Melting heat transfer characteristics of a composite phase change material fabricated by paraffin and metal foam[☆]

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Abstract

Paraffin has a great potential as the phase change material (PCM) to be applied in many energy-related applications, such as thermal energy storage and thermal management, due to its appropriate phase change temperature and large latent heat. The heat transfer characteristics during phase change of paraffin play a very important role in determining the thermo-fluidic performance of the systems. However, the drawback of small thermal conductivity of PCM hampers its application. In the present study, the composite PCM was fabricated by using copper foam to enhance the thermal conductivity of paraffin, and an experimental setup was built to study the phase change heat transfer characteristics of composite PCM. The evolvement of solid-liquid interface and temperature variation during the melting process were experimentally investigated, and the experimental results were compared with the numerical results obtained by the two-temperature energy model. It was indicated that there was a quite large temperature difference between the ligament of copper foam and paraffin, which was due to the thermal non-equilibrium effect in heat transfer between the paraffin and copper foam. Good agreement between the experimental and numerical results showed that the heat transfer characteristics could be well depicted by the two-temperature energy model, which can be further used to depict the heat transfer in thermal energy storage or temperature management using composite PCM.

Keywords: metal foam; paraffin; phase change heat transfer; two-temperature energy model; composite PCM

Nomenclature

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27	A_m	constant parameter in Eq. (2)-(4)
28	a_{sf}	interfacial surface area, m^{-1}
29	C	inertial coefficient, m^{-1}
30	c	specific heat capacity, $J/kg \cdot K$
31	d	thickness of the enclosure, mm
32	d_f	fibre diameter, m
33	d_p	pore size, m
34	d_k	characteristic length, m
35	Gr	Grashof number
36	g	gravitational acceleration, m/s^2
37	h	thickness of the composite PCM, mm, heat transfer coefficient, $W/m^2 \cdot K$
38	h_{sf}	interfacial heat transfer coefficient, $W/m^2 \cdot K$
39	K	permeability, m^{-2}
40	k	thermal conductivity, $W/m \cdot K$
41	k_{fe}	effective thermal conductivity of paraffin, $W/m \cdot K$
42	k_{se}	effective thermal conductivity of copper foam, $W/m \cdot K$
43	L	latent heat of paraffin, $J/kg \cdot K$
44	l	length and width of the composite PCM, mm
45	m	the thickness of the composite PCM, mm
46	n	the thickness of the plexiglass enclosure, mm
47	Re	Reynolds number
48	Pr	Prandtl Number
49	p	pressure, Pa
50	q	heat flux, W/m^2
51	T	temperature, K
52	T_{m1}	lower limits of melting temperature of paraffin, K
53	T_{m2}	upper limits of melting temperature of paraffin, K
54	u,v,w	velocity in x, y and z directions, m/s
55	x,y,z	cartesian coordinates
56	Greek symbols	
57	α	thermal expansion coefficient, K^{-1}
58	β	liquid fraction

59	ε	porosity
60	μ	dynamic viscosity, kg/m·s
61	ρ	density, kg/m ³
62	τ	time, s
63	χ	tortuosity coefficient
64	ω	pore density, PPI
65	Subscripts	
66	f	solid paraffin
67	$init$	initial
68	l	liquid paraffin
69	s	copper foam
70	td	thermal dispersion
71	w	wall

72

73 1. Introduction

74 With the rapid development of human society and economy, energy consumption has drastically
75 increased in recent years. As a consequence, large quantities of greenhouse gases and pollutants, such as
76 carbon dioxide and sulphur dioxide, are emitted into atmosphere, which consequently contributes to the
77 global warming and environment pollution. Therefore, there arises an issue of improving energy efficiency
78 in order to reduce the energy consumption, in which thermal energy storage can contribute to change the
79 pattern of energy utilization to save energy. Thermal energy storage is an effective way to balance the
80 mismatch of the energy supply and energy demand; furthermore, renewable energy resources through
81 thermal energy storage can also be integrated into the energy system to make it more sustainable [1-3].
82 There are in general three kinds of thermal energy storage methods, i.e., sensible heat storage, latent heat
83 storage and chemical heat storage. Sensible heat storage is easy to be implemented due to its simplicity, but
84 the thermal storage capacity is very small, resulting in a large volume of the thermal storage system.
85 Although the chemical heat storage has a very large thermal energy storage capacity, this technology is still
86 at its infant stage and further investigation is apparently necessary to accommodate the practical application.
87 Latent heat storage by solid-liquid phase change is generally considered to be effective and advantageous
88 due to its large heat storage capacity by involving the latent heat of fusion and constant temperature during
89 phase change. So far, latent heat storage has been widely utilized in many applications, such as solar energy

90 system, building energy conservation systems, air-conditioning systems, electricity peak-shaving and
91 industrial waste-heat recovery [4,5]. On the other hand, the characteristic of the constant temperature during
92 phase change can also be applied to achieve the temperature control, which is very important and essential
93 in such cases as electronic cooling and thermal management [6-8]. It is apparent that the heat transfer
94 characteristics are very important in determining the thermo-fluidic performance of a thermal system with
95 PCM as the energy storage and heat transfer medium, through which the heat charging and discharging are
96 realized. Therefore, good heat transfer performance is very essential to maintain large heat charging and
97 discharging rates. However, the small thermal conductivity of PCM always hampers its heat transfer
98 performance, which apparently demands that the thermal conductivity must be enhanced. For example,
99 paraffin is widely used in many energy storage applications since it has large latent heat and good thermal
100 and chemical stabilities [9]. However, paraffin has a low thermal conductivity of about 0.2-0.4 W/(m K)
101 [10]. Apparently, such small thermal conductivity will reduce the heat transfer performance, resulting in
102 very small heat charging and discharging powers, in particular in the case of heat discharging where heat
103 conduction is the dominant heat transfer mechanism. As a result, many efforts have been devoted to
104 develop appropriate methods to enhance the thermal conductivity of PCM.

