Fabrication and Thermal Characterization of the Modularized Thermal Storage Unit

Jinyan Hu, Run Hu, Chao Yuan, Bin Duan, Mengyu Huang, and Xiaobing Luo

Abstract*— Phase change materials (PCMs), due to their extraordinary latent heat storage characteristic, have been widely investigated in the thermal management of electronic devices. However, the current PCM-based heat sinks generally suffer a long heat dissipation time after heat absorption. To address this issue, the modularized thermal storage unit (MTSU) was proposed in this paper. The online charging and offline discharging working modes of the MTSU allow it to cool the intermittent electronic devices with a high duty cycle. In this paper, the MTSU samples were fabricated with paraffin wax as latent heat storage core unit and polymer encapsulation shell. The specific latent heat storage and morphology of the MTSU samples were studied. Afterward, the thermal storage performance of each individual MTSU sample was specially characterized with the sample subjected to the constant heat flux. The MTSU samples showed desirable performance on encapsulating the PCMs and stabilizing the heat source temperature. The safe operation time of the heat source was prolonged by 181% with 16 g of PCM in the vacuum environment. Furthermore, the performance of the MTSU samples on cooling of the electronic devices with a relatively high duty cycle was investigated. The results show that owing to the modularization and replaceability of the samples, the ON/OFF working time ratio of the heat source was greatly enlarged. When cooled by the MTSU sample with 11.42 g of paraffin, the heat source could work with an ON/OFF time ratio up to 6.7 at 4 W and 14.9 at 3 W.

***Index Terms*— Epoxy resin, modularized thermal storage unit (MTSU), phase change material (PCM), thermal management.**

NOMENCLATURE

T	Temperature (°C).
Q	Heating power of the heat source (W).
L	Specific latent heat of paraffin (kJ/kg).
M	Mass (kg).
c_p	Specific heat capacity (J/kg · K).
l	Length of the paraffin core (m).
w	Width of the paraffin core (m).
k	Thermal conductivity (W/m · K).
t	Time (min).
S_{te}^{*}	Modified Stefan number.

Greek Symbols

ρ	Density.
ε	Expansion ratio of paraffin.

Subscripts

P	Paraffin core.
M	Modularized thermal storage unit.
R	Epoxy resin.
Safe	Safe operation.

Superscripts

Theo	Theoretical value.
S	Solid state.
L	Liquid state.
p-s	Paraffin in solid state.
pra	Practical value.

Abbreviations

PCM	Phase change material.
CPCM	Composite phase change material.
MTSU	Modularized thermal storage unit.
DSC	Differential scanning calorimeter.
DAQ	Digital data acquisition.
LED	Light-emitting diode.

I. INTRODUCTION

THE INCREASING growth of input power and the miniaturization of packaging size have led to the great increase of heat flux density in electronic components, resulting in a challenging thermal management issue [1]–[3]. Among the electronic devices, some devices such as the portable devices [4] and some LED lighting devices [2] are intermittently used. For instance, the operating time of the portable devices is generally scattered, and these devices generate the heat only during the working time. For the thermal management of such electronic devices, latent heat storage with PCMs is considered as another promising passive solution, other than the forced air cooling system [5]–[8], owing to the distinctive properties of the PCMs, like large latent heat storage capacity and nearly isothermal heat storage/retrieval processes. Besides, because of the thermal buffer effect of the PCM, the PCM-based heat sinks can be designed based on the nominal heating load of the devices instead of the peak load.

Based on the phase transition behaviors of the PCMs, the working cycle of the PCM-based heat sinks could be separated into two processes, namely, the melting and solidification processes, which are also called the charging and discharging processes of the heat sinks [9]. During the

Manuscript received March 19, 2016; accepted June 6, 2016. Date of publication July 9, 2016; date of current version August 5, 2016. This work was supported by the Natural Science Foundation of China under Grant 51576078 and Grant 51376070. Recommended for publication by Associate Editor A. Bhattacharya upon evaluation of reviewers' comments.

The authors are with the State Key Laboratory of Coal Combustion, School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: jyhu1220@163.com; hurun@hust.edu.cn; yuanchao@hust.edu.cn; huster_duanbin@163.com; 972570073@qq.com; luoxb@mail.hust.edu.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TCPMT.2016.2582503

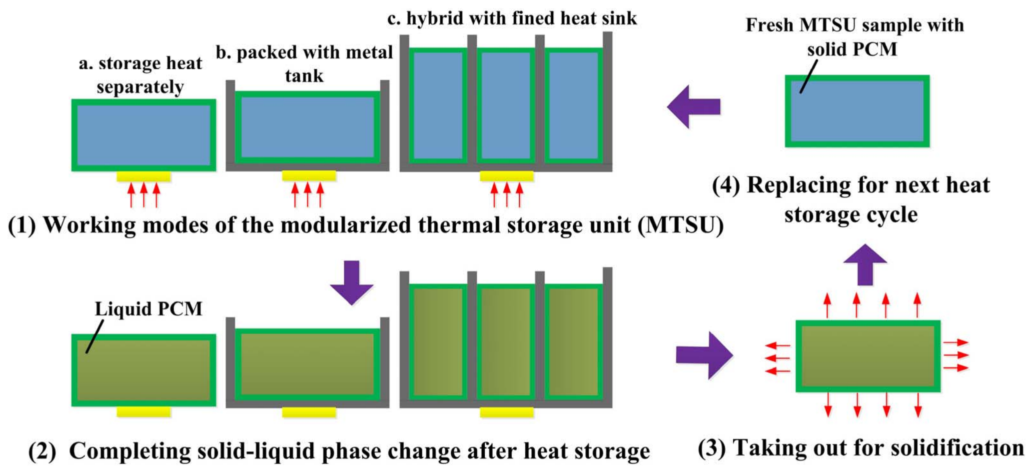


Fig. 1. Working principle of the MTSU samples.

charging process, the PCMs absorb the working heat of the electronic devices and take solid–liquid phase transition. Meanwhile in the discharging process, the PCMs release the stored heat to the ambient and resolidify for next cycle. Notably, when the PCMs melt totally, it is hard for the PCM-based heat sinks to absorb the working heat of electronic devices further. In other words, the devices could not continue to work in the discharging process until the PCM resolidifies again. Moreover, since the thermal conductivity of the PCMs is usually low, it generally takes a long time for the PCMs to complete the discharging process [10]–[12]. The awkward working characteristic of long discharging time restricts the wide application of the PCM-based heat sinks.

