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Experimental study on laminar convective heat transfer of microencapsulated phase change material slurry using liquid metal with low melting point as carrying fluid

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ABSTRACT

The microencapsulated phase change material slurry using liquid metal with low melting point as carrying fluid (MEPCM-LM slurry) is a novel and powerful cooling fluid applied in thermal management of high power electronic devices. The laminar convective heat transfer performances of MEPCM-LM slurry in a tube with constant heat flux were investigated experimentally. The effects of MEPCM volume concentration, Re and heat rate on heat transfer characteristics were also studied. Results indicate that the Fanning friction factor of MEPCM-LM slurry *d* is in good accord with the theoretic values ($f = 16/\text{Re}$), and the MEPCM-LM slurry can be considered as Newton fluid. It is also found that the modified local convective heat transfer coefficient (h_x^*) for MEPCM-LM slurry is higher than that for pure gallium. Furthermore, the h_x^* increases with increasing volume concentration and Re. The h_x^* increases with increasing the heat rate before phase change finished and the variation trend of h_x^* with heat rate is contrary after phase change finished, but the h_x^* is not much influenced by the imposed heat fluxes tested. The kind of MEPCM-LM slurry has good application future in practice.

1. Introduction

In recent years, with the rapid developments of the electronic technique, high degree of integration and enhanced performance has led to high heat dissipation electronic devices [1–3]. Due to a dramatic increase in chip densities and power densities, as well as a continuous decrease in physical dimensions of electronic packages, the heat dissipation in microelectronic packaging is becoming increasingly important [4]. The lifetime and reliability of electronic components fall as the operating temperature increases [5], effective cooling solutions are critical for the design of electronic devices for preventing thermal breakdown and extending working life of semiconductor components. The conventional cooling methods such as air cooling and water cooling are rapidly becoming inadequate for dissipating intense heat loads often encountered in new electronic devices [6]. Furthermore, though some better cooling methods such as thermoelectric cooling [7], jet impingement [8], spray [9], microchannel heat sinks [10], heat pipe [11] and thermosyphon cooling [12] upgrade the cooling performance, these cooling methods have some disadvantages in machining and practical application. Therefore, it is absolutely necessary that new feasible ways will be found to solve the problem of highly efficient thermal management.

New cooling fluid with high heat transfer capability such as liquid metal (LM) and latent functionally thermal fluid (LFTF) have been proposed to enhance the cooling efficiency in recent research. In the year of 2002, Liu and Zhou [13] and Liu et al. [14] used firstly the liquid metals with low melting point and their alloys as cooling fluid to cool the computer chip and achieved the good cooling effect because of high heat conduction of liquid metal. Ma and Liu [15,16] and Ma et al. [17] presented an overall review on chip cooling using liquid metals or their alloys as coolant, illustrated the principles of several typical pumping methods, demonstrated for the first time the a heat-driven liquid metal cooling device in which the whole liquid flow loop was driven by a MFD pump powered by a one-stage thermoelectric device directly using waste heat from the hot chip, and proposed a novel strategy to thaw quickly the frozen low-melting by implanting in advance a wire heater into the liquid metal. Li et al. [18] investigated a novel method to significantly lower the chip temperature using liquid gallium as the cooling fluid and obtained very attractive results. Deng and Liu [19,20] presented a MEMS based microcooling device using liquid metal and numerically simulated the three

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Nomenclature

c	volume concentration of the copperized MEPCM
c_m	mass concentration of the copperized MEPCM
c_p	specific heat capacity (J kg^{-1} K^{-1}))
d	particle diameter (m), tube diameter (m)
f	Fanning friction factor
h^*	modified convective heat transfer coefficient (W m^{-2} K^{-1})
I	current (A)
k	thermal conductivity (W m^{-1} K^{-1})
L	latent heat of fusion (kJ kg^{-1}), length of test tube (m)
$\dot{m}$	mass flow rate
Nu	Nusselt number
Pr	Prandtl number
ΔP	pressure drop (Pa)
q	heat flux density (w m^{-2})
Q	heat rate (W)
Q_v	volume flux of slurry (m^3 s^{-1})
r_0	inner radius of the test tube (m)
Re	Reynolds number
T	temperature (°C)
u	velocity (m s^{-1})
U	voltage drop (V)
V	volume of slurry (m^3)
x	mass ration, at axial position (m)

