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Experimental investigations on the characteristics of melting processes of stearic acid in an annulus and its thermal conductivity enhancement by fins

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Abstract

An experimental rig was set up to study the performance of a thermal storage unit using stearic acid as the heat storage medium. The unit mainly consists of an electrical heating rod and an outer tube, and the space between is an annulus that is filled with stearic acid. The thermal performance of the unit is measured, and the heat transfer characteristics of the melting processes of stearic acid are studied under different heat flux conditions to determine the influence of heat flux on the melting processes. A new type of fin is designed and fixed to the electrical heating rod to enhance the thermal response of the stearic acid. The experimental results show that the fin can improve the heat transfer of the melting process of the thermal storage unit greatly. The equivalent thermal conductivity of the PCM can be augmented by a factor up to 3. The analysis of the experimental results shows that the enhancement mechanism of the fin is attributed to its ability to improve both heat conduction and natural convection very effectively. The influences of the fin size and pitch on the enhancement are also studied and analyzed and it is found that these two parameters can both affect the thermal conductivity enhancement significantly.

Keywords: Melting; Latent heat thermal storage; Enhancement; Fins; Experimental; Phase change materials

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Nomenclature

c_s specific heat of solid PCM, J/(kg·°C)
L latent heat, J/kg
q dimensionless heat flux defined in Ref. [10]
q_w heat flux, W/m^2
Ste^* modified Stefan number

Greeks
α_s thermal diffusivity of solid PCM, m^2/s
δ thickness of PCM slab, m
ρ_s density of solid PCM, kg/m^3
τ_m total dimensionless melting time that is calculated when melting starts
τ_{pr} dimensionless pre-heating time needed for heating PCM's highest temperature to its melting point

1. Introduction

Phase change materials (PCMs) are the most attractive thermal energy storage media due to their significant reduction in storage volume and isothermal behavior during charging and discharging processes compared with sensible heat storage systems using water, heat transfer fluids and various solid materials, such as magnetite, sandstone, concrete etc. as energy storage media. However, PCM storage technology is still not practical because it is difficult to find an ideal PCM that possesses certain desirable thermodynamic, kinetic, chemical, technical and economic characteristics, among which high thermal conductivity, large latent heat, low supercooling and good stability are the most important. Salt hydrates and their eutectics and the other inorganic PCMs usually have very high values of latent heat and thermal conductivity, which are important for heat transfer processes. They exhibit, however, serious supercooling, which means they will remain in the liquid state well below their melting points and, thus, fail to discharge the stored latent heat at the expected temperature. On the other hand, supercooling seldom occurs in organic PCMs. Their main unwanted behavior is slow thermal response due to their low thermal conductivity. Therefore effective augmentation methods for the liquid–solid phase change are the key issue that limits their practical application in latent heat energy storage technology.

Various methods for PCM thermal conductivity enhancement have been proposed and studied by many researchers. Some of the most common methods are attaching fins to heat transfer walls, dispersing metal particles or rings or carbon fibers of high conductivity into PCMs [1–5]. Dispersing high conductivity materials into PCMs is less practical compared with inserting fins into PCMs since the substances dispersed in PCMs usually sink to the bottom or float to the top of the container due to their different densities from PCMs.

The use of finned tubes with different configurations has been reported by various researchers as an efficient method to improve the charging/discharging performance of latent heat energy storage systems. Velraj et al. [1] concluded from their study that the configuration of fins that forms a

V-shaped area for the PCM gives maximum benefit to the conductivity enhancement. Eftekhar et al. [4] investigated experimentally a different heat transfer enhancement method for melting of paraffin by constructing a model that consists of vertically arranged fins between two isothermal planes which not only provides additional conduction paths but also promotes natural convection within the molten PCM. Their photographs of the molten zone indicate that a buoyant flow induced in the neighborhood of the vertical fin causes rapid melting of the solid wax. Sparrow et al. [6] conducted an experimental study for outward solidification on a longitudinal finned vertical tube. Padmanabhan et al. [7] have also studied the phase change process occurring in a cylindrical annulus with uniformly spaced longitudinal rectangular fins and annular fins. Velraj et al. [8] presented a theoretical and experimental study on a thermal storage unit consisting of a cylindrical vertical tube with internal longitudinal fins and a cylindrical vessel containing water. Sauer [9] described a latent heat storage concept that employs inward solidification and outward melting simultaneously. The system consisted of two concentric pipes forming an annulus within which the PCM is stored. Through the inner pipe the warm fluid is circulated, and the cold fluid surrounds the outer tube. Fins are uniformly placed in the PCM region spanning the entire annulus.