In the last few decades, efforts have been extensively made and a lot of methods were proposed to resolve the problem of long discharging time. The main purpose of these methods is to increase the resolidification rate of the PCM by enhancing the heat transfer performance. According to the heat transfer enhancing approaches, these methods could be categorized into two groups. One is enhancing the inner heat conduction of the heat sink by improving the thermal conductivity of the PCM. In recent studies, measures have been taken to improve the thermal conductivity of PCMs including the following:

1) dispersing high thermal conductivity particles into PCMs, such as metal powder, carbon nanotubes, graphene, or other nanomaterials [13]–[15];
2) impregnating high-conductivity porous matrix with PCMs, like expanded graphite and metal foam [16]–[18];
3) adding metal structures with different configurations into the PCM, like metal rings and plate/pin fins [19]–[21].

The other group to accelerate the PCM resolidification is enhancing the external heat convection of the PCM-based heat sink by increasing the exposed fin area. Krishnan *et al*. [22] and Stupar *et al*. [23] immersed some part of the fins in the PCM and left the other part exposed to the ambient to promote the resolidification of PCM by natural convection. In [24], an external finned heat exchanger was fixed upside the PCM-based heat sink to enhance the convection heat transfer. Meanwhile in [25], the plate-fin and pin-fin hybrid heat sinks were fabricated with PCM inserted into the cavities inside the pin fins and plate fins. Though both categories of methods could effectively increase the PCM resolidification rate and reduce the discharging time, some new problems are brought about. For the former group methods, because of the addition of the thermal conductive additives, the quantity of the PCMs has to decrease, which will result in the decreasing of the total heat storage capacity. Meanwhile, for the latter ones, as a large inner space of the heat sink was reserved to conduct the convection heat transfer, much sacrifice was made in the heat storage capacity and compactness of the system. Besides, when the electronic devices are operated with a high duty cycle and have a quite short working interval time (on the order of several minutes) or work in an enclosed space with a relatively high temperature, neither of the two group methods could make much sense. For example, in [26], the CPCM with the paraffin wax saturated in metal foam was packed inside the Li-ion battery of the electric vehicles to cool the battery. They found that the discharging time of the battery was about 50 min with a discharge current of 10 A, while the time the vehicles had to stop for the CPCM cooling was about 240 min. Therefore, it is urgent to develop some alternative methods to overcome the problem of long discharging time.

Inspired by the online-discharging and offline-charging working mode of the driving batteries of electronic devices [27], in this paper, an MTSU with replaceability is proposed and investigated to address the long discharging time issue of the PCM-based heat sink for the cooling of the electronic devices with intermittent working load. The MTSU sample is fabricated through encapsulating the PCM in a regularly shaped enclosure. Owing to its modularization, the MTSU can be operated as a separate heat sink or packed in the metallic heat sink or inserted in the finned heat sink to form the hybrid heat sink. The working principle of the MTSU-based heat sink is shown in Fig. 1. When the electronic devices work, the MTSUs absorb the working heat and maintain the devices temperature within the safe operation limit. Meanwhile, at the working intervals of the devices, the completely charged MTSUs could be quickly removed from

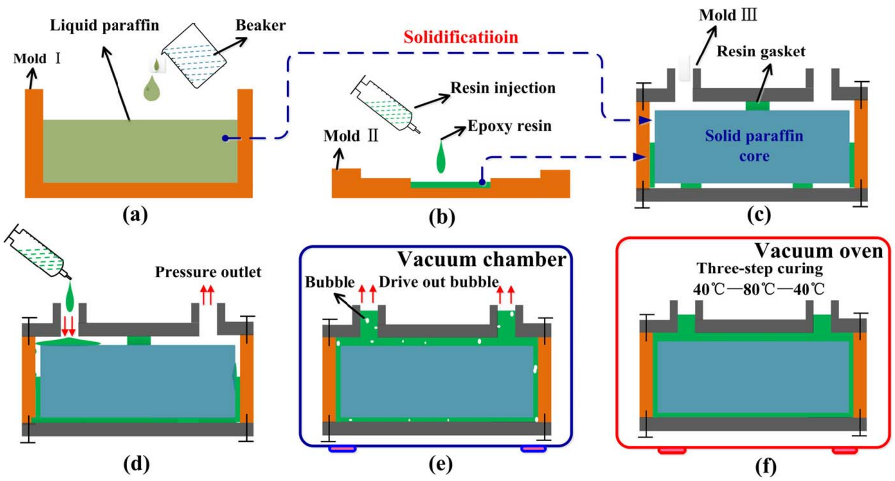


Fig. 2. Flowchart of the preparing processes of the MTSU samples. (a) Preparing of the paraffin core. (b) Preparing of the resin gasket. (c) Fixing the paraffin core with resin gaskets. (d) Injection of the epoxy resin. (e) Driving out the bubbles. (f) Curing the MTSU sample.

the heat storage system and replaced with a new one. In this way, the electronic devices could start for the next working cycle fast without waiting for the long discharging time of the PCM.

To realize the modularization and replaceability of the MTSUs for electronics cooling, the samples should have desirable performance on PCM encapsulation and temperature stabilization for a relatively long time to meet the heat dissipation demand in the working cycle of the devices. In this paper, to verify the modularization idea and examine the thermal storage properties of the MTSU samples, several samples encapsulated with different paraffin mass were prepared and studied. The thermal storage performance of the each individual MTSU sample was specially characterized with the samples subjected to the constant heat flux. During the test, the effect of the modified Stefan number to the safe operation time of the heat source was studied to guide the design of the MTSU samples. Furthermore, the performance of the MTSU samples on cooling of the electronic devices with a relatively high duty cycle was investigated.

II. Experiments

A. Fabrication of MTSU Samples

1) Material: The paraffin wax, OP44E (purity larger than 96%; RUHR, China) was selected as the PCM. Epoxy resin (Ausbond, USA) was chosen as the encapsulation shell material for its preferable thermophysical properties, like chemical and mechanical resistance, toughness, and low density. All the raw chemicals are analytical reagents, and the further purification is unnecessary.

2) Fabrication of MTSU Samples: Considering the cooling target, the MTSU should be fabricated with a relatively small volume and light weight. During the preparation process, the casting molding method was adopted. To make the demolding process easier, the molds were manufactured with the inner surfaces polished. Moreover, the mold-releasing agent, polyvinyl alcohol, was applied and uniformly coated on the surfaces of the molds. The epoxy resin components, resin and hardener, were mixed with 5:1 mass ration. Then, a vacuum oven was applied to get rid of the bubbles inside the liquid resin.