105 The widely used methods to enhance the thermal conductivity of PCM include adding high thermal
106 conductivity matrix into PCM, installing fins on the wall of heat exchanger, encapsulation of PCM and
107 fabricating composite PCM [11]. Kamkari and Shokouhmand [12] experimentally investigated melting
108 process of lauric acid in a transparent rectangular enclosure with and without horizontal partial fins. The
109 melting process was visually observed, and the experimental results indicated that increasing the number of
110 fins decreased the melting time and increased the total heat transfer rate. They also found that increasing the
111 number of fins and decreasing the wall temperature could improve the melting enhancement ratio and
112 overall fin efficiency. It has been widely agreed that encapsulation of PCM can be an effective measure to
113 enhance the heat transfer because the ratio of surface to volume is significantly increased [13]. Furthermore,
114 the supercooling of PCM might also be alleviated by encapsulation. Fang et al. [14] prepared
115 microencapsulated paraffin composites with SiO₂ shell by sol-gel methods, and the thermo-physical
116 properties were investigated. Compared with the pure paraffin, the melting temperature of paraffin with
117 87.5% encapsulation ratio decreased by 0.8 °C. Furthermore, they found that the SiO₂ shells could improve
118 the thermal stability of the encapsulated paraffin composites due to the synergistic effect between the
119 paraffin and SiO₂. Karkri et al. [15] prepared microencapsulated paraffin wax/HDPE composites, and
120 experimentally investigated the heat storage characteristics of the composites. It was found that the latent,
121 sensible and total heat of the composites increased as the paraffin content increased.

The effective thermal conductivity of PCM can be significantly enhanced by composite PCM which is fabricated using high thermal conductivity matrix [16-19]. Mills et al. [16] fabricated composite PCM using paraffin wax and expanded graphite (EG), and it was found that paraffin wax/expanded graphite composite PCM had a thermal conductivity 20–130 times larger than that of pure paraffin. The composite PCM with higher bulk density had higher thermal conductivity. Zhang et al. [17] prepared EG/paraffin composite PCM and experimentally investigated thermal energy storage characteristics, which indicated that the heat charging time duration was reduced by 68% compared to the pure paraffin. Mattawee and Assassa [18] dispersed aluminium powder into paraffin wax and studied the effect of the mass fraction of aluminium powder on thermal conductivity enhancement of paraffin wax in a latent heat storage system. The experimental results showed that the charging time was reduced by approximately 60% for the composite PCM with 50wt% of aluminium powder, and the heat transfer rate increased as mass fraction of aluminium increased. Apparently, higher thermal conductivity will benefit the heat storage and retrieval through reducing the charging and discharging time. However, it has been verified that the loading of PCM in the composite PCM will be decreased as the mass fraction of higher thermal conductivity material increases. Therefore, it is very important to maintain PCM at a high mass fraction to retain large thermal energy storage capacity while enhancing the thermal conductivity to reduce the heat charging and discharging time.

Metal foam owns a very high porosity, continuous connective structure and good mechanical strength. Metal foam as the thermal conductivity promoter has been applied in a variety of applications due to its abundant pores and good connectivity of the ligament. The high thermal conductivity of the ligament can enhance the effective thermal conductivity of PCM, while the open-cell porous structure allows for the flow of liquid PCM and large specific contact surface area between PCM and ligament of metal foam, resulting in a significant heat transfer enhancement. Xiao et al. [19] fabricated the composite PCMs using different metal foams and paraffin, and the measurement of thermal conductivities of the composite PCMs was carried out by an in-house-made apparatus using the steady-state method. It was indicated that the thermal conductivity could be drastically enhanced. For example, the thermal conductivities of the paraffin/copper foam composite PCM with the porosity of 88.89% and pore size of 25 PPI was about forty-four times larger than that of pure paraffin. Jackson and Fisher [20] filled paraffin in the copper foam, aluminium foam and graphite foam with different pore sizes, and the transient responses of the composite PCMs in thermal energy storage system were investigated, where the graphite foam performed the best. Furthermore, a larger pore size could result in more drastic temperature changes of paraffin due to natural convection inside the pores and a smaller pore size could avoid temperature spikes. Fleminga et al. [21] built a shell-and-tube latent heat storage unit using water as the phase change material and aluminum foam as heat transfer

enhancer. The experimental results indicated that the metal foam significantly increased the heat transfer during both solidification and melting process, which was attributed to the thermal conductivity enhancement.

It can be understood from the above context that the metal foam can largely enhance the thermal conductivity, resulting in a better heat transfer performance. However, the detailed heat transfer characteristics of such composite PCM is very important for the performance evaluation of a thermal energy storage system, which calls for further investigation. Furthermore, it is apparent that there is a significant difference of the thermo-physical properties between the ligament of metal foam and PCM, which leads to the hypothesis of local thermal equilibrium in composite PCM might not be completely valid [22]. Therefore, the thermal non-equilibrium model should be considered in the numerical modelling, where two energy equations for ligament of metal foam and PCM are modelled separately and coupled by the interphase heat transfer. Chen et al. [23] used the two-temperature energy model to analyze the thermal energy storage process of a solar flat-plate collector with paraffin/aluminium foam composite PCM. They found that the melting rate of paraffin was greatly improved by using aluminium foams, and the temperature distribution in paraffin with aluminium foams was more uniform than that of paraffin without aluminium foams. Xu et al. [24] studied thermal non-equilibrium heat transfer in a metal foam solar collector with no-slip boundary conditions. They compared the results of Brinkman model and Darcy model, and found that the difference between those models was apparent for a small duct, while the difference was mild for a large duct. Qu et al. [25] studied the heat transfer performance of paraffin saturated in copper foam for a thermal management system for a high-power lithium ion battery. The local thermal non-equilibrium model was also used, and the comparison between the numerical results and experimental results was carried out. They found that the surface temperature of battery was significantly reduced with the composite PCM, and the temperature difference between the metal foam and paraffin confirmed the feasibility of the thermal non-equilibrium model. Li et al. [26] numerically and experimentally studied the melting of paraffin saturated in the open-cell copper foam. They investigated the effects of porosity and pore density on the temperature distribution. It was concluded that the melting heat transfer was well enhanced by copper foam, although it might suppress local natural convection. However, the model used in the investigation was different from the realistic situation, i.e., only two-dimensional model was investigated, and the boundary conditions were considered adiabatic, which were different from the practical situation.

It can be understood from the above context that the thermal conductivity of PCM can be largely enhanced by using metal foam, resulting in a large heat charging and discharging rates, which indicates that

186 the composite PCM can be very useful in thermal energy storage and temperature management systems.
187 Although it has been well accepted that the two-temperature energy model should be used to describe the
188 heat transfer characteristics of the composite PCM due to very large difference of the thermo-physical
189 properties of PCM and metal foam, the heat transfer characteristics of such composite PCM have not been
190 fully understood. For examples, the heat transfer between the PCM and ligament of metal foam is described
191 by the empirical equations that depict the forced convection heat transfer around the cylinder [27]; however,
192 the temperature difference between the PCM and ligament of metal foam has not been experimentally
193 measured and compared with the numerical results to validate the numerical modelling.

