International Communications in Heat and Mass Transfer 94 (2018) 96–105

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Comparative study on thermal performance of MEPCM suspensions in parallel and divergent minichannel heat sinks

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ARTICLE INFO

Keywords:
Divergent minichannels
Minichannel heat sink
Hydrothermal performance
MEPCM suspension
Forced convection effectiveness

ABSTRACT

In this work, the augmentation in the hydrothermal performance of parallel and divergent minichannel heat sinks (MCHSs) containing microencapsulated phase change material (MEPCM) suspensions is investigated. Accordingly, the effect of diverging minichannels with the angles of 1.38° and 2.06° on the pressure drop and heat transfer performance in the presence of 2%, 5%, and 10% MEPCM particles at different Reynolds numbers from 238 to 1375, under various different heat fluxes of 3.2×10^4, 4×10^4, and 4.8×10^4 W/m^2, with the inlet temperature of 34 ± 0.2 °C is evaluated. The results also compared with the corresponding data in a parallel MCHS. It was found that the implementation of MEPCM suspension yielded to the increase of both the heat transfer and pressure drop. Diverging the minichannels and incrementing its angle significantly reduced the pressure drop penalty, especially at higher Reynolds number and greater mass fractions. The heat transfer effectiveness was also increased by diverging the minichannels with the angle of 1.38°, especially for higher concentrations and higher heat fluxes. The increment of the divergence angle to 2.06° had a detrimental impact on the thermal performance of the suspension and decreased the heat transfer coefficients to even less that that in the parallel MCHS. The results reveal that diverging the minichannels can effectively intensify the contribution of MEPCM suspensions in heat sinks in a certain range of parameter combinations.

1. Introduction

For more than two decades, the implementation of microencapsulated phase change material (MEPCM) suspensions as working fluid in cooling/heating applications (i.e., thermal energy storage) has received increasing attention due to the advantage of latent heat absorption [1–3]. Fang et al. [4] studied the melting process of hollow cylinder MEPCM composites and revealed that the duration of the phase change process is dependent on the concentration of PCM particles and more energy is converted to latent heat for higher fraction of MEPCM particles. Moreover, they investigated the effect of presence of additives, and found that the duration of phase change process is decreased and the homogeneity of the temperature distribution is increased in the presence of these additives. These phenomenon was attributed to the high thermal diffusivity of additives. Ho et al. [5] investigated the transient thermal energy storage of MEPCM suspension in an enclosure. They reported that the rate of melting process is directly proportional to the Stefan number. In addition, the thermal latent heat storage was found to be mainly dominated by the subcooling number. In another study, Ho et al. [6] reported that incrementing the temperature difference leads to the faster transient response. In addition, they proposed new correlation for correlating the accumulated energy through the hot wall in terms of the Fourier number *Fo*, subcooling parameter Sb_c, Stefan number Ste_m. Wang et al. [7] analyzed the influence of porosity in phase change composites and disclosed that the carbon network structure would be significantly denser by addition of 24 wt% expanded graphite, corresponding the achievement of 24-fold increase in the thermal conductivity compared to the pristine paraffin. Su et al. [8] performed an investigation on the implementation of MEPCMs for solar thermal energy storage applications. They showed that the encapsulation efficiency and core material content were increased due to the nucleating agent (ammonium chloride). The type of emulsifier was also found to significantly affect the morphology of the capsules. They noted that their synthesized MEPCM materials had an overall effective thermal conductivity of nearly two times higher than that of the most PCM storage units. Siao et al. [9] conducted a study on

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https://doi.org/10.1016/j.icheatmasstransfer.2018.03.023

Nomenclature

A	base area of the heat sink (m^2)
A_{base}	total base area of the heat sink (m^2)
C_p	specific heat of the water ($J\,kg^{-1}\,K^{-1}$)
D_h	hydraulic diameter of channel (m)
$\bar{h}$	average heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
H_{ch}	height of channel at inlet (m)
k	thermal conductivity of the coolant ($Wm^{-1}\,K^{-1}$)
k_s	base block thermal conductivity ($Wm^{-1}\,K^{-1}$)
L_{ch}	channel length (m)
N	number of channels
$\overline{Nu}$	average Nusselt number
Δp	pressure drop along the channel (kPa)
Re	Reynolds number
q_{eff}	effective heat input carried by the working fluid ($W\,m^{-2}$)
q_{eff}''	imposed heat flux ($W\,m^{-2}$)
$\dot{V}$	volumetric flow rate (cm^3/min)
Sb_{in}^*	modified inlet subcooling parameter, $(T_m - T_{in}) / \Delta T_{ref}$
Ste^*	Stefan number
T	temperature (K)
T_{tc}	temperatures of embedded in the base block of the heat sink (K)
T_w	local wall temperature (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

