

USING ORGANIC PHASE-CHANGE MATERIALS FOR ENHANCED ENERGY STORAGE IN WATER HEATERS: AN EXPERIMENTAL STUDY

Jifen Wang,^{1,2,*} Huaqing Xie,¹ Zhixiong Guo,^{3,*} Le Cai,^{1,2} & Kai Zhang^{1,2}

¹School of Science, College of Art and Science, Shanghai Polytechnic University, No. 2360 Jinhai Rd., Pudong District, Shanghai, 201209, China

²Research Center of Resource Recycling Science and Engineering, Shanghai Polytechnic University, Shanghai 201209, China

³Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey, Piscataway, NJ 08854-8058, USA

*Address all correspondence to: Jifen Wang, School of Science, College of Art and Science, Shanghai Polytechnic University, No. 2360 Jinhai Rd., Pudong District, Shanghai, 201209, China, E-mail: wangjifen@sspu.edu.cn; or Zhixiong Guo, Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey, Piscataway, NJ 08854-8058, USA, E-mail: guo@jove.rutgers.edu

Original Manuscript Submitted: 9/7/2018; Final Draft Received: 9/10/2018

Organic phase-change material for enhanced energy storage was prepared by adding SiO₂ particles in a certain proportion into molten palmitic acid (PA) with stirring and intensive sonication at a constant temperature. The thermal properties of the SiO₂/PA composite were experimentally characterized. As compared with pure PA, the latent heat capacity of the composite with the addition of 3 wt% SiO₂ particles is increased by 51.7 kJ/kg, reaching 214.7 kJ/kg, which is the highest value among the composites tested with varying SiO₂ ratio from 1 to 5 wt%; the thermal conductivity of the 3 wt% SiO₂/PA composite is also increased by 12% at 30°C (solid state) and 7% at 70°C (liquid state), respectively. A water heater was built and tested with embedded capsules containing the 3 wt% SiO₂/PA composite and pure PA, respectively. The lab-built phase-change water heater is much smaller in size than an ordinary household water heater in comparison and uses reduced electrical power. However, it responds faster and has a larger volume ratio of hot water output to water heater size. During the turning-off test, the water heater with 3 wt% SiO₂/PA can provide 2.23 times hot water volume of heater size; while the ordinary water heater can only provide 1.41 times hot water volume of tank size.

KEY WORDS: energy storage enhancement, organic phase-change material, latent heat, composite, water heater

1. INTRODUCTION

Use of phase-change materials (PCMs) for latent heat energy storage is a promising and efficient solution for storing thermal and solar energy (Zhang and Faghri, 2017; Tabassum et al., 2018; Aumporn et al., 2018). Phase-change energy storage material (PCESM) absorbs or releases heat when it changes phases from solid to solid, solid to liquid, liquid to gas, or the reverse. PCESMs include inorganic, organic, and composite PCMs. It may be difficult to use inorganic PCESMs in practical applications due to their drawbacks such as easy undercooling, potential corrosion, and phase separation (Zalba et al., 2003). Organic PCESMs include paraffin, higher fatty acids, polyolefin, and alcohols, among others (Sharma et al., 2009). The organic PCMs have a higher latent heat of fusion at moderate temperatures (Tian and Zhao, 2011; Wang et al., 2012; Zhao et al., 2013). They have good application prospects due to their distinct features as compared to the inorganic counterparts, such as good solid forming, being less corrosive, and stable performance. However, the thermal conductivity of most organic PCESMs is poor (Mortazavi et al., 2017), which limits their storage/exothermic efficiency.

It is of great interest to find effective ways to enhance the thermal conductivity for organic PCESMs (de Gracia and Cabeza, 2017; Wang et al., 2012; Zhao et al., 2010). A common method is to make composite PCESMs with the addition of high thermal conductivity materials (Reddigari et al., 2012; Teng et al., 2013). Adding small particles to organic PCMs to achieve high thermal conductivity and stable performance has gained popularity (Jamekhorshid et al., 2017). For example, putting paraffin into a copper-powder-sintered frame by the vacuum perfusion method was used to prepare form-stable PCMs. Previous studies showed that the prepared PCMs through such means have increased the latent heat and thermal conductivity by several times (Li et al., 2017). Chen et al. (2016) prepared a kind of phase-change composite by impregnating styrene-*b*-(ethylene-co-butylene)-*b*-styrene/paraffin/high-density polyethylene into metal foam. The latent heat of the composite measured by differential scanning calorimetry (DSC) reached 151.6 kJ/kg. The thermal conductivity was 2.14 W/m·K when the composite was absorbed into the copper foam. Without the copper foam, however, the thermal conductivity of the material was just 0.27 W/m·K. Wang et al. (2009, 2012) prepared several composites using graphene nanoplatelets and carbon nanotubes to improve the organic matrix. These composites increased the thermal conductivity and kept a high enthalpy. Form-stable PCMs were prepared by adding graphene nanoplatelets into a palmitic acid (PA) (Silakhori et al., 2015). The thermal conductivity and heat capacity of the composite with the graphene nanoplatelets loading of 1.6% were about 0.43 W/m·K and 151 kJ/kg, respectively. The thermal conductivity of the composite has increased by 34.3% in comparison with the pure matrix. Recently, Wen et al. (2018) prepared a form-stable composite by a vacuum impregnation method using diatomite as the supporting material and a mixture of capric-lauric acid as the phase-change material. The expanded graphite was added to improve the thermal conductivity of the composite. DSC results showed that the composite material melted at 23.6°C with a latent heat of 87.3 kJ/kg.