In this paper, the effects of heat flux on melting processes are investigated experimentally. Copper fins of spiral twisted configuration of different widths and pitches were designed and used to enhance the PCM thermal conductivity.

2. Experimental set up and procedures

The experimental set up is shown in Fig. 1. The apparatus used include a cylindrical tube, an electrical heating rod, the data acquisition/switch unit, T-type thermocouples, HP data logger and a Pentium III PC. The PCM tube is made of stainless steel with an inner diameter of 46 mm and a length of 550 mm. The electrical heating rod and the tube are placed concentrically. The rod is also made of stainless steel and has a diameter of 19.9 mm and runs through the whole length of the tube with an effective heating length of 550 mm. Four thermocouples are distributed evenly along the radial direction at the same section of 255 mm from the bottom end of the tube. The radial locations of the thermocouples from the rod axes are 10, 14.33, 18.66 and 23 mm, respectively. The outside of the tube is well insulated with a porous polythene insulator. The test section

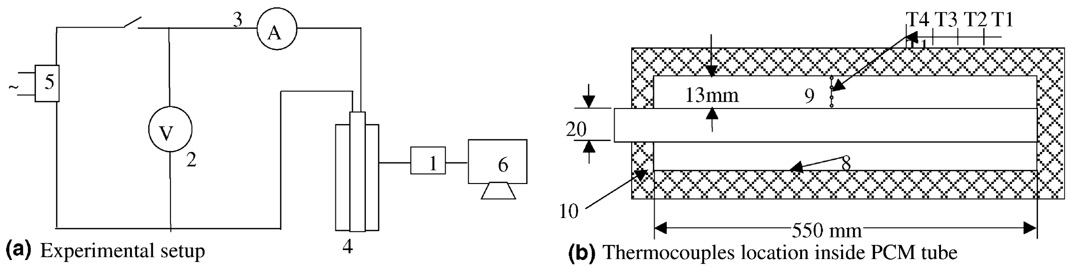

Fig. 1. Experimental set up: (1) HP data logger; (2) voltage gauge; (3) ampere meter; (4) phase change tube; (5) power supply; (6) PIII PC; (7) electrical heating rod; (8) stainless steel tube; (9) thermocouples and (10) insulation layer.

can be placed vertically or horizontally. Analytically pure stearic acid is used as the phase change material. DSC analysis of it was performed, and the result shows that the solid–liquid transition temperature of this stearic acid is 67.7 °C, and the latent heat is 224.3 kJ/kg. The stearic acid is filled into the annulus that was formed by the tube and the electrical heating rod, and 10% of the whole volume is left empty to allow the PCM to expand freely.

In order to obtain a uniform initial temperature, before a new test starts the whole tube was placed in a water bath whose temperature is constant at 26 °C for 3–6 h. Then, the tube is fixed to the test rig vertically or horizontally according to the experimental requirement. Switching on the electrical heating rod, the melting process of the stearic acid starts. Temperature signals are obtained and recorded by the data acquisition system until the outermost thermocouple T1 reaches 80 °C. The temperatures of all the thermocouples were recorded at intervals of 60 s. The time constants of the thermocouples are estimated to be less than 7 s. The measurement system permits the temperature difference to be measured at the accuracy of 0.2 °C.The heating heat flux is changed by altering the voltage. The heat flux mentioned below is referred to the heat flux on the outer wall of the electrical heating rod. The experimental results reported in this paper are all obtained under the condition that the PCM tube is vertically placed.

