PERFORMANCE ENHANCEMENT IN LATENT HEAT THERMAL STORAGE SYSTEM USING PARAFFIN WAX: A REVIEW

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Abstract: In recent years, the energy conservation and environmental protection have become the most important issues for humanity. Phase change materials for thermal energy storage can solve the problem of energy and environment to certain problems. The latent heat storage system using the Phase Change Materials (PCM) can effectively store the thermal energy. PCM has the advantages of high storage density of storage process. The present work reviews the thermal energy storage using PCMs for different applications and also shows various methods for enhancing the thermal conductivity of PCMs. Further it is observed from previous studies that the latent heat energy storage system efficiency can be improved through various modifications in the system. The study have also been made with addition of fins with different configurations, by making different encapsulations for PCM and for different volume of storage materials.

IndexTerms: Phase change materials, Fin bifurcation, Triple concentric tube, encapsulations.

Introduction

Storage of thermal energy is very important in many engineering applications. Phase change materials (PCM) possess a great capacity of accumulation of energy in their temperature of fusion thanks to the latent heat. These materials are used in applications, where it is necessary to store energy due to the temporary phase shift between the offer and demand of thermal energy. The basic types of thermal energy storage techniques are described as sensible heat storage and latent heat storage. In sensible heat storage, the temperature of the storage material varies with the amount of energy stored for in solar heating systems water is used for heat storage in liquid-based systems. Alternatively, the thermal energy can be stored as latent heat in which energy is stored when a substance changes from one phase to another by either melting or freezing. The temperature of the substance will remain constant during phase change.

This review article deals with the volume-based system, organic phase change materials and inorganic phase change materials based system. This paper presents a review on these performance enhancement techniques in order to provide information on relative merits and demerits of the various possible enhancement techniques.

Yang Liu et al on their work on a novel heat transfer enhancement in a novel latent heat thermal storage equipment are observed that the Fig. 1 shows the schematic and 2D axisymmetric view of the basic and novel encapsulated cylindrical capsule containing a PCM. The LHS capsule absorbs and releases heat from and to the hot and cold heat transfer fluid in which the capsule is immersed. As both the capsule configurations are symmetric about the vertical axis, a 2D axisymmetric model is developed in the present study. A constant temperature heat and cold source is given at the boundary of the model to minimize the charging and discharging process that exists in the steam accumulator. During the charging cycle, heat is transferred from the hot boundary to the PCM through the encapsulation. PCM releases the stored heat due to the interaction with the cold boundary. Sodium nitrate and SS304 are selected as the PCM. Charging time of the LHS capsule is defined with respect to the temperature rise of the PCM. The LHS capsule is said to be fully charged when the entire PCM is melted. Discharging time of the LHS capsule is defined with respect to the temperature decrease of the PCM. The LHS capsule is said to be fully discharged when the entire PCM is solidified. Energy gets stored in the PCM in two forms during charging, viz. sensible and latent heat. Initially, when the PCM is in the solid state, the rate of SHS would be greater than the rate of LHS due to the higher temperature difference between the initial temperature and solidus temperature of the PCM. Once the PCM starts melting, the rate of LHS would become greater. In the following sections, validation and grid independent, results are obtained from the simulations of the basic and novel encapsulated LHS capsules during charging and discharging processes are presented. The parametric studies are carried out by fixing the initial average temperature of the PCM as 291/321 °C during the charging and discharging process. [1]

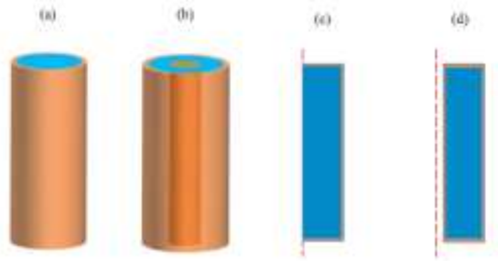


Fig.1Schematic of (a) basic and (b) novel capsules, 2D and symmetric view(c) basic and (d) novel capsules

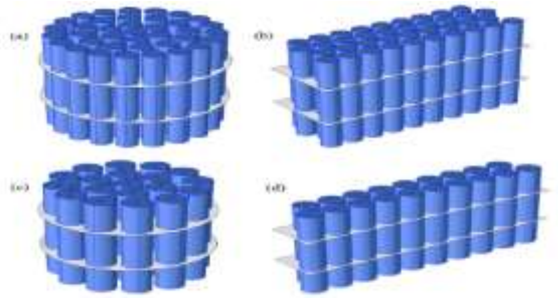


Fig.2 Volume occupancy of basic capsule in (a) circular and (b)rectangular arrangement and novel capsule in (c)circular and (d) rectangular arrangement