Use of PCESMs could improve the efficiency of water heaters (Bouhai et al., 2018). A water heater is a necessary household appliance for most families. Regardless, the drawbacks of big volume and long response time limit the use of traditional water heaters (Faegh and Shafii, 2017). If PCESMs were used in a water heater, however, the heat storage density would increase, leading to reduced volume and shorter response time. Further, it could use cheap valley electricity to store heat, enabling the energy-saving effect of shifting peak and filling valley.

Before the occurrence of phase change, an organic PCESM is solid at room temperature. The low thermal conductivity of organic PCESMs such as paraffin and fatty acids can easily cause

local overheating and even ignition during the rapid heating process. Therefore, such materials cannot be heated directly by an electrical heating tube. A heat storage system was designed using inorganic PCM LiBr–H₂O (Zhang et al., 2014), and tests showed increased effectiveness in providing domestic hot water as compared to traditional water heaters. A solar water heater using a phase-change storage tank of organic PCESM paraffin wax was built, in which solar energy was collected and stored in the phase-change storage tank by a finned pipe (Naghavi et al., 2017). Water absorbs the heat by a set of pipes with fins located inside the tank. Results showed the dependence of system efficiency on weather. Another research used paraffin wax PCESM in a solar water heater, and showed that adding PCESM leads to increased heating efficiency by about 36.33% (Chaichan and Kazem, 2015). In the design of phase-change water heaters, water pipes were usually buried in the PCMs, and the phase-change heat storage module was heated separately. The energy stored in the PCESM needs to be transported by additional circulating pumps. Such an approach has some obvious disadvantages: it is costly and fragile, and noisy in operation. Installation of accessories takes up a large amount of volume, resulting in low space utilization. The auxiliary energy heating system also causes serious heat loss (Moghadassi et al., 2010).

In this study, organic PCESM was prepared by adding SiO₂ particles into molten PA with stirring and intensive sonication at a constant temperature. The thermal properties of the SiO₂/PA composite were characterized and measured. Both the SiO₂/PA composite and pure PA were used as PCESM in a phase-change water heater that was designed and built in the laboratory. The current phase-change water heater is mainly a heat storage tank filled with thermally conducting oil, in which the PCESM capsules and coiled water pipe are immersed. The oil is heated up directly by an embedded electric heater. The hot oil indirectly heats up the water pipe and PCESM capsules. Cold tap water entering the coiled pipe in the heat storage tank is heated by the oil and PCESM capsules at high temperature via latent and sensible heat transfer. This new design provides a comfortable user experience of out-of-the-box hot water. Experimental tests and comparison with a traditional commercial water heater show that this compact design occupies less space, responds faster, and has a larger volume ratio of hot water output to water heater size. Due to rapid phase-change heat transfer and large energy storage in PCESMs, users can cut off electrical power after preheating the phase-change water heater to avoid the risk of electric shock.

2. EXPERIMENTS

The lab-built phase-change water heater is 21 cm × 51 cm × 40 cm in size excluding the external insulation layer. It is schematically sketched in Fig. 1.

The outer steel shell of the tank was encased in an insulating board to reduce heat loss. The total thickness of the shell and the board is 10 ± 0.5 mm. Organic PCESMs are enclosed in stainless steel circular-tube capsules of 8 mm in diameter. The PCESM capsules are immersed in the heat conduction oil in the tank. The electrical heater inside the tank heats the oil directly. The hot oil heats the water pipe and PCESM capsules evenly. The electrical heater stops heating when the monitoring temperature sensor inside the tank indicates a preset temperature at 75°C. Then the outlet valve in the water pipe is open and the outlet water temperature is adjusted to 40°C by mixing the hot water with the cold water from another water pipe. In the present experiments, the inlet cold water is directly from tap water and the outlet hot water temperature is maintained at $40 \pm 1^\circ\text{C}$. During use, the cold water inside the coiled water pipe is heated as it flows through the water heater. In other words, users can use fresh hot water any time.

