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Impact of ultrasound on the melting process and heat transfer of phase change material

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Abstract

Latent heat storage (LHS) in a phase change material (PCM) has gained a growing interest in the building sector, due to its higher energy storage density and smaller temperature swing compared to sensible heat storage. However, low thermal conductivity of PCMs, particularly paraffin, presents a major obstacle to their successful applications in building products. In response to this issue, various heat transfer enhancement technologies through adding high conductivity materials such as metal foam and carbon fiber, have been proposed in previous studies. Although these technologies have received positive results, most of them suffers from the fact that the storage density will be reduced. To overcome this limitation, a heat transfer enhancement method using ultrasound was proposed in this study, and a series of experiments were conducted based on an experimental platform able to simulate the working condition of a domestic hot water system. The aim is to evaluate the impact of ultrasound on the charging/melting process of PCMs. Results show that, compared to the case without ultrasound, the charging time of the LHS unit reduced 60.69% and the average heat transfer coefficient increased 250.97% as the inlet temperature and flow rate of hot water were set at 60℃ and 3L/min, respectively. Moreover, much more bubbles were generated during the charging process, thereby improving both the natural convection of PCM and heat transfer between PCM and hot water.

Keywords: Phase change material; Melting process; Heat transfer; Ultrasound; Energy storage

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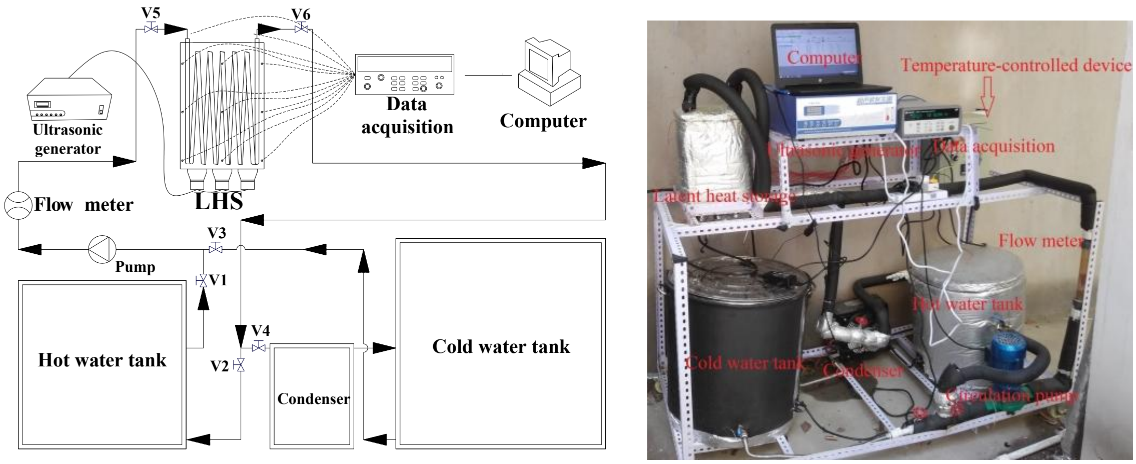
1. Introduction

Owing to its higher energy storage density and smaller temperature swing compared to sensible heat storage, latent heat storage (LHS), particularly phase change material (PCM), has gained a growing interest in the building sector, such as solar domestic hot water systems [1], building heating and air conditioning [2] and building envelopes [3] . However, low thermal conductivity of PCMs, particularly paraffin, presents a major obstacle to their successful applications in building products [4]. In response to this issue, various heat transfer enhancement technologies have been proposed in previous studies, these technologies include using fins [5-8] and adding high conductivity materials such as metal foam [8], expended graphite [9, 10] and carbon fiber [11]. Although these technologies have received positive results, most of them suffer from the fact that the storage density will be reduced because of the space occupied. To address this issue, a heat transfer enhancement method using ultrasound was proposed in this study. Such method has been successfully applied in heat exchangers [12, 13] and food drying [14, 15]. Compared to traditional heat transfer enhancement technologies, its cavitation and physical effects allow for mixing of the fluid and breaking of the laminar boundary layer, thereby improving both the natural convection of PCM and heat transfer between PCM and hot water. The aim of this paper is to evaluate the impact of ultrasound on the melting process and heat transfer of PCM. To achieve this goal, an experimental set-up was established and a series of tests were conducted.

