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Influence of Fins on Solidification of Phase Change Material in Rectangular Capsule

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Abstract - This work presents an experimental study of phase change material solidification in a rectangular latent heat energy storage system (LHESS). Plain and Finned capsules were used to determine the performance of LHESS. The PCM used in this study was pure water which has desirable thermal properties for LHESS and the heat transfer fluid used is Brine solution. The parameters were the flow rate and the temperature of HTF during the freezing and melting. The phase-change period for PCM in the capsules at the edge was shorter than that at the center due to smaller porosity at the center than the edge in case of both the capsule. The finned capsule requires 22.72% less time for solidification than plain rectangular capsule. The HTF inlet temperature has more effect on solidification process than HTF flow rate.

Keywords - Plain and finned capsule, Phase Change Material (PCM), surface area, Heat transfer Fluid, Latent heat storage

I. INTRODUCTION

Energy demands in the industries, service and commercial sectors vary as per the need. These demands can be satisfied by smoothing the temporal variations with the help of thermal energy storage (TES) systems. A latent heat thermal energy storage (LHTES) can be advantageous relative to sensible heat storage in applications with small temperature swings because of its nearly isothermal storage operation.

Thermal energy storage (TES) has attracted research attention because of its application in bridging the gap between energy supply and demand. Current thermal energy storage systems can be categorized by the method they use to store energy such as sensible heat storage, latent heat storage and thermochemical heat storage [1]. Among all these energy storage methods, latent heat thermal energy storage systems show more potential due to their advantages of high energy storage density and almost constant temperature during phase change [2] .

TES has been a main topic in research for the last 20 years. Experimental and numerical studies have been conducted focusing on thermal behaviour of phase change materials (PCMs), melting and solidification of PCMs, PCM containers and convective heat transfer problems within PCMs. Zalba et al. [3] reviewed the history of latent heat energy storage system (LHESS) including PCMs, the heat transfer mechanism and applications. Sharma et al. [4] summarized the investigations of available TES systems focusing on thermal properties of various PCMs. Comprehensive information of TES systems and applications can be found in Dincer and Rosen’s book. [5]

Latent heat energy storage system (LHESS) uses phase change material as the energy storage medium. Energy is stored during melting and released during solidification. Various applications are found in the open literature in the area of space heating [Halawa et al., 6], space cooling [Badescu, 7], domestic hot water systems [Stritih, 8] and incorporating PCMs into building elements [Athienitis et al., 9, Pasupathy et al. 10]

The selection of a proper PCM for a certain system should be done carefully, and the compromise between PCM melting temperature and practical temperature range of the designed system should be