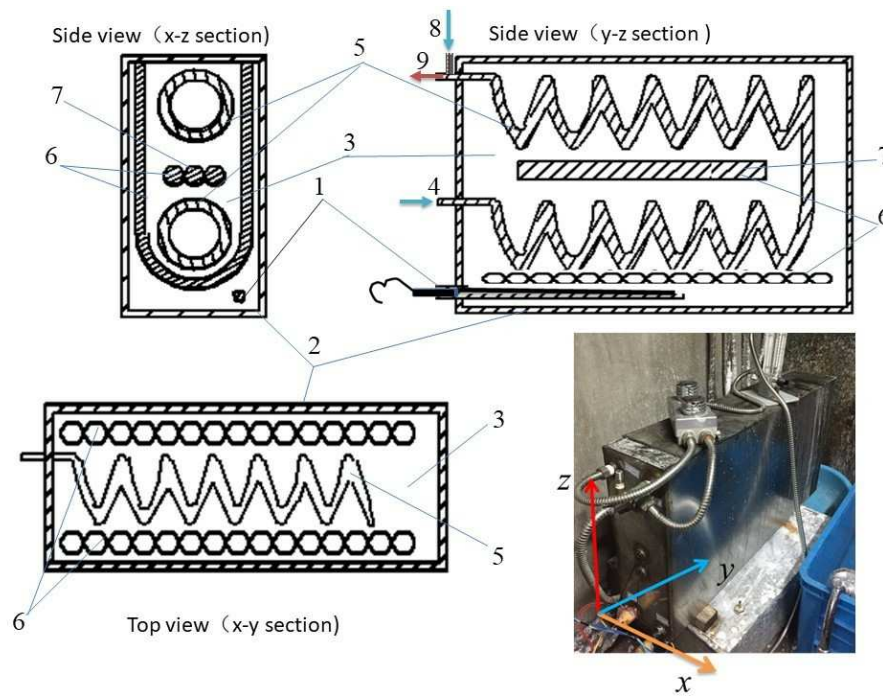


FIG. 1: Schematic diagrams and a real photo of the lab-built phase-change energy storage material (PCESM) water heater: 1, electrical heater; 2, shell; 3, heat conduction oil; 4, cold water entry and temperature measuring point; 5, coiled water pipe; 6, PCESM capsules; 7, a monitoring temperature sensor; 8, cold water for mixing; 9, hot water outlet and temperature measuring point

The silica particles (SiO_2) used in this study were purchased from Aladdin Chemical Reagent (Shanghai) Co., Ltd. The PA used in this study with a factory-specified melting point of 62.5°C – 64°C was bought from Sinopharm Chemical Reagent Co., Ltd. in Shanghai. The SiO_2 solid particles were characterized through Fourier transform infrared (FTIR) and X-ray diffraction (XRD) analyses. The SiO_2 /PA composite was prepared by adding silica particles to the molten PA at a certain ratio with stirring at a constant temperature of 75°C for 60 min and then with ultrasonic treatment at a constant temperature of 70°C for an additional 120 min. The melting temperature (T_m) and latent heat capacity (L_s) of the pure PA and the composites of different SiO_2 ratios were measured using a DSC instrument (Diamond DSC, Perkin Elmer, USA) with a heating rate of $5^\circ\text{C}/\text{min}$ and in a temperature range of 15°C – 70°C . The short-hot-wire method was used to measure the thermal conductivities (k) of the pure PA and the composites. Details on such measurements have been described in our previous studies (Wang et al., 2009, 2010).

3. RESULTS AND DISCUSSION

3.1 Analysis of the Particles

Figure 2 shows the XRD pattern of the SiO_2 particles. The insert transmission electron microscopy (TEM) picture of the particles is courtesy of Aladdin Chemical Reagent (Shanghai)

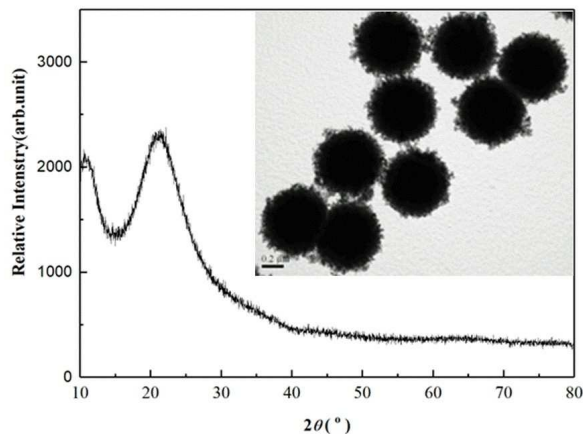


FIG. 2: X-ray diffraction pattern of the SiO₂ particles

Co., Ltd. XRD patterns were observed by a D8-Advance diffractometer using Cu K α X-ray at 40 kV and 100 mA. It is seen from the figure that the peak at 20.8° is the (1 0 0) characteristic peak of α -SiO₂ particles. A shifted (2 0 0) characteristic peak at 10.9° might also exist. Other characteristic peaks are not obvious. Thus the particles are spherical and in α type crystal.

