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Effect of thermal performance on melting and solidification of lauric acid PCM in cylindrical thermal energy storage

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Abstract: In this experimental study, a designed vertical shell and tube type thermal energy storage system, with the effect of natural convection during melting and solidification process is investigated. The temperature variation at different positions both in axial and radial locations are measured during melting and solidification process of lauric acid PCM. Results revealed that 0.4 kg of lauric acid PCM required the time of 4800 seconds for the completion of the melting process (i.e., liquid fraction=1) within the predicted designed cylindrical thermal energy storage system. Fourier number, Rayleigh number, and Nusselt number justified that natural convection occurs in the designed thermal energy storage system. Due to 7.91% increment in the thermal gradient, energy storage rate is greater 8.012% at axial height 0.0846m than the axial height 0.0423m. It also observed, after 4800 seconds heat transfer rate decreases gradually and within the time range of 4200-5400 seconds, it is decreased with 6.72%.

Keywords: Lauric acid, thermal energy storage, Rayleigh number, natural convection.

1. Introduction:

After the fuel crisis and rise in energy prices researches started work on alternative energy sources, i.e. renewable energy. Renewable energy is energy from natural resources, for example, solar light, wind velocity, tides and waves in the ocean, geothermal heat, etc. These energy resources are rapidly becoming more efficient but its installation cost is high and it depends on the geographical location. Now a day of research work on the thermal energy storage system. With the help of this system, thermal energy can be stored in the form of sensible heat, latent heat and thermochemical reactions. The basic materials used in TES are phase change materials. These PCMs have properties to restore thermal energy during the melting process and release this energy during the solidification process. TES systems have been used in a wide range of applications. Gopal et al. [1] presented an experiment on TES that was integrated with a diesel engine. It was observed that 6.13% of the total energy of the fuel is saved by using the TES system. By experimental investigation, Pandiyarajan et al. [2] 10-15% of fuel power are stored by integrating TES with a diesel engine. Ben et al. [3] worked on concentrated solar thermal power (CSP) generation systems. Luisa et al. [4] used TES for achieving thermal comfort in buildings during the variation in atmospheric temperature. Sundaram [5] investigated with the comparative heat transfer performance of shell and tube PCM TES. Low thermal conductivity is the major drawback of PCMs. Sharma et al. [6] reduced the overcome regarding the low thermal conductivity of PCMs by adding nanoparticles. It observed that thermal conductivity of PCM improved by 12.7, 20.6, 46.6 and 80% for nanoparticle mass fractions of 0.5, 1.3 and 5% respectively. Nermen et al. [7] observed Paraffin wax composites with nanoparticles have greater thermal conductivity and latent heat than microcrystalline wax composites. Addad et al. [8] added nanofluid with a 5% nanoparticles concentration as heat transfer fluid and reduced the charging/discharging period by about 20%. Edadi et al. [9] were investigated numerically and justify with experimental work of melting process, heat transfer, and energy storage characteristics by using bio-based nano PCM filled in a vertical cylindrical latent heat storage system. Xiao et al. [10] were