194 Since the composite PCM can be used for thermal energy storage and temperature control, the
195 thermo-fluidic characteristics are apparently of the fundamental importance for the performance evaluation
196 in the practical application. In the present study, the heat transfer characteristics during the melting of a
197 composite PCM are experimentally and numerically investigated, where the paraffin is used as the phase
198 change material, and copper foam is used to enhance the thermal conductivity. The temperatures of both
199 paraffin and ligament of copper foam are measured so that the temperature difference can be obtained, and
200 the comparison between the experimental and numerical results is also conducted to understand the heat
201 transfer characteristics and mechanisms. Meanwhile, the evolution of the solid-liquid phase boundary is
202 visualized and the temperature field is also captured by the infrared camera to add supplementary
203 information. Moreover, the thermal energy storage characteristics are also evaluated and discussed.

204 **2. Experimental Setup**

205 Fig. 1 shows the experimental setup used to study the heat transfer characteristics of paraffin/metal
206 foam composite PCM, which was consisted of four parts: rectangular enclosure with the composite PCM,
207 heating system, data acquisition system and infrared camera or conventional camera. The rectangular
208 enclosure was covered by the thermal insulation materials to reduce the heat loss to the surroundings during
209 experiments. The heating was supplied by a DC voltage power supply, and the electric voltage and current
210 were measured to determine the heat flux supplied to the composite PCM in the experiments.

211 Fig. 2 shows the schematic illustration of the rectangular enclosure and the composite PCM. In the
212 experiments, the composite PCM with a dimension of about 100.0 mm×100.0 mm×10.0 mm was used,
213 which was fabricated by infiltrating paraffin into copper foam with the porosity of 97.0 % and pore size of
214 25 PPI. In order to guarantee high impregnation ratio of the composite PCM, the vacuum impregnation was
215 used in the fabrication, and the detail of fabrication process can be found in [28]. It has been determined
216 from the measurement that the impregnation ratio of the composite PCM fabricated in the present study was

above 95%, and about 85.0g paraffin was filled in the copper foam with the vacuum assistance. The composite PCM was then encaged in a rectangular enclosure made of plexiglass with a thickness of 5.0 mm, and the left side of the composite PCM was attached with a porcelain heater which was used to supply heating to melt PCM. A gap of about 5.0 mm between the top surface of the composite PCM and inner plexiglass enclosure surface was left to accommodate the volume expansion of molten paraffin.

In the experiments, a typical location, i.e., the center of the composite PCM, was chosen to monitor the temperatures of the PCM and ligament of copper foam by using two pre-calibrated T-type thermocouples with the diameter of about 0.1 mm, where one thermocouple was inserted into PCM and fixed by carefully wiring through the pore of copper foam and the other was soldered on the surface of the ligament of copper foam to measure the temperature difference between the PCM and copper foam. The evolvement of the solid-liquid interface was observed by a conventional camera to investigate the melting process of the composite PCM. Meanwhile, the temperature field of the outer surface of the plexiglass enclosure was captured by an infrared camera (ThermaCAMTM, FLIR SC325) set in front of the enclosure, where the outer surface of the plexiglass enclosure was sprayed black using a typical paint with the surface emissivity of about 0.95.

Using the electric voltage and current of the heater measured in the experiment, the typical heat flux supplied to the composite PCM could be estimated as: $q=6207.51-0.0108t$ (W/m²) considering a slight variation of the electric resistance of the heater during heating in the experiments. The temperatures along with the electric voltage and current were recorded by the data acquisition system, and they were then stored in a computer for further analysis, where the images recorded by the infrared camera or conventional camera were also stored for further analysis. In the experiments, the thermocouples were calibrated against a standard thermometer with an uncertainty of about 0.5 °C, and the infrared camera was also calibrated against the thermocouples and its uncertainty was determined to be about 1.0 °C. It was estimated that the uncertainty of the supplied heat flux was about 3.13%. The uncertainties of all the parameters are listed in Table 1.

3. Numerical Investigation

3.1 Mathematical Model

Fig. 3 shows the schematic illustration of the computational domain of the paraffin/copper foam composite PCM, where the length, width and thickness were about 100.0 mm×100.0 mm×10.0 mm, respectively. The left side was subjected to a heat flux which could be approximately described as

248 $q=6207.51-0.0108t$ (W/m²) in the experiments. In order to imitate the practical condition of the
 249 experiments, the effect of the enclosure with the thickness of about 5.0 mm, i.e., plexiglass, on the heat
 250 transfer was taken into consideration in the numerical modelling. The following assumptions were made in
 251 the present numerical investigation:

- 252 (1) The liquid paraffin was considered as incompressible Newtonian fluid, and the density was subjected to
 253 the Boussinesq approximation.
- 254 (2) The copper foam was assumed homogeneous and isotropic, and the flow of the liquid paraffin in copper
 255 foam was laminar flow, and the volume expansion of the paraffin during phase change was neglected.
- 256 (3) The heat loss was mainly due to the heat transfer dominated by natural convection between the thermal
 257 insulation materials and ambient, and the heat transfer coefficient was considered to be constant which
 258 was determined by the average surface temperature measured in the experiments.

259 In the numerical calculations, the enthalpy-porosity model and melting model were used to describe
 260 the phase change heat transfer of paraffin, and the two-temperature energy model was used to depict the
 261 thermal non-equilibrium between the paraffin and ligament of copper foam. The follows was the set of the
 262 equations used to describe the flow and heat transfer characteristics of PCM and copper foam in the
 263 numerical investigation.