Figure 3 plots the FTIR spectra of the SiO₂ particles. A strong suction exists around 680 cm⁻¹, where the Si-O bond extends and vibrates symmetrically. The peak around 868 cm⁻¹ is the Si-O-H antisymmetric stretching vibration characteristic peak. The characteristic peaks at 1577 and 1755 cm⁻¹ are due to the bending vibration of the H-OH bond. The peaks at 2358 and 2388 cm⁻¹ might be the oxidation state of carbon impurities vibration peaks.

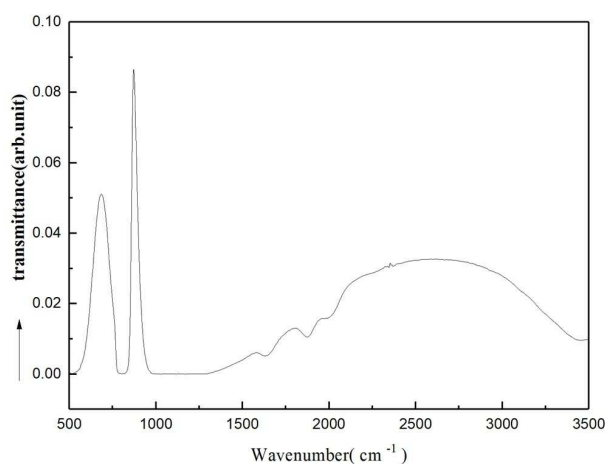


FIG. 3: Fourier transform infrared spectra of the SiO₂ particles

3.2 Analysis of the Composites

DSC analysis can provide important information such as the melting point (T_m) and latent heat capacity (L_s) of a material. Figure 4 shows the measured L_s with varying SiO_2 ratio in the PA. The L_s in this work is obtained by integrating the heat absorption peak, with measurement error less than 1%. It is seen that the L_s for the four composites (SiO_2 weight ratio varies from 1% to 5%) is greater than that of the pure PA matrix material (i.e., the case with zero SiO_2 ratio). The enhancement of latent heat in the composite might be caused by the interaction of the matrix with the additive in solid state (Jin et al., 2017). The reaction force between the additive silica and the matrix material is stronger than the dispersive force. Hydrogen bonding between the polar hydroxyl group on the SiO_2 particle's surface and the carboxyl group in PA requires absorbing more energy during melting. The highest L_s value is found for the 3 wt% SiO_2 /PA composite, reaching 214.7 ± 2 kJ/kg, an increase by 51.7 kJ/kg as compared with pure PA. This value is much greater than the latent heat found for other PCESMs mentioned in the introduction. For example, the PCM prepared by impregnating styrene-*b*-(ethylene-co-butylene)-*b*-styrene/paraffin/high-density polyethylene into a metal foam had a value of 151.6 kJ/kg (Chen et al., 2016); that by adding graphene nanoplatelets (1.6%) into PA was 151 kJ/kg (Silakhori et al., 2015); and that of expanded graphite, diatomite, and a mixture of capric-lauric acid was 87.3 kJ/kg (Wen et al., 2018).

Figure 5 shows the measured melting temperature, T_m , of the pure matrix material and the composites. The measured T_m here is the temperature at the intersection point between the half peak height tangent line and the baseline. The measurement error is no more than 0.5%. As shown in the figure, the T_m of the composite is very close to and slightly above the T_m of the pure matrix material. The T_m of the 1 wt% SiO_2 /PA composite is $64.4 \pm 0.3^\circ\text{C}$, which is the highest T_m found here, about 0.7°C higher than the T_m for pure PA. The melting process in the composite may have been hampered by strong van der Waals forces between the surface structure of the SiO_2 particles and the PA molecules, and even hydrogen bonds might have formed between Si-O-H on the particles and $-\text{COOH}$ of PA. There is no clear correlation between the