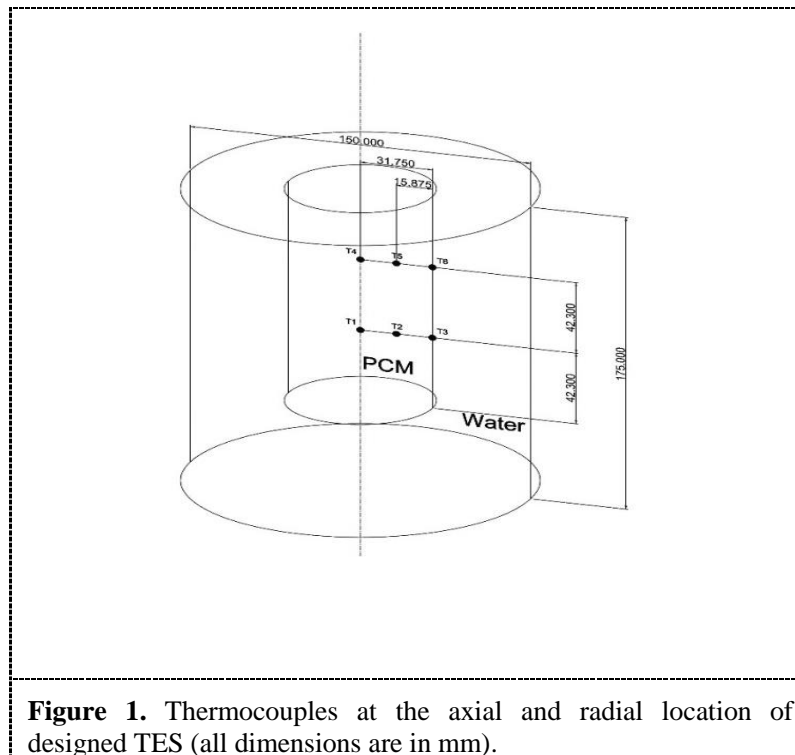


found improvement in the melting rate of the thermal heat storage system with the effect of natural convection during melting process in horizontal shell and tube type thermal energy storage unit. Gabor et al. [11] have developed a two-grade heat storage system was developed. Dincer et al. [12] investigated the exergy and energy analysis for heat storage systems with various parameters related to storage systems such as charging and discharging periods, energy and exergy efficiencies for charging. Cardenas and Leon [13] worked on inorganic salt compositions and metallic alloys, as storage media in a higher temperature thermal energy storage system, thermophysical properties database to facilitate the material selection task for high-temperature applications. Nicholas and Patrick et al. [14] have reviewed the use of thermal energy storage for thermally buffering vehicle system. Vehicle systems with transient thermal profiles are classified according to operating temperatures in the range of 0-800°C and taken 700 available materials from a number of material classes. Raja et al. [15] designed compact shell-tube heat exchanger, and TES tank with paraffin wax and ethylene glycol as PCM and this system integrated with a diesel engine and recovered 14% waste heat from engine exhaust. Rajagopal and Natarajan [16] recovered 6 to 7% of the energy in exhaust heat and stored in the TES tank. Prabhu and Asokan [17] extracted 86450J/kg of heat energy extracted from the shell and tube heat exchanger that was nearly 7% of fuel energy. Shen et al. [18] have investigated the latent heat of composite PCMs (Lauric acid/modified Sepiolite composite) exhibited 125200J/kg at 42.5°C (melting temperature) and 113900J/kg at 41.3°C (freezing temperature) and thermal conductivity 0.59W/m-K. Qinqchao et al. [19] analyzed the volumetric change rate, freezing and melting times of PCM mixed with water by using effective heat capacity method.

From the above literature review, it is observed that additive and geometrical design are more important influence factor to enhance the TES systems. The present TES system only works on geometrical design having a different dimension of a copper cylindrical container with lauric acid PCM. It is useful in the recovery of waste energy from the internal combustion engine.

2. Experimental Description

The experiment is conducted in a copper cylindrical tube filled with PCM placed in a stainless steel cylinder water tank having the dimensions shown in table 1. Thermophysical properties of lauric acid are included in table 2. The water is heated from 28°C to 80°C with the help of magnetic stirrer with a hot plate. The cylindrical water tank well insulated to prevent the heat losses from the outer surface of the container, thereby increases the energy capacity. For measuring temperature in a copper cylindrical tube at various points, PT100 used having temperature range -200°C to 850°C. The temperature measuring devices are placed as shown in Fig 1. Temperature controller with J type thermocouple is used having temperature range -210°C to 750°C and $\pm 1\%$ occur to measure the temperature of the water. The melting and solidification time of PCM have been taken with a regular interval of 600 seconds. The experimental uncertainties for the measurements of experiment parameters are shown in table 3.

