Integrated Design and Process Technology, **IDPT-2003**
Printed in the United States of America, June, 2003

EXPERIMENTAL INVESTIGATIONS ON THE CHARACTERISTICS AND AUGMENTATION OF MELTING PROCESSES OF STEARIC ACID IN AN ANNULUS

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ABSTRACT

A thermal storage unit using stearic acid as the heat storage media is designed and studied experimentally. The unit mainly consists of an electrical heating rod and an outer tube, and in-between is an annulus that is filled with stearic acid. The thermal performance of the unit is measured and heat transfer characteristics of melting process of stearic acid is studied under different heat flux conditions to determine the influence of heat flux on the melting process. A new fin is designed and is fixed to the electrical rod to enhance the thermal response of stearic acid and the influences of the fin size and pitch on the enhancement are studied and analyzed.

INTRODUCTION

Phase change materials (PCMs) are the most attractive thermal energy storage media due to their significant reduction in storage volume and the isothermal behavior during charging and discharging process compared with sensible heat storage systems using air and water as energy storage media. However the PCM storage technology is still not practical because it is difficult to find an ideal PCM. Salt hydrates and their eutectics and the other inorganic PCMs have high values of latent heat and thermal conductivity, which are important for heat transfer processes. They have, however, serious supercooling, which means they will remain in 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.

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 [Velraj et al, 1999; Jun Fukai et al, 2000; Chow et al, 1996; Eftefkhar et al, 1984]. Dispersing high conductivity materials into PCMs is less practical compared with inserting fins into PCMs since the substances dispersed in PCMs usually sink down to the bottom or float up 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 charge/discharge performance of LHTS systems. Sparrow et al conducted an experimental study for outward solidification on a longitudinal finned vertical tube. Padmanabhan et al [1986] have also studied the phase change process occurring in a cylindrical annulus with uniformly spaced longitudinal rectangular fins and annular fins. Velraj et al [1997] presented an 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. Velraj et al[1999] concluded from their study that the configuration that forms a V-shaped area for PCM gives maximum benefit to the fin arrangement. Sauer [1982] describes a latent heat storage concept that employs inward solidification and outward melting simultaneously.

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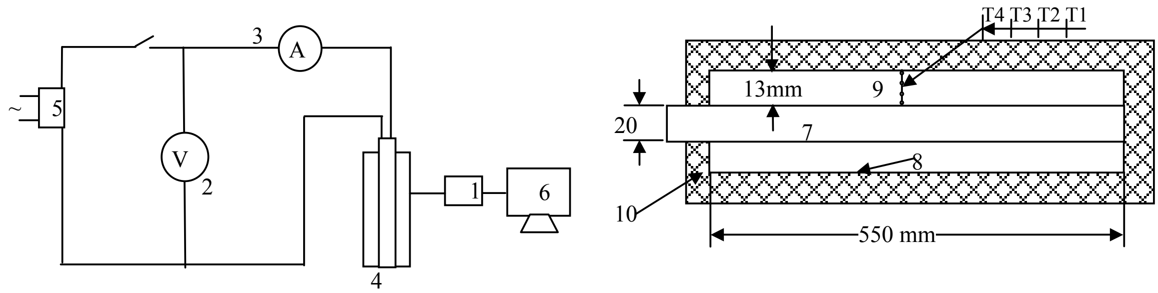
The system consists of two concentric pipes forming an annulus within which the PCM is stored. Through the inner pipe the warm fluid is circulated and the cold fluid surrounds the outer tube. Fins are uniformly placed in the PCM region spanning the entire annulus. Eftekhar et al [1984] investigated experimentally 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.

In this paper, the effects of heat flux on melting process are investigated experimentally. Copper fins made of different widths and pitches were utilized to enhance the PCM thermal conductivity.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup 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 of a diameter of 19.9mm and runs through the whole tube with a heating length of 550mm. 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 are from the rod axes are 10mm, 14.33mm, 18.66mm and 23mm respectively. The outside of the tube is well insulated with a cellular polythene insulator. The test section can be placed vertically or horizontally. The analytically pure stearic acid is used and its solid-liquid transition temperature is 67-70°C. The stearic acid is filled into the annulus and 10% of the whole volume is left empty to allow PCM to expand freely.

In order to obtain a uniform initial temperature, the tube was first placed into a water bath whose temperature is constant at 26°C. Then the tube is fixed to the test rig vertically or horizontally. Data acquisition would be stopped as soon as the outermost thermocouple T1 reaches 80°C. The temperatures of all the thermocouple were recorded at every minute. The time response of the thermocouples is less than 7 seconds. The measurement system permits the temperature difference to be measured at the accuracy of 0.1℃.The heat flux is changed by altering the voltage. The heat flux mentioned below is actually referred to the heat flux on the outer wall of the electrical heating rod.