3. Results and discussions

3.1. Melting curves

Fig. 2 shows the temperature variations with time of various radial positions at a heating heat flux of 1558 W/m^2. During the initial period of heating, the energy released by the electrical heating rod is absorbed and stored by the stearic acid in the form of sensible heat. This heat is used to raise the temperature of the stearic acid gradually to its melting point. As soon as T4 (approximately equal to the wall temperature of the electrical heating rod) is equal to or higher than the melting point, the melting process starts. Before melting begins, the heat transfer through the stearic acid is of the pure conduction characteristic. The temperature increases almost linearly

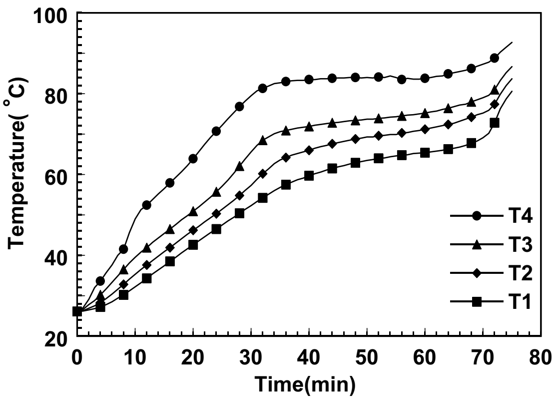

Fig. 2. Temperature variation with time, 1558 W/m^2.

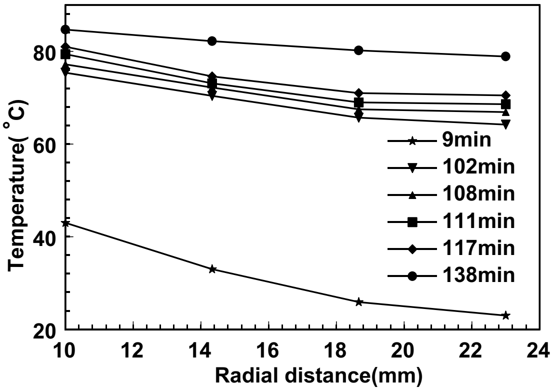

Fig. 3. Temperature profile at different times, 882 W/m^2.

with time. Because of the low thermal conductivity of the PCM, the temperature near the rod rises very quickly. However, after the temperature of the PCM reaches its melting point, the melting process starts. The temperature rising rates of the PCM are significantly slowed during this period. The heat absorbed by the phase change interface is equal to the energy stored as latent heat plus the heat transferred to its neighboring region. It is this mechanism that causes the different trends of the temperature variations at the different locations. For instance, the temperature of the outermost thermocouple T1 almost increases linearly with time during the whole process, which is quite different from T4 that has an apparent constant temperature period. This is because the outer layer next to T1 (the outside wall of the tube) is well insulated, the heat transferred from the inner side to it is all stored and, thus, raises its temperature. Similar results were reported by Sari and Kaygusuz [10–12].

Fig. 3 depicts the temperature distribution along the radial direction at different times. It can be seen that the gradients of the temperature profiles at 102, 108, 111, 117 and 138 min are much smaller than that of the temperature profile at 9 min. The reason for this is as follows. At 9 min, the temperature of the steric acid is well below its melting point and the PCM of the whole region is in the solid state. Thus, the heat transfer through the PCM is by pure thermal conduction. Therefore, the gradient of the temperature profile of the stearic acid at 9 min is relatively large due to the low thermal conductivity of stearic acid. However, as time elapses, the temperature of the PCM gradually reaches its melting point and melting begins. Since melting will absorb a great amount of heat at a relatively constant temperature, the temperature-rising rate slows down. As the melting process proceeds, the liquid region becomes larger and larger, and thus, natural convection is playing a more and more important role. The equivalent thermal conductivity is, thus, increased due to this enhanced natural convection effect. This again makes the stearic acid temperature profile of the PCM, especially in the liquid region, more, even compared with that at the earlier stages.