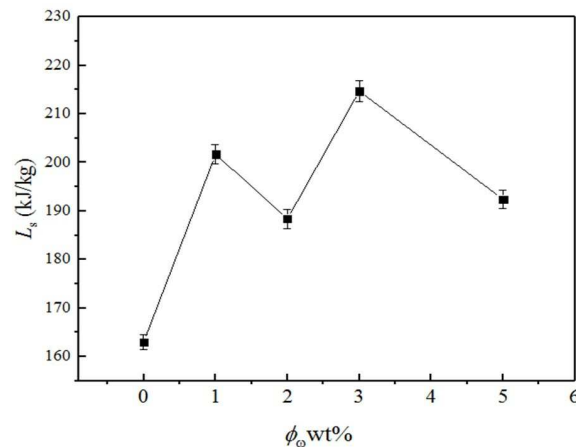


FIG. 4: The L_s of palmitic acid and composites

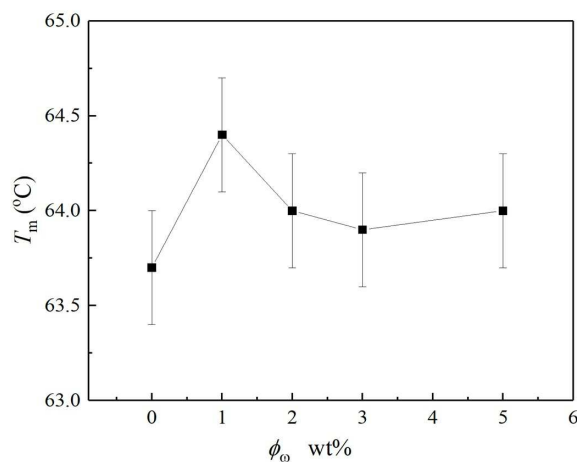


FIG. 5: The measured T_m of palmitic acid and composites

melting temperature of the composite and the silica content amount. This phenomenon is a result of the joint action of SiO_2 particles to accelerate the melting of the composite by enhancing its thermal conductivity and the van der Waals force between the functional groups on the surface of the particles and the matrix molecules to prevent melting. The peak of T_m in Fig. 5 is because the retardation effect is greater than the acceleration effect when the particle concentration is low. In a previous work (Wang et al., 2008), multiwalled carbon nanotubes (CNTs) with diameter of 30 nm and average length of 50 μm were added to molten PA to prepare CNT/PA composites; and the melting temperature of the CNT/PA composite was slightly reduced by 0.07, 1.08, 1.79, and 2.4°C, respectively, for 0.5%, 1.0%, 2.0%, and 5.0% CNTs as compared with pure PA. The latent heat capacity in the CNT/PA composites had also reduced in comparison with pure PA.

The thermal conductivity of the PCESMs in both solid and liquid states is very important for practical applications. Figure 6 shows the measured thermal conductivity of the PA and composites at 30°C and 70°C, respectively. It is seen that the thermal conductivity increases with the loading of the SiO_2 particles. The enhancement of thermal conductivity is 2%, 12%, and 25% at 30°C and 3%, 7%, and 17% at 70°C for 1 wt%, 3 wt%, and 5 wt% SiO_2 , respectively. The thermal conductivity is much greater at 30°C (solid state) than at 70°C (liquid state). The PA molecules in solid are partially crystallized while the molecules in liquid are in a disordered state with unfavorable direct heat conduction. Thus the thermal conductivity of the composite in the solid state is higher than that in the liquid state. Regardless, heat transfer in the liquid substance can be effectively enhanced by convection, compensating its low thermal conductivity drawback. It should be mentioned that enhancement of thermal conductivity through addition of particles depends on the phase state of a substance (solid or liquid), but is a weak function of temperature at each state (Wang et al., 2012).

3.3 Test of the Water Heater with PCESMs

We designed and built a PCESM water heater, shown in Fig. 1. The key design parameters of the water heater are listed in Table 1, in which Size means the size of the capacity of the tank

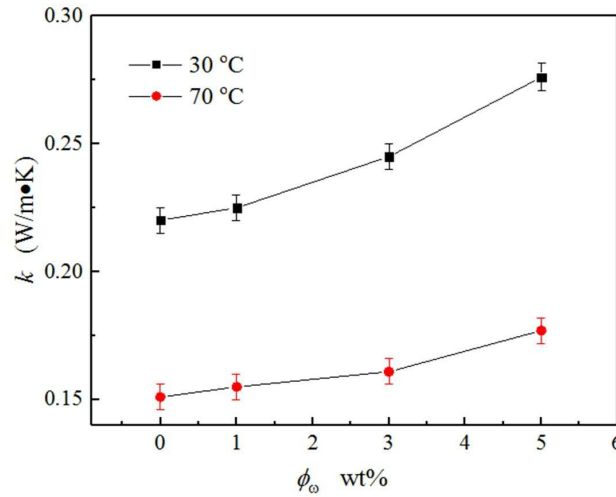


FIG. 6: The measured thermal conductivity of palmitic acid and composites

TABLE 1: Key parameters of the water heaters

Model	Size (L)	Power (W)	Weight (kg)
Made I	42.8	2000	19.4
Made II	42.8	2000	19.6
Bought	80 ^a	3000 ^a	32 ^b

^aFactory-specified value.

^bMeasured value. Factory-specified value was 30 kg.

without external insulation layer, Power means the power of the electrical heater, and Weight means the total weight of the water heater without insulation layer.

The additive PCESM for enhanced heat storage in the lab-built water heater is either pure PA or 3.0 wt% SiO₂/PA composite. Made I in Table 1 means the lab-built water heater with addition of pure PA, and Made II is the lab-built water heater with use of 3.0 wt% SiO₂/PA; this composite has the highest L_s and the second highest thermal conductivity among the PCESMs analyzed. The total weight of the embedded PCESM (either the pure PA or the composite) is 12 kg. The water outflow rate in the tests is controlled at 5 L/min. For comparison, an A.O. Smith electric water heater (CEWH-80PEZ5) without use of PCESM is tested and marked as Bought.