The model developed is based on a coupled conjugate heat transfer problem, which simultaneously solves the convective flow and phase change behavior of PCM. The biggest problem in the modeling of an LHS capsule is the incorporation of latent heat required to melt/solidify the PCM. This issue is solved by using the Effective heat capacity method, which includes both specific heat and latent heat of the PCM in a single term called EHC. Bonacina et al first developed the EHC [2] and Muthukumar et al, later used with slight improvements by several authors [3]. The heat capacity of the PCM is modified as shown in Eq. (1) and EHC is calculated using in Eq. (2).

$$C_p = \begin{cases} C_{p,s} \text{ for } T < T_s \\ C_{p,EEF} \text{ for } T_s \leq T \leq T_l \\ C_p, \perp \text{ for } T > T_l \end{cases} \quad (1)$$

$$C_{p,EEF} = \frac{C_{p,s}+C_{p,L}}{2} + \frac{L_f}{T_L - T_s} \quad (2)$$

Energy stored/discharged:

The energy stored and discharged rate can be calculated using the below equation,

$$E_s = m\left[C_p(T - T_{ini}) + L_f\theta\right]$$
$$E_d = m[C_p(T_{ini} - T) + L_f(1-\theta)]$$

PCM thermo physical measurement:

The thermal property analysis of the modified paraffin as PCM was conducted by using DSC 204HP differential scanning calorimetric in a temperature range 20-85ºC. The temperature increase rate was 1ºC/min with nitrogen protection. The melting process started at the temperature of 41.30ºC and ended at 44.74ºC with a latent heat of 170.4 J/g. in addition, the density of solid and liquid paraffin is 0.85g/cm3 and 0.78g/cm3, respectively, and the specific heat is 3.22kJ/kgK at the room temperature. The thermal conductivity is considered to be 0.21W/mºC for both solid and liquid phase

In this work they compared the basic and novel system, the novel volume is reduced by 1.8% of the basic volume. And the charging and discharging time is reduced due to the surface area available for the heat transfer. In this setup, the both basic and novel are compared for the charging time reduction is 48.4% as compared to the basic setup. And the discharging reduction is 63.9% as compared to the basic system. Advantage using novel system:

(i) Better storage performance while up scaling the LHS capacity.
(ii) Effective space utilization with less volume occupancy.
(iii) Lesser encapsulation shell cost/mass with reduced capsule material.

Alvaro et al worked on finned plate latent heat thermal energy storage system for the domestic application. In this system, a conventional hot water storage tank is presented and compared with a specific design of the presented LHTES system. First, the hot water storage tank is described and secondly, the proposed system is detailed. For the analysis a constant temperature of 65ºC is selected for the charging and 50ºC for the discharging. These temperature levels are typical for domestic heating applications. The purpose of the work is to reduce the volume of conventional to current setup [4].

There is an implicit need for optimizing the design of different Latent Heat Thermal Energy Storage (LHTES) configurations. Dutil et al had decided that the Mathematical modeling is the best approach for applying any optimization method to the design of these systems, and a wide number of modeling approaches have been used for the simulation of LHTES systems of different nature[5]. There is various solution has been including exact analytical solutions [6], numerical methods [7], simplified analytical approaches [8] and simplified numerical methods [9]. PCM RT60ºC temperature range 53-61ºC. The current setup volume is reduced to half of it conventional volume. The current system is more efficient than the conventional system, volume, heat loses.

Fig.3 2D view of a generic LHTES consisting of 12 finned plate

Note The modified model is more cost compared to the conventional storage system because of the raw materials (aluminum).

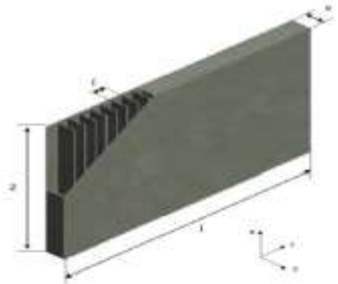


Fig.4 3D view of a single finned plate

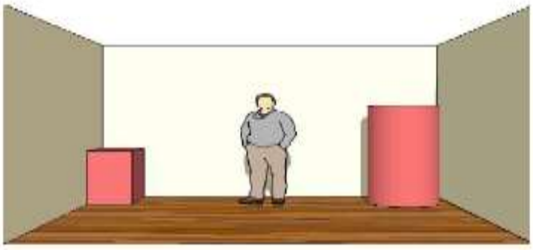


Fig.5 Spatial view of both system

This work proves that, the more compact thermal storage systems can get using the benefits of the PCM. The result of the LHTES system presents the very suitable alternative to conventional hot water tanks, especially when there is lack of space. The costs of LHTES should be still reduced to be economically competitive. This could be achieved using cheaper PCM.

