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# A Review - An Optimization of Macro-encapsulated Paraffin used in Solar Latent Heat Storage Unit

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***Abstract* - Solar thermal is an alternative energy conversion process. There is a wide application of solar thermal energy in our domestic life and industrial area. The design and development of latent heat energy storage unit, as part of a complete latent heat storage system to provide an optimum tuning between heat demand and heat supply, is of vital importance, and one of the greatest efforts in thermal solar energy research. The storage of latent heat energy using phase change materials (PCM's) is an effective way of storing thermal energy due to their high energy storage density and the isothermal nature of the storage process. Paraffin is one of various PCM's which is used to absorb heat from the heat transfer fluid (HTF) during the charging process and release it again during the discharge process. The conduction and convection criterion of heat transfer enable the paraffin to store this heat as latent heat.**

**Macro-encapsulation comprises the inclusion of PCM's such as paraffin in some form of package such as tubes, pouches, spheres, panels or other receptacle. These containers can serve directly as heat exchangers or they can be incorporated in building products.**

**An inserting of metal foam can improve the equivalent thermal conductivity of a foam-paraffin wax composite and reduced the time required to melt, also enhanced the temperature gradients in TESS while melting and solidification. An addition of metal foam to both PCM (paraffin) and HTF sides can lead to increase heat transfer of HTF during cooling as it is during the heating. By dispersion of metal powders and ceramic particles in macro-encapsulated paraffin can be improved the thermal conductivity and thus can overcome the poor rate of heat transfer in the thermal energy storage system, also the performance of paraffin like charging and discharging time and the melting process are improved. By an optimized materials selection and designing of macro-capsules (tubes, spheres, balls, etc.) can be improved the heat conductivity during melting and solidification processes, the inner surface between paraffin and HTF and thus the efficiency of the storage unit.**

***Keywords—Solar latent heat, Paraffin, Macro-encapsulation of Paraffin, Metal foams, Ceramic particles***

## 1. INTRODUCTION

Due to the environmental context and to reduce dependence on fossil fuels and thus to reduce carbon footprint, new efficient and economical technologies for thermal energy storage (TES) in a definite volume appear as the subject of research for long time. The storage unit is required because of the non-constant nature of solar energy, thus, an optimization of efficient energy storage materials will directly influence the utilization efficiency of solar thermal energy storage systems.

Thermal energy storage is achieved by increasing the internal energy of a material as sensible heat, latent heat, and thermo-chemical heat, or combination of these (figure 1.1). Sensible heat storage system uses the specific heat capacity of the substance and the temperature of a material. Temperature of the substance increases during charging and decreases during discharging. Latent heat storage (LHS) is based on absorption or liberation of heat when a storage material undergoes a phase change. Thermo-chemical systems refer to the energy absorption and energy release in breaking and reforming molecular bonds in a completely reversible chemical reaction.

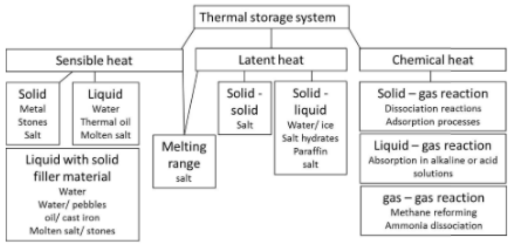


Fig. 1.1: Classification of heat storage media [1]

Phase change materials (PCM's) attract attention as thermal energy storage materials because their energy densities are much higher than those using sensible heat. The idea to use phase change materials for the purpose of storing thermal energy is to make use of the latent heat of a phase change, usually between the solid and the liquid state. Since a phase change involves a large amount of latent energy at small temperature changes, PCMs are used for storing heat with large energy densities in combination with rather small temperature changes.

On one hand, the successful usage of PCMs (Paraffin) is a high energy storage density, but on the other hand it is very important to be able to charge and discharge the energy storage with a thermal power, that is suitable for the desired application.

The low thermal conductivity of Paraffin used as PCMs is the major drawback of latent thermal energy storage. It limits the power that can be extracted from the thermal energy storage. To overcome this problem, extension of the heat transfer area and enhancement of the thermal conductivity using some techniques like additive injection, inserting of metal foams, dispersion of ceramic nanoparticles, special containment for Paraffin and so on may be useful.

