



EXPERIMENTAL ANALYSIS ON STRATIFICATION OF THERMAL STORAGE USING PHASE CHANGE MATERIAL

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Abstract:

A latent heat storage system comprising of Phase Change Material (PCM) OM65 encapsulated in spherical capsules and stacked in a cylindrical vessel to form packed bed PCM containment is taken for experiment. The phase change material OM 65 used in thermal storage is useful to store latent heat at 65°C. At this temperature heat stored is very useful for many of the process industries. This paper not only deals with storing the heat but also deals about the stratification of the PCM containment. The operating parameters like mass flow rate, thermo physical properties of the Heat Transfer Fluid (HTF) and OM 65 PCM have been considered. The inlet temperature of the HTF has been raised according to the heater input to the PCM containment. The temperature profiles of the PCM containment and the HTF were determined using J-type thermocouples and it is recorded by AI8000+ DAQ. These temperature values are used to determine the variation in Stratification number, Richardson number, storage charging efficiency, charging efficiency for the system which has been reported.

Key Words: Thermal Storage, PCM, Stratification

Nomenclature:

g	acceleration due to gravity
H	Height of the tank between the top and the bottom layer of the PCM ball, m
$\dot{V}$	Flow rate of the HTF, $m^3 sec^{-1}$
v_{sf}	Superficial velocity, $m sec^{-1}$
ΔZ	Height of the control volume. m
Q_{abs}	Heat absorbed by the PCM, W
t	Instantaneous time, sec
m_{pcm}	mass of the PCM
C_{ps}	Specific heat of the solidus PCM $J/kg^{-1} K^{-1}$
L_{pcm}	Latent heat of fusion of the PCM J/kg^{-1}
N	Number of temperature measurement nodes
Str	Stratification number
Ri	Richardson number
$\frac{\partial T}{\partial y}$	Temperature gradient along the height of the Storage tank
T	Temperature

Greek Symbols:

β	Coefficeint of thermal expansion K^{-1}
τ	Non dimensional time
ρ	density kgm^{-3}

Subscript:

ch	charging
i	inlet
ini	initial
ins	instantaneous
sf	superficial
avg	average
tp	top
bt	bottom
o	outlet
k	temperature measurement nodal point counter

Abbreviations:

TES	Thermal Energy Storage
HTF	Heat transfer fluid
PCM	Phase change material
HDPE	High density Poly Ethylene
LHTES	The Latent Heat Thermal energy storage

1. Introduction: The rise of importance of renewable forms of energy comes with its own challenges. Solar energy can be used but it is intermittent in supply where as the demand in energy is continuous. The need for continuous supply of heat can be

overcome by thermal storage. Always a back up of thermal storage is a necessity for continuous supply of heat. Thermal storage can be done both in sensible heat or latent heat. This heat helps to replenish the heat reserve and supply heat in the night time and also try to maintain the supply. There are different types of thermal energy storage (1). The Latent Heat Thermal energy storage (LHTES) is better than Sensible heat thermal energy storage as latent heat is much greater when compared to sensible energy capacity. LHTES charge and discharge at a constant temperature and also have very high heat capacities when compared to sensible heat. These materials are not so costly and also can be procured easily. The latent heat capacities are much greater than sensible heat. Even for low temperature application in process industries OM65 usage will be adequate to supply for preheat applications. Various types of research in thermal storage has been done where [2] Mark A Rosen et al., showed in the paper about six different models of temperature distribution which can improve stratification and can increase the thermal storage efficiency and also imply that it can further increase the exergy storage capacity. The review of 150 thermal energy storage materials used in research [3] by Luisa F Cabeza et al., and the associated heat transfer technologies is useful to understand the thermal energy storage and its applications. Another research [4] Atul Sharma et al have investigated different properties of PCM types, thermal energy storage units, applications of PCM's, different techniques for solving Stefan number problem, numerical investigation methods and the formulation of enthalpy method to the phase change problem, Experimentation using PCM in thermal storage for a water tank was done by [5] Ashmore, Mawire et al, experimentally investigated 3 different cases of simultaneous charging and discharging with initially unstratified storage tank, stratified storage tank, initially unstratified at the top and stratified at the bottom of the PCM containment. Experimentally it was found that water could be boiled at the end of two hours and sufficient amount of energy could be stored in the containment. [6] G. Senthilkumar et al., has added Phase change material on the top of the thermal storage tank which has enhanced the stratification and further increased the charging efficiency. By maintaining various HTF inlet temperatures the stratification was analysed in the PCM containment by using non dimensional numbers like Stratification number, Richardson number, charging efficiency and cumulative charge fraction.