Gagliardi et al had worked in the performance of a PCM latent heat storage system with innovative fins. He was compared and analyzed three different shapes of set up, the results shows that optimized fins bring a significant improvement in the performance of the system. An increase of 24% in the system efficiency is achieved using optimized fins with two bifurcations. The results also indicates an interesting aspect, the optimal fin shape depends on the considered operating time of the LHTES unit. This is a significant result and clearly shows that optimization methods should properly advance to effectively account transient behavior, and the graphical abstract is given below,

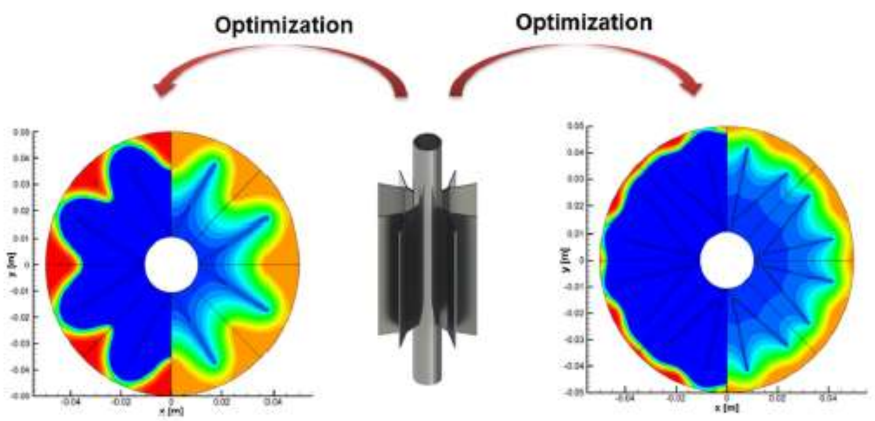


Fig.6 Graphical abstract

Mathematical modeling and numerical approach. In the present analysis the solidification of PCM in the unit is investigated using the following form of the energy equation:

$$\partial/\partial t\ (\rho h)=\nabla.(k\nabla T)$$

Where q and k are respectively the density and the thermal conductivity of the PCM. Specific enthalpy h of the PCM is formulated according to the enthalpy method:

$$h=h_{ref}+\int_{Tref}^{T} Cpdt + \gamma L$$

Gagliardi et al compared the initial model, single bifurcation and double bifurcation. The changes in the setup are modified from the initial setup. By comparing the three system the discharge efficiency is increased in the double bifurcation. The result is given below by the chart, by comparing the three set up the double bifurcation gives the gives the better performance [10].The effect of natural convection in the liquid PCM is neglected, thus the continuity and momentum equations are not necessary. Jegadheeswaran et al said the solidification process is dominated by heat conduction [11] and Kuravi et al said natural convection is present only at the beginning of the process. Thus, buoyancy can be neglected as pointed out [12]. Consequently, the analysis can be carried out considering just a transversal 2D cross-section of the unit is shown in the below figure.