Fig. 2 shows the preparing processes of the MTSU samples. First, the rectangular paraffin core was prepared with mold I [Fig. 2(a)]. During this process, the liquid paraffin was poured into mold I and crystallized in a vacuum oven (LS-VO20, Thermofiher, USA). Then, the resin gasket with a thickness of 2 mm was molded by mold II. Third, the prepared paraffin core was put into mold III, and the gaskets were used to retain a fixed distance between the core and the mold inner surfaces. After that, the liquid epoxy resin was injected into mold III to fill the preserved space around the paraffin core. Next, mold III was sent into a vacuum chamber to get rid of the bubbles inside by a molecular pump (EXT75DX, Edwards, U.K.). Finally, the mold was placed in the oven for the curing. Considering the volume expansion of the liquid paraffin wax, a specific curing profile was proposed. At first, the composite was heated at 40 °C (below the paraffin melting temperature) for 1 h. Then, an annealing step at 80 °C for 6 h was conducted to ensure the full curing of resin. Afterward, 2-h 40 °C cooling treatment was conducted to make the paraffin solidify. In this paper, three MTSU samples with different mass fractions of paraffin wax were prepared. In addition, for comparison, a pure epoxy resin sample was also prepared.

B. Characterization Techniques of Physical Properties

1) Differential Scanning Calorimeter Test: The phase change properties in the melting and solidification processes of the paraffin wax and epoxy resin were investigated through DSC (TA, Q2000, USA) [28]. For each sample, the DSC measurements were conducted with the heating and cooling rate of 0.5 °C/min in the temperature range from 20 °C to 70 °C. The accuracy of temperature measurement and calorimeter is within ±0.01 °C and ±0.03%, respectively.

2) Specific Latent Heat Storage Test: With resin shell, the specific latent heat storage of the MTSU sample, denoted by L_M, decreases, which could be calculated as

$$L_M = \frac{m_p}{m_M} \cdot L \tag{1}$$

TABLE I
THERMOPHYSICAL PROPERTIES OF PARAFFIN WAX AND EPOXY RESIN

Materials	Density (kg/m^3)	Thermal conductivity (W/m·K)	Specific heat capacity (kJ/kg·K)
Paraffin wax	845(liquid)/860(solid)	0.2 (liquid and solid)	2.0(liquid)/2.2(solid)
Epoxy resin	1500	0.51	1.5

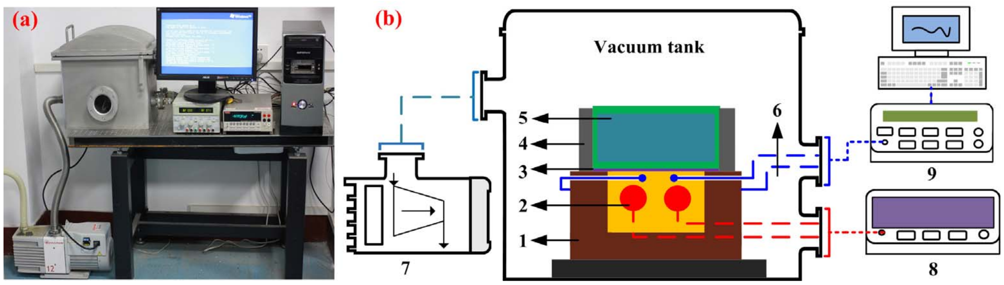


Fig. 3. (a) Prototypes of the experimental setup. (b) Schematic of the experimental setup. 1: insulation holder. 2: heat source assembly. 3: thermal grease. 4: radiation insulator. 5: MTSU sample. 6: thermocouples. 7: vacuum pump. 8: power supply. 9: data acquisition system.

where m is the mass of sample and L is the paraffin melting heat. To determine the latent heat storage capacity of the MTSU sample, the theoretical specific latent heat storage was predicted first for a given paraffin core mass. The mass of the MTSU sample could be theoretically determined by

$$m_M^{\text{theo}} = \left[\left(\frac{m_p(1+\varepsilon)}{\rho_p^s \cdot l \cdot w} + 0.004\right) \cdot (l + 0.004) \cdot (w + 0.004) - \frac{m_p(1+\varepsilon)}{\rho_p^s}\right] \cdot \rho_r + m_p \quad (2)$$

$$\varepsilon = \frac{\rho_p^s - \rho_p^l}{\rho_p^l} \cdot 100\% \quad (3)$$

where ρ is the material density, l and w correspond to the length and width of the paraffin core, and ε is the volume expansion ratio. In these equations, the shrinking of paraffin was considered during the preparation process in Fig. 1(f). Then, the theoretical specific latent heat storage of the MTSU sample was obtained by $L_M^{\text{theo}} = (m_p/m_M^{\text{theo}}) \cdot L$.

Actually, there still exist some voids in the MTSU samples, which will result in the deviation between the theoretical and practical values of the MTSU mass. The practical specific latent heat storage of the MTSU sample was calculated with $L_M^{\text{pra}} = (m_p/m_M^{\text{pra}}) \cdot L$. In this paper, the specimen mass was determined by an electronic balance with an accuracy of 0.01 g and the dimension was measured by a Vernier caliper with an accuracy of 0.1 mm. The tested physical properties of the paraffin wax and epoxy resin are given in Table I.

3) Experimental Setup and Approach: The diagrammatic sketch and prototype of the experimental setup are shown in Fig. 3. The experimental system was fixed in a vacuum tank that was vacuumized to a vacuum degree of 10^2 Pa by a turbo-molecular pumping system to minimize the effect of natural convection. In the vacuum tank, the MTSU sample was located on the upper surface of a heat source assembly that was fixed on a polyvinyl-fluoride insulation plate. As seen in Fig. 3, the heat source assembly consists of a dc power supply (DH1718G-4) and a copper block (20 mm × 20 mm × 20 mm) embedded with two-wire wound cartridge heating rods capable of 60 W. Thermal grease with a thermal conductivity of 1.5 W/m · K was tucked on the interfaces between the sample and the heat source. The temperature variations were automatically recorded by two K-type thermocouples that were linked to a DAQ system (Agilent 34970A). The thermocouples were distributed in the middle of the heat source through the holes drilled inside the copper plate. Both thermocouples were calibrated, and the accuracy was ±0.2 °C. During the experiments, different heating powers ranged from 2.5 to 4 W in steps of 0.5 W were applied to the MTSU samples. A safe operation limit temperature was set as 90 °C, above which the electronic chips begin to fail to work [2].