taken into account. Most of the research on PCM problems has been carried out within the temperature range of 0-65°C which is suitable for domestic heating and cooling [Agyenim et al., 2]
Best-known PCM is water. It has been used for cold storage for more than 2000 years. Today, cold storage with ice is state of the art and even cooling with natural ice and snow is used again. For temperatures below 0 °C, usually water- salt solutions with a eutectic composition are used. Several material classes cover the temperature range from 0 °C to about 130 °C. Paraffin's, fatty acids, and sugar alcohols are organic materials. Salt hydrates are salts with a large and defined amount of crystal water. Clathrates are crystalline structures in which molecules of one type are enclosed in the crystal lattice of another. When the enclosed molecule is from a gas and the surrounding crystal structure is water, the clathrate is also called a gas hydrate. They cover a temperature range from about 0 °C to 30 °C. At temperatures above 150 °C, different salts and their mixtures can be applied. [11].
In most cases, except for some applications of water-ice, the PCM needs to be encapsulated. The two main reasons are to hold the liquid phase of the PCM, and to avoid contact of the PCM with the environment, which might harm the environment or change the composition of the PCM. Further on, the surface of the encapsulation acts as heat transfer surface. In some cases, the encapsulation also serves as a construction element, which means it adds mechanical stability. Encapsulations are usually classified by their size into macro- and microencapsulation.
PCM melts more quickly than it solidifies because natural convection speeds up the melting of PCM. In solidification the heat transfers by conduction in solid PCM out from the storage. If there is a temperature gradient in liquid PCM, natural convection exists in the liquid–solid interface. But even very strong natural convection has a negligible effect on the solid–liquid interface position compared to the effect of heat conduction in solid PCM [12, 13]
One of the serious problems associated with the operation of PCM storage system is the heat transfer in and out of the element containing the PCM and requires heat transfer enhancement techniques [14]
Number of researchers worked on increasing the rate of heat transfer in PCM. Numbers of techniques are there to increase heat transfer rate.
Various methods have been investigated for increasing the thermal conductivity of PCMs. The methods include dispersing high conductivity particles within the PCM [3], inserting a metallic matrix [3, 15], adding chunks of metal tubing into the PCM [16], inserting carbon fibers either arranged along a brush or randomly oriented [17, 18], impregnating a porous graphite matrix with PCM [19], finned tubes of different configurations [20-22], multitubes [21] and micro-encapsulation of the PCM [23, 24].
Velraj and Seeniraj [25] experimentally studied the effect of fins in a finned cylindrical enclosure for solidification and found that total PCM solidification time was reduced by 1/nfins, where nfins is the number of fins within the cylindrical enclosure.
Kalaiselvam Siva et al. [26] analysed geometries filled with the same volume of PCM, and concluded that cylinder provides a better encapsulation than a sphere. Cylinder has 38% more surface area than sphere thereby giving 47% reduction in complete solidification time. The dimensions of the selected cylinder were such that the radius is not large as it would lead to increase in solidification time. Hence selection of configuration plays a vital role in TES systems.
The thickness of fins on the heat transfer enhancement effect was also studied [27]. It was observed that thin fins might experience a certain temperature gradient while thick fins can help to provide a uniform temperature along the length. However, the fins should not be so thick as to reduce the PCM volume significantly or overly increase the weight of the LHESS
In order to overcome this limitation as well as to enhance the solidification and melting phenomenon in PCM, a new finned PCM encapsulation for storing and releasing the energy is introduced in this article. In this study, fins located inside the rectangular PCM encapsulations have been investigated for achieving enhanced heat transfer which helps to improve the charging and discharging

characteristics of the PCM considerably. The aim of the study presented here is (i) to evaluate geometrical design with fin (ii) to investigate the effect of Heat transfer fluid flow rate and effect of its inlet temperature.

II. EXPERIMENTAL METHODOLOGY

Experimental work was performed for PCM based energy storage system. Experimental setup as shown in figure 2 consists of constant temperature bath insulated with glass wool containing heating and cooling coil to supply a constant temperature heat transfer fluid.

The capsules containing PCM were kept in insulated charging discharging cylinder through which heat transfer fluid was passed to store and remove the energy from Phase change materials. The encapsulation was maintained under constant wall temperature.

Temperature controller with electric stirrer was used in both the tank and bath to maintain the uniformity of temperature. RTD's with temperature range –50 ^{o}C to 350 ^{o}C were mounted in PCM capsules as shown in figure 3 and 4 and also at pipe entry and exit and in heating bath and connected to Accel smart scan data acquisition system. Brine solution was used as heat transfer fluid whose temperature can be varied between -15 ^{o}C to 40 ^{o}C. Flow was measured by flow meter and controlled by valves. 0.5 H.P. electric pump was used to maintain constant fluid flow. Alarm was used to indicate level of fluid in constant temp bath.

PCM was encapsulated in capsules of different shapes. Regarding the corrosive characteristics of a particular PCM capsule material also needs to be carefully selected because some PCM's were compatible with most of metals but have tendency to soften some plastics. One capsule was plain and one was provided with internal fins to estimate the solidification analysis of PCM. The experiment was conducted for regular rectangular geometry and geometry with solid fins.

The material for capsules was G.I. with following thermo physical properties.

Table 1. Thermo physical properties of G.I.