264 Continuity equation:

$$265 \frac{\partial \rho_f}{\partial \tau} + \nabla(\rho_f U) = 0 \quad (1)$$

266 Momentum equations:

$$267 \frac{\rho_f}{\varepsilon} \frac{\partial u}{\partial \tau} + \frac{\rho_f}{\varepsilon^2} \left(\frac{\partial(uu)}{\partial x} + \frac{\partial(uv)}{\partial y} + \frac{\partial(uw)}{\partial z} \right) = -\frac{\partial p}{\partial x} + \frac{\mu}{\varepsilon} \nabla^2 u - \left(\frac{\mu}{K} + \frac{\rho_f C}{K^{1/2}} |u| \right) u - \frac{(1-\beta)^2}{\beta^3 + \omega} A_m u \quad (2)$$

$$268 \frac{\rho_f}{\varepsilon} \frac{\partial v}{\partial \tau} + \frac{\rho_f}{\varepsilon^2} \left(\frac{\partial(vu)}{\partial x} + \frac{\partial(vv)}{\partial y} + \frac{\partial(vw)}{\partial z} \right) = -\frac{\partial p}{\partial y} + \frac{\mu}{\varepsilon} \nabla^2 v - \left(\frac{\mu}{K} + \frac{\rho_f C}{K^{1/2}} |v| \right) v - \frac{(1-\beta)^2}{\beta^3 + \omega} A_m v + \rho g \alpha (T_f - T_0) \quad (3)$$

$$269 \frac{\rho_f}{\varepsilon} \frac{\partial w}{\partial \tau} + \frac{\rho_f}{\varepsilon^2} \left(\frac{\partial(wu)}{\partial x} + \frac{\partial(wv)}{\partial y} + \frac{\partial(ww)}{\partial z} \right) = -\frac{\partial p}{\partial z} + \frac{\mu}{\varepsilon} \nabla^2 w - \left(\frac{\mu}{K} + \frac{\rho_f C}{K^{1/2}} |w| \right) w - \frac{(1-\beta)^2}{\beta^3 + \omega} A_m w \quad (4)$$

270 Due to the facts that there were quite big differences between the thermo-physical properties of
 271 paraffin and copper foam, the thermal non-equilibrium always presented for paraffin and copper foam in a
 272 transient heat transfer process. Therefore, the two-temperature energy equations were used in the present
 273 numerical investigation, where the heat transfer between the paraffin and ligament of copper foam was
 274 considered.

275 Energy equations:

276 For paraffin:

$$\varepsilon \rho_f (c_f + L \frac{d\beta}{dT_f}) \frac{\partial T_f}{\partial \tau} + \rho_f c_f (u \frac{\partial T_f}{\partial x} + v \frac{\partial T_f}{\partial y} + w \frac{\partial T_f}{\partial z}) = (k_{fd} + k_{fe}) \nabla^2 T_f + h_{sf} a_{sf} (T_s - T_f) \quad (5)$$

For copper foam:

$$(1 - \varepsilon) \rho_s c_s \frac{\partial T_s}{\partial \tau} = k_{se} \nabla^2 T_s - h_{sf} a_{sf} (T_s - T_f) \quad (6)$$

Where, ρ_f , μ , α , L , k_{fe} were the density, dynamic viscosity, thermal expansion coefficient, latent heat and effective thermal conductivity of paraffin, respectively. T_{m1} and T_{m2} were the lower and upper limits of the melting temperatures of paraffin, and c_f and c_l were the specific heat capacities of solid paraffin and liquid paraffin, respectively. ε , ρ_s , c_s and k_{se} were the porosity, density, specific heat capacity and effective thermal conductivity of copper foam, respectively. A_m was a constant parameter, which was between 10^5 and 10^8 . K and C were the permeability and inertial coefficient, respectively, which was introduced in detail in the following context. T_f and T_s were the temperatures of the paraffin and copper foam, respectively.

In the numerical calculation, the liquid fraction was determined by eq. (7), and $\beta=0$ at solid phase and $\beta=1$ at liquid phase. When the paraffin was in the mushy region, the liquid fraction was within 0 and 1.

$$\beta = \begin{cases} 0, & T_f < T_{m1} \\ (T_f - T_{m1}) / (T_{m2} - T_{m1}), & T_{m1} \leq T_f < T_{m2} \\ 1, & T_f \geq T_{m2} \end{cases} \quad (7)$$

In the numerical calculation, the effect of the enclosure on the heat transfer was also taken into consideration, where the heat transfer in the enclosure was governed by heat conduction, and the enclosure and composite PCM was thermally coupled by the continuity of the heat flux and temperature.

3.2 Thermo-physical Properties

The thermo-physical properties of the paraffin, copper foam and plexiglass are listed in Table 2. The melting temperature and latent heat of paraffin were determined by the differential scanning calorimetry (Perkin Elmer, DSC 8000), and the DSC curve of paraffin is shown in Fig. 4. The results indicated that the melting temperature range of paraffin was within 54.43~64.11°C, and the latent heat was determined to be about 175.24 kJ/kg. The other thermo-physical properties of paraffin were adopted from reference [29]. The thermo-physical properties of copper are from [30] and they were used to estimate those of copper foam.

301

302 3.3 Estimation of the parameters of copper foam

303 3.3.1 Structural parameters of copper foam

304 The porosity ε and pore density ω were the basic parameters of metal foam, which were 97.0%, and
 305 25PPI in the present study. The other important parameters of the metal foam, such as the pore size d_p , fibre
 306 diameter d_f could be determined by the following equations [31-32],

$$307 \quad d_p = \frac{22.4 \times 10^{-3}}{\omega} \quad (8)$$

$$308 \quad d_f = 1.18 \sqrt{\frac{1-\varepsilon}{3\pi}} d_p \quad (9)$$

309 The interfacial surface area, a_{sf} , can be determined by:

$$310 \quad a_{sf} = \frac{3\pi d_f}{d_p^2} \quad (10)$$

311 The characteristic length d_k can be formulated as:

$$312 \quad d_k = \frac{\chi}{3-\chi} d_p \quad (11)$$

313 where, χ was the tortuosity coefficient of the copper foam relating to the porosity, which was formulated as:

$$314 \quad \chi = 2 + 2 \cos\left(\frac{4\pi}{3} + \frac{1}{3} \cos^{-1}(2\varepsilon - 1)\right) \quad (12)$$

315

316 3.3.2 Permeability and inertial coefficient

317 Because of the laminar flow driven by the pressure gradient in the porous medium, the relationship
 318 between the pressure gradient and velocity is usually required and it can be determined by permeability
 319 which is a complicated parameter and hardly experimentally determined. In the present study, permeability
 320 K and inertial coefficient C were determined by following equations [31-32], where $1/K$ represented the
 321 viscous resistance. Two parameters of $1/K$ and C were used in the enthalpy-porosity model, which were
 322 formulated as follows.