The experimental process is introduced as follows. The MTSU samples encapsulated with 11.42 g of paraffin were selected as the representative samples to conduct the investigation. The thermal storage system was taken out from the vacuum tank, and the MTSU sample was exposed to the ambient in this part of work. The ambient temperature was maintained at 20 °C throughout the experiment. Apart from this, the experimental system setup is also shown in Fig. 3. To emulate the working characteristic of the electronic devices with high duty cycles, the heat source worked intermittently with a working interval time of 7.5 min. Two different heating loads of 3 and 4 W were imposed to the thermal storage system during the experiment. For comparison, the cooling performance of the MTSU sample without replaceability was also studied.

III. RESULTS AND DISCUSSION

A. Phase Change Behavior of Paraffin Wax and Epoxy Resin

The DSC curves for the heating and cooling processes of the paraffin and epoxy resin are shown in Fig. 4. From the results, it is observed that the curve of the epoxy

TABLE II
PHYSICAL PROPERTIES OF THE MTSU SAMPLES

Properties	Sample 1	Sample 2	Sample 3	Epoxy resin
MTSU volume (mm^3)	30×30×17	30×30×24	30×30×32	30×30×15
Paraffin core volume (mm^3)	26×26×13	26×26×20	26×26×28	
Weight of MTSU (g)	17.72	24.34	29.96	20.25
Weight of paraffin core (g)	7.43	11.42	16.01	

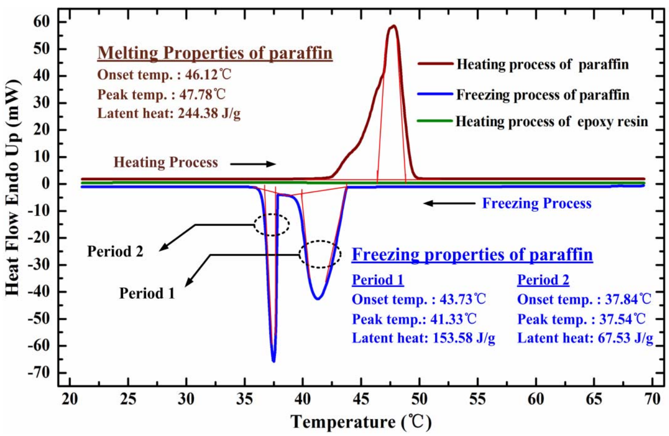


Fig. 4. DSC test of the paraffin wax and epoxy resin.

resin is quite stable and no phase transition occurs during the heating process, which confirms that, as the encapsulation material, epoxy resin has stable physical properties. As for paraffin wax, the heat flow signals exist intense fluctuation because of the phase transition. The melting and crystallization temperatures, which correspond to the onset temperature on the curves, are obtained. Meanwhile, the melting enthalpy and crystallization enthalpy are calculated by numerical integration of the total area under the peaks of the solid–liquid and liquid–solid phase transitions. The exact phase transition properties of the paraffin wax are listed in Fig. 4. Additionally, comparing the melting and freezing curves, an interesting phenomenon is seen that the freezing process of the paraffin is not exactly the reverse evolution of the melting process. In the melting process, there exists one endothermic peak, while for the solidification process, there are two exothermic peaks that separate the process into two periods. Moreover, because of the subcooling effect, the freezing start temperature of the paraffin shifts left for about 6 °C from the melting finish temperature.

B. Morphology of MTSU Samples

The overall and cross-sectional views of the MTSU sample are shown in Fig. 5. As seen from the images, the paraffin core is tightly coated and well encapsulated by the epoxy resin shell with a thickness of 2 mm. The physical properties of the MTSU samples are summarized in Table II.

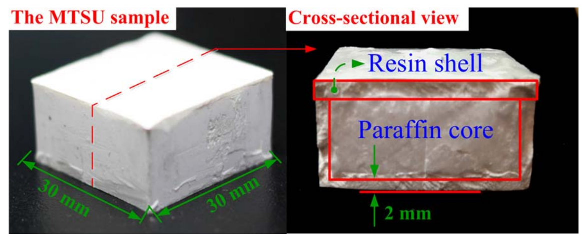


Fig. 5. Picture of the MTSU sample (left) and its sectional view (right).

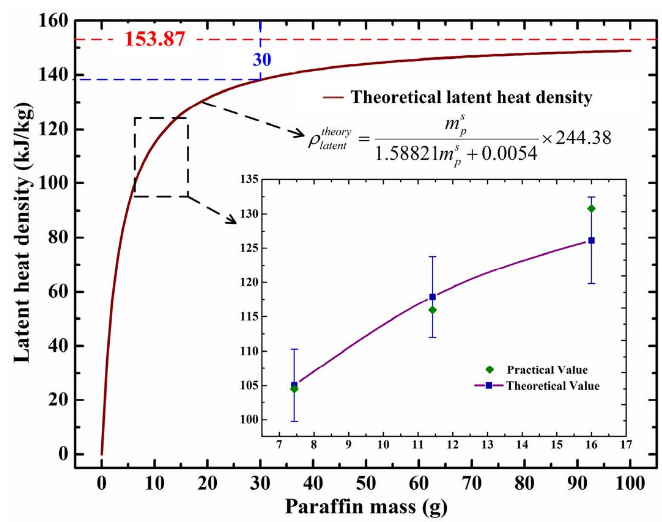


Fig. 6. Practical and theoretical values of specific latent heat storage.

C. Specific Latent Heat Storage of MTSU Samples

The theoretical and practical values of the specific latent heat storage of the MTSU samples are shown in the embedded figure in Fig. 6. From Fig. 6, it is seen that specific latent heat storage increases as the paraffin mass increases. When the paraffin mass is 16 g, the measured specific latent heat storage of the MTSU sample is 130.51 kJ/kg. Comparing the practical values to the theoretical ones, it is seen that practical values are within the range of the error bars allowing a biggest error of ±5%, which indicates that the MTSU samples are well prepared in this paper.