(a) Experimental setup (b) Thermocouples location inside PCM tube

Fig. 1 Experimental setup

1: HP data logger; 2: Voltage gauge; 3: Amperometer; 4: Phase change tube; 5: Manostat; 6: PIII PC;
7: Electrical heating rod; 8: Stainless steel tube; 9: Thermocouples; 10: Insulation layer

RESULTS AND DISCUSSION

Melting curves

During the initial period of heating, the energy transferred from rod to stearic acid is absorbed by stearic acid in the form of sensible heat. This heat is used to raise the temperature of stearic acid to its melting point. As soon as T4 (approximately equal to the wall temperature of the heating rod) is equal to or higher than the melting point, the melting process starts. Before melting begins, the heat transfer through stearic acid is pure conduction. Due to the low thermal conductivity of the PCM, the temperature near the rod raises very quickly. During the

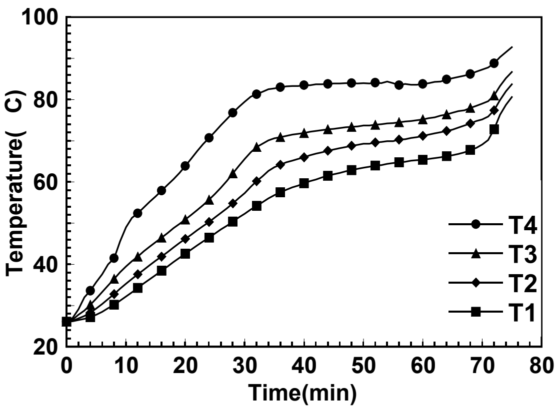


Fig. 2. Temperature variation with time, 1558W/m^2

melting process, the heat absorbed by the phase change interface is equal to the energy stored as latent heat plus the heat transferred to its neighbor region. It is due to this mechanism that causes the different trend of temperature variation at the different location. For instance, the temperature of the outermost thermocouple T1 almost raises 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 inner side to it is all stored and thus to raise its temperature

. Fig.3 depicts the temperature distribution in radial direction at different times. It can be seen the gradients of the temperature profiles at 102min, 108min, 111min, 117min and 138min are much smaller than that of the temperature profile at 9min. The reason for this is as follows. At 9min, the temperature is well below the melting point and the whole region of PCM is in solid state. Thus the heat transfer is pure conduction, and therefore the slope of the temperature profile of stearic acid is large due to the low thermal conductivity of the stearic acid. However as time lapses, the temperature of PCM gradually reaches its melting point and melting begins, which certainly slows down the temperature raising. As melting proceeds, the liquid region increases and thus natural convection is playing a more and more important role, this again makes the stearic acid temperature profile of the liquid region more even.

The effects of the heating heat flux

The location of the solid-liquid interface versus time

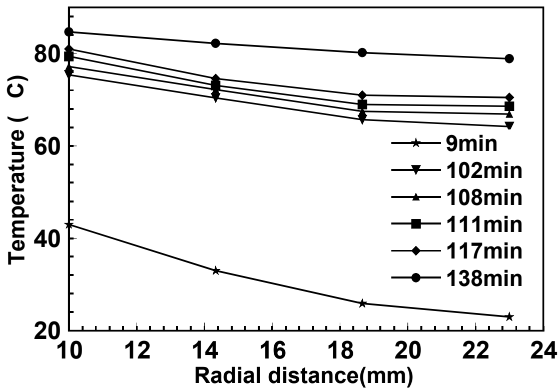


Fig. 3. Temperature profile at different times, 882W/m^2

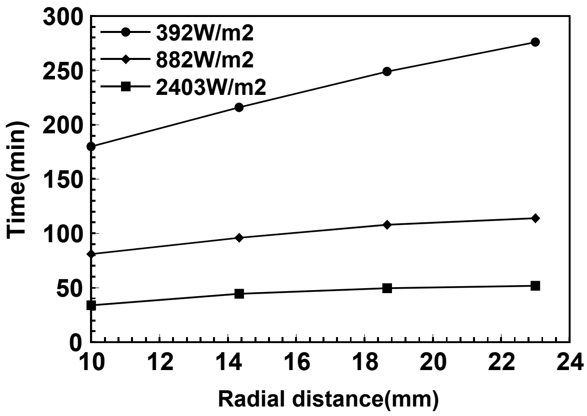


Fig. 4. Interface front immigration: the influences of heat flux

is shown in Fig 4. As the heating heat flux is increased from 392 W/m^2 to 2403 W/m^2, the time for the onset of the melting process is significantly shortened. This can be explained by the following equation [Liu and Ma, 2002],