3.2. The effects of the heating heat flux

The locations of the solid–liquid interfaces versus time are shown in Fig. 4. As the heating heat flux is increased from 392 to 2403 W/m^2, the time for the onset of the melting process is

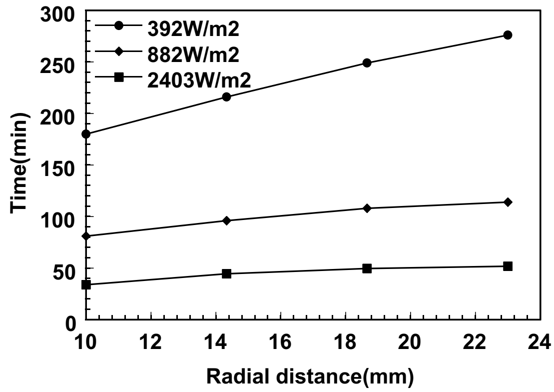

Fig. 4. Interface front immigration: the influences of heat flux.

significantly shortened, roughly from 180 to 35 min. This can be explained by the following equation that was developed by Liu and Ma [13]

$$\tau_{\mathrm{pr}} = \frac{1}{q} - \frac{1}{3}$$

which simply states that the pre-heating time is in inverse proportion to the heat flux. The total melting time (the time needed for melting all the PCM in the annulus that is in solid state) is correspondingly reduced from 100 to 25 min roughly, which again can be explained from the results of the numerical study by Liu and Ma [13] that the total melting time is a function of the modified Stefan number only, that is

$$\tau_{\mathrm{m}} = f(Ste^{*})\ Ste^{*} = Ste * q = \frac{c_{\mathrm{s}} q_{\mathrm{w}} \delta}{\rho_{\mathrm{s}} \alpha_{\mathrm{s}} L}$$

since the PCM and configuration remained the same and the only variable in Ste^{*} is the heating heat flux. Therefore the total melting time is related only to the heat flux applied.

3.3. The effects of fins

In this study, a new fin is designed in order to enhance the melting process of stearic acid. The fin is made of copper and has the shape of a spiral twisted tape of thickness 0.25 mm, which can effectively enhance both the conduction and natural convection heat transfer. A series of experiments are conducted with and without fins. The main results are summarized as follows.

3.3.1. The influences of fins on the temperature profile

Fig. 5 compares the temperature profiles at various melting stages with and without fins. The fins used in Fig. 5 are 7.5 mm in width, 0.25 mm in thickness and has a pitch of 30 mm. It can be seen that the temperature profiles of the stearic acid with fins at 9, 18 and 30 min, are significantly more even than those without fins. This also means that the temperatures at different radial positions become closer to each other due to the existence of the fins. Fins accelerate the speed of heat

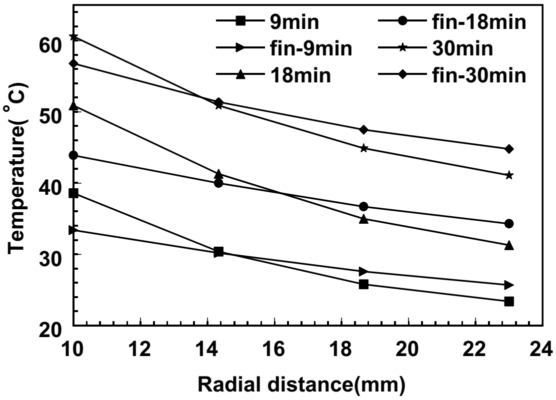

Fig. 5. Temperature profile with/without fins at a heat flux of 1558 W/m^2.

transfer from the electrical heating rod to and through the stearic acid. Using the data as depicted in Fig. 5, one can find that the temperature difference across the PCM is greatly reduced by attaching fins to the electrical heating rod. At 9 min, the temperature difference is reduced from 16.2 to 7.3 °C, and at 18 min, the difference is reduced from 20.8 to 9.2 °C and at 30 min is from 20.5 to 12.3 °C. If one assumes that the equivalent thermal conductivity of the PCM is in inverse proportion to this temperature difference, which is a good approximation even for unsteady heat conduction, then we can estimate the thermal conductivity enhancement of the stearic acid from these data: at 9, 18 and 30 min the equivalent thermal conductivity is increased by 121%, 125% and 67%, respectively. These results prove that inserting these new fins into the PCM is a very effective method for enhancing the melting process. In Fig. 5, under the heating conditions given, the stearic acid does not melt until 60 min in the case with fins, hence the heat transfer during this period is of pure conduction and, thus, the slopes of these curves are relatively large.