Moreover, to help to design the MTSU sample for different cooling loads' demand, the theoretical latent heat storage density of the MTSU sample is also predicted with

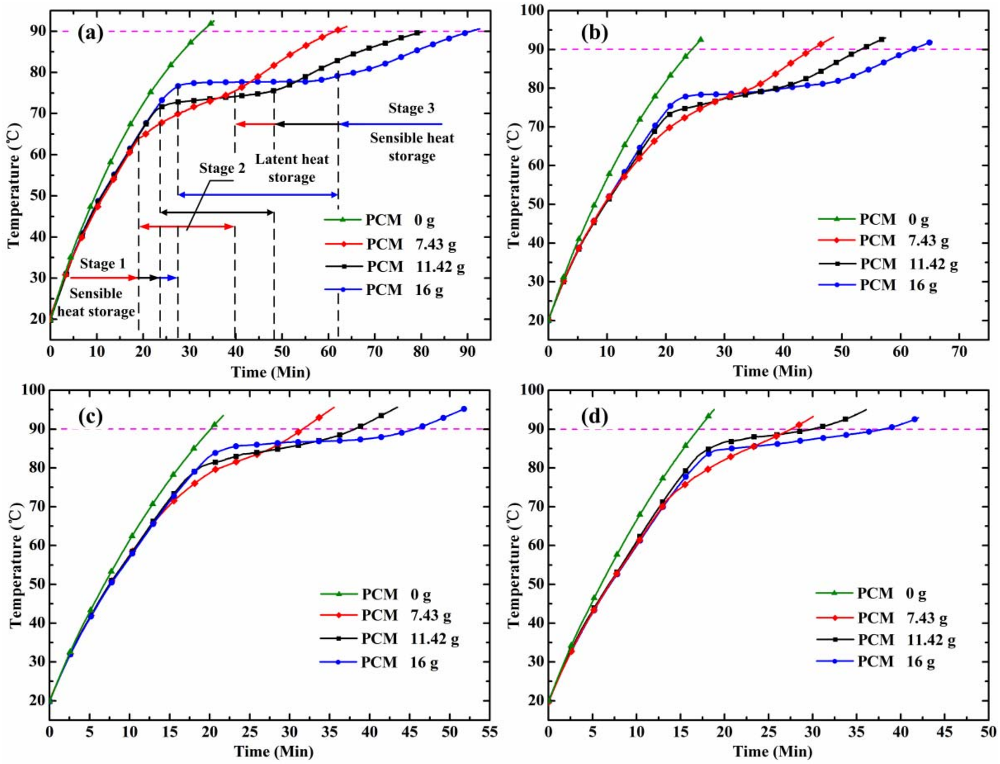


Fig. 7. Heat source temperature curves at different heating powers. (a) 2.5 W. (b) 3.0 W. (c) 3.5 W. (d) 4.0 W.

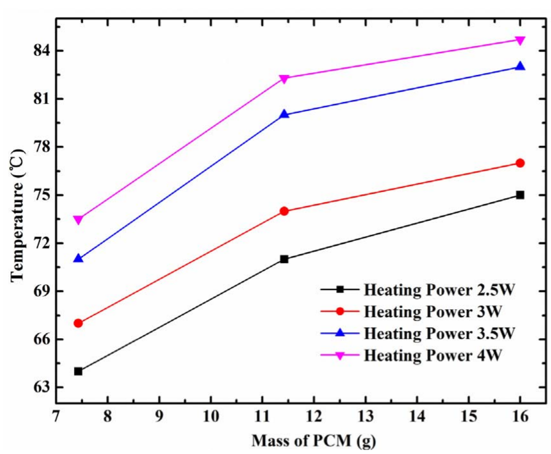


Fig. 8. Heat source temperature at the first turning point of the temperature curves.

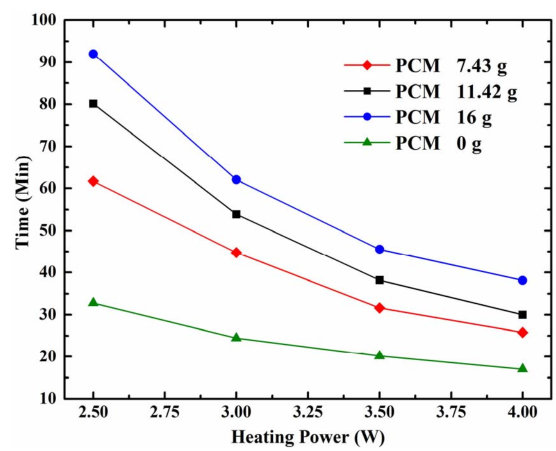


Fig. 9. Safe operation time of the MTSU samples under different experimental conditions.

the curve in Fig. 6. It is seen in the paraffin mass range from 0 to 30 g that the latent heat density sharply increases with the increasing paraffin mass, while as the paraffin mass goes over 30 g, the latent heat storage density increases slightly, approaching an ultimate value of 153.87 kJ/kg.

D. Thermal Storage Performance of MTSU Samples

1) Temperature Variation of Heat Source: Fig. 7 shows the heat source temperature variation versus time at different heating powers when cooled by the MTSU samples with PCM masses of 0, 7.43, 11.42, and 16 g, respectively. Comparing the temperature curves, it is seen that for the pure epoxy resin sample, the heat source temperature goes up linearly and the temperature rising rate reaches 4.12 °C/min at 4 W. Meanwhile for the MTSU samples, the temperature curves show obvious turning points that divide the temperature rising process into three stages, as characterized in Fig. 7(a). It is indicated that the MTSU samples could effectively stabilize the heat source temperature and extend the working time of the electronic devices, compared to the resin sample. Owing to the large amount of heat absorption by the MTSU samples during the phase transition of the paraffin core, the second stages of the curves are more stable than that of the other two stages. At stages 1 and 3, the heat is mainly absorbed as the sensible heat, which has a much lower heat storage capacity.

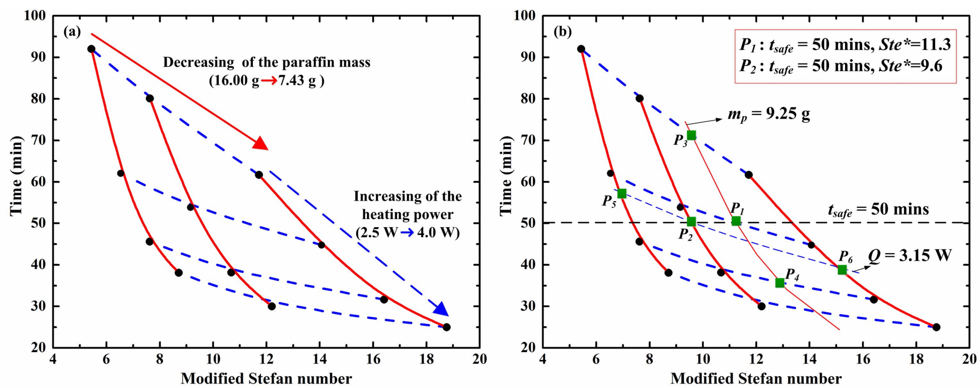


Fig. 10. (a) Effect of the modified Stefan number. (b) Preliminary designed MTSU system with modified Stefan number.

