Thermal Analysis of Thermal Energy Storage Systemwith Phase Change Material

C. Uma Maheswari*, R. Meenakshi Reddy**
*(Assistant Professor, Department of ME, SVCET, Chittoor, AP, India)
**(Professor, Department of ME, SVIT, Anantapur, AP, India)

ABSTRACT

Due to fast depletion of conventional energy sources and ever increasing demand of energy, many researchers started paying attention to renewable energy sources.Thermal Energy Storage (TES) is one of the key technologies for energy conservation and has recently been developed to a point where it can have a significant impact on modern technologies.

The present work deals with the study of a spherical container, filled with spheres containing either paraffin wax or stearic acid as Phase Change Materials (PCM) and water occupying the space left between the spheres. The ANSYS is used for modeling the PCM inside the spheres with simple 2D model. Detailed thermal analysis simulations of the solid liquid phase change are performed. Simulations of the charging and discharging modes are performed and results obtained are compared against previous theoretical results. The results are compared for paraffin and stearic acid with different sizes of the spheres and a fin inserted in the sphere. It is observed that in these cases, the time taken to complete the phase change in the sphere changes as the size changes and paraffin takes less time compared to stearic acid. When a rectangular cross sectional copper fin is inserted into the sphere radially the time taken is reduced, hence output is increased.

***Keywords* -** Phase change materials, paraffin, Stearic acid, Thermal analysis, TES.

I. INTRODUCTION

A lot of research work was carried out on sensible heat storage (SHS) materials and systems in the past and the technology for their utilization was also well developed. Beasley and Clark have provided an excellent review of such efforts in the case of packed bed Sensible Heat Source (SHS) systems[1]. Dincer et al. presented a detailed investigation of the availability of SHS techniques for solar thermal applications, selection criteria for SHS systems, as well as the economics and environmental impacts of SHS systems [2]. Thermal performances of solar water heating systems integrated with SHS system were investigated experimentally [3, 4, 5].

Thermal energy storage using the latent heat concept as an alternative to SHS offers a good option because of its high storage density and the nearly constant temperature heat storage and removal characteristics during charging and discharging processes. Several investigators have studied, theoretically and experimentally, the performance of thermal energy storage employing phase-change material in a wide variety of geometries. Saitoh and Hirose performed theoretical and experimental investigation of the transient thermal characteristics of a phase-change thermal energy storage unit using spherical capsules [6]. Beasly et al. developed a computational model to study the transient thermal response of a packed bed of spheres containing a phase change material usingone dimensional separate phase formulation. Results from model were compared with the experimental results of a commercial size of the thermal storage bed packed with polypropylene spheres containing paraffin wax for both the energy storage and recovery periods using air as heat transfer fluid [7]. Barba and spiga analyzed the behavior of encapsulated salt hydrated used as PCM in a heat transfer system of a domestic hot water tank employing three different geometrical configurations of the PCM containers. Their study showed that spherical capsules yielded against the slab or the cylindrical geometry [8]. Nallusamy et al studied the thermal performance of a packed bed latent heat thermal energy storage unit integrated with solar water heating system. The experimental results showed that the packed bed Latent Heat Source (LHS) system reduced the size of the storage tank appreciably when compared to conventional storage system. The LHS system employing batchwise discharging of hot water from the TES tank is best suited for applications where the requirement is intermittent[9]. Kalaiselvam et al. analyzed the behavior of three paraffins, 60% n-tetradecane + 40% n-hexadecane, n-tetradecane, and n-pentadecane[10]. Ella Talmatsky and Abraham Kribus studied annual simulations were done to compare the performance of a storage tank with PCM to a standard tank without PCM. A model was constructed to describe the heat storage tank with and without PCM [11]. Meenakshi Reddy et.al studied the charging process of a spherical LHS capsule with stearic acid, and paraffin as PCMs. His experimental results demonstrated that, compared to the stearic acid capsule, paraffin capsule melts faster[12].