For enhancement in storage [7] M. K. Sharp et al., has shown that 10 to 15 % of increase in improvement in the system performance is obtained if stratification is maintained in the storage tank. Based on this research the stratification is maintained till the end. [8] Promod B. Salunke, has reviewed in detail the effect of Phase change Material (PCM) shell's thermal conductivity It says that a core to coating ratio of the shell enhances the thermal storage capacity. With high thermal conductivity a lower shell size and high temperature of HTF results in quick melting of the PCM and heat transfer enhancement in microencapsulated PCM was also found. Nallusamy et al [9] have constructed, designed TES and integrated with constant temperature bath/solar collector to study the performance of the storage unit using paraffin as the PCM. Charging with various temperature inlet and continuous and batch-wise discharging characteristics were reported. An experiment to simulate the practical conditions in low temperature ambience was done by the study of temperature stratification for a solar water heater by C. Garnier [10] in the Scottish conditions where the radiance fluctuated between 900 W/m^2 to less than 400 W/m^2 . Whereas in India the solar radiation will not be less than 1400 W/m^2 . A numerical model was created and validated with the experimental values. Practically the PCM used in application of waste heat was shown by V. Pandiayaraj et al [11] who had done experimental investigation on shell and tube heat exchanger and thermal storage and found that 10% to 15% of heat can be successfully retrieved using this thermal storage application along the exhaust of a diesel storage unit. Also the characteristics of Heat lost, charging rate, charging efficiency and the percentage of heat saved are reported. There are numerical investigation being done by [12] Felix regin et al., based on the type of heat transfer fluid temperature, mass flow rate and the phase change temperature range on the thermal performance of various radii capsules and found that charging and discharging characteristics of PCM capsules of smaller diameter is significantly more efficient compared to the larger diameter PCM capsules. Due to intermittent supply of solar energy a thermal storage for any solar application becomes highly important; the conception of thermal stratification allows wide variety of design embodiment. [13] Y.M Han et al., gives an idea of various types of thermal storage and also mentions the influencing factors for any thermal storage tanks. It states that the influencing factors are inlet and outlet condition, thermal leakage, static and dynamic operating conditions. To assess the efficiency improvement of stratification a standard non dimensional numbers like Stratification number and the impact of Richardson number has been analyzed and their influence on geometry has been studied. The experimental set up and various components have been discussed in this paper for use in experimentation for thermal stratification in a tank.

2. Experimentation:

The experimental setup as illustrated in the fig 1 consists of a heater to simulate the solar heat, where in water is circulated as the heat transfer fluid (HTF) in a loop, along with a data acquisition system to record the temperatures. The Heat simulator has a capacity of 10 liter HTF with 3 KW immersion rod. A PCM containment is a cylindrical vessel of diameter 300 mm and of height 375 mm, designed to accommodate 45 balls arranged in 5 layers with 9 balls in each layer. 4 rod meshes were interspaced between the layers and a support mesh was placed at the bottom to provide space for the circulating water. Polyurethane foam of 30mm thickness is used as an insulation material to reduce the heat transfer. This containment is enclosed on top with a header. To allow the HTF into the container, the header is attached at its center with half an inch diameter pipe. The output hot water from the heater is circulated to the PCM containment. The HTF which is collected at the bottom is pumped back with a controlled flow rate of 1 liter per minute using the valves. The PCM was procured from Pluss, India and its thermophysical properties of the PCM are given in Table 1. J-type thermocouple which has a higher sensitivity of about $50 \mu\text{V}/^\circ\text{C}$ and can measure for the temperature range of -40 to $+750^\circ\text{C}$ are used. 5 thermocouples (TB1 To TB5) are attached to the PCM balls by drilling holes in them as shown in Fig. 1. Around 5 thermocouples TL1 to TL5 are inserted along the height of the tank to measure temperature stratification within the layers of fluid. The header is attached with a thermocouple named as Tin.