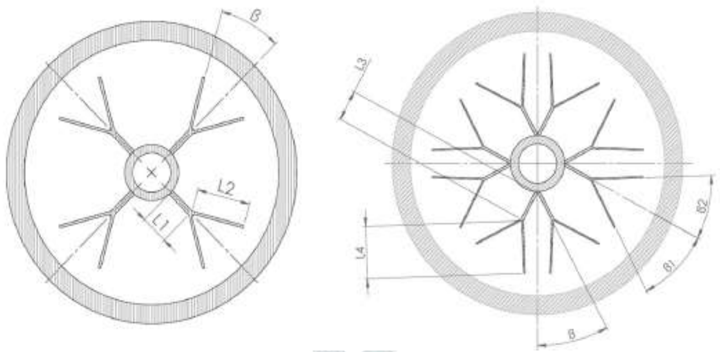


Fig.7 Fin configuration. (Left) single bifurcation (right) double bifurcation

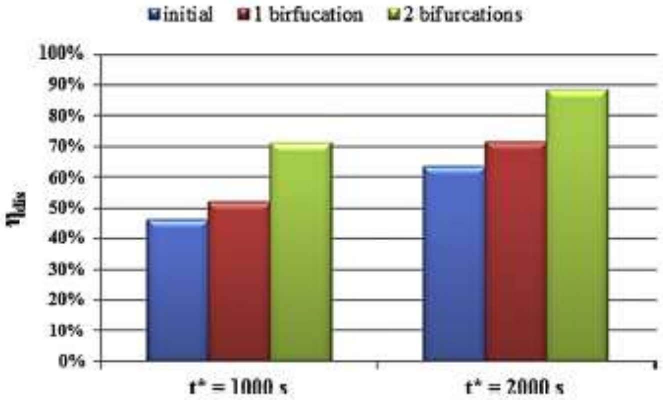
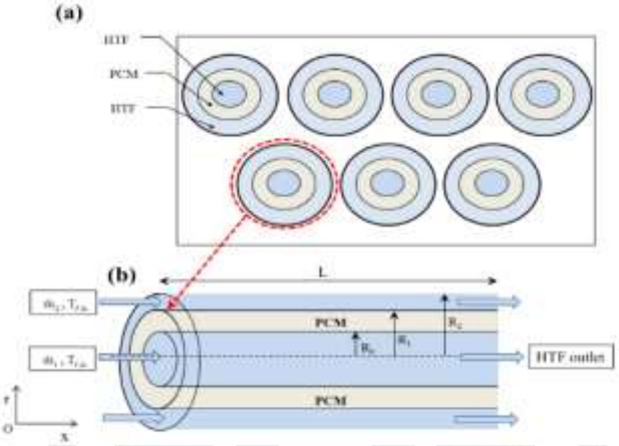


Fig.8 Discharge efficiency for the various designs

The results indicate that optimal tree shaped fins brings substantial performance improvements. The discharge efficiency increases of about 24% when optimal fins with two bifurcations are used.

Radouane et al worked on Thermal performance analysis of combined solar collector with triple concentric-tube latent heat storage systems. It consists of a flat-plate solar collector connected with a storage unit containing seven horizontally packed triple concentric-tube storage systems, as shown in Fig. 9 a. The HTF flows both in the inner and the outer tubes of the triple concentric-tube storage systems. During the charging process, the HTF heated in the solar collector flows through the storage unit and transfers solar thermal energy to PCM which stores it as latent thermal energy. As the triple concentric-tube storage systems composing the storage unit are similar, the computational domain can be represented by a triple concentric-tube storage system as shown in Fig. 9 b. The HTF and the commercially available kind of PCM used in the present study are water and RT50, respectively. In this work the double and triple concentric-tube latent heat storage systems [13].

Bechiri et al had researched in the double concentric-tube heat exchangers incorporating PCM have been widely researched during the last three decades. The research efforts include analytical [14], Elbahjaoui et al at numerical [15] and Gasia et al at experimental [16] approaches. Vyshak et al worked in double concentric-tube latent heat storage systems are known for their higher storage performance compared to other configurations of storage systems [17], most PCMs have low thermal conductivity, which significantly limits the heat transfer rate and delays the charging process. Elbahjaoui et al worked in order to overcome this disadvantage and accelerate the melting rate of PCM, several techniques have been proposed in the literature, including the dispersion of high conductive nanoparticles in PCM. [18], Jourabian et al had an insertion of the porous matrix into PCM [19], and Rabienataj Darzi et al had used the fins. [20]. Apart from these techniques which reduce the amount of base PCM in the storage system, Abdulateef et al the enhance in the heat exchange surface between PCM and HTF through the use of triple concentric-tube latent heat storage systems has recently received a significant attention [21].In this set of the current numerical model was compared with that obtained by the in this system seven horizontally parallel triple concentrictube is used.



The Fig.9 (A) shows the triple concentric-tube latent heat storage systems. Fig.9 Schematic representation of (a) the complete storage unit and (b) the triple concentric tube storage system

The Fig.9 (A) shows the triple concentric-tube latent heat storage systems. This setup is compared with the other to set up. By using the triple concentric-tube System the efficiency is more compared to the other two systems. In this system seven horizontally parallel triple concentric tube is used. This set up the Inner Diameter of 2cm, Middle Diameter of 14.4cm, Outer Diameter of 15.5cm, Length is 1m and the Area of collector 2m^2 and the Medium of fluid is water and the PCM used as RT50 (a type of wax & organic PCM). The PCM begins to melt much earlier in the double concentric- tube storage unit than in the triple concentric-tube storage unit. During the whole charging period, the temperature of HTF at the outlet of the triple concentric-tube storage unit is much lower than that of the double concentric-tube storage unit. The flat-plate solar collector combined with the triple concentric-tube storage unit has higher instantaneous and average collection efficiencies than that connected with the double concentric-tube storage unit. The triple concentric-tube storage unit stored much higher solar thermal energy by sensible and latent heats than the double concentric-tube storage unit. Furthermore, the triple concentric-tube storage unit has higher final sensible and latent storage efficiencies.