The objective of the present work is to obtain the thermal-transient analysis of spherical diameter of PCM capsules among three different diameters (60, 50 and 40mm) for better efficiency of sensible and latent heat thermal energy storage unit integrated with constant heat source. Two different materials stearic acid and paraffin, are used PCMs for storing and retrieving the heat energy. Different diameters of the high-density polyethylene (HDPE) spherical capsules filled with PCM were used which are always surrounded by a SHS material in the TES tank. The water used as Heat Transfer Fluid(HTF) to transfer heat from the constant temperature heat source to TES tank also acts as SHS material. Parametric studies are carried out to examine the effects of the diameter when a copper fin is inserted.

II. EXPERIMENTAL SET UP

A schematic diagram of the experimental setup is shown in Fig.1. This consists of an insulated cylindrical TES tank, which contains PCM encapsulated spherical capsules, solar flat plate collector, flow meter and circulations pump. The stainless steel tank has a capacity of 51 liters (360 mm diameter and 504 mm height) to supply hot water for a family of 5 to 6 persons. Flow distributor is provided on the top of the tank to make uniform flow of HTF. The storage tank is insulated with glass wool of 50 mm thick. The outer diameters of spherical capsules are 60, 50 and 40mm and these are made of HDPE with wall thickness of 2.50 mm as shown in the Fig. 2.

The total number of capsules in storage tank in case of paraffin and stearic acid for different diameters are 152, 245 and 870 & 146, 235 and 836 respectively of 60, 50 and 40 mm to store the 10,000 KJ of heat. The spherical capsules are uniformly packed in layers and each layer is supported by wire mesh. The paraffin is used as PCM that has a melting temperature of 61 ± 2^0C and latent heat of fusion of 213 KJ/Kg. Water is used as both SHS material and HTF. Stearic acid is used as another PCM that has a melting temperature of 57 ± 1^0C and latent heat of fusion of 198 KJ/Kg.

A flow meter with accuracy of ±2% is used to measure the flow rate of HTF and a centrifugal pump is employed to circulate the HTF through the storage tank. The TES tank is divided into four segments i.e. at x/L =0.25, 0.5, 0.75 and 1.0 (L is length of the TES tank, mm; x is the axial distance from the top of the TES tank, mm; x/L is the dimension less axial distance from the top of the TES tank) along its axial direction and the Resistance Temperature Detectors (RTD) with an accuracy of ±0.3^0C are placed at the inlet, outlet and four segments of the TES tank to measure the temperatures of HTF. Another four numbers of RTDs are inserted into the PCM capsules and they are placed at four segments of the TES tank to measure the temperatures of PCM. The position and number of RTDs are also designated in Fig.1. The RTDs are connected to a temperature indicator, which provides instantaneous digital outputs.