β	divergence angle of minichannels
ε	average heat transfer coefficient ratio
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	coolant density ($kg\,m^{-3}$)
ω	mass fraction

Abbreviations

PCM	phase change material
MEPCM	microencapsulated phase change material
MCHS	minichannel heat sink

Subscripts

bf	based fluid
eff	effective
in	inlet
out	outlet
w	wall

the transient thermal behavior of MEPCM suspensions in a partitioned enclosure under differential heat input applied by two horizontal isothermal surfaces. It was obtained that the net energy storage varies directly relative to the time and reaches to the steady state condition more quickly at elevated temperature gradients between hot and cold walls. Ho et al. [10] focused on the thermal behavior of MEPCM suspensions flowing through a circular tube and showed that the local and average values of the heat transfer coefficient were enhanced up to 42% and 14%, respectively, by adding 10 wt% MEPCM particles into the base fluid. They noted that there is an optimum range of flow rate which results in the highest suppression in the wall temperature profile, contributing to the elevated forced convection.

Another technique for improvement of the efficiency of cooling systems is the miniaturization of the heat sinks, which has led to the fabrication of the micro- and minichannel heat sinks (MCHSs). Recently, significant attentions have been conducted on the performance intensification of heat transfer using MCHSs. In particular, various researchers have investigated the contribution of MEPCM suspensions to augment the cooling/heating efficiency in various devices such as MCHSs. The implementation of MEPCM to MCHSs has offered remarkable cooling efficiencies. Rao et al. [11] investigated the thermal enhancement in a minichannel with the hydraulic diameter of 2.71 mm by employing MEPCM suspensions with the average size of 4.97 μm as the coolant. It was found that the concentration of MEPCM particles and the flow rate of the working fluid significantly affect the cooling performance. They varied the MEPCM concentration from 0 to 20 wt% and obtained that 5% MEPCM particles always yields to higher cooling performance. However, further augmentation in the fraction of MEPCM particles is only effective at low flow rates. Ho et al. [12] focused on the hydraulic and thermal performance of MEPCM suspensions in a minichannel heat sink. They showed that by implementing these suspensions, the heat transfer effectiveness can experience a significant enhancement (about 52%) at low Reynolds number of 133 and the low latent-sensible heat ratio of 0.0472. Later, Ho et al. [13] performed an experimental study on heat dissipation intensification in a minichannel heat sink containing MEPCM suspensions. They examined a minichannel with dimensions of 50 × 1.5 × 1 mm in length, depth and width, respectively. Various particle concentration from 0 to 10 wt% was studied and it was observed that the optimum concentration of 2 wt % MEPCM particles provides the best cost of performance, within the Reynolds number range of 133–1515. Dammel et al. [14] applied MEPCM particles with the average diameter of 5 μm inside a minichannel heat sink and noted that there is a certain range of parameter combinations in which the implementation of MEPCMs as the coolant is advantageous. They clarified that the supplied heat has to be in the same order of magnitude as the available latent heat storage potential. Moreover, the average time taken by particles to flow inside the minichannels has to be maintained close to the characteristic time for heat conduction along the cross section of the minichannels. They added that on one hand, the subcooling temperature should be low enough so that the phase change material becomes completely solid; and on the other hand, the inlet temperature should be adjusted moderately less than the theoretical melting temperature in order to boost the effectiveness of the presence of MEPCM particles. Due to the superior thermal conductivity of nanoparticles, several researchers investigated the contribution of hybrid suspensions of nanoparticles and phase change materials in minichannel heat sinks. Ho et al. [15] studied the simultaneous implementation of MEPCM particles and Al_2O_3 nanoparticles as the coolant in a minichannel heat sink. Their results showed that the hybrid suspension can effectively improve the thermal performance up to 56% due to the enhancement of thermal conductivity and specific heat. They also examined the thermal resistance and wall temperature effectiveness along with the variation of Nusselt number at different concentrations of additives and various Reynolds number [16]. Accordingly, new correlations were proposed which had a very good agreement with the experimental results. In another study, Ho and Gao [17] evaluated the thermal behavior of MEPCM particles and Al_2O_3 nanoparticles hybrid suspension and showed the performance of the hybrid suspension is highly dependent on the temperature.

Besides the advantage of PCM suspensions as the coolant in minichannel heat sink, the geometry of the minichannels is of fundamental importance in this manner. Accordingly, various investigations are conducted to examine different configurations and dimensional aspects of minichannels to improve their cooling/heating performance [18–20]. The effect of fin spacing is concerned by Jajja et al. [21] and it