Table 2 shows the test parameters and results. In the table, $T(\text{inlet})$ is the inlet cold water temperature, $T(\text{outlet})$ is the temperature of the outlet hot water, $t(\text{re})$ is the time to reheat the water tank to 75°C after cold down to 38°C, $R(\text{flow})$ is the water flowrate at the outlet. $V(\text{off})$ is the total volume of the released hot water during the test when the electrical power is turned off, which is called the turning-off test; $V(\text{on})$ is the total volume of the released hot water keeping the electrical power on, which is called the turning-on test in this work. To compare water heaters of different sizes, the volume ratio of hot water output to the water heater size, defined as $r_v = (V_{\text{water}}/V_{\text{heater}}) \times 100\%$, is a key factor. Table 2 also lists

TABLE 2: Test results

Model	$T(\text{inlet})$ (°C)	$t(\text{re})$ (min)	$R(\text{flow})$ (L/min)	$T(\text{outlet})$ (°C)	$V(\text{off})$ (L)	$r_{v(\text{off})}$ (%)	$V(\text{on})$ (L)	$r_{v(\text{on})}$ (%)
Made I	19 ± 2	58	5.0	40.0 ± 1	79 ± 0.5	184	112 ± 0.5	262
Made II	19 ± 2	65	5.0	40.0 ± 1	96 ± 0.5	224	141 ± 0.5	329
Bought	21 ± 2	68	5.0	40.0 ± 1	113 ± 0.5	141	140 ± 0.5	175

and compares the volume ratios for both power turning-off and turning-on tests among the two PCSEM water heater modules and the commercial water heater. It should be mentioned that in the volume ratio calculation, V_{heater} for the Bought is the factory-specified water tank size; while for Made I and II it is the oil and PCESM tank size.

From Table 2, it is seen that the reheat time $t(\text{re})$ for the lab-built water heater Made I with addition of pure PA has the shortest response time, about 11% faster than Made II with addition of 3.0 wt% SiO_2/PA composite. This is because both the melting temperature and the latent heat capacity of the PA are lower than the counterpart of the composite. The thermal conductivity of the PCESM also affects the response time. The Made II also responded faster than the Bought by about 5%, although the electrical heater power for the Bought was 50% stronger than that of the PCESM water heater as seen in Table 1. The water heater of the Bought has the biggest $V(\text{off})$, 113 L versus 79 and 96 L for Made I and II, respectively. However, the heater size (80 L) of the Bought is almost twice that of the phase-change water heater (42.8 L). To compare their performance under size, it is meaningful to examine the volume ratio of hot water output to water heater size. The larger the volume ratio, the better the performance. The r_v calculated is 184% for Made I, 224% for Made II, and 141% for the Bought at the turning-off test, respectively. Thus the water heater with PCESM has a larger r_v value than the commercial water heater without PCESM. An r_v value of 223% for Made II means that the Made II water heater can provide 2.23 times hot water (40°C) volume of heater size at a time. To compare the yield of hot water under the same size (e.g., 80 L), multiplying r_v with 80 L yields 148 L and 179 L hot water for Made I and II, respectively, much greater than the hot water volume 113 L for the Bought. In such a scenario, users can cut off electrical power after preheating the oil and PCSEM in the tank, and the heater can still supply enough hot water for a shower to avoid the risk of electric shock. Thus, such a PCSEM water heater is safer and could use cheaper valley electricity to store heat, enabling the energy-saving effect of shifting peak and filling valley. It should be mentioned that the hot water volume has direct volume measurement error as well as indirect error due to temperature measurement uncertainty with $T(\text{outlet})$ and tap water used for mixing the exit hot water. The indirect error is the major error source in the present volume ratio calculation. Thus, the relative error of volume ratio is estimated at about 5%.

During the turning-on tests, Made I with the pure PA can provide 112 L hot water and Made II with the 3.0 wt% SiO_2/PA composite can produce 141 L hot water continuously; the Bought can provide 140 L hot water. The compact PCESM water heater of Made II could provide 1 L more hot water than the Bought although its size is just 53.5% of the Bought, and its heater power is 33.3% less. The volume ratio of hot water output to water heater size ranks from 329% for Made II, 262% for Made I, to 175% for the Bought. This turning-on volume ratio for Made II is almost twice of the Bought. Thus, the present phase-change water heater of Made II with 3.0 wt% SiO_2/PA composite is much more efficient.