**Table1.** The dimension of cylindrical containers.

Containers	Outer diameter (m)	Thickness (m)	Length(m)
Copper cylindrical tube	6.35×10^{-2}	1.64×10^{-3}	12.7×10^{-2}
Strain steel cylindrical container	15×10^{-2}	0.55×10^{-3}	17.5×10^{-2}

Table 2. Thermophysical properties of lauric acid PCM.

Properties	Lauric acid[14]
Melting temperature (°C)	41-44.2
Latent heat of fusion (J/kg)	177.4×10^3 - 211.6×10^3
Thermal conductivity (W/m-K)	0.139-0.192
Specific heat (J/kg-k)	1.76×10^3 - 2.14×10^3 (s) 2.15×10^3 - 2.27×10^3 (l)
Density (kg/m ³)	1007(s) 848-870(l)

Table 3. Measured Uncertainties.

Variable	Uncertainty value (%)
Time taken	±0.3
Mass of PCMs	±0.5
Mass of water	±0.6
Temperature	±0.2

3. Thermal performance evaluation of TES:

Energy storage rate for the predicted TES system can be defined by [9],

$$E = \int_0^t \dot{Q}(t) dt \quad (1)$$

$$\dot{Q}(t) = (\pi D) \int_0^l \left(k \frac{\partial T}{\partial r} \right)_{r=R} dz + (2\pi) \int_0^R \left(k \frac{\partial T}{\partial z} \right)_{z=l} r dr \quad (2)$$

Liquid fraction can be defined by [10],

$$f = \begin{cases} 0, & \text{if } T < T_s \\ \frac{T - T_s}{T_l - T_s}, & \text{if } T_s < T < T_l \\ 1, & \text{if } T > T_l \end{cases} \quad (3)$$

Fourier number can be defined by,

$$Fo = \alpha t (l^2)^{-1} \quad (4)$$

$$\text{where, } \alpha = k(\rho c_p)^{-1}$$

Rayleigh number can be defined by,

$$Ra = g\rho\beta l^3 (T_w - T_m)(\alpha\mu)^{-1} \quad (5)$$

Nusselt number of a predicted design TES can be defined by [20],

$$Nu = 0.59 \times Ra^{0.25}, \text{ if } Ra = 10^4 - 10^9 \quad (6)$$

$$Nu = 0.59 \times Ra^{0.33}, \text{ if } Ra = 10^{10} - 10^{13} \quad (7)$$

$$Nu = hl(k)^{-1} \quad (8)$$

where, h is heat transfer coefficient,

$$h = \dot{q}_s \{A (T_w - T_R)\}^{-1} \quad (9)$$

where, \dot{q}_s is heat transfer rate and $A = 2\pi r \times l$

4. Result and discussion:

The temperature at measuring points shown in Figs.2-5 during melting and solidification process. Fig.2-3 observed that variation in temperature in the radial direction of the tube is 6-8°C and in case of the axial direction of the tube is 1-2°C during the melting process. The temperature variation in the radial direction more than the axial direction because the radial direction is depending on both conduction and convection mode of heat transfer whereas in axial direction it depends only on natural convection resulting due to buoyancy force. It also observed that temperature at the axial points increased suddenly 10-12°C in time interval 4800-5400seconds. This is due to after 4800 seconds, PCM at the center melted and settled down suddenly. In Figs.4-5 observed that variation in temperature during the solidification process less in the axial direction than radial direction. The reason behind is solidification process occurred from the wall of the tube to axis of the tube. On the basis of variation in temperature, energy storage rate with axial height is also observed. Energy storage rate at 0.0846m axial height 8.012% greater than the energy rate at 0.0423m axial height. This is due to 7.91% increment in the thermal gradient in the radial direction at 0.0846m axial height than 0.0423m axial height.

