Experimental Investigation of Phase Change Phenomena of Paraffin Wax inside a Capsule

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***Abstract*— The study of melting phenomena of Phase Change Material (PCM) needs to be understood for the design of thermal storage systems. The constrained and unconstrained melting of PCM inside a spherical capsule using paraffin wax (PW) is investigated. The experiments are carried out with different HTF temperatures of 62°C, 70°C, 75°C and 80°C. PCM melting is constrained in spherical capsule using thermocouples used to measure the temperatures in capsule. The visualization of melting process is obtained using digital camera. The qualitative and quantitative information on solid-liquid interface of phase change process is compared. It is observed that, the solid PCM is restricted from sinking to the bottom of the spherical capsule in constrained melting. The objective of this paper is to confirm suitability of PW for enhancing the performance of thermal storage capacity and utilizing PW for domestic solar water heating applications.**

***Keywords*— Constrained melting, unconstrained melting, Phase change material (PCM), Thermal energy storage (TES), Visualization, solid-liquid phase front. paraffin wax (PW) Heat transfer fluid (HTF)**

I. INTRODUCTION

Thermal energy storage using the latent heat of PCM has received considerable attention these days for exploiting temporal energy source such as solar energy. Thermal energy system utilizes the PCM to maintain a constant temperature over a period of time and undergoes cyclic variation of melting and solidification. The heat transfer and fluid movement during this process has an impact on performance. Experimental observations indicate that there is a difference in time for complete melting under constrained and unconstrained conditions.

In TES system, a spherical container is most commonly used for storing PCM. This is mainly due to its low volume to heat transfer surface area ratio [1]. The density difference between the solid and liquid PCM causes a movement of solid up or down. Depending upon the densities, the melting phenomenon changes due to the movement of solid PCM [2, 3]. Differences in the constrained and unconstrained melting of PCM inside the sphere under several constant surface temperature boundary conditions at several initial sub-cooled conditions are investigated by Tan [7]. It was found that under the same experimental condition, unconstrained melting inside the sphere seems to occur at a faster rate than the constrained melting. This is due to the larger rate of heat transfer by conduction from the solid PCM to the spherical glass. Experimental and numerical analysis of melting of PCM inside a Plexiglass spherical container was conducted by Felix et al. [8], where paraffin wax was used as the PCM. Investigation on the effect of the sphere radius, Stefan number, molten fraction and time for complete melting was carried out. The results for both the experimental and numerical were quite identical. It was found that Stefan number and the sphere radius had significant effects on the complete melting time of phase change material. The study of the constrained melting has been reported by [9, 10] and concluded that the conduction mode of heat transfer was dominant in the earlier stage of the melting process. At a later stage, the melting rate increased as the buoyancy-driven convection inside the liquid PCM became more significant.

This paper aims to investigate the differences in the constrained and unconstrained melting of phase change material inside the sphere under several constant surface temperature boundary conditions at several initial sub-cooling conditions. The motivation of the work here is to understand better the melting rate of PW inside the sphere with or without restraining inside the spherical capsule. This would have useful applications to the thermal design of thermal energy storage for domestic solar water heating applications because PW is preferred by number of previous researchers for its suitable properties. Table. 1 lists thermophysical properties of PW.

During experimental investigation, PW melts inside a spherical capsule. In order to compare its performance during constrained and unconstrained melting, thermophysical properties of PW are determined using Differential Scanning Calorimeter (DSC). It is shown in Fig.1

Table I Thermophysical properties of PW

Melting temperature	59.8°C
Specific heat of solid	2.0 kJ/kgK
Specific heat of liquid	2.15 kJ/kgK

Latent heat of melting	190 kJ/kg
Thermal conductivity of solid	0.24 W/mK
Thermal conductivity of liquid	0.22 W/mK
Density of solid at 15°C	910 kg/m^3
Density of liquid at 70°C	790 kg/m^3