Focusing on the second stages of the curves in Fig. 7, it is seen that the latent heat storage time of the CPCM samples extends with the increase in the paraffin core mass and curtails with the increase in the heating power. For instance, for 11.42 g of paraffin core, the second stage time decreases by 90% as the heating power increases from 2.5 to 4 W.

The onset temperatures of the second stages are also studied in this paper. To obtain a desirable cooling performance and ensure the complete extraction of the PCM latent heat before the electronic devices reach the safe limit temperature, the onset temperature of the second stage should be kept at a reasonable level. The temperatures of the turning points under different experimental conditions are characterized and lined up according to the heating powers in Fig. 8. It is seen that the temperature increases with the increase in the heating power and paraffin mass. Due to the low thermal conductivity of the paraffin and resin shell, the onset temperature reaches 84.7 °C at 4.0 W with a paraffin mass of 16 g. Therefore, to obtain an ideal cooling performance of the MTSU sample, measures should be taken to improve the thermal conductivity of the MTSU samples and an optimal melting temperature of the PCM should be selected based on the consideration of the heating power and PCM mass.

2) Study of the Safe Operation Time: As an important target parameter during the MTSU sample design, the safe operation time, known as the time before the electronic device reaches the safe limit temperature, should be designed to meet the working demand of the devices. In this paper, the distribution of the safe operation times, t_{safe}, under different experimental conditions is shown in Fig. 9. It is seen that the safe operation time was effectively prolonged by the MTSU samples. When heated at 2.5 W, the MTSU sample with 16 g of paraffin extends the time duration for about 181%, compared to the resin sample. Moreover, the safe operation time decreases with the increase in the heating power and prolongs with the increase in the paraffin mass. For the thermal design purpose, the influence of the paraffin mass and heating power on the value of t_{safe} was studied with the modified Stefan number [19]. The modified Stefan number is defined as

$$S_{te}^{*} = \frac{Qc_p^{p-s} lw\rho_p}{k_p^s L m_p}. \tag{4}$$

A graphical representation of the effect of the modified Stefan number to the safe operation time is given in Fig. 10(a). In Fig. 10(a), the values of the safe operation time are lined up with B-spline curves according to the paraffin mass or the heating power of heat source. The dashed curves denote the time duration under the same heating power, whereas the solid curves are formed according to the paraffin mass. From Fig. 10(a), it is seen that for each separate curve, the safe operation time sharply decreases with the increase in the modified Stefan number in view of the fact that a higher Q or lower m_p means a higher S_{te}^{*}. Furthermore, as depicted in Fig. 10(a), the solid curves have much steeper slopes than the dashed ones, which indicates that the heating power of the heat source has a more significant influence on the safe operation time. Notably, with the help of the interlacing lines in Fig. 10(a) and (4), the MTSU system could be preliminary designed according to the working demand of the electronic devices. As shown in Fig. 10(b), if the safe operation time is designed to be 50 min with a given heating power of 3.0 W, the modified Stefan number could be obtained with the intersection point (P_1) of the lines, as depicted in Fig. 10(b). Then, the paraffin encapsulated in the MTSU sample could be approximately calculated to be 9.25 g with (4). Similarly, the heating power could be approximately calculated for a given time duration and paraffin mass. Moreover, for a given paraffin mass or heating power, the corresponding B-spline lines could be curved for the further system design of the MTSU. For example, for the given paraffin mass, $m_p = 9.25$ g, the points p_1, p_3, and p_4, which correspond to the points under the heating power of 2.5, 3.0, and 3.5 W, are obtained with (4) and the lines in Fig. 10(b). Then, the points were lined up with B-spline line for a paraffin mass of 9.25 g.

3) Replaceability Study of MTSU Samples: The temperature variations of the heat source at different heating powers are shown in Figs. 11 and 12 when cooled by the MTSU samples encapsulated with 11.42 g of paraffin. In Fig. 11, the heat source was cooled by the MTSU samples with replaceability at different power inputs. During the working time, the heat source was cooled by the MTSU sample and the heat source temperature was maintained below 90 °C, whereas when the temperature reached 90 °C, the power supply was cut OFF. Meanwhile, the MTSU sample was removed from the system,

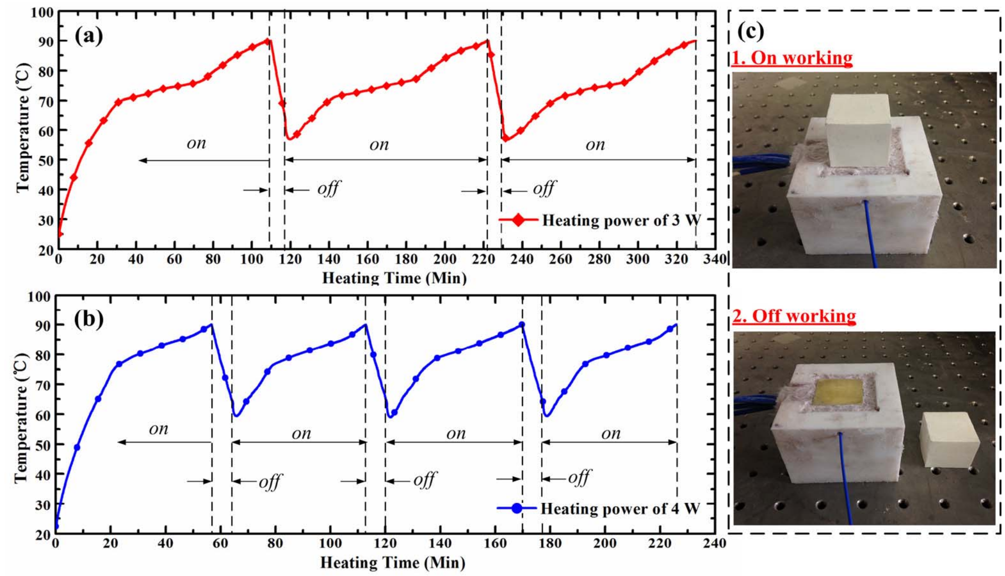


Fig. 11. Heat source temperature variation when cooled by the MTSU sample encapsulated with 11.42 of g paraffin at (a) 3 and (b) 4 W. (c) Operating states of the MTSU sample.