Density g/cm3	7.87
Thermal conductivity	89 W/m0C
Specific Heat	481 J/kg 0C

Figure 1. G.I.capsules with and without fins

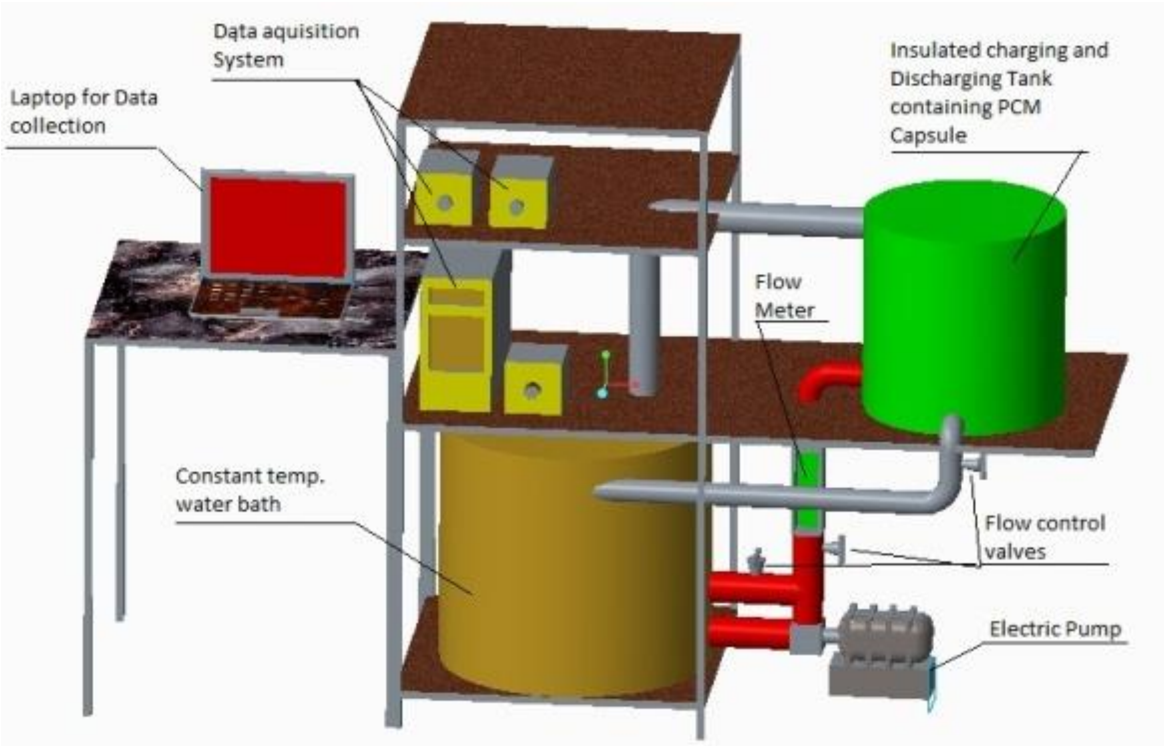

Figure 2. Experimental setup

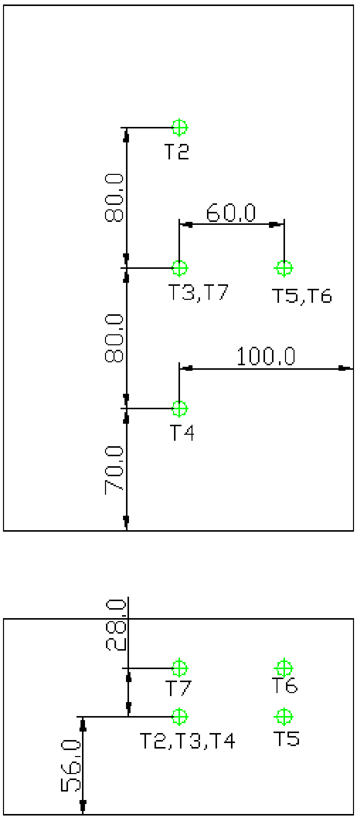

Figure 3. Position of RTD's in Plain capsule

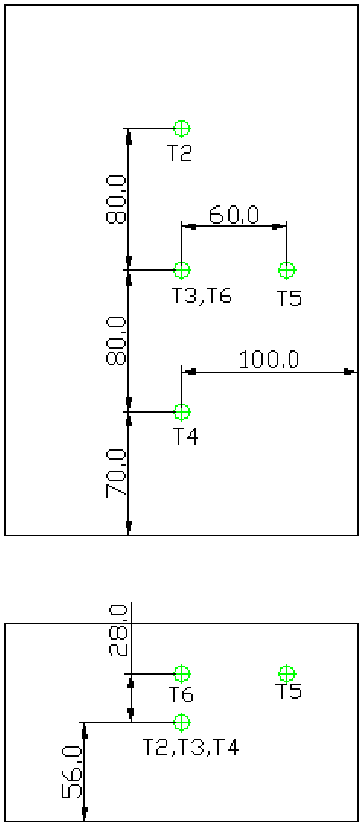

Figure 4. Position of RTD's in finned capsule

Dimensions of both the capsules were selected to have the same volume of PCM. The dimensions were selected by taking the reference of capsules used for Ice Cube formation by conventional methods in Ice factory. The plain rectangular capsule have LxWxH= 200x112x300 dimensions. The capsule with solid fins have dimensions LxWxH = 200x114x300.The fins were arranged at periphery of capsules from inside with dimensions 70x2. Both the capsules contain 6.72 litter of PCM.
The PCM selected in this study was pure water. The range of melting temperature of PCMs could be approximately 0 ^{0}C . The PCM selected in this study exhibited a low transition temperature, which helps to initiate and progress the solidification and melting processes at a faster rate. The selection of this PCM also satisfies the temperature conditions required for the cool storage application and also in formation of ice by conventional methods.

Table 2. Thermo physical properties of Water [Xydatasource; Incropera et al. 28]

Properties/ temperature	0^{0}C	10^{0}C	20^{0}C
Density(kg/m3)	999.84	998.81	998.21
Thermal conductivity (W/m.K)	561.0	587.6	598.4
Dynamic Viscosity (10-6N.s/m2)	1.793	1.126	1.002
Kinematic Viscosity	1.787	1.118	1.004
Specific Heat (kJ/kg.K)	4.2176	4.1945	4.1818
Specific Enthalpy	0	39.8	83.8

Table 3. Thermo physical properties of Brine solution at 15ºC and with 20% solution.