Shilei et al have worked on the performance of heat storage and heat release of water storage tank with PCM. In this work, they have compared the two setups of the module package. In the one setup only four module package with two different PCM. In the other setup, eight module package is used. The second setup have also used two type of PCM. The first figure show the two different type of design module, and the second figure show the module package [22].

Fig.10 The three dimensional profile of PCM storage tank

1. Heat storage entrance, 2.Heat release outlet 3.communication port 4. High melting point PCM module, 5.Heat storage channel, 6.Low melting point PCM module, 7.Heat storage outlet, 8.Heat release entrance.

When studying the thermal performance of the storage tank, in order to reduce heat loss the outer wall of the tank should be installed insulation layer. During the experiment, the outside of the tank could be surrounded by 50 mm thick polyurethane foam insulation to minimize heat penetration. Mehling et al have been insulated the tank with two different insulating materials, to reduce the heat loss factor [23]. Therefore, in the design of the experiment with reference to the above ideas, the water tank is surrounded insulating material also that the outer wall of the tank is approximately insulated. In the simulation, the new water tank and the common water tank are assumed to be insulated the outer wall, to ensure the consistency of simulation and experiment. According to the relevant standard requirements [24], the temperature of the domestic hot water should be controlled at 55ºC to 60ºC, the water temperature should not be less than 45ºC for the homes with hot water supply systems. The inlet hot water temperature is 70ºC and the flow rate is 5 L/min. By comparing the two setup both the two PCM, the four module with the setup gives the better result. For both the PCM.

The results show that $CH_3COONa·3H_2O$ (Sodium Acetate Trihydrate) has a large volume of heat storage per unit volume and a more obvious reheat effect on the cold water in the tank, the reheat effect of $C_{12}H_{24}O_2$ (Lauric acid) on cold water is small. The combination of the two PCMs could extend the exothermic time to improve the use of heat storage tank performance.

Fig.11 PCM package module

The increase in the amount of PCM has a significant effect on the heat release of the tank. Under the conditions which are the heat storage temperature of 70ºC, and the taking heat is 45ºC, and the flow rate is 5L/min, the PCM accounting for 11.12% and19.17% of the tank volume would make the heat release increased by 24.82%and 34.05%.

Yang et al have worked on the heat transfer enhancement in a novel Latent heat thermal storage equipment. In this work they were compared two different phase change material.one is paraffin wax and another one is modified paraffin wax. Thermal energy storage (TES) plays a crucial role in practical applications of the renewable energy [25]. Zalba et al and Eames et al had said that the TES can be generally classified into sensible heat storage, latent heat storage and chemical heat storage [26,27]. However, most available low-temperature PCMs like paraffin and hydrated salts suffer from the general drawback of low conductivity of approximately 0.2 W/m K and 0.5 W/mK, respectively. Zalba et al are worked in the limited thermal conductivity not only decreases the heat transfer rate but also prolongs the duration time of heat storage and release [28]. The melting process started at the temperature of 41.30°C and ended at 44.74 °C with a latent heat of 170.4 J/g. In addition, the density of solid and liquid paraffin is 0.85 g/cm3 and 0.78 g/cm3, respectively, and the specific heat is 3.22 kJ/kg °C at the room temperature shown in Fig 12

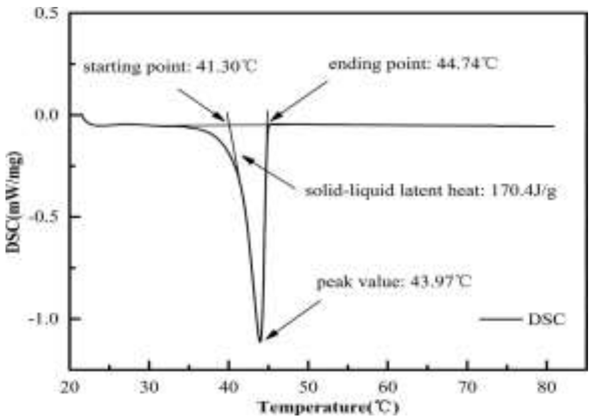


Fig.12 DSC of the modified paraffin with scan rate of 1°C/min

Cui et al and Yang et al said it has a number of merits such as large heat storage capacity, high heat storage rate, controllable heat dissipation rate, independent heat storage units, integrity, compactness, flexibility etc., compared with other works [29,30]. The schematic illustration of the experimental apparatus which was set up to experimentally investigate the thermal performance of the LHTES equipment. The system mainly consists of a thermostatic heating bath, circulating pump and pipeline system, test section and data acquisition system. The circulating water was heated by a thermostatic heating bath at the constant temperature above the melting point. The flow-rate was measured by an electronic flow meter. The HTF flowed through each unit in parallel at overall flow-rate of 0.60 kg/s. Fig 13 shows the schematic diagram of HSU.