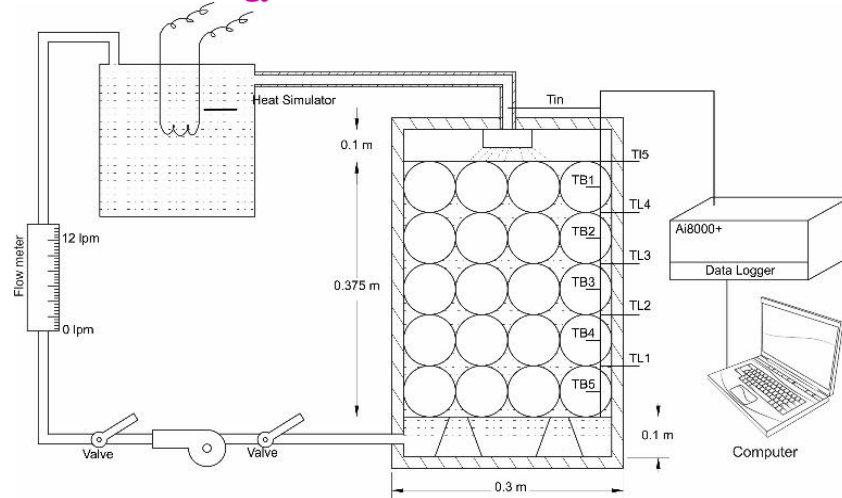


Figure 1: Schematic Layout of the experimental setup

While charging the heat transfer fluid is allowed to circulate over the PCM encapsulated balls to heat them until the HTF temperatures reaches 80°C. The Data acquisition system AI8000+, is a 16 channel thermocouple reader. All the temperatures are fed from the experiment as shown in the diagram to the Data acquisition system. To start with, the water is heated in a solar heat simulator and the hot water circulates from it to the PCM containment and then pumped and circulated back to the simulator. The water circulated is approximately around 1 liter per minute.

Table 1: Technical Specification for OM (Organic Material) 65 PCM

Phase change range (°C)	Liquid Bath Freezing Temp (°C)	Latent Heat of fusion (kJ/kg)	Solid Density (kg/m ³)	Specific Heat (kJ/kgK)		Thermal Conductivity (W/mK)	
				Solid	liquid	Solid	liquid
66-68	65.0	183	924	2.38	2.83	0.19	0.33

The OM 65 balls absorbs the heat from the water. Once the temperature of the balls increases layer by layer gaining sensible heat reaching the melting point 65 °C where all the OM 65 PCM gets melted and latent heat is stored. For the charging procedure of OM 65 balls Fig-2 shows the temperature variation across the balls and Fig-3 shows the temperature variation within the layers.