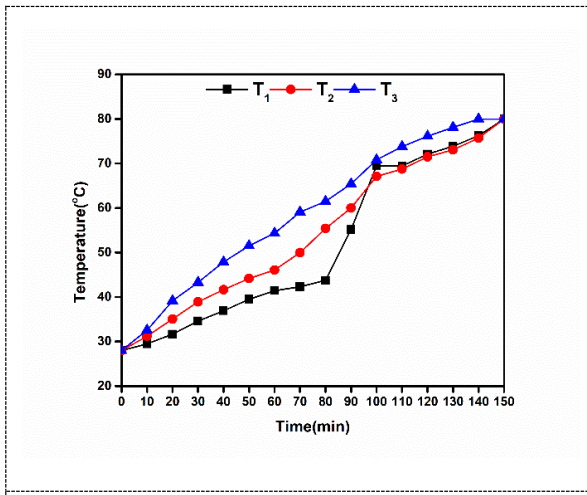


Figure 2.Charging profile at (l=42.3mm)

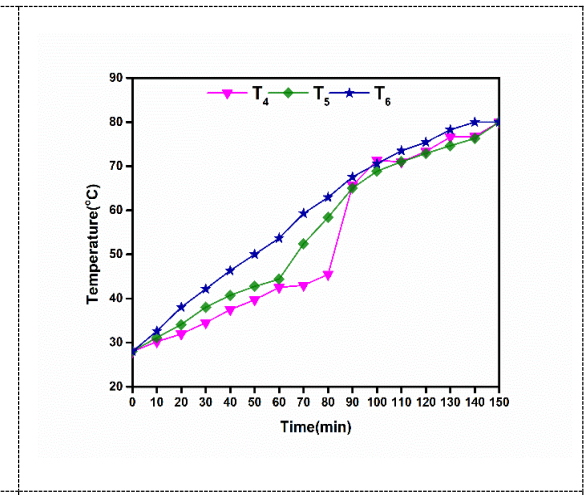


Figure 3.Charging profile at (l=84.6mm)

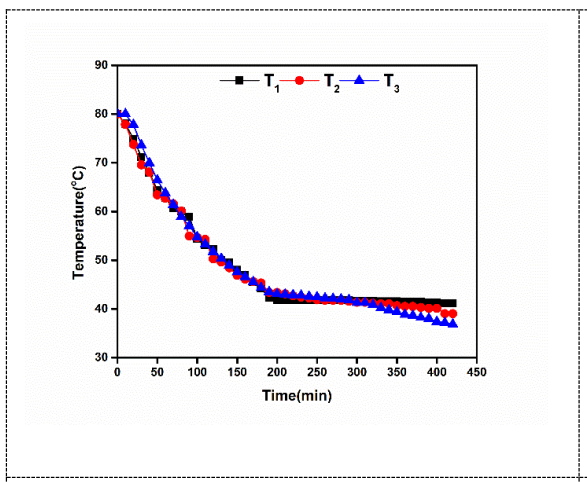


Figure 4. Discharging profile at (l=42.3mm)

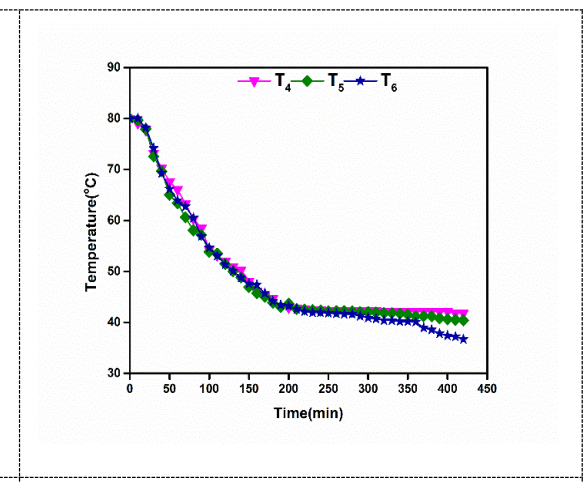


Figure 5. Discharging profile at (l=84.6mm)

