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Cooling performance of MEPCM suspensions for heat dissipation intensification in a minichannel heat sink

C.J. Ho [a], Wei-Chen Chen [a], Wei-Mon Yan [b,*], Mohammad Amani [c]

[a] Department of Mechanical Engineering, National Cheng-Kung University, Tainan 70101, Taiwan
[b] Department of Energy and Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, Taipei 10608, Taiwan
[c] Department of Mechanical and Energy Engineering, Shahid Beheshti University, Tehran, Iran

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ABSTRACT

This research study investigated the cooling performance of a minichannel heat sink that employed suspensions of microencapsulated phase change material (MEPCM) particles as the working fluid. The heat sink made from copper consisted of 10 rectangular minichannels, with a length of 50 mm, depth of 1.5 mm and a width of 1 mm. A uniform heat flux was used for heating the mini channel heat sink and the Reynolds numbers were in the range of 133–1515. The concentration of the MEPCM particles scattered in the water varied from 0 to 10 wt%. The experimental data showed that the wall temperature highly relied upon the Reynolds number and the increment of Reynolds number lead to the reduction of wall temperature for the coolant with or without MEPCM suspension in the minichannel heat sink. Moreover, the wall temperature got reduced for a coolant with MEPCM, compared to that without MEPCM especially at lower Reynolds numbers. Interestingly, the measured results revealed that the coolant with MEPCM particles was effective in cost performance than the pure coolant. The best cooling performance compared to that of pure water was observed for 2% MEPCM concentration within the considered range of flow rates.

1. Introduction

The performance of cooling systems and the problems of removing heat especially from electronic equipment have recently gained significant attention due to the reduction in dimensions of these devices and increase in their heat generation. Therefore, performing optimization processes and novel thermal management are crucial to maintain electronic components at their best efficiency. Microchannel heat sinks have been firstly introduced in early 1981, and the potential rate of 1000 W/cm^2 for heat flux removal has been reported in microchannels for single-phase forced convective cooling. A minichannel heat sink has been constructed from multitude parallel minichannels with different working coolant (i.e., engine oil, water, ethylene glycol). The performance of a minichannel heat sink extremely depends on the specific heat and the thermal conductivity of the coolants due to their limited heat transfer performance. Applying particle materials such as solid nanoparticles or microencapsulated phase change materials (MEPCMs) to a base fluid can offer remarkable thermal intensification.

Numerous investigations have been focused on the minichannel design and applications, which can be generally classified into two main types: first one is by applying different nanofluids (TiO_2, SiC, Al_2O_3, etc.) and the second is to evaluate the scaling effects of micro/minichannels with different structures (i.e. circular fin, rectangular, triangular) [1]. Ijam and Saidur [2] have observed the maximum enhancement of 12.77% for TiO_2–water and 12.43% for SiC–water nanofluid in the cooling performance of a minichannel heat sink with turbulent flow regime. Vafaei and Wen [3] reported the maximum enhancement of 40% in thermal performance of a horizontal minichannel heat sink in the fully developed regime by using Al_2O_3–water nanofluid. It was revealed that the heat transfer intensification of using TiO_2–water and Al_2O_3–water nanofluids overcame the negative impact of increasing pumping power [4,5]. According to Ijam et al. [6], applying TiO_2 and Al_2O_3 nanoparticles into the base fluid at 4 vol% and 0.1 m/s will lead to the maximum pumping power of 0.12437 W and 0.000552 W, respectively. On the other hand, applying alumina nanoparticles may pose a little surface imperfection problem due to the potential sedimentation of nanoparticles which would result in the reduction of thermal performance [7]. Ghasemi et al. [8] investigated the effect of different volume fractions of alumina nanoparticles in the base fluid in a triangular minichannel heat sink under the

* Corresponding author.
E-mail addresses: wmyan1234@gmail.com, wmyan@ntut.edu.tw (W.-M. Yan).