4. CONCLUSIONS

SiO₂ particles are blended into molten PA to prepare phase-change energy storage composite SiO₂/PA. The particles analysed by FTIR and XRD show an α type crystal of spherical shape approximately 2 μ m in diameter with the chemical structure Si-O bond and Si-O-H on the surface. The thermal conductivity of the SiO₂/PA composite is higher than that of pure PA and increases with increasing particle ratio. The enhancement of thermal conductivity is 2%, 12%, and 25% at 30°C and 3%, 7%, and 17% at 70°C for 1 wt%, 3 wt%, and 5 wt% SiO₂/PA, respectively. The composite thermal conductivity is much greater in solid state than in liquid state. The solid-liquid phase-change temperature is slightly higher for the composite than for the pure PA. The highest melting temperature is found for the 1 wt% SiO₂/PA composite, which is $64.4 \pm 0.3^\circ\text{C}$, about 0.7°C greater than that of the pure PA matrix. The latent heat capacity of the composite is also increased as compared with pure PA. The 3 wt% SiO₂/PA composite has the highest latent heat capacity, about 214.7 ± 2 kJ/kg, which is an increase of 51.7 kJ/kg as compared with pure PA. We built a phase-change water heater embedded with 3 wt% SiO₂/PA and pure PA, respectively. The lab-built water heater is only 53.5% of the Bought in size and uses 33.3% less electrical power. Experimental test results show that the Made I and II can reheat the water faster than the Bought. The power turning-off tests show that the volume ratio of hot water output to water heater size is 184%, 224%, and 141% for the lab-built PCESM water heater of Made I (with pure PA) and II (with 3 wt% SiO₂/PA) and the Bought, respectively. During the power turning-on tests, the volume ratio is 262%, 329%, and 175% for the lab-Made I and II and the Bought, respectively. Thus, the phase-change water heater is much more efficient and performs better than the Bought without use of PCESM. The practical significance of a larger turning-off volume ratio with the Made II water heater is that users can cut off electrical power after preheating the oil and PCESM in the tank and the heater can still provide enough hot water for shower to avoid the risk of electric shock. Such a PCSEM water heater is safer and could use cheaper valley electricity to store heat, enabling an energy-saving effect of shifting peak and filling valley.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Nos. 51776116; 51306108); The Major Program of the National Natural Science Foundation of China (No. 51590902); Shanghai Federation of Science and Technology Alliance Project (No. LM201646); and Gaoyuan Discipline of Shanghai–Environmental Science and Engineering (Resource Recycling Science and Engineering).

REFERENCES

- Aumporn, O., Zeghmami, B., Chesneau, X., and Janjai, S., Numerical Study of a Solar Greenhouse Dryer with a Phase-Change Material as an Energy Storage Medium, *Heat Transf. Res.*, vol. **49**, pp. 509–528, 2018.
- Bouhal, T., Rhafiki, T.E., Kousksou, T., Jamil, A., and Zeraouli, Y., PCM Addition inside Solar Water Heaters: Numerical Comparative Approach, *J. Energy Storage*, vol. **19**, pp. 232–246, 2018.
- Chaichan, M.T. and Kazem, H.A., Water Solar Distiller Productivity Enhancement using Concentrating Solar Water Heater and Phase Change Material (PCM), *Case Studies Therm. Eng.*, vol. **5**, pp. 151–159, 2015.