Density(kg/m3)	1152
Thermal conductivity(W/m.K)	0.48
Thermal Capacity (J/kg.K)	3410
Freezing point (^{0}C)	-16.6
Viscosity (Pa.s x 103)	1.8

2.1. Solidification Analysis

Initially empty capsule was weighted. PCM was poured into capsule in melt form which was at 32 ^{0}C much above the fusion temperature. Weight of this filled capsule was also taken. Though the volume of each capsule was 6.72 litters, only 6 litter of PCM was poured to keep Capsule empty by 10.7 % volume to accommodate expansion and contraction. The Heat transfer fluid was maintained at -7 ºC.

The amount of solidification was measured on weight basis. The capsule was kept in the cylinder for 40 minutes and then removed. The weight of solid was measured separately and weight of liquid form was measured separately. The experiment was conducted once again from initial conditions and now the encapsulation was removed after 80 minutes and same procedure was followed till complete solidification occurs. This method of experimentation is found to be correct and hence followed [26].

III. RESULTS AND DISCUSSION

The solidification of PCM was experimentally investigated and results were compared.
Figure 5 shows the photographs of solidification after interval of 40 minutes. The phase change near capsule surface was comparatively at faster rate than core and near about same for both the capsules initially. But after a time period solidification in finned capsule was at faster rate due to geometry.

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Heat transfer was by pure conduction through G.I. material. In finned capsule surface area is increased due to fin as compared to plain cylinder.