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

which simply states that the pre-heating time is inverse to the heat flux. The total melting time is correspondingly reduced from 100min to 25min, which again can be explained from the results of the numerical study by Liu and Ma that the total melting time is a function of the modified Stefan number only, that is,

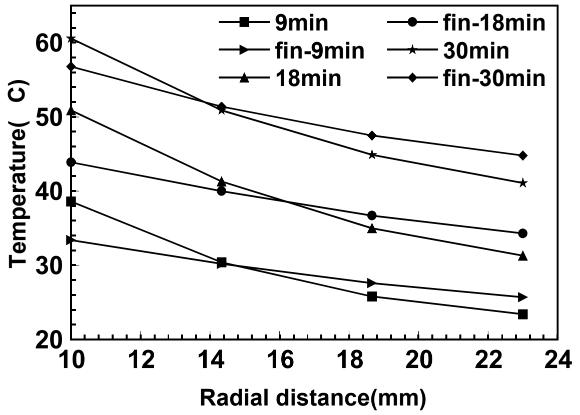


Fig. 5. Temperature profile with /without fins at a heat flux of 1558 W/m^2

$\tau_m = f(Ste^*)$ $\qquad Ste^* = Ste * q = \dfrac{c_s q_w \delta}{\rho_s \alpha_s L}$

Since the PCM and configuration remained 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.

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 a shape of spiral twisted tape, which can effectively enhance both conduction and natural convection heat transfer. A series of experiments are carried out with and without fins. The main results are summarized in Figs. 5 to 10.

Fig.5 compares the temperature profiles at various melting stages with and without fins. It can be seen that the temperature profiles of stearic acid with fins at 9min, 18min, 30min are significantly more even than that without fins. This also means the temperatures at different radial positions become closer to each other due to the existence of fins. Fins accelerate the speed of heat transfer from the electrical rod to the stearic acid. In Fig. 5 under the heating conditions given, the stearic acid does not melt until 60min in the case of that 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 the movement of the melting front location also differs a lot, as shown in Fig.6. As the thermal conductivity of stearic acid is augmented by the

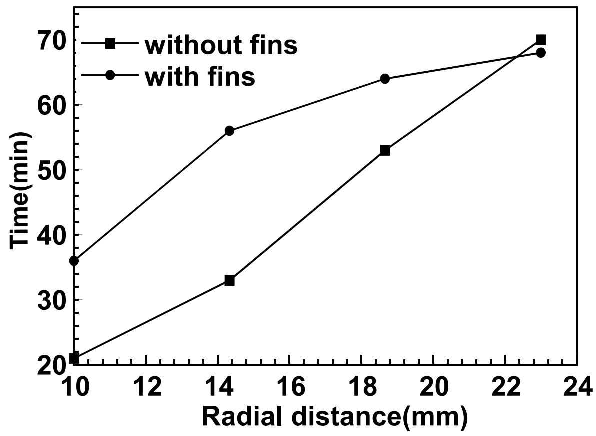


Fig.6. Melting front location: with and without fins 2403 W/m^2

fins, the energy released by electrical 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 20min to 37min.

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 width are manufactured and tested. It should be noted that the total amount of copper inserted into the annulus as fins are the same though these fins are of different width. Fig. 7 gives a comparison of the temperature profiles of the stearic acid with a 0.25cm-in-width fin and that with a 0.75cm-in-width fin. It can be concluded from the figure that the temperature profile of the stearic acid with a

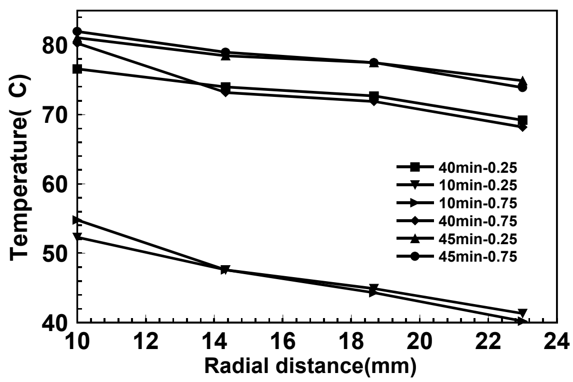


Fig.7. Temperature profile with fins of different width, 3529 W/m^2

0.75cm-in-width fin is steeper than that with a 0.25cm-in-width fin, which proves that fine fins are more effective than large fins in enhancing melting process if a equal amount of the fin material is used. This is mainly because that the effective surface area of the fine fin is a little bit greater than the large fin. It is worthwhile to note that the slopes of the curves of longer times are smaller than that of shorter times, and the influences of the fin width are more significant in the initial period than in the latter period. This is because, as the heating proceeds, more and more solid stearic acid is melted and the natural