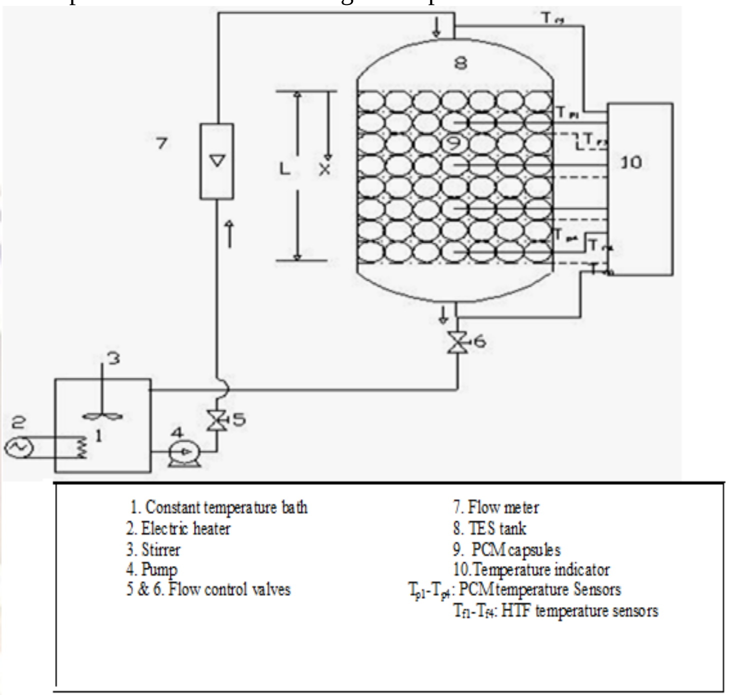


Fig.1 Schematic of Experimental set up

Different sizes of the Spherical capsules made of HDPE are used as PCM containers as spherical shape gives the best performance among the various types of containers.

Fig. 2 Photographic view of different size of the balls

III. THERMAL ANALYSIS

ANSYS 12 software is used to solve the thermal- transient analysis. The tank was subdivided in 24 sections (N_x=24). As in the simple 1D model, only one sphere is simulated in each division, assuming that all the spheres in a section have the same behaviour. When the PCM inside the spheres are changing phase, natural convection is produced due to the difference between solid and liquid densities and gravity action. Following assumptions are made in the present work.

- Incompressible fluid
- Density is considered constant, except in the gravity forces term.
- Constant thermo-physical properties (properties of solid and liquid states are assumed to be equal).

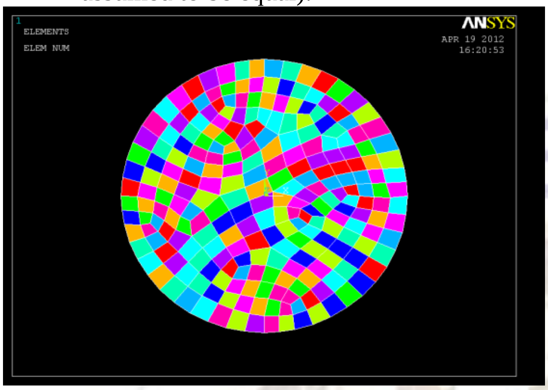


Fig. 3 Meshes of PCM sphere

Fig. 3 shows the meshed element of PCM filled sphere which was analyzed for temperature distribution.

IV. RESULTS AND DISCUSSION

The results of simulating the charging and discharging modes of operation of the thermal energy accumulation system are presented in the Fig. 5. Table 1 shows the different capsule dimensions used for the analysis.

Table 1 Specifications of spherical diameters

Outer diameter	Inner diameter
60 mm	55 mm
50 mm	45 mm
40 mm	35 mm

In charging mode, the whole system is initially at a uniform temperature of 20^0C, and a water flow at 70^0C starts entering the tank through the top. Spheres, which were initially at solid state, start to receive heat and eventually to melt.Figure 4 shows a detail of the liquid flow, enthalpy and temperature maps of a representative sphere in the first section of tank in charging mode, simulated with the ANSYS model, with the finest mesh considered. Natural convection phenomenon is clearly identified.An ascending flow is induced by the higher temperature of the fluid at the capsule shell, arriving to the top of the sphere and then descending to come into contact with the solid part. The liquid flow transfers some of its heat of the solid, getting cooler and descending along the solid boundary.

As the temperature of the capsule is higher than the inner temperature also at the bottom of the sphere, another ascending flow is generated here, with an opposite spinning sense to the one of the main flow. This flow produced a high heat transfer rate locally, accelerating the melting process at the bottom and deforming the initially spherical shape of the solid portion.