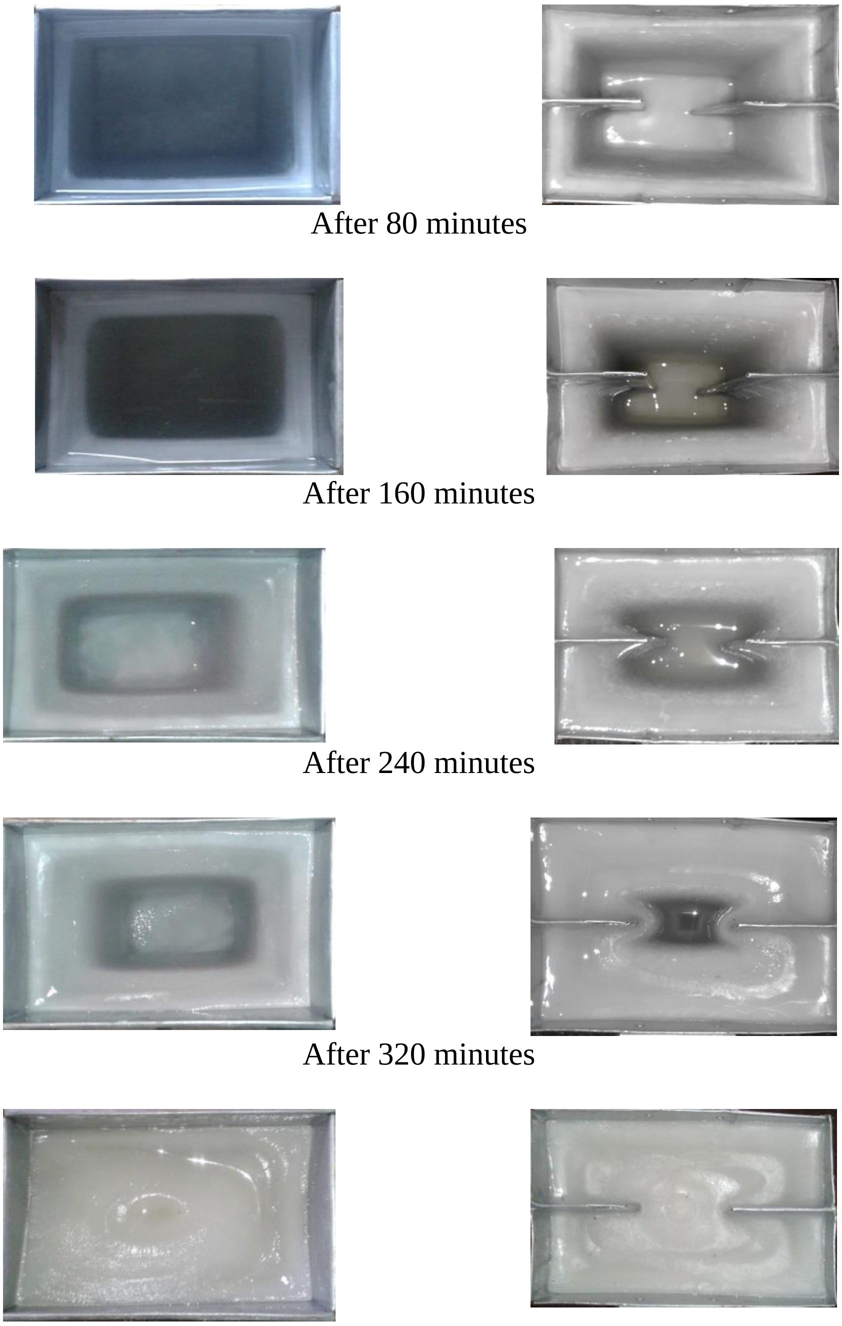

Figure 5. Solidification images of PCM inside the capsule with HTF inlet temperature -70C and flow rate 3 LPM.

The energy stored by the PCM is given by the following equation [39]

$$Q = \int_{Ti}^{Tm} mC_{ps}dT + ma_m\,\Delta h_m + \int_{Tm}^{Tf} mC_{pl}\,dT$$

Where Q is the energy stored (J) , m is the mass of PCM (kg), T is temperature, C_p is the specific heat of PCM, a_m is the PCM melt fraction and Δh_m is the latent heat of fusion (J/kg).

The energy stored and recovered from the LHESS is calculated as

$$\dot{Q} = \dot{m} c_p (T_{in} - T_{out}) \pm u_{\dot{Q}}$$

The C_p of Solution is assumed to be constant. Therefore the measurement errors are calculated using the following equation

$$u_{\dot{Q}} = c_p \sqrt{\left(\frac{\partial \dot{Q}}{\partial \dot{m}} u_{\dot{m}}\right)^2 + \left(\frac{\partial \dot{Q}}{\partial T_{in}} u_{T_{in}}\right)^2 + \left(\frac{\partial \dot{Q}}{\partial T_{out}} u_{T_{out}}\right)^2}$$

The variation of total melt fraction as a function of time for the different heat transfer fluid temperature and mass flow rate is illustrated in figure 6 to 10.