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Nomenclature

A_{base}	total base area of the heat sink (m^2)
COP	cost of performance
c_p	specific heat
D_h	hydraulic diameter of channel (m)
H_{ch}	height of channel at inlet (m)
k	thermal conductivity of the coolant ($Wm^{-1}\,K^{-1}$)
k_s	thermal conductivity of the substrate material (Wm^{-1} - K^{-1})
L_{ch}	channel length (m)
N	number of channels
Re	Reynolds number
$\dot{Q}$	volumetric flow rate (cm3/min)
Ste^*	Stefan number
R_{avg}	averaged thermal resistance
R_{max}	overall thermal resistance ($K\,W^{-1}$)
q_f	heat input carried by the working fluid
T_{tc}	temperatures of embedded in the base block of the heat sink (K)
T_{in}	inlet temperature of coolant (K)
T_{out}	outlet temperature of coolant (K)
T_w	local temperature along the centerline of the heated wall (K)
$\overline{T}_w$	average temperature of the channel bottom wall (K)
$T_{w,\max}$	maximum wall temperature on the heat sink (K)
u_m	average velocity of fluid at the each channel ($m\,s^{-1}$)
W_{ch}	width of channel at inlet (m)
W_{rib}	rib width (m)
Greek	
θ_w	dimensionless wall temperature
ΔP	pressure drop
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	coolant density ($kg\,m^{-3}$)
Ω	pumping power (W)
ω	mass fraction
subscripts	
bf	based fluid
eff	effective
in	inlet
m	hybrid water-based suspensions and based fluid
out	outlet
pcm	phase change material
w	wall

extreme heat flux and showed that the friction factor and heat transfer coefficient increased when the nanoparticle concentration was increased. Sohel et al. [9] revealed that applying 0.25 vol% Al_2O_3 nanoparticles decreases the base temperature of the minichannel heat sink and the thermal resistance, about 2.7 °C and 15.72% compared to the pure water, respectively. Zhang et al. [10] studied the simultaneous influence of applying nanoparticles and using micro-fin structure as two thermal improvement techniques on the heat transfer performance of a multiport minichannel flat tube. They reported the maximum enhancement of 158% in Nusselt number at Re = 3600, and also proposed an optimal heat transfer scheme.

Among the conventional particulate suspensions, MEPCM particles feature a superior effective specific heat and have been employed in various applications because of their capability of thermal energy storage and convective heat transfer performance [11]. This thermal improvement lead to various changes like, the MEPCM particles interaction in the base fluid, the miniaturization of phase change material (PCM), large surface area per unit volume, and absorption latent heat in MEPCM suspensions during the melting process [12]. However, it should be noted that this improvement is limited to a certain extent, due to low latent heat of fusion of PCM and the high viscosity [13]. In fact, the complex behavior of natural heat convective of MEPCM slurries was related to complex thermophysical and rheological properties of these materials during phase change process [14]. Qiu et al. [15] employed MEPCM slurry in a PV/T thermal and power system and revealed that the net overall solar performance can improve about 83%. Chen et al. [16] reported that in spite of the fact that using MEPCM particles unfavorably increases pumping power, their beneficial enhancement in heat transfer proved the great applicability of such materials in heat transfer applications. In another study, Song et al. [17] reported that the thermal performance of MEPCM slurry can be slightly affected by the turbulent degree of the fluid. Huang et al. [18] revealed that applying external heterogeneous magnetic field provides thinner thermal boundary layers and consequently increases heat transfer. However, this enhancement is weaker in higher MEPCM particle concentrations. Allouche et al. [19] investigated the applicability of using MEPCM particles in an air conditioning system and reported the energy storage of <50% by using these materials compared to water after 10 h of charging.

Although a large number of studies have been conducted on the heat transfer characteristics of MEPCM suspensions and several reviews are being published to evaluate the vast application of these materials [20–22], a few investigations have been focused on the effects of MEPCM particles on the thermal performance of the minichannel heat sinks. Dammel and Stephan [23] studied the heat transfer performance of the laminar flow of MEPCM in a rectangular minichannel heat sink. They reported that these suspensions showed Newtonian behavior and the highest degree of latent heat was observed in a particular range of parameter combinations. Rao et al. [24] revealed that the thermal performance of MEPCM suspensions highly depend on the particle concentration and flow rate. According to their results, the influence of suspensions was greater at lower flow rates and they observed notably less thermal performance at higher flow rates compared to water. Similarly, Ho et al. [25] also reported that greater heat transfer enhancement can be observed at lower flow rate of coolant with lower values of latent/sensible heat ratio in a minichannel heat sink. They indicated that the thermal improvement may be reduced at higher latent/sensible heat ratio. This implies the fact that the heat transfer intensification by using MEPCM with higher latent/sensible heat ratio is not significant compared to the distilled water. In another study, Ho et al. [26] investigated the simultaneous influence of adding Al_2O_3 nanoparticles and MEPCM particles into the base fluid on the thermal performance of a minichannel. They reported that the thermal performances of nanofluid and MEPCM particles highly vary according to the flow rate of coolant, whereas that of the hybrid water-based suspension did not depend on the flow rate.

Although the above mentioned studies investigated the flow and heat transfer characteristics in minichannel heat sinks, the scarcity of investigation in this field is obviously due to the com-