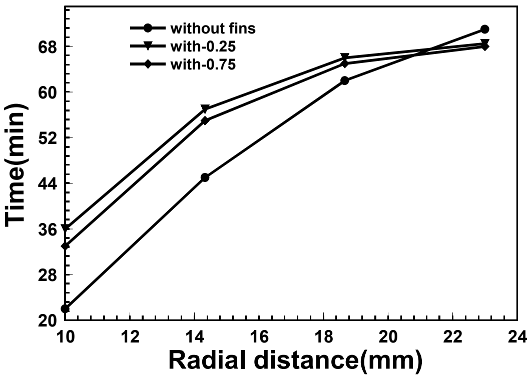


Fig.8.Melting front location: with/ without fins of different width, 2403 W/m^2

convection effects become more and more significant. Fig.8 gives the melting front location variation with time with fins of different widths, which again reveals that the width of fin does have an important effect on enhancing the melting process of stearic acid.

The effect of the pitch of spiral fins

The heating length of the test section is 550mm and the annulus gap is only 13mm. The test section is placed vertically and therefore the natural convection within the annulus is of that in confined spaces. The natural convection is greatly suppressed not far away from the bottom, and the local heat transfer coefficient decreases with the 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 reduces 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, which prove the theory. However, the comparisons in these figures are not on a completely same basis, the amount of the fin materials is different for the two situations: the 30mm-pitch fin uses more material than the 40mm-pitch fin. Therefore these figures not only reveal the effects of the fin pitch but also the effects of the amount of material on the enhancement of melting processes.

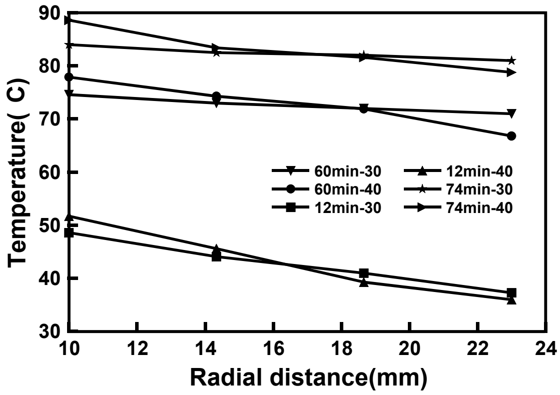


Fig.9. Temperature profile with fins of different pitches, 3529 W/m^2

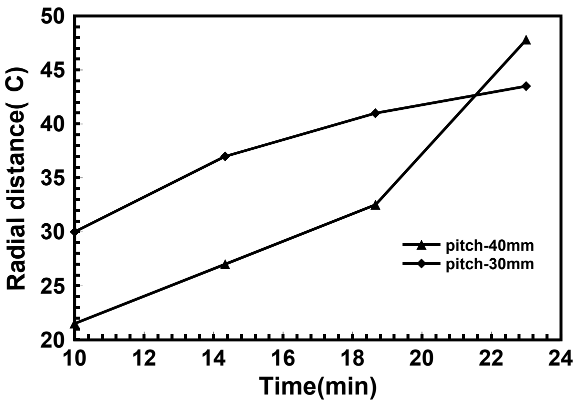


Fig.10. Melting front location with fins of different pitches, 3529 W/m^2

CONCLUSIONS

According to our experimental results and the discussion 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, pre-melting time period is shortened and the whole melting time reduces. A very effective fin is designed to enhance the thermal conductivity of PCM and the experiments show that reduce the fin width can lead to a more effective enhancement of the PCM thermal conductivity. The experimental results also proves that reducing the fin pitch is helpful for enhancing the melting process, since this can generally enhance the natural convection effects though more strict and more precise experiments are needed to verify the pitch effects.

ACKNOWLEDGEMENTS

This work is supported by the Key Project No. G2000026306 of The National Fundamental Research and Development Program, The Ministry of Science and Technology of The PeopleÊs Republic of China, National Natural Science Foundation Project No. 50276001, Beijing Natural Science Foundation Project No. 3032007 and the Key Lab Project KP05040102 of Beijing University of Technology.

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