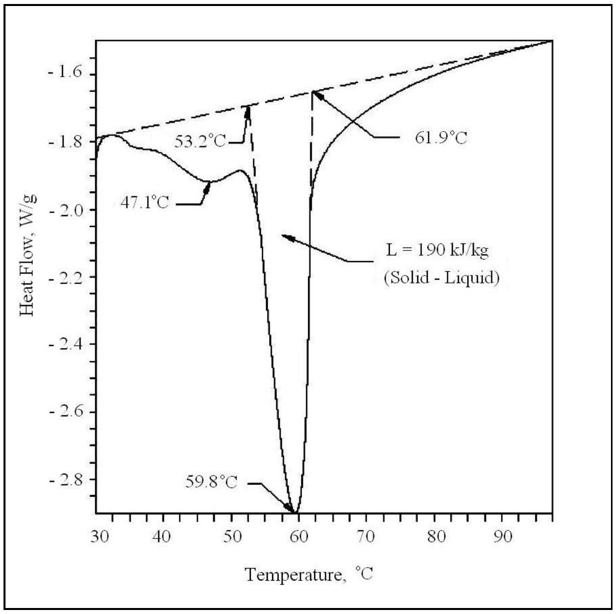

Fig. 1 DSC Curve for Paraffin Wax

II. EXPERIMENTAL SET UP

For investigating the phase change phenomena of the PW PCM inside spherical capsule an experimental set-up is designed, fabricated and commissioned to obtain the relevant data. Fig.2 shows the schematic diagram of the experimental set up. It consists of a test vessel, a spherical capsule, a solar collector simulation unit, a set of K type thermocouples, a data acquisition unit connected to a computer and a digital camera (not shown in the figure). The rectangular test vessel is made up of Plexiglass material with 200 mm X 200 mm cross section and 250 mm height. Plexiglass material is used to visualise melting process of PCM inside the spherical capsule.

Requirement of test set up is a solar simulation unit to replace solar collector. Size of this unit is determined on the basis of surface area specified by MNRE. Solar collector simulation unit is made up of CPVC pipe. Electric coil is inserted in CPVC pipe in order to simulate conditions of solar collector. The unit has two connections through which heat transfer fluid flow from the test vessel to solar simulation unit and vice versa. Borosil glass capsule of 85 mm is used for the visualisation of the melting process. Paraffin wax is used as phase change material because of its favourable properties which make it most suitable material in solar water heating systems. Calibrated K-type thermocouples and data acquisition unit is used to measure temperatures at fixed time intervals at 16 local points inside spherical capsule and at inlet and outlet of solar simulation unit.

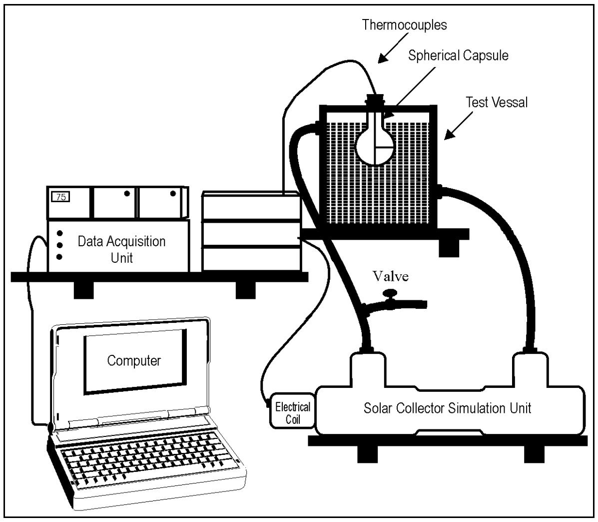

Fig. 2 Schematic diagram of the experimental setup

Fig. 3 (a) shows the position of the thermocouples in a capsule. The thermocouples are mounted inside the Teflon tube to fix up the positions. The distance between each thermocouple is 10 mm for vertical locations (V1 to V7) and 5 mm for horizontal locations (H1 to H7). The thermocouples are connected to the data acquisition unit where the temperatures are recorded during the experiment. The data can then be read from the computer. Fig.2 (b) shows spherical glass capsule without thermocouple to study the melting of PCM inside capsule which is called as unconstrained condition.