Greek symbols

ρ	density (kg m^{-3})
φ	volume ratio
δ	thickness of Cu plating layer
μ	dynamic viscosity (mPa s)
γ	shear rate (s^{-1})
θ	dimensionless inner wall temperature
τ	time (s)

Subscripts

b	bulk fluid (slurry)
b0	slurry without phase change
Cu	copper plating layer
f	liquid gallium
i	inlet
initial	no copperized
m	melting point
o	external wall surface, outlet
p	particle
w	wall

dimensional heat transfer process involved in the cooling chip, designed and tested the cooling system of LED lamp with the liquid $GaIn_{20}$ alloy. Both the experiments and theoretical analysis indicated that liquid metal cooling was a powerful way for heat dissipation of high power electronic devices. USA Nanocooler Company carried through subsequently study and made some progress [13]. Ghoshal et al. [21] designed a chip cooling equipment using liquid metal with high thermal conductivity which realized 200 W/cm^2 heat dissipation capability. On the other hand, many studies have been made in the past on the heat transfer enhancement of LFTF because of its big apparent specific heat. Goel et al. [22] carried out an experimental investigation to evaluate the heat transfer characteristics of microencapsulated phase change material slurry using water as carrying fluid (MEPCM-W slurry) in a laminar tube flow under constant flux. Yamagishi et al. [23] presented a detailed description of MEPCM properties, construction of an experimental rig. Wang et al. [24] and Chen et al. [25,26] investigated experimentally the laminar rheological characteristics and convective heat transfer behaviors of MEPCM-W slurries in a horizontal circular tube under constant heat flux. Hu and Zhang [27] and Zhang et al. [28,29] investigated numerically the flow and heat transfer process of MEPCM-W slurry for a hydrodynamically fully developed flow by using an effective specific heat capacity model and internal heat source model, introduced a modified expression of local convective heat transfer coefficient to enable evaluation for the convective heat transfer of MEPCM slurry, and analyzed the various factors influencing the heat transfer enhancement. It was found that the MEPCM-W slurry can be considered as Newtonian fluid. The Nusselt number for the MEPCM-W slurry is from 1.5 to 4 times higher than for pure water flow while the viscosity is about 5.57 times of that of water. The Stefan number and MEPCM concentration are the most important parameters influencing the heat transfer enhancement of phase change slurries.

All research results show that liquid metal and MEPCM-W slurry could enhance the convective heat transfer because of the high heat conductivity of liquid metal and the big apparent specific heat of MEPCM slurry, respectively. However, the small specific heat of liquid metal and the low heat conductivity of the conventional MEPCM-W slurry are disadvantageous to enhance the convective heat transfer. Therefore, we proposed a novel and powerful way to enhance the convective heat transfer that MEPCM particles are mixed into liquid metal to gain a kind of MEPCM-LM slurry with high heat conductivity and big apparent specific heat synchronously [30], and investigated numerically the convective heat transfer enhancement of MEPCM-LM slurry in laminar flow under constant heat flux [31]. The results show that the heat transfer ability of MEPCM-LM slurry is better than that of MEPCM-W slurry and liquid metal.

The above references show that there is an absence of experimental research on laminar convective heat transfer of the MPCM-LM slurry. In order to better understand the mechanisms of the laminar heat transfer of the novel MEPCM-LM slurry, in this paper, an experimental system which was built to study the flow and heat transfer characteristics is described. The laminar friction and heat transfer characteristics of the MEPCM-LM slurry in circular tube under constant wall heat flux in the hydraulic fully developed region are investigated, including the effects of volume concentration, Re and heat rate on the internal wall temperature and local convective heat transfer coefficient. The experimental results offer important basic for the further practical application of MEPCM-LM slurry.

2. Physical properties of MEPCM-LM slurry

2.1. MEPCM-LM slurry

The microencapsulated Eicosane ($C_{20}H_{42}$) with melamine–formaldehyde shell was prepared by in situ polymerization. The melting temperature and fusion heat of analytical-grade Eicosane were T_m = 36.4 °C, L = 246 J/g, respectively and the core–shell mass ratio was about 0.72. The volume average diameter of MEPCM particles was found to be 12 μm. Because liquid gallium was adopted as carrying fluid, the surface character of initial MEPCM was changed by electroless copper plating for obtaining compatible metal