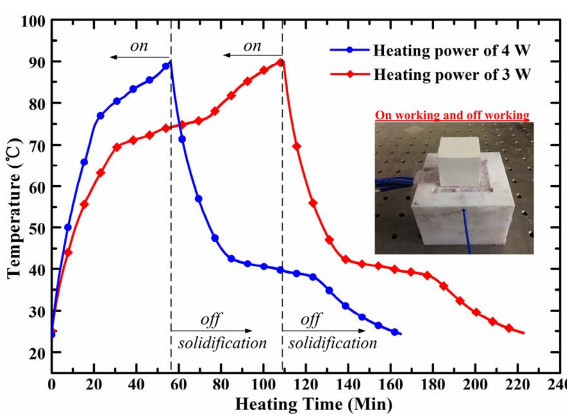


Fig. 12. Heat source temperature curves during the thermal storage and resolidification processes of the MTSU sample encapsulated with 11.42 g of paraffin without replaceability.

leaving the upper surface of the heat source exposed to the ambient. After the OFF time, the heat source recovered to work and another MTSU sample was assembled in the thermal storage system for the heat source cooling in the next cycle, whereas for Fig. 12, the heat source was cooled by the MTSU sample that was fixed in the thermal storage system without replaceability to analogy the working mode of the traditional latent thermal storage systems. Comparing Figs. 11 and 12, it is seen that for both cases, the MTSU sample could effectively maintain the heat source temperature within the safe operation limit for ∼105 min at 3 W and ∼55 min at 4 W, respectively, at each working cycle. However, because of the long solidification process of the MTSU sample, the OFF time in Fig. 12 is much longer than that in Fig. 11. The ratio of ON/OFF time in Fig. 12 is about 0.53 at 4 W and 1.02 at 3 W, whereas when cooled by the MTSU sample with replaceability, the ratio of ON/OFF time was enlarged to be about 6.67 at 4 W and 14.86 at 3 W, which ensures the electronic devices to work with a high duty cycle.

IV. Conclusion

In this paper, the MTSU was proposed to overcome the problem of the long resolidification time of the PCM-based heat sink when applied for the cooling of intermittent low-power electronic devices. The samples were fabricated with the paraffin core macroencapsulated by the epoxy resin through the casting molding method, and a specific curing profile was proposed to make the paraffin well confined. The morphology and thermal properties of the MTSU samples were characterized via the technical approaches including the DSC test. The results show that the MTSU samples were well modularized with compact morphology. The MTSU samples had desirable specific latent thermal storage densities that increase with the increase in the paraffin mass, approaching 153.87 kJ/kg. Afterward, the thermal storage capability of each individual MTSU sample was characterized. The MTSU samples showed desirable performance on encapsulating the PCMs and stabilizing the heat source temperature. The safe operation time of the heat source was prolonged by 181% with 16 g of paraffin in the vacuum environment. During the test, the effect of the modified Stefan number on the safe operation time of the electronic devices was also investigated. It was indicated that compared with the paraffin mass, the heating power has a greater influence on the safe operation time. With the help of the modified Stefan number, the MTSU system could be preliminary designed to meet various cooling requirements of the electronic devices. Furthermore, the performance of the MTSU samples on cooling of the electronic devices with a relatively high duty cycle was investigated. The results show that owing to the modularization and replaceability of the samples, the working ON/OFF time ratio of the heat source was greatly enlarged. When cooled by the MTSU sample with 11.42 g of paraffin, the heat source could work with an ON/OFF time ratio up to 6.7 at 4 W and 14.9 at 3 W.

REFERENCES

[1] L. T. Yeh, "Review of heat transfer technologies in electronic equipment," *J. Electron. Packag.*, vol. 117, no. 4, pp. 333–339, Dec. 1995.

[2] S. Liu and X. Luo, *LED Packaging for Lighting Applications: Design, Manufacturing and Testing*. New York, NY, USA: Wiley, 2011.

[3] R. J. McGlen, R. Jachuck, and S. Lin, "Integrated thermal management techniques for high power electronic devices," *Appl. Thermal Eng.*, vol. 24, nos. 8–9, pp. 1143–1156, 2004.

[4] S. C. Fok, W. Shen, and F. L. Tan, "Cooling of portable hand-held electronic devices using phase change materials in finned heat sinks," *Int. J. Thermal Sci.*, vol. 49, no. 1, pp. 109–117, Jan. 2010.

[5] H. Yin, X. Gao, J. Ding, Z. Zhang, and Y. Fang, "Thermal management of electronic components with thermal adaptation composite material," *Appl. Energy*, vol. 87, no. 12, pp. 3784–3791, Dec. 2010.

[6] W. Wu *et al.*, "Preparation and thermal conductivity enhancement of composite phase change materials for electronic thermal management," *Energy Convers. Manag.*, vol. 101, pp. 278–284, Sep. 2015.

[7] Z. Ling *et al.*, "Review on thermal management systems using phase change materials for electronic components, Li-ion batteries and photovoltaic modules," *Renew. Sustain. Energy Rev.*, vol. 31, pp. 427–438, Mar. 2014.

[8] J. Hu, R. Hu, Y. Zhu, and X. Luo, "Experimental investigation on composite phase-change material (CPCM)-based substrate," *Heat Transf. Eng.*, vol. 37, nos. 3–4, pp. 351–358, 2016.

[9] S. Bellan *et al.*, "Numerical analysis of charging and discharging performance of a thermal energy storage system with encapsulated phase change material," *Appl. Thermal Eng.*, vol. 71, no. 1, pp. 481–500, 2014.

[10] S. K. Saha and P. Dutta, "Thermal management of electronics using PCM-based heat sink subjected to cyclic heat load," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 2, no. 3, pp. 464–473, Mar. 2012.

[11] M. K. Rathod and J. Banerjee, "Thermal stability of phase change materials used in latent heat energy storage systems: A review," *Renew. Sustain. Energy Rev.*, vol. 18, pp. 246–258, Feb. 2013.