From all graphs it is very clear that as mass flow rate of HTF increases the solidification time decreases. This is also true for heat transfer fluid inlet temperature. As the HTF inlet temperature decreases the solidification time decreases. But the impact of initial temperature of HTF is more as compared to flow rate. Time required for complete solidification of PCM under various inputs is tabulated in table 4. Time reduction in plain capsule when flow rate was increased from 3 LPM to 5 LPM for same inlet temperature of HTF was 4.5%. But the time reduction in plain capsule when inlet temperature was reduced from -7 ^oC to -12 ^oC for same flow rate was 12.18 %. Similarly time reduction in finned capsule when flow rate was increased from 3 LPM to 5 LPM for same inlet temperature of HTF was 5.52%. But the time reduction in plain capsule when inlet temperature was reduced from -7 ^oC to -12 ^oC for same flow rate is 12.82 %.

Table 4. Time for complete Solidification of PCM

Flow rate of HTF (LPM)	Temp of HTF (^{o}C)	Time in Hours		% saving in time by Finned Capsule
		Finned Capsule	Plain Capsule	
3	-12	7.41	9.66	23.27
	-7	8.50	11	22.72
	-2	9.08	12	24.30
5	-7	8.03	10.50	23.01
1	-7	8.83	11.50	23.18

Figures 6 to 8 presents comparison between plain and finned capsule for same flow rate and different heat transfer fluid inlet temperature. The flow rate was 3 LPM and at a HTF inlet temperatures were -12^{o}C, -7^{o}C and -2^{o}C respectively

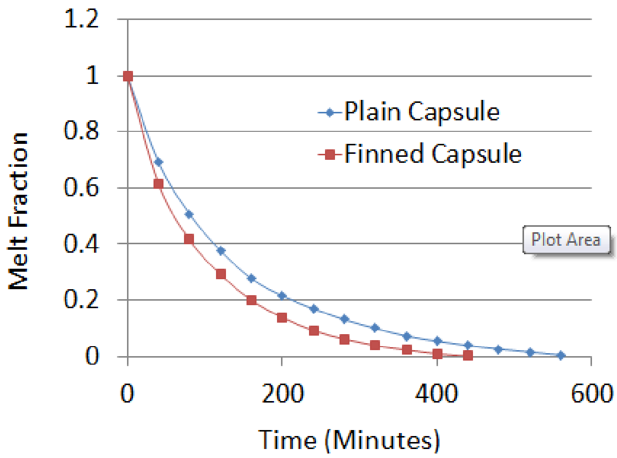

Figure 6. Comparison of plain and finned capsule for HTF temp -120C and flow rate 3 LPM.

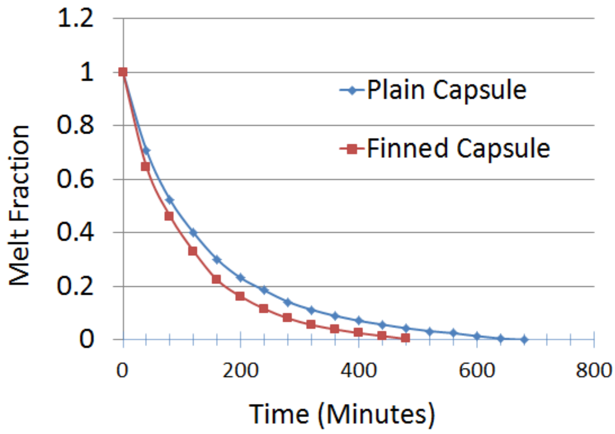

Figure 7. Comparison of plain and finned capsule for HTF temp -7°C and flow rate 3 LPM.

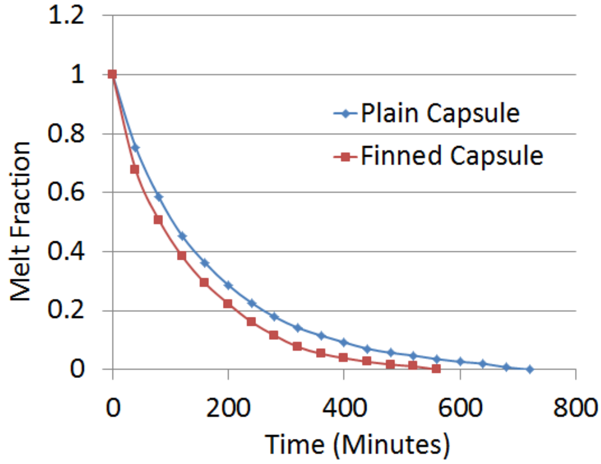

Figure 8. Comparison of plain and finned capsule for HTF temp -2°C and flow rate 3 LPM.