Variation in a liquid fraction as shown in Fig.6. The liquid fraction is obtained with the help of photos which is taken during the experiment. It observed that the melting process started after 600 seconds and completed before 5400 seconds. Result conclude that 0.4kg of lauric acid PCM required 4800 seconds (approx.) for completion of the melting process in the predicted designed system. Variation in a liquid fraction with Fourier number is shown in Fig.7. With Fourier number increases from 0 to 0.028, liquid fraction also gradually increases from 0 to 1. Fourier number is used to the prediction of the temperature response of PCM undergoing transient conductive heating or cooling.

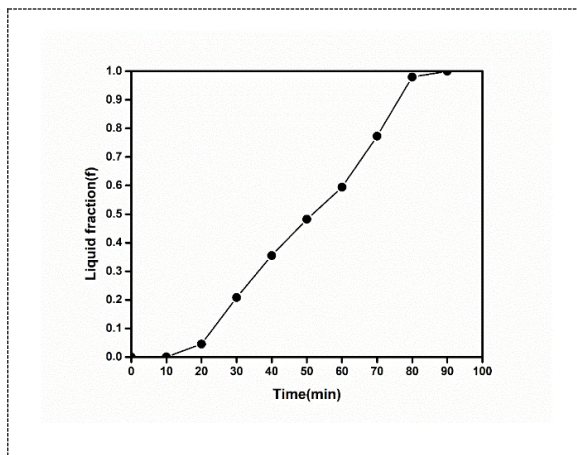


Figure 6. Variation in a liquid fraction with charging time.

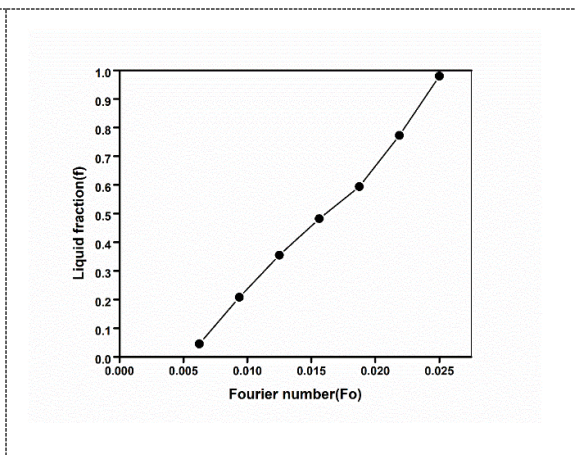


Figure 7. Variation in a liquid fraction with Fourier number.

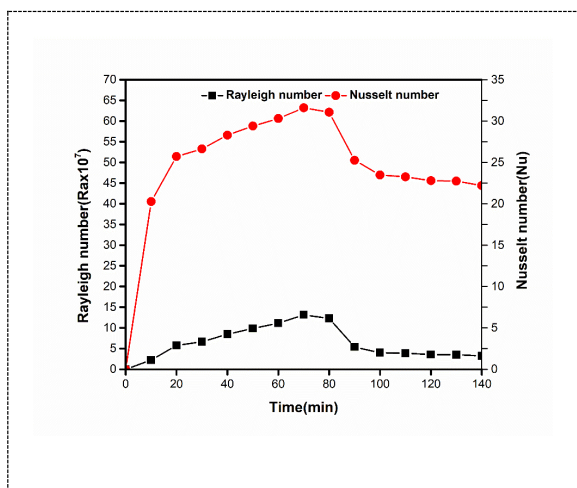


Figure 8. Variation in Rayleigh number and Nusselt number with charging time.