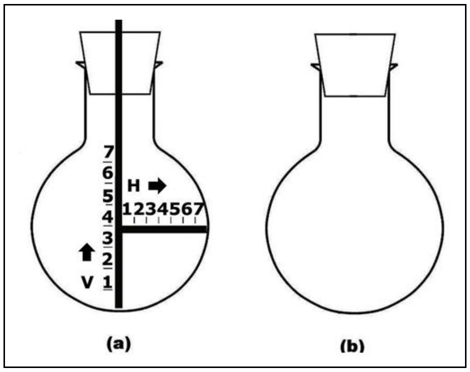

Fig. 3 Schematic of spherical capsule (a) Constrained condition
(b) Unconstrained condition

III. RESULTS AND DISCUSSIONS

Experiments were designed to visualize the melting process in capsule. Two experiments were conducted one for constrained and another for unconstrained. During both conditions capsules were maintained at constant initial temperature of 27°C. When the water in the test vessel has reached the required temperature for the experiment, the capsule is then taken out of the water bucket, submerged and suspended inside the test vessel**.** As the water temperature is higher than the melting temperature of the PCM inside the sphere, the PCM would begin to melt. Phenomenon of melting is captured by digital camera at regular interval of 10 minute. Same procedure is repeated for three HTF temperatures of 62°C, 70°C, 75°C and 80°C for both constrained and unconstrained melting of PCM inside the capsule. The qualitative and quantitative results for HTF temperature at 70°C are discussed as below.

A. Qualitative Analysis

The unconstrained melting involves no thermocouple measurement of PCM inside the spherical capsule. The melting phase front within spherical capsule is shown in Fig. 4.

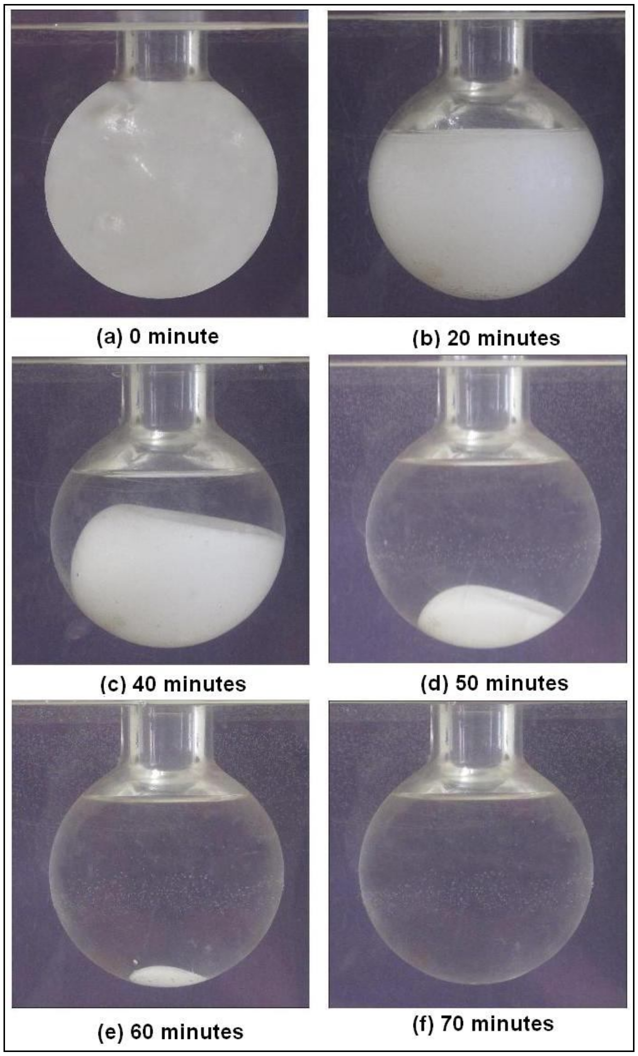
(a) 0 minute
(b) 20 minutes
(c) 40 minutes
(d) 50 minutes
(e) 60 minutes
(f) 70 minutes