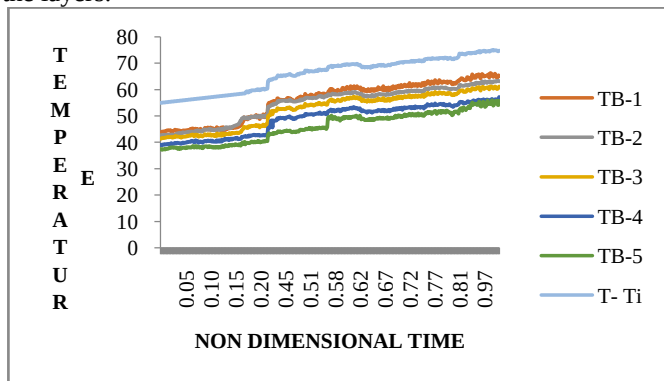


Figure 2: Charging Temperature of balls Vs Non dimensional time

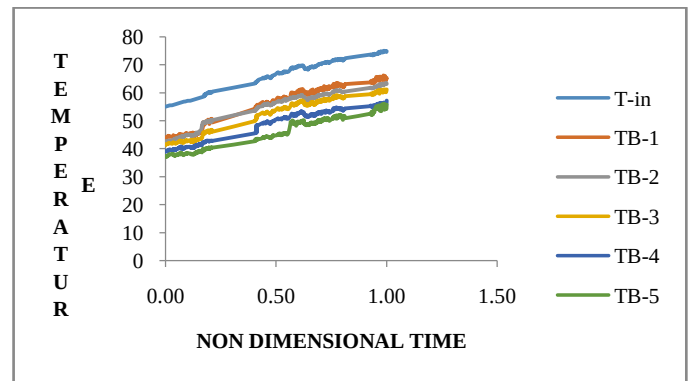


Figure 3: Discharging Temperature of Balls Vs Non dimensional time

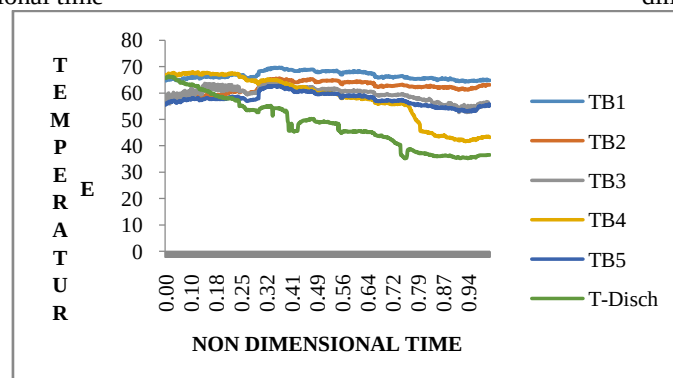


Figure 4: Charging Temperature of Layers Vs Non dimensional time

To measure the discharging properties water is connected in a reverse flow instead of the pump and collected from the top. A thermocouple to measure the discharge temperature of the outgoing water is placed on the top of the tank. So discharging

properties within the balls and across the layer of the water and including outlet water reading as T-Disch is illustrated in Fig. 4 & 5

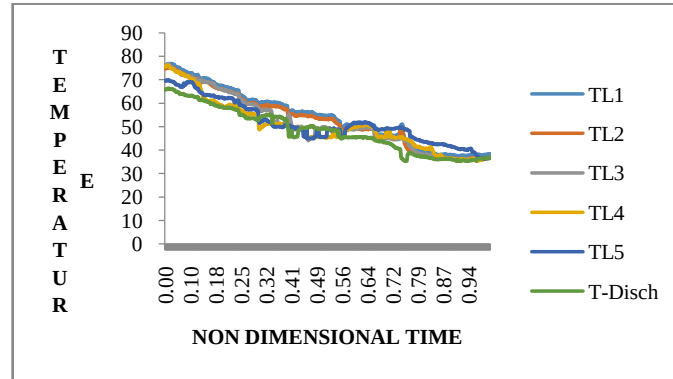


Figure 5: Discharging Temperature of Layers Vs Non dimensional time

After the experiment on simultaneous thermal charging and discharging of the tank is done and the temperatures are recorded, the thermal parameters to characterize the thermal performance of the storage tank are presented in this section.

3. Analysis of Data:

During charging and discharging the net average charging power can be determined as $Q_{ch} = m_{avg} C_p \Delta T$ Where m_{avg} = Average flow rate of 1 Kg / min and $C_p = 4.18$ kJ/Kg where as $\Delta T = 10^\circ\text{C}$ to 12°C is the degree of superheat maintained between HTF and PCM. Total heat absorbed by the PCM at the end of charging process is calculated by equation (1).

$$Q_{abs} = m_{pcm} \cdot C_{p(PCM)} (65-30) + m_{pcm} L_{PCM} \quad (1)$$

Where $m_{pcm} = 5.52$ kg, $C_{ps} = 2.3$ kJ/kgK, & $L_{PCM} = 183$ kJ/Kg.

The heat content to raise the temperature of ball to where the PCM completely forms liquid is 1488 kJ.

The Stratification Number: It is the ratio of the mean of the temperature gradients at each time interval to the temperature gradient at the initial charging process ($t=0$) Fernandez and Seara et al [14] proposed equation (2) for the evaluation of stratification number depending on the temperatures acquired at equidistant points in the Thermal energy storage tanks

$$Str = \frac{(\partial T / \partial y)_t}{(\partial T / \partial y)_{t=0}} \quad (2)$$

Where

$$(\partial T / \partial y)_t = \frac{1}{N-1} \left[\sum_{k=1}^{N-1} \left(\frac{T_k - T_{k+1}}{\Delta Z} \right) \right], (\partial T / \partial y)_{t=0} = \left(\frac{T_i - T_{ini}}{(N-1)\Delta Z} \right)$$

Where here k is the nodal points where the temperature measurements are made, N is the number of nodal points and ΔZ is the distance between the nodal points T_i and T_{ini} which shows the inlet and initial temperatures of the HTF respectively. Richardson number is an effective indicator of stratification performance that considers the various aspects of storage systems such as the geometry of the storage tank, velocity, and the temperature at the top and the bottom layers of the tank. It is given by the ratio of the buoyancy forces to the mixing forces and is calculated by the equation (3)

$$Ri = \frac{g\beta H (T_{tp} - T_{bt})}{v_{sf}^2} \quad (3)$$

$$v_{sf}^2 = \frac{\dot{V}}{\pi r^2}$$

Where T_{tp} and T_{bt} represent the temperature of water measured at the top (TL5) and bottom (TL1) of the TES tank and H is the distance between these locations. $\dot{V}$ and v_{sf} represents the volumetric flow rate and superficial velocity of HTF entering the TES tank and r is the radius of the inlet pipe respectively.