$$323 \quad K = \frac{\varepsilon^2 d_k^2}{36\chi(\chi-1)} \quad (13)$$

$$324 \quad C = \frac{0.00212(1-\varepsilon)^{-0.132} (d_f / d_p)^{-1.63}}{\sqrt{K}} \quad (14)$$

325

326 **3.3.3 Effective thermal conductivity and thermal dispersion conductivity**

327 For the thermal non-equilibrium model, the effective thermal conductivities of paraffin and metal foam
 328 should be applied in the numerical calculation. Due to the complexity of structure of the copper foam, there
 329 were many models having been developed to describe the effective thermal conductivity, as summarized in
 330 [33]. The tetrakaidecahedron cell model proposed by Boomsma and Poulikakos [34] was adopted to
 331 describe the effective thermal conductivity in the present study, as shown by the following equations.

$$332 \quad k_{eff} = \frac{1}{\sqrt{2}(R_A + R_B + R_C + R_D)} \quad (15)$$

$$333 \quad R_A = \frac{4\sigma}{(2e^2 + \pi\sigma(1-e))k_s + (4 - 2e^2 - \pi\sigma(1-e))k_f} \quad (16)$$

$$334 \quad R_B = \frac{(e - 2\sigma)^2}{(e - 2\sigma)e^2k_s + (2e - 4\sigma - (e - 2\sigma)e^2)k_f} \quad (17)$$

$$335 \quad R_C = \frac{(\sqrt{2} - 2e)^2}{2\pi\sigma^2(1 - 2\sqrt{2}e)k_s + 2(\sqrt{2} - 2e - \pi\sigma^2(1 - 2\sqrt{2}e))k_f} \quad (18)$$

$$336 \quad R_D = \frac{2e}{e^2k_s + (4 - e^2)k_f} \quad (19)$$

$$337 \quad \text{Where, } \sigma = \sqrt{\frac{\sqrt{2}(2 - 5/8e^3\sqrt{2} - 2\varepsilon)}{\pi(3 - 4\sqrt{2}e - e)}}, e = 0.339$$

338 The effective thermal conductivities of PCM and copper can be defined as:

$$339 \quad k_{fe} = k_{eff} \Big|_{k_f=0} \quad (20)$$

$$340 \quad k_{se} = k_{eff} \Big|_{k_s=0} \quad (21)$$

341 The thermal dispersion due to the fluid mixing in porous media at the pore scale caused heat transfer
 342 enhancement, which should be considered in the numerical calculation. This effect can be described by the
 343 model based on the stochastic phenomena proposed by Georgiadis and Catton [35], as formulated in the
 344 following equation:

$$345 \quad k_{td} = \frac{0.36}{1 - \varepsilon} \rho_f c_f d_f \sqrt{u^2 + v^2 + w^2} \quad (22)$$

346 **3.3.4 Interstitial heat transfer coefficient**

347 It is apparent that the heat transfer between the PCM and ligament of metal foam is very essential in
 348 estimating the heat transfer performance of the composite PCM. However, it is difficult to describe the heat
 349 transfer between the metal foam and PCM accurately due to the complex structure of metal foam and

350 complicated flow behaviour at pore scale. In the present study, a simplification was made in a way that the
 351 ligaments of the copper foam were considered as the smooth cylinders. Therefore the laminar flow of liquid
 352 paraffin in copper foam was resembled as the flow around cylinder, where many empirical correlations of
 353 interstitial heat transfer coefficient could be found in the references. Following the previous studies [33], the
 354 empirical equations provided by Zhukauskas [26] were used to determine the interstitial heat transfer
 355 coefficient, which was formulated as:

$$356 \quad h_{sf} = \begin{cases} 0.76 \text{Re}^{0.4} \text{Pr}^{0.37} k_f / d_f, & 0 < \text{Re} \leq 40 \\ 0.52 \text{Re}^{0.5} \text{Pr}^{0.37} k_f / d_f, & 40 < \text{Re} \leq 1000 \\ 0.26 \text{Re}^{0.6} \text{Pr}^{0.37} k_f / d_f, & 1000 < \text{Re} \leq 20000 \end{cases} \quad (23)$$

357 **3.4 Initial and Boundary Conditions**

358 The initial temperatures for paraffin and copper foam were at constant temperature that equalled the
 359 ambient temperature, which was given by the following equation.

$$360 \quad T_f = T_s = T_{init}, \quad 0 \leq x \leq l, \quad 0 \leq y \leq m, \quad 0 \leq z \leq n \quad (24)$$

361 The initial values of the velocity for paraffin at the three directions were zero, and the no-slip velocity
 362 condition at the wall was applied.

363 The boundary conditions for the governing equations were given in the following equations. The left
 364 boundary of the composite PCM was subjected to heating, which could be estimated as: $q=6207.51-0.0108t$
 365 (W/m^2) in the experiments. Although the rest five boundaries of the enclosure were covered by the thermal
 366 insulation materials, the heat loss should be considered in the numerical calculation. It was apparent that the
 367 natural convection dominated the heat transfer on the outer surface of the thermal insulation, as shown in
 368 Fig. 3, and the boundary conditions were formulated as follows.

$$369 \quad -\lambda \frac{\partial T}{\partial x} = q, \quad \tau > 0, \quad x = 0, \quad y \in [d, l+d], \quad z \in [d, h+d]; \quad (\text{heating boundary}) \quad (25)$$

$$370 \quad -\lambda \frac{\partial T}{\partial x} = h_w(t_w - t_o), \quad \tau > 0, \quad x = l+d, \quad y \in [0, l+2d], \quad z \in [0, h+2d]; \quad (\text{right boundary}) \quad (26)$$

$$371 \quad -\lambda \frac{\partial T}{\partial y} = h_w(t_w - t_o), \quad \tau > 0, \quad x \in [0, l+d], \quad y = 0 \text{ or } l+2d, \quad z \in [0, h+2d]; \quad (\text{top and bottom boundaries}) \quad (27)$$

$$372 \quad -\lambda \frac{\partial T}{\partial z} = h_w(t_w - t_o), \quad \tau > 0, \quad x \in [0, l+d], \quad y \in [0, l+2d], \quad z = 0 \text{ or } h+2d; \quad (\text{front and back boundaries}) \quad (28)$$

373 Where, l was the length and width of the composite PCM, h was the thickness of the composite PCM, d was
 374 the thickness of the enclosure. The heat transfer coefficient of natural convection between the thermal
 375 insulation material and ambient could be estimated by the empirical correlations [30]:

$$h = \frac{0.62\lambda}{L}(Gr Pr)^{1/5} \quad (\text{horizontal plate}) \quad (29)$$

$$h = \frac{0.59\lambda}{L}(Gr Pr)^{1/4} \quad (\text{vertical plate}) \quad (30)$$

3.5 Numerical procedure

In the present numerical investigation, the uniformly structured grid with hexahedral cells was applied to investigate the melting phase change heat transfer of the composite PCM. The numerical calculation was performed using a commercially available CFD program Fluent 14.5. In order to depict the heat transfer in the copper foam as well as the interfacial heat transfer between the ligament of copper foam and paraffin, a UDF (user define function) program was developed. The governing equations were discretized by the finite volume method. Pressure and velocity fields were computed by the second Order Implicit Method for Pressure-Linked Equations (SIMPLE) algorithms.

