water-based suspensions of Al_2O_3 nanoparticles and/or MEPCM particles has been illustrated in the related work [34] and therefore only its brief features are presented here. First, the ultra-pure Milli-Q water was used to be the base fluid. To formulate the water-based suspensions of Al_2O_3 nanoparticles and/or MEPCM particles, the commercial Al_2O_3 nanoparticles with a density of 3600 kg/m^3 and an average particle size about 33 nm and 99.95% purity (Nanotech, Kanto Chemical Co. Inc., Japan) and laboratory made MEPCM particles having *n*-eicosane as the core phase change material and the particle size in the range of 4–10 μm were, respectively, employed in an ultrasonic vibration bath for at least 2 h [32,34].

The effective thermophysical properties of the water-based suspensions include the density ρ , the specific heat c_p , the thermal conductivity k , and the dynamic viscosity μ . The measured results of these effective thermophysical properties of water-based suspensions of Al_2O_3 nanoparticles and/or MEPCM particles show an increase in thermal conductivity and heat capacity relative to pure water. Meanwhile, significant increase in the effective dynamic viscosity was found for the water-based suspensions, as compared with that of pure water. The more details are available in the related works [34,35].

3. Data reduction

In this work, the electric input power q_o applied during the experiments for the PCM suspensions was corrected to account for wall heat conduction losses through the housing and insulation, which was estimated comparing the supplied heat input to the

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