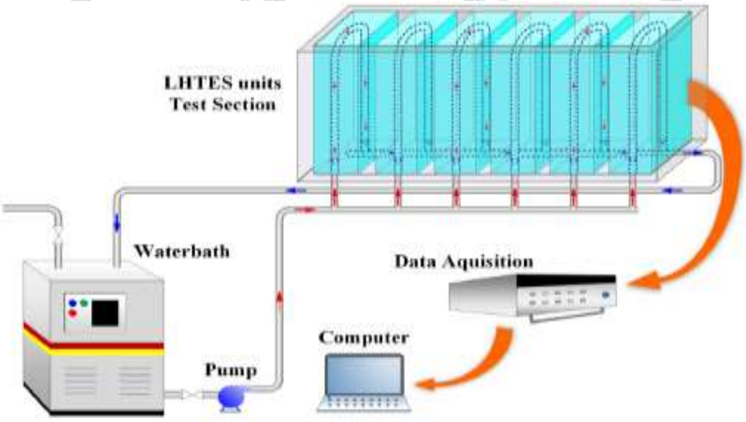


Fig.13 Schematic configuration of the experimental apparatus

And fig 14 shows Schematic illustration of (a) the HSU with composite PCM and (b) thermocouple distribution dimension unit: mm.

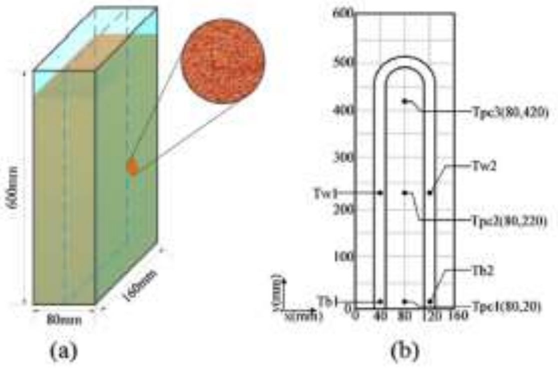


Fig.14Schematic illustration of (a) the HSU with composite PCM and (b) thermocouple distribution dimension unit: mm.

Martinelli et al and Ibrahim et al, had research for the phase change composite of the PCM and the copper foam, the well-known Thermal Equilibrium Model was adopted in present study as given in other literatures [31,32]. As per Agyenim et al, the thermal energy storage capacity in the HSU is contributed both by PCM and copper foam separately and can be calculated [33]. The Fig.15 shows the Temperature evolution of composite PCM during discharging process.

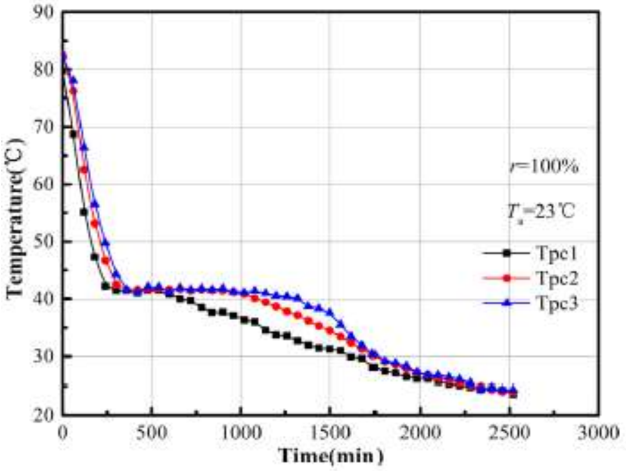


Fig.15 Temperature evolution of composite PCM during discharging process.

Compared with the HSU with PCM only, the effect of adding copper foam in the HSU on thermal performances were notable in the Conditions of low inlet HTF temperature during charging process high ambient temperature and opening ratio of 100% during discharging process. The U-tube rectangular HSU with composite PCM showed good heat transfer performance during the heat storage and dissipation processes. The heat storage capacity and heat storage rate reached 1907.1 kJ and 198.7 W, respectively, at an HTF temperature of 85 °C. Moreover, the dissipation rate of 13.3W was achieved at 100% opening ratio and the ambient temperature of 23°C in natural convection mode. Increased HTF inlet temperature expedited the heat transfer rate in the unit and shortened the storage time duration during the charging process. For the HSU filled with composite PCM, the heat storage time was reduced from 220 mins to 160 mins and the heat storage rate increased from 118.4W to 198.7W when the inlet temperature changed from 65 °C to 85 °C. More uniform temperature distributions were obtained in the HSU with composite PCM than the HSU with PCM only due to the enhancement of thermal conductivity by copper foam.