2. Experimental setup

2.1. Description of the experimental setup

An experimental setup was developed and illustrated in Fig.1. It is mainly comprised of a hot water tank, a cold water tank, a condenser, a lab-scale rectangular shell-and-tube LHS unit, a circulation pump, a flow meter, an ultrasonic generator and a data acquisition system. The LHS unit is comprised of a rectangular stainless steel shell (300×200×100mm) and a W-typed copper coil with a spiral stainless steel fin. The copper coil includes a number of copper tubes with the diameter of 9.52mm and thickness of 0.7mm. The main features of the LHS unit is shown in Table 1. The space between the shell and tube is filled by 46# paraffin, which thermos-physical characteristics are shown in Table 2.



(a) (b)

Fig.1. (a) Layout photograph of the experimental setup; (b) Actual photograph of the experimental setup

The temperatures both of PCM and hot water were measured using PT 100 sensors with class A accuracy. All these sensors were calibrated and connected to the data loggers (Agilent 34972A). The flow rate of hot water was measured using a rotameter having a range of 40-400L/h with an accuracy of ±4%.

Table 1. Main features of the LHS unit.

Characteristic	value
Material	304 stainless steel
Overall dimensions	200×100×300mm
Thickness of rectangular shell	2mm
Length of copper coil	1.2m
Diameter of copper pipes	9.52mm
Thickness of copper pipes	0.7
Surface area of finned copper pipe	0.18m^2
Mass of paraffin	4.5kg

Table 2. Thermo-physical characteristics of 46# paraffin

Property	value
Latent heat[kJ/kg]	230
Phase change temperature[℃]	41.8-53.5
Specific heat capacity[kJ/(kg・K)]	3.22
Thermal conductivity[W/(m・K)]	0.21
Coefficient of thermal expansion[1/ K]	0.0025

2.2. Performance indices

The instantaneous power of heat transfer between the hot water and PCM during charging processes is determined by the flow rate and temperature difference of hot water, and it can be calculated by Eq.(1)

$$P = \rho q c_p (T_{out} - T_{in}) \tag{1}$$

Where ρ,q,c_p,T_{out},T_{in} are the density, flow rate, specific heat capacity, outlet temperature and inlet temperature of hot water, respectively.

The overall heat transfer coefficient can be calculated using newton's law:

$$K = \frac{P}{A\left(\frac{T_{out}+T_{in}}{2} - T_{ave,PCM}\right)} \tag{2}$$

Where A, $T_{ave,\ pcm}$ are the heat transfer area of heat coil and the average temperature of PCM, respectively.

3. Results and discussion

3.1. Effects of ultrasound on PCM melting behavior

Fig. 2 shows the picture of PCM melting behavior at different time points with the inlet temperature and flow rate of hot water set at 70℃ and 3L/min, respectively. The initial temperature of PCM was 30℃. PCM melting behavior without ultrasound is shown in Fig. 2(a). It can be seen that the PCM at the top have completely melted in the liquid phase after 2h. This indicates that the heat transfer rate at the top is higher than that in the middle and at the bottom. The main reason is that density gradient, volumetric expansion and upward rise of high temperature molecules of PCM in the LHS unit. The PCM surface height increased after 6h, caused by the density difference between solid and liquid phases of the PCM. Fig. 2(b) shows PCM melting behavior with ultrasound. It is noticed that the PCM surface height after 4h is almost equal to that after 6h without ultrasound. This implies that the heat transfer of PCM has been intensified by the usage of ultrasound. Clearly, many bubbles were generated in the melted PCM, which was mainly caused by the cavitation effect of ultrasound. Such effect improves both the natural convection of PCM and heat transfer between PCM and hot water.

1 hour (without US) 2 hour (without US) 4 hour (without US) 5 hour (without US) 6 hour (without US)

Fig. 2(a) Picture of PCM melting behavior without ultrasound during charging process

0 hour (with US) 1 hour (with US) 2 hour (with US) 3 hour (with US) 4 hour (with US)

Fig.2(b). Picture of PCM melting behavior with ultrasound during charging process