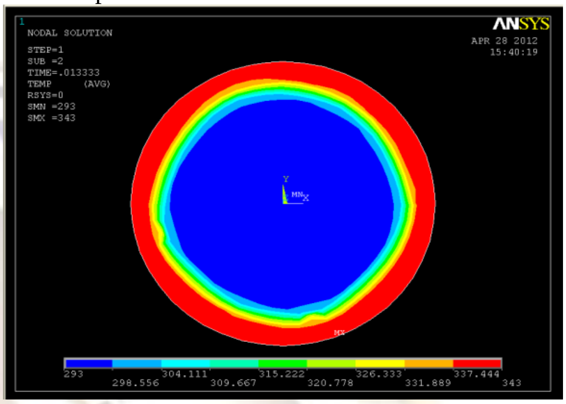
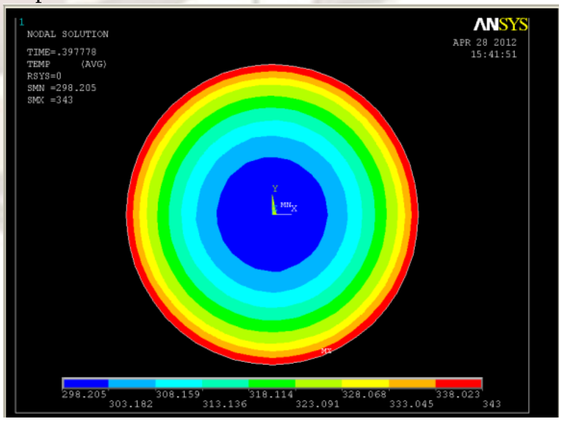


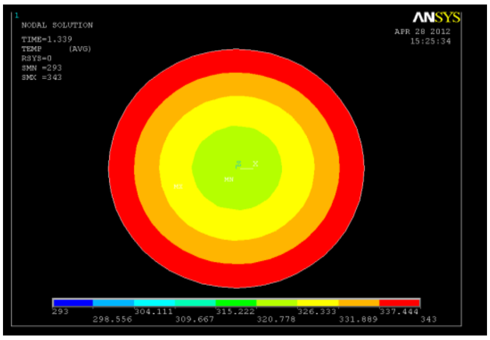
Fig. 4 Nodal solutions of temperature map and contours at initial condition

The resulting temperature map and solid shape are appreciably different from the concentric ones that would be obtained if the convection were not present. It should be noted that, in this work, forces acting on the solid have not been considered. These tend to bring the solid portion down to the bottom of the capsule at some moment of the melting deviating its evolution from the described by our model. These effects should be considered in future works.

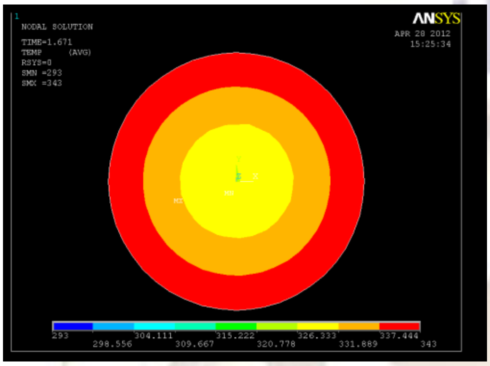
The numerical results of the simulations of the spheres are presented in the Figures, where simplified analysis for constant phase change temperature is included.