The charging efficiency of the TES system is the ratio of instantaneous heat transfer to the maximum heat transfer, at a given temperature and flow rate of the HTF at the inlet and it is determined by the equation (4) proposed by Ramana et al [15]

$$\eta_{ch}(t) = \frac{T_i - T_o(t)}{T_i - T_{ini}} \quad (4)$$

Where T_i and $T_o(t)$ are the fixed inlet and time variable outlet temperature of the HTF respectively and the T_{ini} is the initial temperature of the fluid in the storage tank. Chan et al [16] has defined thermal energy storage efficiency of the charging process as the actual energy change at time t divided by the maximum energy change after the ideal plug flow replacement of the entire volume as in equation (5)

$$\eta_{storage}(t) = \frac{T_{avg}(t) - T_{ini}}{T_i - T_{ini}} \quad (5)$$

Where T_i , T_{ini} and $T_{avg}(t)$ are the inlet temperature of the HTF, initial mass weighted average temperature of the fluid in storage tank.

4. Results and Discussion:

The experimentation for both sensible heat and latent heat charging has been done for OM 65. The total energy stored in the balls was found to be 1148 kJ with Sensible heat energy capacity and latent heat capacity of 1010.16kJ & 137.84kJ respectively. The sensible charging time was found to be 42.5 minutes and with an average of around 12 degrees superheat maintained in the inlet temperature of heat transfer fluid. The variation in temperature along the height with respect to charging time is shown in the figure 2. Numerical calculation was done for the data acquired in the experiment. The instantaneous

stratification numbers, Richardson number, storage charging efficiency and charging efficiency has been calculated and illustrated in figure 6, 7, 8 & 9 respectively. The stratification number depicts the difference between stratification of sensible and combined TES system with respect to a function of non dimensional time τ .

$$\tau = \frac{t_{ins}}{t_{total}} \text{ where } t_{ins} = \text{instantaneous time \&}$$

Initially the stratification number decreases due to mixing of the hot fluid and the cold fluid in the tank then it increases until it gets the peak value which reflects the depth of penetration of temperature from the inlet temperature which depends on the rate of diffusion, flow rate of HTF, the velocity of fluid entering the tank and inlet temperature of the HTF. The stratification is maintained almost till the end.

As seen from the graph, a clear sign in stratification number is noticed between the sensible and combined TES system. The peak of Stratification is observed at 30% of time which shows the tank remains stratified till the end starting at 0.3 of the whole time as shown in the Fig-5.

Richardson Number is the non dimensional number often used to study the stratification behavior in PCM containment. Greater Richardson number represents better stratification behavior. Fig 7 represents the Richardson number verses the Non dimensional time. As observed in Fig: 7 it is higher at 0.3 for the given flow rate. This period indicates that the sensible heating of Solid PCM in combined thermal energy system is due to low specific heat, the rise in temperature also was higher leading to higher Richardson No.

However Ri first reduces at a faster rate initially due to mixing of the layers and then increases as there is an increase in heat transfer by the PCM at the top due to phase change. In the sensible heat Richardson number is useful for comparing the Stratification performance between two systems and we can observe as quoted in Kumar et al.,[6] the Ri for 1liter / min for OM 48 was 13 where as for OM 65 it is around 3 for same 1 liter /min and reaches to the maximum at the 0.3 of the total charging time.

The storage charging efficiency increase to 90.2 till the 0.35 of the time and later on shows that charging efficiency remains steady. Initially it is sensible heat energy and later on the latent heat energy being stored as shown in Fig:8.

Charging Efficiency is the ratio of Instantaneous heat transfer to maximum heat transfer as shown in Fig 9. It shows the behavior of the charging efficiency with respect to the non dimensional time. In Sensible heat transfer the charging efficiency remains high upto 22% of the time initially and gradually reduces upto 12%. At 0.80 of the total time across it reaches the latent heat transfer temperature at 65°C and further reduces. The sensible TES has higher charging efficiency when compared to the combined TES.