3.2. Effects of ultrasound on charging time

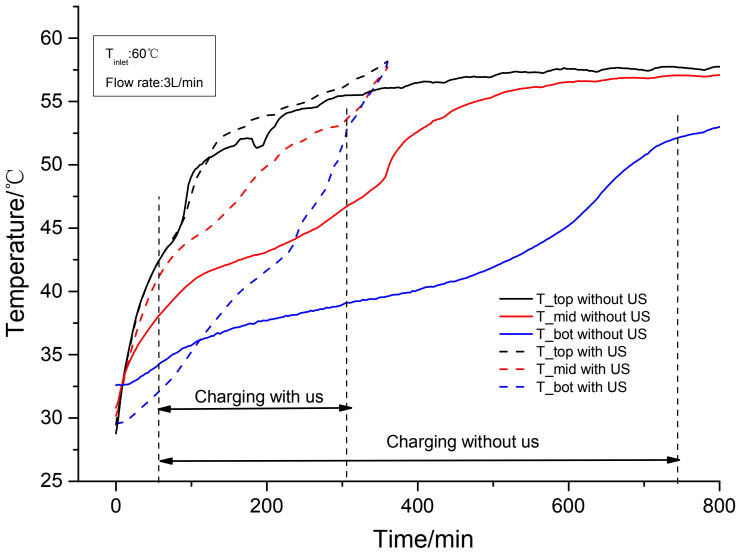


Fig. 3. Temperature profiles of PCM during charging process both with and without ultrasound

Fig.3 shows the temperature profiles of PCM at top, middle and bottom levels during the charging process both with and without ultrasound. The temperature and flow rate of hot water were set at 60℃ and 3L/min, respectively. As shown in Fig.3, the time length for PCM charging process at the three levels is different. In particular, the charging time required for the PCM without ultrasound at the top, middle and bottom levels is 108min, 354min and 669min, respectively. Meanwhile, such time for the case with ultrasound is reduced to 83min, 198min, 261min, respectively. It can be explained by the fact that the charging process has been accelerated by using ultrasound. Note that the PCM at the bottom level required the longest charging time both with and without ultrasound, and thus its charging time can represent the charging time of the LHS unit. Therefore, it is clear that the charging time of the LHS unit for the case with ultrasound is reduced 60.69% compared to the case without ultrasound. Furthermore, it is noticed that the charging time difference between with and without ultrasound at the bottom level is higher than that at the top and middle levels. This is due to the fact that the PCM at the bottom level of LHS unit is closer to the ultrasonic heads. Thus, such PCM received stronger vibration and cavitation effects of ultrasound compared to the PCM at the top and middle levels.

3.3. Effects of ultrasound on overall heat transfer coefficient

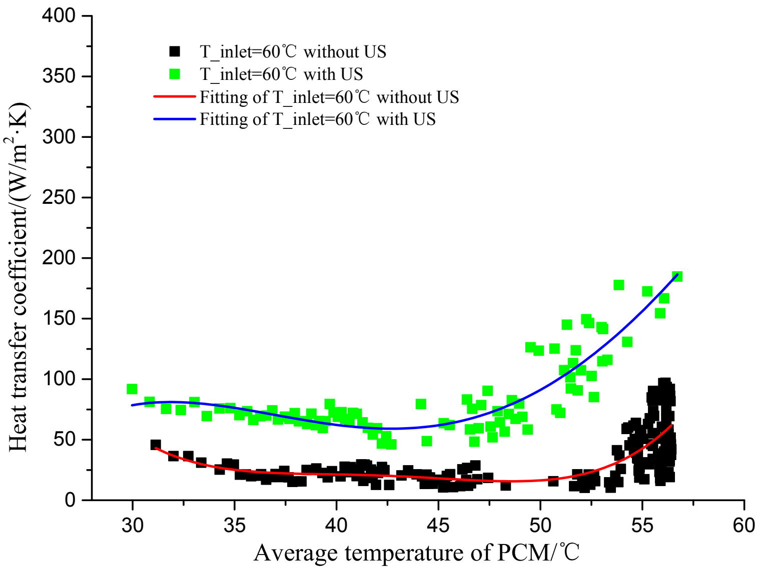


Fig.4. Overall heat transfer coefficient of LHS unit during the charging process

Fig. 4 shows the overall heat transfer coefficient change over the average temperature of PCM in the LHS unit both with and without ultrasound. The temperature and flow rate of hot water were set at 60℃ and 3L/min, respectively. The overall heat transfer coefficient represents heat transfer capacity between the PCM and hot water in the LHS unit. As shown in Fig.4, it is observable that the overall heat transfer coefficient of the LHS unit has a similar trend between with and without ultrasound. The overall heat transfer coefficient in the case with ultrasound is relatively steady until the average temperature of PCM in the LHS unit reaches 46.45℃, while this temperature increases to 52.36℃ in the case without ultrasound. Then the overall heat transfer coefficient has a marked increase in both cases. The main reason is that the effect of natural convection increases with more PCM translated from solid to liquid. Moreover, it is evident that the overall heat transfer coefficient in the case with ultrasound is higher than that in the case without ultrasound. In particular, the increase of heat transfer coefficient ranges from 97.3% to 458%, with an average of 250.97%. The maximum increase is achieved at 51.06℃ of PCM, and the corresponding overall heat transfer coefficient is 101.76W/(m^2·K) and 18.23 W/(m^2·K) in the case with and without ultrasound, respectively.