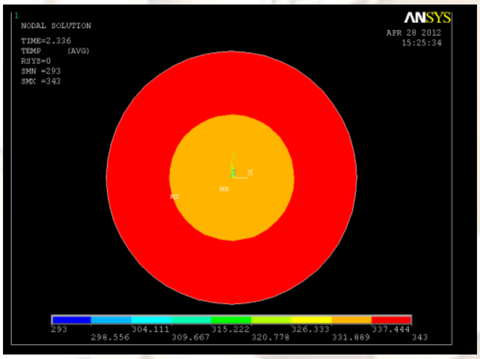
(a) After 0.39 minutes



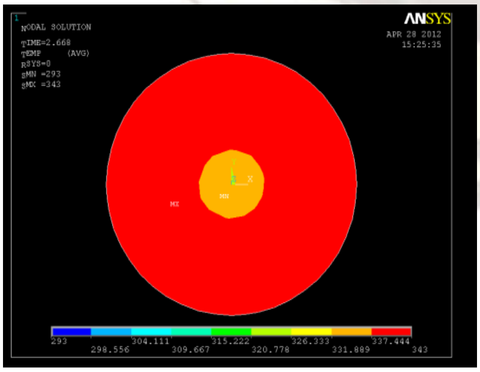
(b) After 1.339 minutes



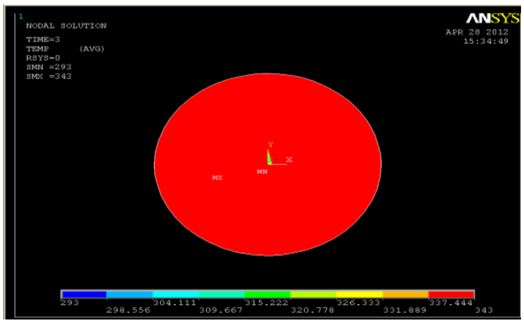
(C) After 1.67 MINUTES



(d) After 2.336 minutes



(e) After 2.668 minutes



(f) After 3 minutes

Fig. 5 Temperature distribution stages of Paraffin sphere

Figure 5 shows the simulations obtained at different time steps. The figures 5 (a) to (f) shows the temperature distribution from heat transfer fluid towards the centre of the node in the PCM sphere. The time taken to complete the temperature distribution is noted for different size of the spheres and for different PCM materials such as paraffin and stearic acid. The values are tabulated and comparison study is made.

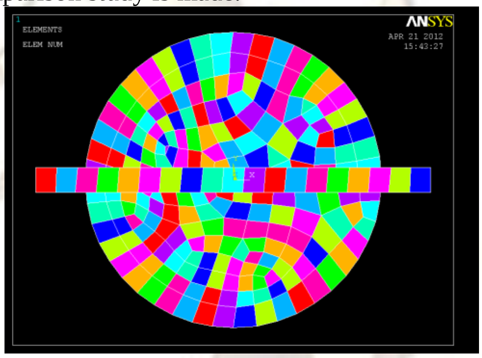


Fig. 6 Meshed model of fin type PCM sphere

Figure 6 shows the meshed model of a PCM sphere when a copper fin is inserted in to it radially which increases the speed of temperature distribution.

Table 2 Comparison of temperature distribution in different sizes and materials

Sl. No.	Size of the sphere	Time taken to complete	
		Paraffin wax	Stearic acid
1	60 mm	3 min	3.5 min
2	50 mm	2 min	2.5 min
3	40 mm	1.2 min	1.55 min
4	60 mm + copper fin	2.724 min	3.2 min

Comparing the three different sizes of spheres, the time taken for full phase change is tabulated as follows in Table 2.

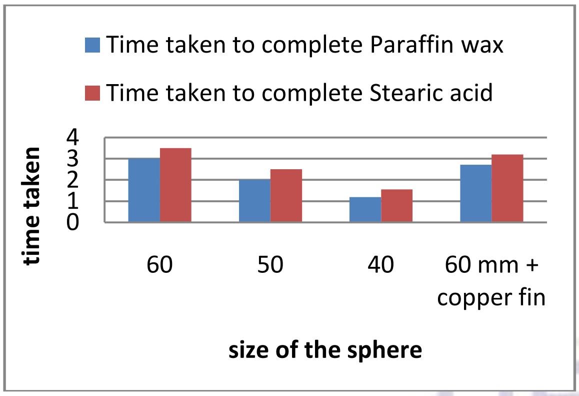


Fig. 7 Comparison of time taken for different sizes of spheres

Figure 7 shows the graph of time taken to complete the phase change for different size of the spheres with and without fin. It is observed from the from the Fig. 7 that in these cases, the time taken to complete the phase change in the sphere, changes as the size changes and paraffin takes less time compared to stearic acid. When a rectangular cross sectional copper fin is inserted into the sphere radially the time taken is reduced, hence output is increased