The speed of movement of the melting front location also differs a lot, as shown in Fig. 6. When the thermal conductivity of the stearic acid is augmented by the fins, the energy released by the electrical heating rod can be more easily transferred to the outside part, and the heat absorbed by the innermost layers of stearic acid is greatly reduced. Thus, the time for the onset of melting increases from 20 to 37 min.

3.3.2. The effects of fin width on melting process

In order to study the influences of the fin geometry on the heat transfer enhancement, various fins of different widths are manufactured and tested. It should be noted that the total amount of copper inserted into the annulus as fins are all the same in this series of experiments, though these fins are of different width. Fig. 7 gives a comparison of the temperature profiles of the stearic acid inside the annulus with a 2.5 mm width fin and that with a 7.5 mm width fin. It can be concluded from the figure that the temperature profile of the stearic acid with a 7.5 mm width fin is steeper than that with a 2.5 mm width fin, which proves that fine fins are more effective than large fins in enhancing the melting process if an equal amount of fin material is used. This is mainly because the effective surface area of the fine fin is a little greater than that of the large fin, and thus, much smaller and many more sub-sections of the annulus result from the fine fins. Dividing a vertical

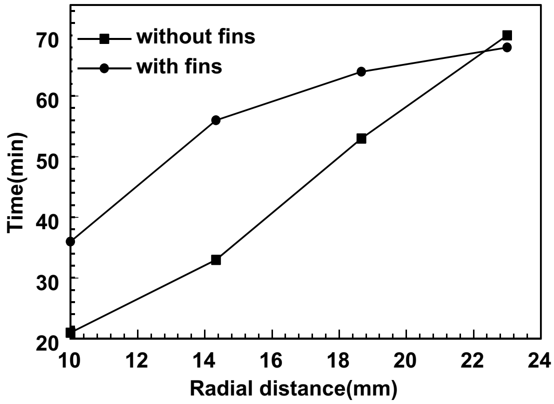

Fig. 6. Melting front location: with and without fins 2403 W/m^2.

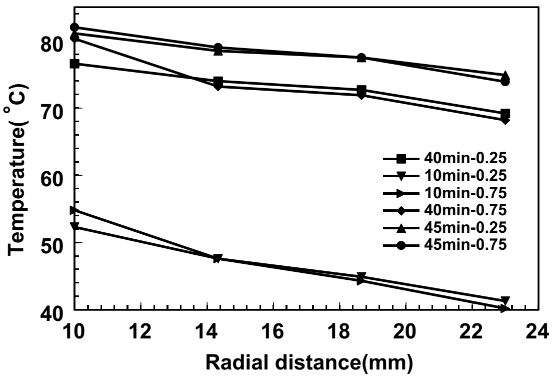

Fig. 7. Temperature profile with fins of different width, 3529 W/m^2.

narrow gap into smaller sub-sections usually benefits the enhancement of natural convection. It is worthwhile to note that though the gradients of the temperature profiles at longer times are smaller than those at shorter times, the influences of the fin width are actually more significant in the longer time period than in the initial period. This is because, as the heating process proceeds, more and more solid stearic acid is melted, and the natural convection effects become more and more significant and, thus, the enhancement of natural convection is more significant. Using the data depicted in Fig. 7, one can estimate the ratio of the equivalent thermal conductivity of the PCM with the 2.5 mm width fins to that with the 7.5 mm width fins: at 10 min, this ratio is equal to 1.3, at 40 min, it is 1.7 and at 45 min it is 1.5. Fig. 8 gives the melting front location variation with time with fins of different widths, which again reveals that the width of the fin does have an important influence on enhancing the melting process of the stearic acid.