Robynne et al have worked on a Latent Heat Energy Storage System Coupled with a Domestic Hot Water Solar Thermal System. In this work on the outline the initial steps in the development of an SDHW energy storage system using PCM, with emphasis on the numerical and experimental studies used to access the phase change and thermal behavior of the selected PCM. Lauric acid was selected as the PCM based on the melting temperature range which was targeted by studying solar data from an existing solar hot water system in Halifax, Nova Scotia, Canada [34]. Due to the low thermal conductivity of PCMs, additional work is required to develop and validate a design to enhance heat transfer to the storage material using fins.

Agyenium et al is worked in the solar thermal energy for domestic hot water heating are one of the most cost-effective and efficient areas of alternative energy exploitation. The use of phase change materials (PCMs) in latent heat energy storage systems (LHESS) can reduce the volume and weight of storage due to their high storage density, and overcome major obstacles in the further deployment of solar thermal energy [35]. As per Fernandez et al LESS have high energy densities compared with sensible heat storage systems [36], and A. Sharma et al said that have been shown to store up to 14 times more heat per unit volume than sensible heat storage materials [37]. Fig 16 shows the schematic diagram of LHSS for Solar domestic hot water. Qarnia et al are performed in the energy storage using PCMs in combination with solar collectors have been studied mathematically [38] and Kaygusuz et al by experimentally.

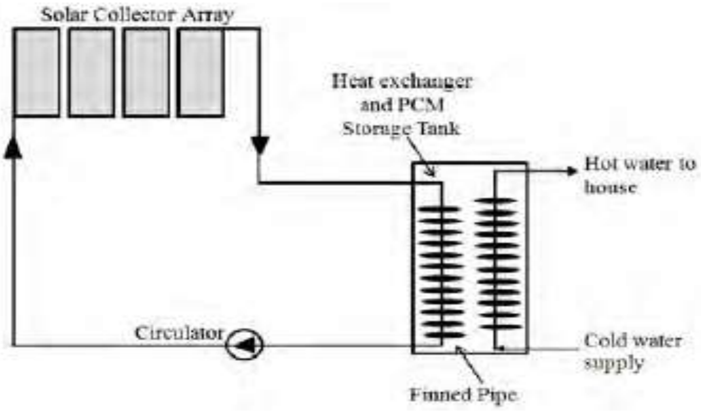


Fig.16 Schematic diagram of LHSS for Solar domestic hot water

The PCM is selected based on its phase change temperature range and the operating temperatures of the SDHW system. A melting temperature range of 42ºC to 48°C and solidification temperature range of 35 to 40ºC were targeted by studying the solar data from an existing SDHW system in Halifax, Canada, Rekstad et al have been researched in the Salt hydrates (e.g. Glauber's salt and sodium acetate) tested in the DSC showed significant supercooling, which is a common and undesirable phenomenon for these materials [39]. The experimental setup used to study the melting and solidification behavior of lauric acid in a cylindrical container with horizontal copper fins is shown schematically in Fig. 17a. Experimental setup to study phase change behaviour. Fig. 17b PCM container.

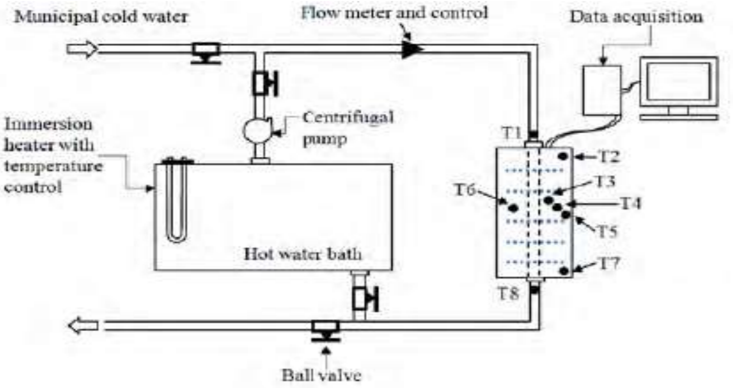


Fig.17 (a) Experimental setup to study phase change behaviour

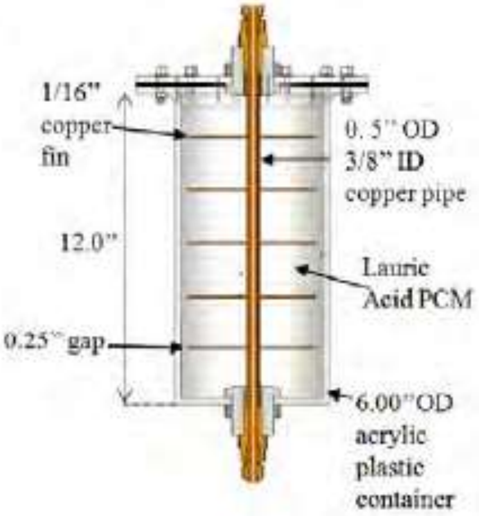


Fig.17 (b) PCM container

Ogoh's et al had a method of numerically modeling for the melting process [41]. The simulated time of melting was 11.5 hours, and 10 hours for cooling. It's took approximately 8 hours to run. Figure 18 presents the temperatures measured experimentally by thermocouples T1 to T8 during the charging process.