Fig. 4 Unconstrained melting phase fronts at 70^{o}C

Solid PW is opaque white at the start of experiment as shown in Fig. 4 (a). Melting of PCM at top is relatively very small as in Fig. 4 (b), this is due to heat conduction at the inner wall, the solid PCM has sunk to the bottom of spherical capsule and is in contact with the spherical glass. Fig. 4 (c) and (d) show that warm liquid flows up along the inner wall, the cooler liquid PCM replaces it, thus causing natural convection in the liquid at the top half. Fig. 4 (e) shows portion of solid PCM stuck to the bottom of sphere and Fig. 3 (f) shows complete melting of PCM which is transparent.

The constrained melting is carried out by having teflon tube inside the spherical capsule. The constrained melting phase front within the spherical capsule is shown in Fig 5.

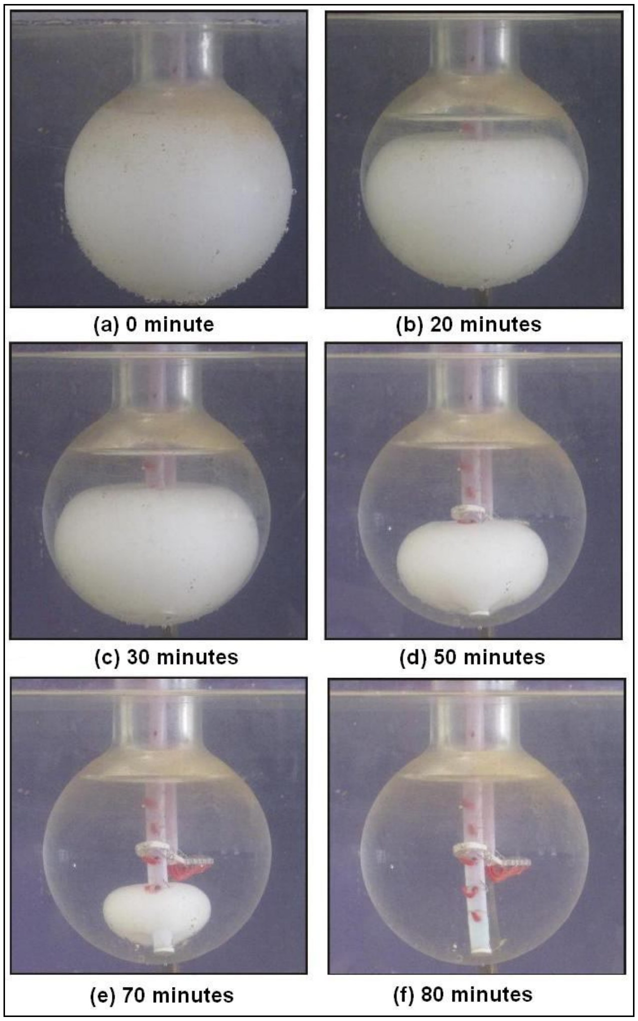
(a) 0 minute
(b) 20 minutes
(c) 30 minutes
(d) 50 minutes
(e) 70 minutes
(f) 80 minutes

Fig. 5 Constrained melting phase fronts at 70^{o}C

Fig. 5 (a) shows solid PW opaque white at the start of experiment. Melting of PCM can be seen in fig. 5 (b) and (c) and this is due to heat conduction at the inner wall of the spherical capsule. It is observed that melting starts from top and solid PCM is in contact with wall at bottom. During this stage heat conduction is dominant. As melting progresses, fig. 5 (d) shows the increasing layer of liquid PCM at top and liquid PCM is also observed at the bottom of spherical capsule. But it is relatively very small. Thus, heat conduction is significantly reduced.