4. Conclusions

A heat transfer enhancement method using ultrasound was proposed in this study, and a series of experiments were conducted based on an experimental platform able to simulate the working condition of a domestic hot water system. The impact of ultrasound on the charging/melting process of PCMs was evaluated. Results show that, compared to the case without ultrasound, the charging time of the LHS unit reduced 60.69% and the average heat transfer coefficient increased 250.97% as the inlet temperature and flow rate of hot water were set at 60℃ and 3L/min, respectively. Moreover, much more bubbles were generated during the charging process, thereby improving both the natural convection of PCM and heat transfer between PCM and hot water.

This study demonstrates the effectiveness of ultrasound on the melting process and heat transfer of phase change material. Our future studies will focus on the establishment of the mathematical model of LHS units with ultrasound. Based on the model, the influence of different diameters of LHS unit, different frequencies and locations of ultrasound will be analysed, and their optimal design parameters will be identified. Its different applications will also be investigated such as solar domestic hot water systems and solar-assisted cooling systems.

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References

[1] Amagour, M.E.H., et al., Experimental investigation and comparative performance analysis of a compact finned-tube heat exchanger uniformly filled with a phase change material for thermal energy storage. Energy Conversion and Management, 2018. **165**: p. 137-151.

[2] Palomba, V., V. Brancato, and A. Frazzica, Experimental investigation of a latent heat storage for solar cooling applications. Applied Energy, 2017. **199**: p. 347-358.

[3] Lei, J., J. Yang, and E.-H. Yang, Energy performance of building envelopes integrated with phase change materials for cooling load reduction in tropical Singapore. Applied Energy, 2016. **162**: p. 207-217.

[4] Cabeza, L.F., et al., Materials used as PCM in thermal energy storage in buildings: A review. Renewable and Sustainable Energy Reviews, 2011. **15**(3): p. 1675-1695.

[5] Fan, L.-W., et al., An experimental and numerical investigation of constrained melting heat transfer of a phase change material in a circumferentially finned spherical capsule for thermal energy storage. Applied Thermal Engineering, 2016. **100**: p. 1063-1075.

[6] Cao, X., et al., Numerical investigation on optimal number of longitudinal fins in horizontal annular phase change unit at different wall temperatures. Energy and Buildings, 2018. **158**: p. 384-392.

[7] Ma, Z., et al., Investigation on the thermal performance of a high-temperature latent heat storage system. Applied Thermal Engineering, 2017. **122**: p. 579-592.

[8] Meng, Z.N. and P. Zhang, Experimental and numerical investigation of a tube-in-tank latent thermal energy storage unit using composite PCM. Applied Energy, 2017. **190**: p. 524-539.

[9] Li, Z., et al., Experimental and numerical study on the effective thermal conductivity of paraffin/expanded graphite composite. Solar Energy Materials and Solar Cells, 2014. **128**: p. 447-455.

[10] Wang, F., et al., Highly stable graphite nanoparticle-dispersed phase change emulsions with little supercooling and high thermal conductivity for cold energy storage. Applied Energy, 2017. **188**: p. 97-106.

[11] Nomura, T., et al., High thermal conductivity phase change composite with percolating carbon fiber network. Applied Energy, 2015. **154**: p. 678-685.

[12] Gondrexon, N., et al., Intensification of heat and mass transfer by ultrasound: application to heat exchangers and membrane separation processes. Ultrason Sonochem, 2015. **25**: p. 40-50.

[13] Tam, H.K., et al., Experimental study of the ultrasonic effect on heat transfer inside a horizontal mini-tube in the laminar region. Applied Thermal Engineering, 2017. **114**: p. 1300-1308.

[14] Contreras, M., et al., Intensification of heat transfer during mild thermal treatment of dry-cured ham by using airborne ultrasound. Ultrason Sonochem, 2018. **41**: p. 206-212.

[15] Yao, Y., Enhancement of mass transfer by ultrasound: Application to adsorbent regeneration and food drying/dehydration. Ultrason Sonochem, 2016. **31**: p. 512-31.