Three-dimensional numerical calculation was conducted in the present study. The grid sensitivity was checked first to guarantee that the numerical results were grid-independent. We tested different meshes with 118272, 231000 and 477048 grids, and the numerical results indicated that the difference of three grids was within 0.2%. Thus, a grid size of about 231000 was used in the numerical calculation to balance the accuracy of results and computational time. Furthermore, we checked the effects of the time step on the numerical solution, where three time steps: 0.2 s, 0.5 s and 2 s were tested. The numerical results indicated that the time step of 0.5 s was enough to maintain the accuracy without increasing too long computational time, therefore the time step of 0.5 s was used in the numerical calculation. And convergences of the solution were checked at each time step of the numerical calculation to guarantee the numerical stability, and the convergence criteria for the residuals of continuity equation, velocity components and energy equation were 10^{-4} , 10^{-4} and 10^{-8} , respectively. When the convergence criteria were satisfied, the solutions were obtained.

4. Results and Discussion

4.1 Evolvement of the solid-liquid interface of the composite PCM

Fig. 5 shows both the experimental and numerical results of the evolvement of the solid-liquid interface of the composite PCM on the central plane of the cavity, i.e, the plane of $z=10.0$ mm at 1000 s, 2000 s, 3000 s, 4000 s and 5000 s, respectively. It can be seen from experimental results shown in Fig. 5 (a) that the interface was almost vertical at the initial stage of heating because the influenced region was close

to the heating surface when the heat transfer was dominated by heat conduction. With the elapse of time, more paraffin was melted and the hotter liquid paraffin moved upward under the effect of the buoyancy. Therefore, the paraffin on the top melted more rapidly than that on the bottom, and the interface began to curve gradually. Such phenomenon indicated that heat transfer was dominated by heat conduction when the fraction of liquid paraffin was very small at the initial stage of heating. With the continuing of heating process, more paraffin became molten, natural convection accelerated the phase change of the paraffin on the top, and made the paraffin there melt more rapidly than on the bottom.

Fig. 5 (b) is the numerical results of the evolvement of the solid-liquid interface. It can be found that the numerical results agreed quite well with the experimental results. There was apparently a mushy region between the liquid and solid paraffin; in addition, the mushy region on the top was narrower than that on the bottom, which indicated that paraffin in mushy state flowed downward because of a larger density than that of liquid paraffin. However, it can be seen from the figure that paraffin in the numerical results melted slightly faster than that in the experiments, in particular in the top region of the composite PCM. This might be attributed to the reason that the effect of the natural convection might be exaggerated due to inaccurate estimation of the non-Darcy effect term in the case of paraffin. Furthermore, the heat absorbed by the thermal insulation material was not considered in the numerical calculation. Therefore, the heat losses in the experiments might be more than those in the numerical calculation, resulting in the faster melting in the numerical calculation.

4.2 Variation of the temperature of the composite PCM

Fig. 6 shows the variation of the temperatures of both the numerical and experimental results with time at the monitor point. Due to the technical difficulty of mounting two thermocouples at the exactly same location, the locations of mounting the thermocouples in PCM and on the surface of ligament of copper foam shifted slightly. Therefore, the location for the temperature measurement on the ligament of the copper foam was at the plane of $z=10.0$ mm and was about 55.0 mm from the left surface and 41.0 mm from the bottom, and the location for the temperature measurement in the paraffin was chosen to be 57.0 mm from the left and 41.0 mm from the bottom on the same plane.

As can be seen in Fig. 6, the numerical results agreed reasonably with the experimental results. At the initial stage, the temperature seemed to increase very fast first in the sensible heat storage region. However, it should be noted that although temperature increased fast at first, the increment of the temperature was inhibited as it approached to the melting temperature. During the phase change, the temperature of paraffin increased slowly due to the involvement of the latent heat. After paraffin was melted, the increasing rate of the temperature of paraffin began to increase again, which can be attributed to the fact that the appearance of

natural convection accelerated the temperature increasing rate of paraffin. The temperature of paraffin was affected by both natural convection and heat conduction simultaneously at this stage. When the temperatures of paraffin and copper foam were high enough, the effect of heat loss came into play an important role, which slowed down the temperature increase. Therefore, the temperature increasing rate of paraffin and copper became smaller.

In the experiments, the temperature measurement by the temperature sensors can only reflect the characteristics of several local spots, and it is very difficult to obtain the temperature field of the entire domain. While such information could be possibly provided by using the infrared camera. In the present study, infrared camera was adopted to detect the temperature of the outer surface of the plexiglass enclosure, i.e., the plane of $z=20.0$ mm. Shown in Fig. 7 (a) and (b) are the comparison of the experimental results with the numerical results of the evolution of the temperature fields of the front outer surface of the enclosure at 2000 s, 3000s, 4000 s and 5000 s, respectively. It can be seen from Fig. 7 (a) that the temperature contours was slightly curved at 2000 s, which indicated that a small part of paraffin was melted and the natural convection started to appear. With the melting of the paraffin, the effect of natural convection was enhanced so that the temperature of paraffin on the top increased more rapidly than that on the bottom, and the temperature contours gradually curved.

It was seen from the numerical results shown in Fig. 7 (b) that the temperatures in the numerical results was higher than those in the experimental results, in particular at the top-left corner of the composite PCM. This might be attributed to the fact that the heat losses from the heating surface were not considered in the numerical calculation so that the temperature of the region near the heating surface was higher than that in the experiment. It should be noted that the heat transfer surface must be exposed to the infrared camera during temperature measurement, and there must be heat loss from the higher temperature of the enclosure surface to the ambient, resulting in lower temperature than in the real situation. Furthermore, we can also find that the temperature contours in the numerical results were more crooked than those in the experiment results.