In Fig. 5 (e), Teflon tube holds the solid PCM onto the tube restraining the solid from sinking down to the bottom of spherical capsule despite the effect of gravitational force and buoyancy force due to the difference in density. The oval shape of phase front is caused by the natural convection when the liquid layer increases. Natural convection occurs as the result of the warm liquid PCM rises along the hot wall while the cooler liquid in the centre flows down to replace the warmer fluid. Fig. 5 (f) shows complete melting of PCM which is transparent.

B. Quantitative Analysis

In order to obtain liquid fraction, digital images captured at different time intervals are taken into AutoCAD software. Liquid fraction is measured at time interval of 10 min and graph of liquid fraction verses time for both constrained and unconstrained drawn and analyzed at different Stefan numbers 0.024, 0.114, 0.171 and 0.227 at initial PCM temperature of 27^{o}C.

Stefan number (Ste) describes the operating condition of the capsule undergoing melting, given that the heat transfer temperature T_{HTF} directly affects the value of Stefan number and is defined as:

$$Ste = Cp_l \, (T_{HTF} - T_m) / L$$

Where Cp_l is the specific heat of the liquid PCM, *L* is the latent heat of PCM and T_m is the melting temperature of PCM and T_{HTF} is the heat transfer fluid temperature. The Stefan number represents the heat capacity of the liquid relative to the latent heat of fusion for melting problem.

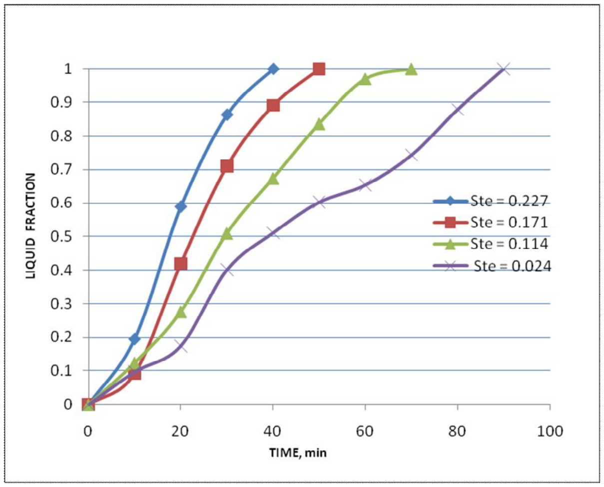

Fig. 6 Liquid fraction versus time for various Stefan numbers during unconstrained melting

1) Effect of Stefan number on unconstrained melting: Fig. 6 shows the variation of the unconstrained liquid fraction versus time for various Stefan numbers. It is revealed from the graph that for the Stefan number of 0.227, PW completely melts within 40 min compared to 50, 70 and 90 min for Stefan numbers 0.171, 0.114 and 0.024 respectively.

2) Effect of Stefan number on constrained melting: Fig. 7 shows the variation of the constrained liquid fraction versus time for various Stefan numbers. It is found from the graph that for the Stefan number of 0.227, PW completely melts within 55 min compared to 60, 80 and 115 min for Stefan numbers 0.171, 0.114 and 0.024 respectively. Finally, it can be stated for the qualitative analysis that, higher the Stefan number (i.e. higher HTF temperature) the shorter is the time for complete melting for constrained as well as unconstrained conditions.