Figure 9 and 10 presents comparison for plain and finned capsule when heat transfer fluid inlet temperature was kept constant and HTF flow rate was varied. HTF inlet temperature was -7 °C and flow rate 5 LPM and 1 LPM respectively.

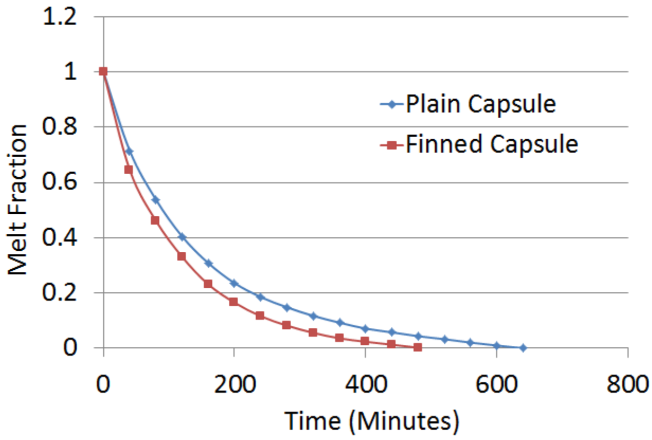

Figure 9. Comparison of plain and finned capsule for HTF temp -7°C and flow rate 5 LPM.

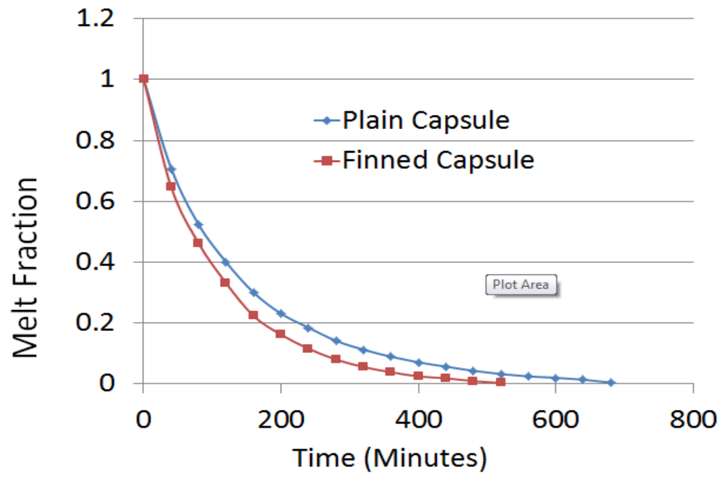

Figure 10. Comparison of plain and finned capsule for HTF temp -7^{0}C and flow rate 1 LPM.

IV. CONCLUSION

For the analyzed geometries filled with the same volume of PCM, fined capsule provides a better encapsulation than a plain rectangular capsule. The finned capsule requires 22.72% less time for solidification than plain rectangular capsule.

The selection of configuration plays a vital role in TES systems. Reduction in charging time can be achieved by placing fins inside the encapsulations such that it protrudes to the centre, thereby aiding better heat transfer process. With the presence of fins, centre of the encapsulation reaches the external temperature at a faster rate. This high reduction in solidification time makes the best choice for PCM configurations.

In case of plain capsule, the reduction in solidification time, when flow rate was increased from 3 LPM to 5 LPM, was 4.5%. But the time reduction in the same capsule when inlet temperature was reduced from -7^{o}C to -12^{o}C, was 12.18 %. Similarly time reduction in finned capsule when flow rate was increased from 3 LPM to 5 LPM, was 5.52%. But the time reduction in the same capsule when inlet temperature was reduced from -7^{o}C to -12^{o}C was 12.82 %. These results show that the effect of change in Heat Transfer Fluid inlet temperature was more than the effect of change in heat transfer fluid flow rate.

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