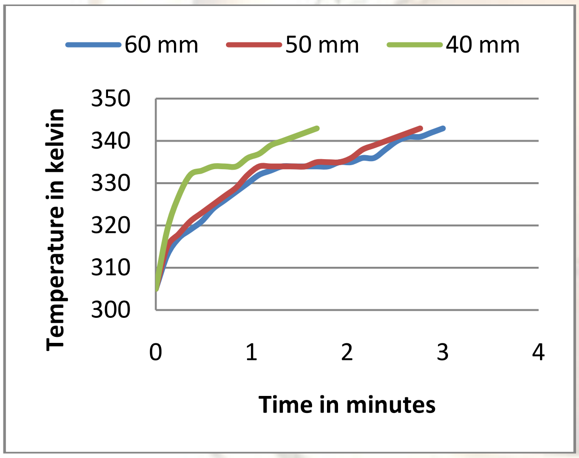


Fig. 8 Temperature profiles for different sphere sizes

Figure 8 shows the temperature distribution of different sizes of balls. It is seen from the Fig. 8 that the phase change occurs at a constant temperature in the theoretical predictions whereas a near constant temperature is observed in the experimental investigation. The reason is that the PCMs do not have single melting point and they melt normally over a temperature range. It is already mentioned that the paraffin and stearic acid which is used as PCM in the present investigation, has the melting temperature in the range of 59^0C to 61^0C. The temperature rise in the experimental results is lower than the numerical predictions after the complete melting of PCM at any segment. This is due to the higher specific heat value of the liquid PCM in the actual case than the value provided in the numerical computation.

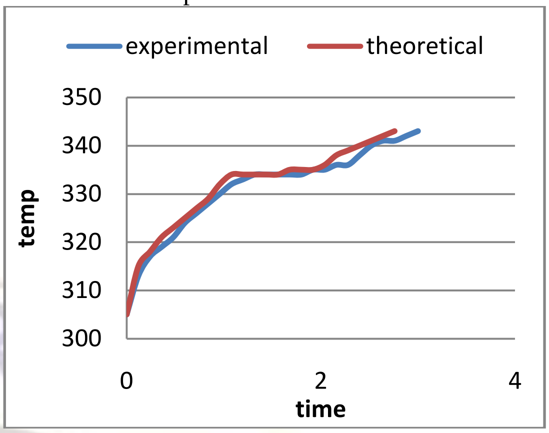


Fig. 9 Theoretical and experimental temperature profiles

Figure 9shows the comparison of theoretical and experimental temperature histories of the PCM in the TES tank for the case of constant HTF inlet temperature. It is observed from the Fig. 7 that the experimental values are slightly lower than the theoretical values during most of the charging period as in constant HTF inlet temperature case. A small temperature difference between theoretical and experimental values is found. It is due to the limitations of the maximum temperature obtainable in the experiment (70 – 73 ^{0}C) due to the type of heat source used whereas in the theoretical analysis a linear increase in heat flux is observed that increases the HTF inlet temperature linearly with time.

During the melting process all the numerical methods give almost the same results for the temperature of the PCM when the PCM is in a solid state. First of all the PCM starts to melt when the effective heat capacity method with a wide temperature range is used. The melting starts at 60^0C. The PCM melts a little too quickly when the experimental and theoretical results are compared. All the numerical results compare quite well to the experimental results of the temperature of the PCM.

During the solidification process all the theoretical methods give uniform results for the temperature of the PCM in a liquid state. When solidification begins the effective heat capacity method with a wide temperature range gives almost the same results as the enthalpy method.The phenomena which were observed in the storage without fin can also be seen in the results from the storage with the fin. During the melting process the theoretical method gives the most precise results for the temperature of the PCM in the middle of the storage. At the sides of the storage the PCM melts too quickly.

One reason for the difference between the theoretical and experimental results in the material properties of the PCM is assumed that the density and the heat conductivity of the PCM are constant. If the temperature dependent material properties are known, the theoretical methods will give more precise results for the temperature of the PCM. Thus, the material properties of the PCM should be well known in order to obtain sufficiently accurate results with the numerical methods.Another reason for the differences between the theoretical and experimental results may be in the placement of the thermocouples. The storage is filled with the liquid PCM. The placement of the thermocouple may have been slightly changed. After the storage is filled up it is impossible to check the placement of the thermocouple.