4.3 Temperature difference between the ligament of copper foam and paraffin

Shown in Fig. 8 is the temperature difference between the ligament of copper foam and paraffin at the monitor point, where the results were obtained from those in Fig. 6. The variation of the temperature difference in Fig. 8 can be divided into three stages. At the initial stage, heat conduction was the dominant heat transfer mode. The thermal conductivity of copper foam was much larger than that of paraffin, which resulted in higher temperature of copper foam than that of paraffin. Gradually, the temperature difference remained stable as the temperature approached the melting point. With the elapse of time, paraffin entered

melting stage, and the temperature increase of paraffin was slowed down compared to the initial stage due to the involvement of the latent heat. Meanwhile, the temperature of copper foam still kept increasing, resulting in an increase in temperature difference. The temperature difference displayed a second peak at this stage, as shown in Fig. 8. After paraffin was fully melted, the appearance of natural convection enhanced the heat transfer of liquid paraffin, leading to the temperature difference decreasing gradually. Finally, the temperature of paraffin gradually approached or might be even higher than that of the ligament of copper foam due to the enhanced heat transfer by natural convection of liquid paraffin. It can be concluded that the temperature of paraffin was affected mainly by natural convection but not heat conduction between paraffin and copper foam at this stage, in particular when the temperature of paraffin was higher than copper foam.

It can also be seen from Fig. 8 that the two-temperature energy model can well describe the melting heat transfer characteristics of paraffin/copper foam composite PCM. However, it was indicated from the figure that the second peak in the numerical result appeared slightly earlier than that in the experimental result. This might be attributed to the fact that the latent heat of fusion in the enthalpy-porosity model and melting model adopted in the present study was averagely allocated in the phase change temperature range; while paraffin absorbed most of the latent heat near the peak of the melting temperature in the experiments, as shown by the DSC curve in Fig. 4. Therefore, the appearance of the peak of the temperature difference in the experiment was delayed compared to that in the numerical calculation.

Shown in Fig. 9 are the temperature fields of the copper foam and paraffin and the temperature difference fields between the copper foam and paraffin on the plane of $z=10.0$ mm at 1000 s, 2000 s, 3000 s, 4000 s and 5000 s, respectively. It can be seen that the temperature of copper foam was generally higher (represented by light blue in Fig. 9 (c)) than that of paraffin in solid PCM region because heat conduction dominated the heat transfer in solid region. It should be noted that the temperature difference was larger in mushy region (marked in Fig. 9 (c)). This was because that paraffin in mushy region was at melting stage, where the temperature difference was the largest during the entire melting process, as shown in Fig. 8. After paraffin was melted, natural convection occurred in liquid PCM region and dominated the heat transfer of paraffin, where the temperature difference was very small or even negative, as represented by dark blue in Fig. 9 (c).

It can be seen from the temperature difference fields in Fig. 9 (c) that the temperature difference was larger on the right and bottom boundaries but smaller on the left boundary. Such phenomena can be explained as follows. The right and bottom boundaries were almost in the solid PCM regions, and the heat loss to the ambient was mainly conducted through the paraffin due to the high porosity of the copper foam,

which suppressed the temperature increase of paraffin. Therefore, the temperature of paraffin on right and bottom boundary increased slower, and the temperature difference was larger. But on the left boundary, the heat transfer in liquid paraffin was dominated by natural convection because of its large flow velocity, as shown in Fig. 5 (c), leading to the fact that the temperature of paraffin was slightly higher than copper foam.. As away from the left boundary, the flow velocity of liquid paraffin decreased rapidly and the influence of natural convection was weakened. Therefore, heat conduction dominated the heat transfer in this region, leading to higher temperature of copper foam. As a result, the temperature of copper foam was higher than paraffin in this region.

4.4 Heat transfer characteristics of pure paraffin and paraffin/copper foam composite

There is a quite large difference between the heat transfer characteristics of pure paraffin and those of paraffin/copper foam composite. In order to compare the heat transfer characteristics of pure paraffin and paraffin/copper foam composite, the temperature fields, solid-liquid interfaces and velocity fields of pure paraffin and copper foam/paraffin composite on the plane of $z=10.0$ mm at 1000 s, 2000 s, 3000 s, 4000 s and 5000 s are shown in Fig. 10, Fig. 9 (b), Fig. 5 (b) and (c), respectively. It can be seen from the melting process of pure paraffin in Fig. 10 (a) and (b) that the solid-liquid interface of paraffin at 1000 s was crooked more than that of paraffin/copper foam composite shown in Fig. 5 (b), where the interfaces was almost vertical at 1000 s. Such phenomena indicated that natural convection played an important role in the heat transfer even at the initial stage for pure paraffin. With the elapse of time, more paraffin was melted and the natural convection was strengthened to make the interface of pure paraffin more crooked. It can also be seen from Fig. 10, Fig. 9 (b) and Fig. 5 (b) that the temperature contours and solid-liquid interfaces of pure paraffin were more crooked than that of copper foam/paraffin composite, which was attributed to the fact that the flow of liquid paraffin was suppressed by the porous structure of copper foam, and the effect of natural convection was impaired compared to the case of pure paraffin.

Comparing the temperature fields of pure paraffin and paraffin/copper foam composite shown in Fig. 10 (a) and Fig. 9 (b), it can be found that the temperature distribution of pure paraffin was not uniform, in particular in the region of the solid-liquid interface, which led to that the mushy region of pure paraffin was narrower than that of paraffin/copper foam composite. Furthermore, the temperature of solid paraffin could not increase very quickly due to the small thermal conductivity. In the case of paraffin/copper foam composite, the temperature distribution was more uniform, indicating that the temperature of paraffin in solid region increased very quickly because the copper foam enhanced the heat conduction in solid region. As can be seen from Fig. 5 (b) and Fig. 10 (b), the melting of paraffin/copper foam composite was slower than pure paraffin at the initial stage, which might be attributed to the fact that a part of heat was absorbed

by solid paraffin on the right side due to larger effective thermal conductivity of the paraffin/copper foam composite. Gradually, paraffin/copper foam composite melted faster than pure paraffin at the later stage.