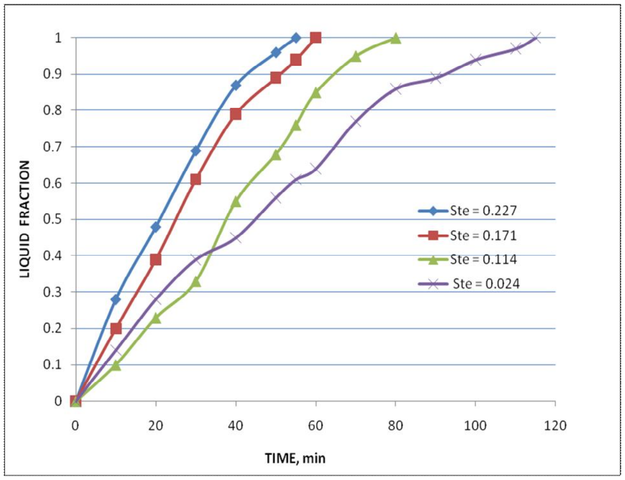

Fig. 7 Liquid fraction versus time for various Stefan numbers during constrained melting.

IV. CONCLUSION

The experimental set up has been designed to facilitate the visualisation of melting phenomenon. The visualise study confirms that unconstrained melting is faster than the constrained melting. Under the constrained melting conditions, the flow pattern shows that the melting occurs around the PCM inwards the centre of the capsule. The solid PCM is restricted from sinking by the tube inside the sphere. There is no contact of the solid PCM with the spherical glass. Melting is mainly through the natural convection in the liquid at the top and bottom halves of the solid PCM. The solid-liquid phase front is rather smooth at the top half. The top half melts at a faster rate than the bottom half. Natural convection cells are also formed at the bottom half, thus causing the waviness profile at the bottom. For the unconstrained melting, the melting pattern could be seen clearly. The solid PCM sinks to the bottom of the sphere. This is due to heavier density of the solid PCM than the liquid PCM. Under the same experimental condition, unconstrained melting seems to occur at a faster rate than the constrained melting. This is due to larger rate of heat transfer by conduction from the solid PCM to the spherical glass capsule.

REFERENCES

[1] L. Bilir, Z. Ilken, Total solidification time of a liquid phase change material enclosed in cylindrical/spherical container, *Applied Thermal Engineering* 25 (2005) pp.1488–1502

[2] Saitoh T, Hirose K. High Rayleigh numbers solutions to problems of latent heat thermal energy storage in a horizontal cylindrical capsule. *ASME J Heat Transfer* 1982;104:545–53.

[3] Bareiss M, Beer H. An analytical solution of the heat transfer process during melting of an unfixed solid phase change material inside a horizontal tube. *Int. J Heat Mass Transfer* 1984;27:739–46

[4] Arnold D. Dynamic simulation of encapsulated ice stores, part 1 – the model. *ASHRAE Transactions* 1996;96:1103–10.

[5] Bedecarrets JP, Strub F, Falcon B, Dumas JP. Phase change thermal energy storage using spherical capsules: performance of a test plant. *International Journal of Refrigeration* 1996;19:187–96.

[6] Kousksou T, Bedecarrets JP, Dumas JP, Mimet A. Dynamic modeling of the storage of an encapsulated ice tank. *Applied Thermal Engineering* 2005;25:1534–48.

[7] F.L. Tan Constrained and unconstrained melting inside a sphere, *International Communications in Heat and Mass Transfer* 35 (2008) 466–475

[8] A. Felix Regin, S.C. Solanki, J.S. Saini, Experimental and Numerical analysis of melting of PCM inside a spherical capsule, in *9th AIAA/ASME Joint Thermophysics and Heat Transfer Conference*, 5–8 June, San Francisco, California, AIAA 2006-3618, 2006.

[9] J.M. Khodadadi, Y. Zhang, Effects of buoyancy-driven convection on melting within spherical containers, *International Journal of Heat and Mass Transfer* 44 (2001) 1605–1618.

[10] S. K. Roy, S. Sengupta, Gravity-assisted melting in a spherical enclosure: effects of natural convection, *International Journal of Heat and Mass Transfer* 33 (1990) 1135–1147.