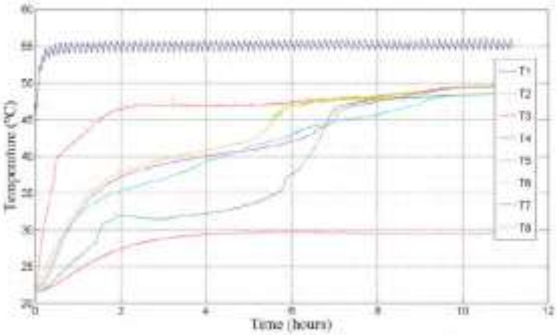


Fig.18 Temperatures measured experimentally by thermocouples T1 to T8 during the charging process.

The region in the upper corner of the container experiences a fast increase in temperature (T2) after 6 hours, mainly due to the onset of natural convection in this region. The lauric acid does not reach the melting temperature in the bottom corner (T7).

Figure 19 shows the numerically obtained temperatures in the system during charging. The black contour line represents the melting interface.

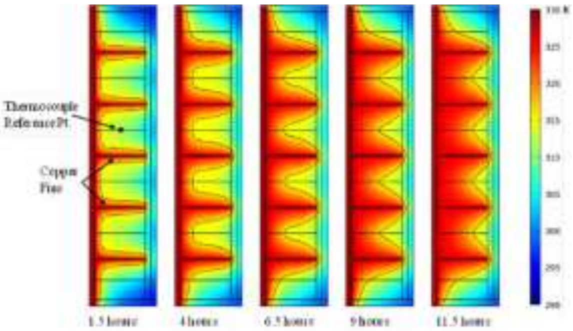


Fig.19 Numerically obtained temperatures in the system during charging.

The melting and solidification behavior of lauric acid inside a cylindrical container with a horizontal finned pipe was examined experimentally and numerically. Results for the charging experiment, when compared to the numerical simulations, clearly showed that a mushy region appeared in the system. The presence of natural convection in the liquid melt played a significant role in speeding up the heat transfer and melting process.

Conclusion

The paper has reviewed the various performance enhancement techniques on LHESS with paraffin wax. A comprehensive review on the synthesis, characterization, and property of PCM with paraffin wax as the base PCM has been made, and the following conclusion were drawn,

- In the encapsulation, basic model is compared to the novel capsules model. The novel basic system gives more efficiency by reducing the charging and discharging time 48.4% and 63.9%.
- Addition of rectangular fins in the latent heat energy storage system reduced the volume by 50%. When compared to the conventional setup.
- The fin configuration results indicate that optimal tree shaped fins brings substantial performance improvements, the discharge efficiency increases of about 24% when optimal fins with two bifurcation are used.
- Experiment were done on single, double and triple concentric-tube energy storage system to compare their performance. The triple concentric-tube storage unit stored much higher thermal energy by latent heat than the double concentric-tube storage unit.
- Addition of two PCMs (Sodium Acetate Trihydrate and Luaric acid) in two different storage tank, the heat release from the water is increased by 24.82% and 34.05%.
- Novel latent heat thermal storage equipment is filled with composite PCM, by increasing the inlet heat transfer fluid temperature the heat storage time is reduced to 27.27% and the heat transfer rate increased by 67.8%.

Nomenclature

c_p	Specific heat, $Jkg^{-1}\ K^{-1}$
T	Temperature, ◦C
S	Source term, Nm^{-1}
E_s	Total energy stored, J
E_d	Total energy discharged, J
L_f	Latent heat of fusion, $J\ kg^{-1}$

Greek Symbols

θ	Melt fraction

Symbols

∇	Differential operator

Abbreviations

PCM	Phase Change Material
EHC	Effective Heat Capacity
LHS	Latent Heat Storage
DSC	Differential Scanning Calorimeter
LHTES	Latent Heat Thermal Energy Storage System
RT60	Reverberation Time

HTF	Heat Transfer Fluid
TES	Thermal Energy Storage
HSU	Hype Static Union
SDHW	Solar Domestic Hot Water
LHESS	Latent Heat Energy Storage System

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