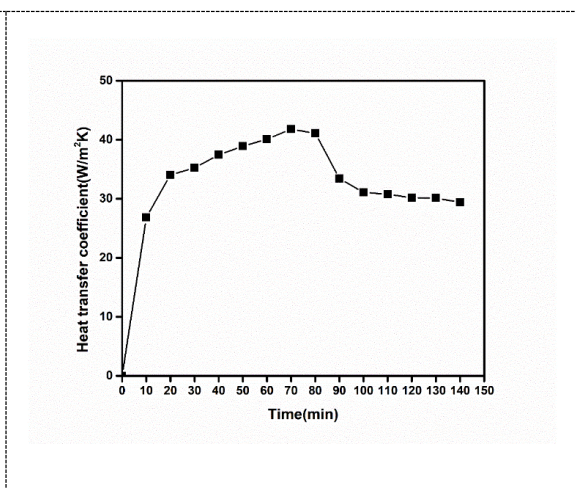
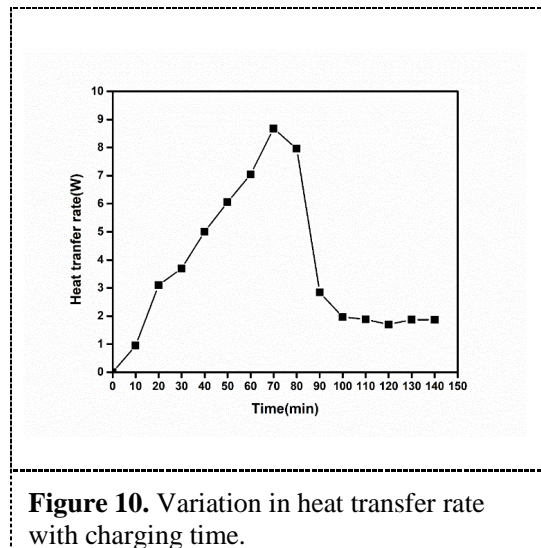


Figure 9. Variation in heat transfer coefficient with charging time.



Variation in Rayleigh number shown in Fig.8 and it was in the range of $0-10^7$ order, which justified that experiment is based on natural convection process. On the basis of Rayleigh number, observed variation in Nusselt number, heat transfer coefficient and a heat transfer rate that is shown in Figs. 8-10. It is noticed that Rayleigh number, Nusselt number, the heat transfer coefficient and heat transfer rate are having the highest performance for 0.4kg PCM based TES system at 4200 seconds of charging time. Within the time range of 4200-5400 seconds, heat transfer coefficient and heat transfer rate are decreased by 20.9% and 67.2% respectively during the melting process. This may be due to the completion of the melting process of PCM and after 4200 seconds, convection heat transfer mode dominated.

5. Conclusion:

Present experimental analysis on the TES system with lauric acid PCM concluded that in radial and axial directions the temperature variations ranges of 6-8°C and 1-2°C respectively for the designed cylindrical TES system. In the case of the solidification process, the variation in temperature in the axial direction is less compared to the radial direction. In designed TES system, for 0.4 kg of lauric acid PCM required 4800 seconds for the completion of the melting process. It is also observed that in the designed TES system, heat transfer coefficient and heat transfer rate both are decreased rapidly within a time range of 4200-5400 seconds. Due to the enhanced thermal performance of lauric acid PCM, it can be considered as the potential candidate for the TES system.

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NOMENCLATURE

A	Area(m ²)	T _R	Temperature of the PCM at the axis
cp	Specific heat capacity (J/kg.K)	T _s	Temperature of solid region of PCM(K)
D	Equivalent diameter(m)	T _w	Inner wall temperature(K)
f	Liquid fraction	Greek symbols	
g	Gravitational acceleration (m/s ²)	α	Thermal diffusivity(m ² /s)
k	Thermal conductivity(W/m-K)	ρ	Density(kg/m ³)
l	Height(m)	β	Expansion coefficient(1/K)
r	Radius of copper tube	μ	Dynamic viscosity(Pa.s)
t	Time(s)	Abbreviation	
T ₁	Temperature of liquid region of PCM(K)	PCM	Phase change material
T _m	Phase change temperature(K)	TES	Thermal energy storage