70% of the TES for the PCM containment is done for the 0.73 of the total time which can be read from the Fig 8. The sensible heat gain as we know covers around 29.3 % of the total heat gain.

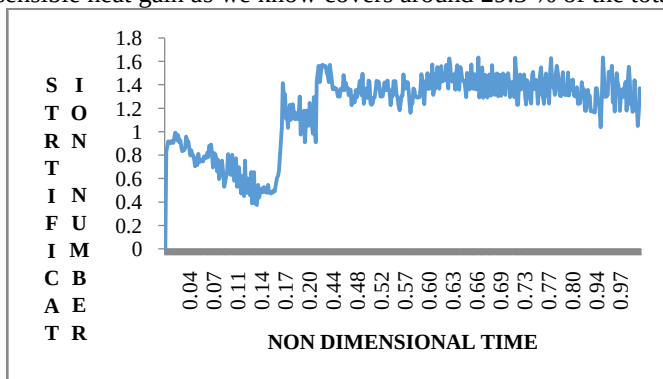


Figure 6: Stratification number Vs Non dimensional time

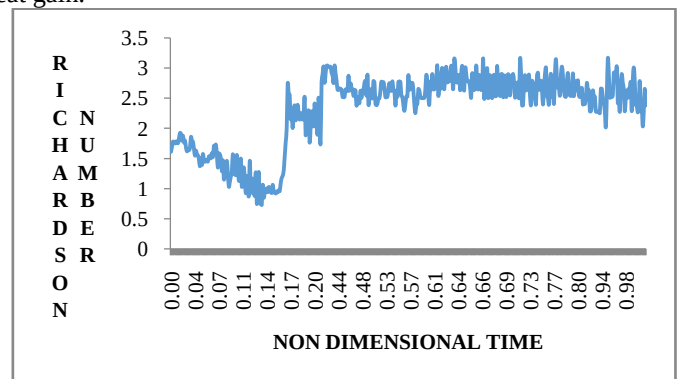


Figure 7: Richardson number Vs Non dimensional time

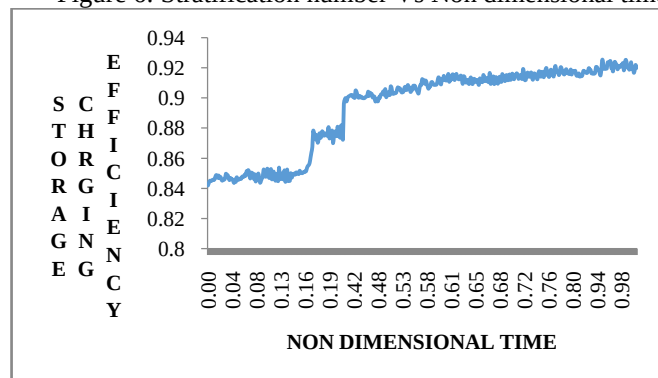


Figure 8: Storage charging efficiency Vs Non dimensional time

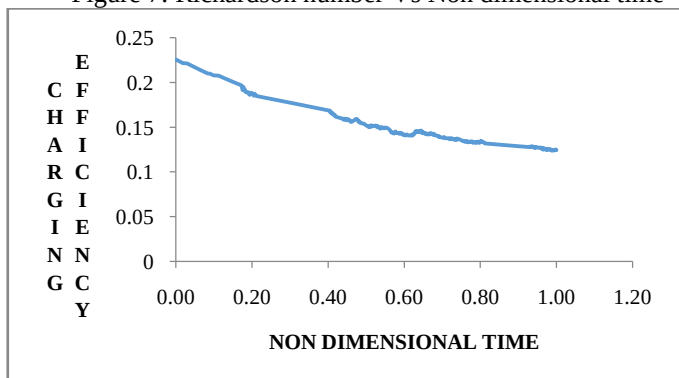


Figure 9: Charging efficiency Vs Non dimensional time

5. Conclusion:

The stratification behavior between a hot water storage tank and that filled with PCM for a charging process is combined with latent heat storage. This PCM containment is charged and the temperatures for charging are recorded with the DAq. The