V. CONCLUSIONS

A thermal energy storage system has been developed for the use of hot water at an average temperature of 45^0C for domestic applications using combined sensible and latent heat storage concept. Charging experiments are conducted on the TES unit to study its performance by integrating it with constant heat source. The temperature histories of HTF & PCM and energy storage characteristics during charging process for various size of capsules (60mm,50mm and 40mm) and different PCMs (Paraffin and stearic acid) are studied.

Detailed thermal-transient analysis simulations of the solid liquid phase change are performed. Simulations of the charging modeis performed and results obtained are compared against previous results and found that they are closely related with experimental methods. The results are compared for paraffin and stearic acid with different sizes of the spheres and a fin inserted in the sphere. It is observed that in these cases, the time taken to complete the phase change in the sphere changes as the size changes and paraffin takes less time compared to stearic acid. When a rectangular cross sectional copper fin is inserted into the sphere radially the time taken is reduced, hence output is increased. The quantity of water discharged is also is almost same in paraffin and stearic acid, with slight variation of 3-4%. This is because of latent heat, thermal conductivity and specific heat quantities for both PCMs are almost same with 5-7% variation. But the cost of stearic acid is around Rs.48 per kg where as paraffin cost is Rs.75 in the Indian market. So economically the stearic acid is going to give the same output at less initial cost. Hence stearic acid is best option for Thermal Energy Storage System.

REFERENCES

[1] Beasley. D.Eand Clark. J.A, Transient response of a packed bed for thermal energy storage,*International Journal of Heat& Mass Transfer, 27(9)*, 1984, 1659-1669.

[2] Dincer.I, Dost. S andXianguo. L, Performance analysis of sensible heat storage systems for thermal applications, *International Journal of Energy Research, 21*, 1997, 1157-1171.

[3] Collares-Pereira. M, Gordon. J.M, Rabl. A andZarmi. Y, Design and optimization of solar industrial hot water systems with storage, *Solar Energy, 32(1)*, 1984, 121-133.

[4] Sodha. M.S, Sharma. A.K, Sawhney. R.L and Kumar. A, Experimental performance of built-in-storage solar water heating systems in laboratory and field conditions, *International Journal of Energy Research, 21*, 1997, 275-287.

[5] Reddy. K.S, Avanti. P andKaushika. N.D, Finite time thermal analysis of ground integrated-collector-storage solar water heater with transparent insulation cover, *International Journal of Energy Research, 23*, 1999, 925-940.

[6] Saitoh. T and Hirose. K, High performance phase-change thermal energy storage using spherical capsules, *Chemical Engineering Communication, 41*, 1986, 39-58.

[7] Beasley. D.E andRamanarayanan. C, Thermal response of a packed bed of spheres containing a phase change material, *International Journal of Energy Research, 13*, 1989, 253-265.

[8] Barba. AandSpiga. M, Discharge mode for encapsulated PCMs in storage tanks, *Solar energy, 74(2)*, 2003, 141-148.

[9] Nallusamy. N, Sampath. S and Velraj. R, Study on performance of a packed bed latent heat thermal energy storage unit integrated with solar water heating systems, *Journal of Zhejiang University science A, 7(8)*, 2006, 1422-1430.

[10] Kalaiselvam. S, Veerappan. M, Arul Aaron.A and Iniyan. S, Experimental and analytical investigation of solidification and melting characteristics of PCMs inside cylindrical encapsulation, *International Journal of Thermal Sciences, 47*, 2007, 858–874.

[11] Ella Talmatskyand Abraham Kribus, PCM storage for solar DHW: An unfulfilled promise?,*Solar Energy ,82*, 2008, 861-869.

[12] Meenakshireddy. R,Nallusamy. N, Anjaneya Prasad. B and Hema Chandra Reddy. K., Thermal energy storage system using phase change materials: constant heat source, *International Journal of Thermal Sciences, 16(4)*, 2012, 1097-1104.