3.3.3. The effects of the pitch of spiral fins

The heating length of the test section is 550 mm and the annulus gap is only 13 mm. The test section is placed vertically, and therefore, the natural convection within the annulus is of that in

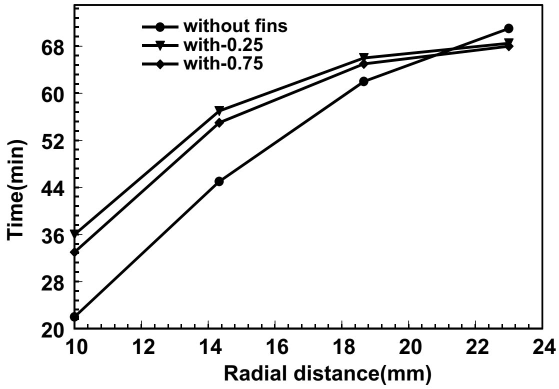

Fig. 8. Melting front location: with/ without fins of different width, 2403 W/m^2.

confined spaces. The natural convection is greatly suppressed not far away from the bottom, and the local heat transfer coefficient decreases sharply with distance from the bottom of the tube. Therefore, if the annulus is divided into several smaller sections, the natural convection will certainly be enhanced. The spiral fins used in our study actually divide the PCM into many small sections, each section can be treated as a shorter tube and, thus, the natural convection effects are augmented during the melting process. Therefore, it can be concluded that reducing the fin pitch to a reasonable value can significantly improve the heat transfer enhancement. Fig. 9 and Fig. 10 are some of our experimental results. Using the data corresponding to Fig. 9, we can estimate the ratio of the equivalent thermal conductivity of the PCM with 30 mm pitch fins to that with 40 mm pitch fins. As time elapses from 12 to 60 min and then to 74 min, the ratio is increased from 1.38 to 2.75 and then to 3.33, which prove the theory. However, the comparisons in these figures are not on a completely identical basis because the amount of the fin materials is different for the two situations: the 30 mm pitch fin uses more material than the 40 mm pitch fin. Therefore, these figures not only reveal the effects of the fin pitch but also include the effects of the amount of the fin material of large thermal conductivity on the enhancement of the melting processes.

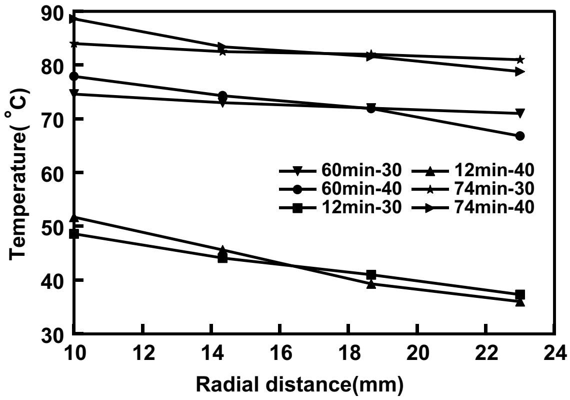

Fig. 9. Temperature profile with fins of different pitches, 3529 W/m^2.

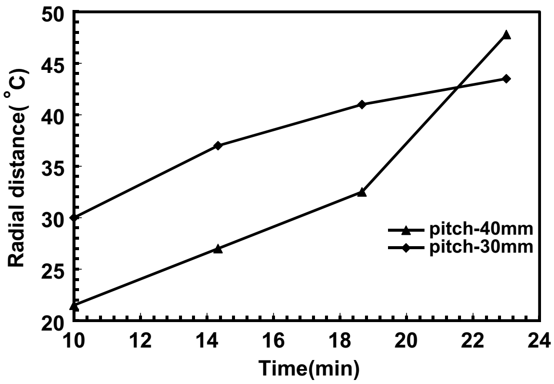

Fig. 10. Melting front location with fins of different pitches, 3529 W/m^2.

4. Conclusions

According to our experimental results and the discussions given above, we may conclude that the heating heat flux has important influences on both the pre-melting time and total melting time. With the increase of heating heat flux, the pre-melting time period is shortened, and the whole melting time is also reduced. A very effective fin is designed to enhance the thermal conductivity of the PCM. The experimental results show that the thermal conductivity enhancement of these fins is closely related to time and the configuration of fins. During the initial period when that the PCM has not been melted the equivalent thermal conductivity can be increased by 67%. As the melting process proceeds, the enhancement effects become more and more significant. The equivalent thermal conductivity can be increased by a factor up to 3. Our results also prove that reducing the fin width can lead to a more effective enhancement of the PCM thermal conductivity. The experimental results also reveal that reducing the fin pitch is helpful for enhancing the melting process, since this can generally enhance the natural convection effects, though strict and more precise experiments are needed to verify the pitch effects.

Acknowledgement

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