The thermal energy storage characteristics can be estimated from the numerical results. For example, the mean charging powers of the pure paraffin and composite PCM were estimated to be about 4.19 W and 4.28 W at 3000 s by calculating the total enthalpy, and the efficiencies were about 67.63% and 69.10% by calculating the ratio of the total enthalpy to the input energy, respectively. It was indicated that the charging power and efficiency of the composite PCM were larger due to the better heat transfer performance and reduction of heat loss, which could be understood from the temperature distributions of the composite PCM and pure paraffin, as shown in Fig. 9 and Fig. 10. In the case of thermal energy discharging, the advantages of the mean discharging power and efficiency of composite PCM over those of pure paraffin were even apparent due to reason that the heat transfer was dominated by heat conduction where the effective thermal conductivity was the main influential factor in the thermal energy discharging.

The velocity fields of pure paraffin and paraffin/copper foam composite are shown in Fig. 10 (c) and Fig. 5 (c), respectively. In the case of paraffin/copper foam composite, liquid paraffin circulated around the liquid region due to uniform temperature. In the case of pure paraffin, liquid paraffin circulated at the initial stage, i.e., 1000 s and 2000 s. However, when the paraffin on the top was fully melted, liquid paraffin could not form large circulation due to non-uniform temperature in this region, as can be seen from Fig. 10 (a). The temperature of liquid paraffin on the top was higher and the temperature of liquid paraffin was relatively lower on the bottom; therefore the buoyancy hampered liquid paraffin on the top to flow downward and forced liquid paraffin to flow transversely. As a result, liquid paraffin on the top flowed downward in an “S” style. Furthermore, it can be seen that the velocity of liquid paraffin in pure paraffin was much larger than that in copper foam, where the maximum velocity of liquid paraffin was about 4.562×10^{-3} m/s, and that of liquid paraffin in copper foam was only about 5.187×10^{-4} m/s. This can be attributed to the effect of inertial and viscous resistances of copper foam, and the flow of liquid paraffin in copper foam was restricted.

Conclusion

In the present study, the melting heat transfer characteristics of the paraffin/copper foam composite PCM were experimentally and numerically investigated. A three-dimensional mathematical model was established to study the heat transfer mechanisms of the paraffin/copper foam composite PCM during the melting process. Meanwhile, an experimental setup was built to conduct the experiments, in which the

temperature measurement of the paraffin and ligament of the copper foam was carried out, and the visualization of the evolvement of the solid-liquid interface by conventional camera and the temperature fields measured by infrared camera were carried out. The comparison of the heat transfer characteristics between pure paraffin and paraffin/copper foam composite was also conducted. The following conclusions can be drawn:

(1) At the initial stage, heat conduction was the dominant mechanism of heat transfer, and the temperature of copper foam was slightly higher than that of paraffin. In the melting stage, the temperature of paraffin increased slowly due to large latent heat involved, and the temperature of copper foam was higher than that of paraffin. When the paraffin was melted, the temperature of liquid paraffin was affected by both natural convection and heat conduction simultaneously, and the temperature difference between copper foam and paraffin tended to decrease. When the natural convection dominated the heat transfer, the temperature of paraffin was even higher than that of copper foam. Due to the effect of buoyancy, paraffin on the top boundary melted faster than that on the bottom, which led to a curved solid-liquid interface.

(2) Compared to the pure paraffin, paraffin/copper foam composite showed a better heat transfer performance because of the high thermal conductivity of copper foam. The temperature distribution of paraffin/copper foam composite was more uniform than that of pure paraffin. Nevertheless, the flow of liquid paraffin was hampered by the porous structure of copper foam, and the effect of natural convection in the composite PCM was weaker than that in pure paraffin.

(3) The comparison of the temperature difference between the ligament of copper foam and paraffin obtained from the experiments and numerical calculation showed reasonable agreement, which indicated that the two-temperature energy model can be used to describe the heat transfer of the composite PCM. There was a quite large temperature difference between the ligament of copper foam and paraffin due to thermal non-equilibrium, which must be taken into consideration in the heat transfer modelling. And the further temperature measurement by the infrared camera showed reasonable agreement with the numerical results. It can be concluded that such numerical modelling can be further applied to the investigation of the thermal energy storage and thermal management by using the composite PCM.

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673 Fig. 1 Schematic illustration of the experimental setup. The composite PCM is shown by the side-view.

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675 Fig. 2 Schematic illustration of the rectangular enclosure with the composite PCM

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Fig. 3 Computational domain of paraffin/copper foam composite PCM with the plexiglass enclosure

Fig. 4 The melting curve of paraffin from DSC

Fig. 5 The evolvement of the experimental (a) and numerical (b) solid-liquid interface and velocity fields (c) of paraffin/copper foam composite

Fig. 6 Comparison of the numerical results with the experimental results of temperatures in the paraffin and on the ligament of copper foam

(a)

(b)

Fig. 7 The evolvement of temperature fields on the outer surface of the enclosure

(a) experimental results, (b) numerical results

Fig. 8 Comparison of the numerical results with the experimental results of temperature difference between paraffin and copper foam

Fig. 9 Temperature fields of the copper foam (a) and paraffin (b) and the temperature difference fields (c)

Fig. 10 The temperature fields (a), solid-liquid interfaces (b) and velocity fields (c) of pure paraffin

Table 1 Summary of the uncertainty

Parameters	Uncertainty
Measured parameter	
Size of copper foam (mm)	0.02
Temperature measured by thermocouples (°C)	0.5
Temperature measured by infrared camera (°C)	1.0
Porosity of copper foam (%)	0.5
Voltage (V)	0.001
Derived parameter	
Volume of copper foam (%)	0.24
Heat flux (%)	3.13

Table 2 Thermo-physical properties of paraffin, copper foam and plexiglass

Parameters	Value
Density of paraffin (kg/m ³)	785
Latent heat of paraffin (kJ/kg)	175.24
Melting temperature of paraffin (°C)	54.43~64.11
Thermal conductivity of paraffin (solid/liquid) (W/m·K)	0.3/0.1
Specific heat capacity of paraffin (J/kg·K)	2850
Dynamic viscosity of liquid paraffin (kg/m·s)	0.000365
thermal expansion coefficient of paraffin (K ⁻¹)	0.0003085
Density of copper foam (kg/m ³)	8920
Specific heat capacity of copper foam (J/kg·K)	380
Thermal conductivity of copper foam (W/m·K)	401
Thermal conductivity of plexiglass (W/m·K)	0.11