- Chen, P., Gao, X., Wang, Y., Xu, T., and Fang, Y., Metal Foam Embedded in Sebs/Paraffin/Hdpe Form-Stable PCMs for Thermal Energy Storage, *Sol. Energy Mater. Sol. Cells*, vol. **149**, pp. 60–65, 2016.
- de Gracia, A. and Cabeza, L.F., Numerical Simulation of a PCM Packed Bed System: A Review, *Renew. Sustain. Energy Rev.*, vol. **69**, pp. 1055–1063, 2017.
- Faegh, M. and Shafii, M.B., Experimental Investigation of a Solar Still Equipped with an External Heat Storage System using Phase Change Materials and Heat Pipes, *Desalination*, vol. **409**, pp. 128–135, 2017.
- Jamekhorshid, A., Sadrameli, S.M., Barzin, R., and Farid, M.M., Composite of Wood-Plastic and Micro-Encapsulated Phase Change Material (MEPCM) used for Thermal Energy Storage, *Appl. Therm. Eng.*, vol. **112**, pp. 82–88, 2017.
- Jin, L., Zhang, R.B., and Du, X.L., Computational Homogenization for Thermal Conduction in Heterogeneous Concrete after Mechanical Stress, *Constr. Build. Mater.*, vol. **141**, pp. 222–234, 2017.
- Li, Z.T., Wu, Y.X., Zhuang, B.S., Zhao, X.Z., Tang, Y., Ding, X.R., and Chen, K.H., Preparation of Novel Copper-Powder-Sintered Frame/Paraffin Form-Stable Phase Change Materials with Extremely High Thermal Conductivity, *Appl. Energy*, vol. **206**, pp. 1147–1157, 2017.
- Moghadassi, A.R., Parvizian, F., Abareshi, B., Azari, and Alhajri, I., Optimization of Regenerative Cycle with Open Feed Water Heater using Genetic Algorithms and Neural Networks, *J. Therm. Anal. Calorim.*, vol. **100**, pp. 757–761, 2010.
- Mortazavi, B., Yang, H.L., Mohebbi, F., Cuniberti, G., and Rabczuk, T., Graphene or H-Bn Paraffin Composite Structures for the Thermal Management of Li-Ion Batteries: A Multiscale Investigation, *Appl. Energy*, vol. **202**, pp. 323–334, 2017.
- Naghavi, M.S., Ong, K.S., Badruddin, I.A., Mehrali, M., and Metselaar, H.S.C., Thermal Performance of a Compact Design Heat Pipe Solar Collector with Latent Heat Storage in Charging/Discharging Modes, *Energy*, vol. **127**, pp. 101–115, 2017.
- Reddigari, M.R., Nallusamy, N., Bappala, A.P., and Konireddy, H.R., Thermal Energy Storage System using Phase Change Materials—Constant Heat Source, *Thermal Sci.*, vol. **16**, pp. 1097–1104, 2012.
- Sharma, A., Tyagi, V.V., Chen, C.R., and Buddhi, D., Review on Thermal Energy Storage with Phase Change Materials and Applications, *Renew. Sustain. Energy Rev.*, vol. **13**, pp. 318–345, 2009.
- Silakhori, M., Fauzi, H., Mahmoudian, M., Metselaar, H., and Mahlia, T., Preparation and Thermal Properties of Form-Stable Phase Change Materials Composed of Palmitic Acid/Polypyrrole/Graphene Nanoplatelets, *Energy Build.*, vol. **99**, pp. 189–195, 2015.
- Tabassum, T., Hasan, M., and Latifa, B., Thermal Energy Storage through Melting of a Commercial Phase-Change Material in a Horizontal Cylindrical Annulus, *J. Enhanced Heat Transf.*, vol. **25**, pp. 211–237, 2018.
- Teng, T.P., Cheng, C.M., and Cheng, C.P., Performance Assessment of Heat Storage by Phase Change Materials Containing MWCNTs and Graphite, *Appl. Therm. Eng.*, vol. **50**, pp. 637–644, 2013.
- Tian, Y. and Zhao, C.Y., A Numerical Investigation of Heat Transfer in Phase Change Materials (PCMs) Embedded in Porous Metals, *Energy*, vol. **36**, pp. 5539–5546, 2011.
- Wang, J.F., Xie, H.Q., and Xin, Z., Thermal Properties of Heat Storage Composites Containing Multiwalled Carbon Nanotubes, *J. Appl. Phys.*, vol. **104**, 113537, 2008.
- Wang, J.F., Xie, H.Q., and Xin, Z., Thermal Properties of Paraffin based Composites Containing Multi-Walled Carbon Nanotubes, *Thermochimica Acta*, vol. **488**, pp. 39–42, 2009.
- Wang, J.F., Xie, H.Q., Xin, Z., and Li, Y., Increasing the Thermal Conductivity of Palmitic Acid by the Addition of Carbon Nanotubes, *Carbon*, vol. **48**, pp. 3979–3986, 2010.
- Wang, J.F., Xie, H.Q., and Xin, Z., Investigation on Microstructure and Thermal Properties of Graphene-Nanoplatelet/Palmitic Acid Composites, *J. Nanoparticle Res.*, vol. **14**, p. 952, 2012.

- Wen, R., Zhang, X., Huang, Z., Fang, M., and Liu, Y., Preparation and Thermal Properties of Fatty Acid/Diatomite Form-Stable Composite Phase Change Material for Thermal Energy Storage, *Sol. Energy Mater. Sol. Cells*, vol. **178**, pp. 273–279, 2018.
- Wang, Y., Chiao, S.M., Hung, T.F., and Yang, S.Y., Improvement in Toughness and Heat Resistance of Poly(Lactic Acid)/Polycarbonate Blend through Twin-Screw Blending: Influence of Compatibilizer Type, *J. Appl. Polym. Sci.*, vol. **125**, pp. E402–E412, 2012.
- Zalba, B., Marín, J.M., Cabeza, L.F., and Mehling, H., Review on Thermal Energy Storage with Phase Change: Materials, Heat Transfer Analysis and Applications, *Appl. Therm. Eng.*, vol. **23**, pp. 251–283, 2003.
- Zhang, X., Li, M., Shi, W., Wang, B., and Li, X., Experimental Investigation on Charging and Discharging Performance of Absorption Thermal Energy Storage System, *Energy Convers. Manage.*, vol. **85**, pp. 425–434, 2014.
- Zhang, Y.W. and Faghri, A., Heat Transfer Enhancement in Latent Heat Thermal Energy Storage System, *J. Enhanced Heat Transf.*, vol. **24**, pp. 173–181, 2017.
- Zhao, C.Y., Lu, W., and Tian, Y., Heat Transfer Enhancement for Thermal Energy Storage using Metal Foams Embedded within Phase Change Materials (PCMs), *Sol. Energy*, vol. **84**, pp. 1402–1412, 2010.
- Zhao, W.H., Neti, S., and Oztekin, A., Heat Transfer Analysis of Encapsulated Phase Change Materials, *Appl. Therm. Eng.*, vol. **50**, pp. 143–151, 2013.