results of temperature reading for the balls and layers are compared and analyzed. The figures for the analysis of the temperature profile across the height of the tank, were shown. The analysis of stratification was done by using the Stratification number and Richardson number along with the storage charging efficiency and the Charging efficiency. These analyses were used to characterize the thermal stratification for both the TES. Based on the experimental investigation the following conclusion are made. In STES system the stratification behavior depends only on the flow rate of the HTF whereas in the combined TES it depends on both the flow rate and temperature difference between the inlet temperature of HTF and PCM due to inherent low thermal conductivity of the PCM. For any experimental condition the initial temperature rise in the bottom most section of the TES tank was comparatively high causing higher heat loss and hence reduced rate of charging. The HTF flow across the PCM balls causes more retention of heat when compared to without the balls. The plot of the Stratification number Richardson Number variation decreases and later on gets steady with respect to time, and charging efficiency decreases with time and the storage efficiency increasing with time and reaches maximum very early, which helps to depict the performance of the PCM containment for charging and discharging properties. OM65 being a higher temperature melting point of 65°C can be used for pre heating applications in the process industries.

7. References:

1. Dincer I, Rosen M A, Thermal energy storage: Systems and applications
2. Mark A Rosen, "The Exergy of Stratified Thermal energy storages "2001 Elsevier Science Ltd. Feb 2001
3. Luisa F.Cabeza, Christian Sole, Albert Castell, Eduar Oro, And Antoni Gil, "Review of Solar Thermal Storage Techniques and Associated heat transfer technologies". Proceedings of IEEE, Vol-100, February 2012
4. Atul Sharma, V.V. Tyagi, C.R.Chen, D.Buddhi. "Review of thermal energy storage with phase change materials and applications". Renewable and Sustainable energy Reviews, 2009
5. Ashmore Mawire, Simeon H. Taole, Robert R.J, Van den Heetkamp. "Experimental investigation on simultaneous charging and discharging of an oil storage tank". Energy conservation and management, Oct 2012, Volume 65, Pgs 245-254.
6. G. Senthil Kumar, D Natarajan, L.A. Chidambaram, V. Kumeresan, Y.Ding, R.Velraj. "Role of PCM addition on stratification behavior in a thermal storage tank - An experimental study". Energy 2016. Vol-115, Pgs-1168-1178.
7. M. K. Sharp and R. I. Loehrke. "Stratified Thermal Storage in Residential Solar Energy Applications", Journal of Energy, Vol. 3, No. 2 (1979), pp. 106-113.
8. Pramod, B. Salunkhe. Prashant, S. Shembekar "A review on effect of phase change material encapsulation on the thermal performance of a system", Renewable and sustainable energy reviews, Aug 2012. Volume 16, Pgs 5603-5616.
9. N. Nallusamy, S. Sampath, R. Velraj, "Experimental investigation on a combined sensible heat and latent heat storage system integrated with constant/ varying solar heat sources. Renewable energy, April 2006.
10. C. Garnier, J. Currie, T. Muneer "Integrated Collector storage solar water heater: Temperature stratification, Applied Energy, January 2009.
11. V. Pandiyarajan, M.Chinna Pandian, E Malan, R. Velraj, R.V Seeniraj. "Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system". Energy Policy, June 2011, Vol-39, Pgs 6011-6020.
12. A. Felix Regin, S. C. Solanki, J.S.Saini "An analysis of a packed bed latent heat thermal energy storage system using PCM capsules: Numerical Investigation". Renewable Energy, December 2009.
13. Y. M Han, R.Z. Wang, Y.J.Dai, "Thermal Stratification within the water tank." Renewable and sustainable energy reviews, Mar- 2008, Volume 13, Pgs 1010-1026.
14. Fernández Jose, Seara Francisco, J. Uhi'a, Jaime Sieres, "Experimental analysis of a domestic electric hot water storage tank. Part ii: dynamic mode of operation". Applied Thermal engineering, Vol-27 Issue-1, January 2007, Pages 137-144.
15. A. S. Ramana, R. Venkatesh, V. Antony, Aroul Raj, R. Velraj. "Experimental investigation of the LHS system and comparison of the stratification performance with the SHS system using CFD simulation", Solar Energy, Volume 103, May 2014, Pages 378-389.
16. A. M. C. Chan, P. S. Smereka and D. Giusti, A Numerical Study of Transient Mixed Convection Flows in a Thermal Storage Tank, Aug 01, 1983, J. Sol. Energy Eng 105(3), 246-253.