[12] R. K. Sharma, P. Ganesan, V. V. Tyagi, H. S. C. Metselaar, and S. C. Sandaran, "Developments in organic solid–liquid phase change materials and their applications in thermal energy storage," *Energy Convers. Manag.*, vol. 95, pp. 193–228, May 2015.

[13] H. Babaei, P. Keblinski, and J. M. Khodadadi, "Thermal conductivity enhancement of paraffins by increasing the alignment of molecules through adding CNT/graphene," *Int. J. Heat Mass Transf.*, vol. 58, nos. 1–2, pp. 209–216, Mar. 2013.

[14] L.-W. Fan *et al.*, "Effects of various carbon nanofillers on the thermal conductivity and energy storage properties of paraffin-based nanocomposite phase change materials," *Appl. Energy*, vol. 110, pp. 163–172, Oct. 2013.

[15] J.-N. Shi *et al.*, "Improving the thermal conductivity and shape-stabilization of phase change materials using nanographite additives," *Carbon*, vol. 51, pp. 365–372, Jan. 2013.

[16] S. Mancin, A. Diani, L. Doretti, K. Hooman, and L. Rossetto, "Experimental analysis of phase change phenomenon of paraffin waxes embedded in copper foams," *Int. J. Thermal Sci.*, vol. 90, pp. 79–89, Apr. 2015.

[17] Y. Tian and C. Y. Zhao, "A numerical investigation of heat transfer in phase change materials (PCMs) embedded in porous metals," *Energy*, vol. 36, no. 9, pp. 5539–5546, Sep. 2011.

[18] Z. Zhang and X. Fang, "Study on paraffin/expanded graphite composite phase change thermal energy storage material," *Energy Convers. Manag.*, vol. 47, no. 3, pp. 303–310, Feb. 2006.

[19] R. Baby and C. Balaji, "Experimental investigations on phase change material based finned heat sinks for electronic equipment cooling," *Int. J. Heat Mass Transf.*, vol. 55, nos. 5–6, pp. 1642–1649, Feb. 2012.

[20] S. Mahmoud, A. Tang, C. Toh, R. Al-Dadah, and S. L. Soo, "Experimental investigation of inserts configurations and PCM type on the thermal performance of PCM based heat sinks," *Appl. Energy*, vol. 112, pp. 1349–1356, Dec. 2013.

[21] S. Mat, A. A. Al-Abidi, K. Sopian, M. Y. Sulaiman, and A. T. Mohammad, "Enhance heat transfer for PCM melting in triplex tube with internal–external fins," *Energy Convers. Manag.*, vol. 74, pp. 223–236, Oct. 2013.

[22] S. Krishnan, S. V. Garimella, and S. S. Kang, "A novel hybrid heat sink using phase change materials for transient thermal management of electronics," *IEEE Trans. Compon. Packag. Technol.*, vol. 28, no. 2, pp. 281–289, Jun. 2005.

[23] A. Stupar, U. Drofenik, and J. W. Kolar, "Optimization of phase change material heat sinks for low duty cycle high peak load power supplies," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 2, no. 1, pp. 102–115, Jan. 2012.

[24] Y. Kozak, B. Abramzon, and G. Ziskind, "Experimental and numerical investigation of a hybrid PCM–air heat sink," *Appl. Thermal Eng.*, vol. 59, nos. 1–2, pp. 142–152, Sep. 2013.

[25] D.-W. Yoo and Y. K. Joshi, "Energy efficient thermal management of electronic components using solid-liquid phase change materials," *IEEE Trans. Device Mater. Rel.*, vol. 4, no. 4, pp. 641–649, Dec. 2004.

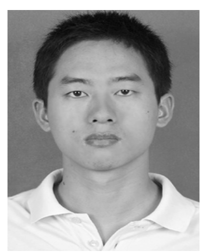
[26] W. Q. Li, Z. G. Qu, Y. L. He, and Y. B. Tao, "Experimental study of a passive thermal management system for high-powered lithium ion batteries using porous metal foam saturated with phase change materials," *J. Power Sour.*, vol. 255, pp. 9–15, Jun. 2014.

[27] S. K. Kamarudin, F. Achmad, and W. R. W. Daud, "Overview on the application of direct methanol fuel cell (DMFC) for portable electronic devices," *Int. J. Hydrogen Energy*, vol. 34, no. 16, pp. 6902–6916, 2009.

[28] J. McHugh, P. Fideu, A. Herrmann, and W. Stark, "Determination and review of specific heat capacity measurements during isothermal cure of an epoxy using TM-DSC and standard DSC techniques," *Polym. Test.*, vol. 29, no. 6, pp. 759–765, 2010.

Jinyan Hu received the B.E. degree in energy and power engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2012, where he is currently pursuing the Ph.D. degree in engineering thermophysics.

His current research interests include PCM and its application in the thermal management of electronic devices.



Run Hu received the bachelor's and Ph.D. degrees from the Huazhong University of Science and Technology (HUST), Wuhan, China, in 2010 and 2015, respectively.

He became a Lecturer with HUST in 2015. His current research interests include high-power light-emitting diode packaging and thermal management for electronics.

Chao Yuan received the B.S. degree from the School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan, China, in 2012. He is currently pursuing the Ph.D. degree in engineering thermophysics.

His current research interests include thermal interface materials and filling in packaging.

Bin Duan received the B.S. degree from the School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan, China, in 2012. He is currently pursuing the Ph.D. degree in engineering thermophysics.

His current research interests include the design, manufacturing, and reliability study of micropump.

Mengyu Huang received the B.S. degree from the School of Thermal Energy and Power Engineering, Shanghai University of Electric Power, Shanghai, China, in 2014. She is currently pursuing the master's degree with the Huazhong University of Science and Technology, Wuhan, China.

Her current research interests include lattice Boltzmann method and its applications in fluid flow and heat transfer analysis of light-emitting diode.

Xiaobing Luo received the B.E. degree in thermal energy and powering engineering and the M.E. degree in engineering thermophysics from the Huazhong University of Science and Technology, Wuhan, China, in 1995 and 1998, respectively, and the Ph.D. degree in engineering thermophysics from Tsinghua University, Beijing, China, in 2002.

He was with Samsung Electronics, Seoul, South Korea, from 2002 to 2005, as a Senior Engineer. He became an Associate Professor with the School of Energy and Power Engineering, Huazhong University of Science and Technology, in 2005, where he also became a Full Professor in 2007. His current research interests include light-emitting diode, heat and mass transfer, microfluidics, microelectromechanical systems, and sensors and actuators.