*1.1. Solar Heat Energy*

Solar energy refers to the conversion of the sun's rays into useful forms of energy. These forms of energy can be electrical, chemical, mechanical or thermal energy. Thermal energy storage systems are classified into three kinds (Figure 1.2):

1. Sensible heat storage which is based on storing thermal energy by heating or cooling a liquid or solid storage medium.
2. Latent heat storage which refers to a heat storage system that uses the energy absorbed or released during a change in phase (e.g. a solid melting to liquid) , without changing temperature (isothermal).
3. Thermo-chemical storage in which chemical reactions are used to store
   and release thermal energy [2-3]

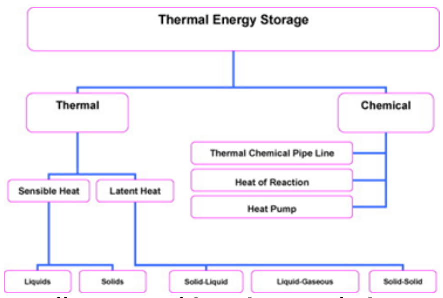


Fig. 1.2: Different types of thermal storage of solar energy [2].

In the last decade, the thermal energy storage (TES) by solar power has become a popular research topic. An optimization of efficient energy storage materials will directly influence the utilization efficiency of solar thermal energy storage systems by an adjustment of the temporal mismatches between the load and the intermittent or variable energy source. An optimization of efficient and cost effective thermal energy storage systems is necessary for the utilization of solar energy.

*1.2. Latent Heat Storage Materials (PCM's)*

A latent heat storage refers to a heat storage system that uses the energy absorbed or released during a phase transition, without a change in temperature (isothermal). Phase change materials have high heats of fusion, which melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Temperature of PCM remains constant during the phase change, which is useful for keeping the subject at a uniform temperature. Heat is absorbed or released when the material changes from solid to liquid and vice versa, for that, these materials are classified as latent heat storage (LHS) units. The heating and cooling effect of PCM's is represented in figure (1.3).

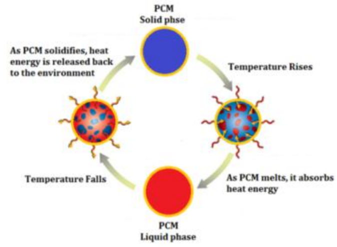


Fig. 1.3: The heating and cooling effect of PCM's (4)

PCMs can be classified into (organic, inorganic and eutectic), which can be identified as PCMs from the point of view melting temperature and latent heat of fusion. Figure (1.4) shows a classification of latent heat storage materials.

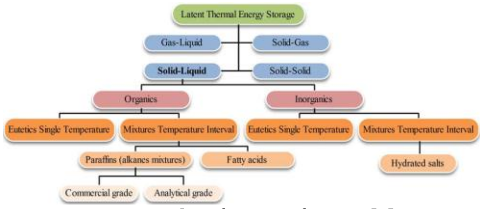


Fig. 1.4: Classification of PCMs [5]

The storage capacity of the phase change materials is equal to the phase change enthalpy at the phase change temperature + sensible heat stored over the whole temperature range of the storage (Figure 1.5).

The PCM continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase.

When the ambient temperature around a liquid material falls, the PCM solidifies, releasing its stored latent heat.

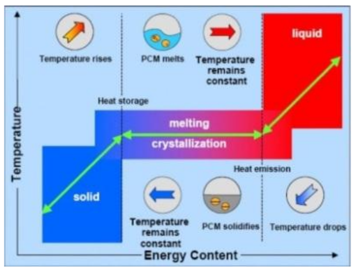


Fig. 1.5: Temperature vs energy storage for PCMs [6]

There are a large number of organic and inorganic chemical materials, which can be abbreviated as PCM from the point of view melting temperature and latent heat of fusion (fig. 1.6). A large number of PCM's are available in any required temperature range from −5 up to 190 $^{0}$C [7-8].

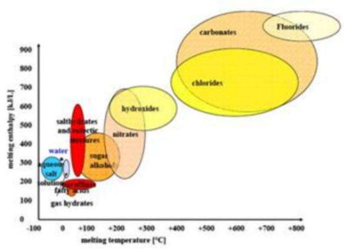


Fig. 1.6: Melting enthalpy of various phase change material groups in relation to their melting temperature [9].

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An ideal PCM must be characterized by a suitable phase change temperature and a large melting enthalpy. These features have to be fulfilled in order to store and release heat at all. However, there are more requirements for most, but not all applications. These requirements can be classified into physical, technical, and economic requirements [10-5-11].

- Physical requirements which refers to the storage and release of heat:
  - Suitable phase change temperature.
  - Large phase change enthalpy.
  - Reproducible phase change, also called cycling stability.
  - Little supercooling.
  - Good thermal conductivity.
- Technical requirements which refers to the construction of a storage:
  - Low vapor pressure.
  - Small volume change.
  - Chemical stability of the PCM.
  - Compatibility of the PCM with other materials.
  - Safety constraints.
- Economic requirements which refers to the development of a marketable product:
  - Low price.
  - Good recyclability.

PCM's can also be included in containers of different shapes and sizes. There are three possibilities to integration of phase change materials into thermal energy system [9], as shown in figure (1.7):

a. PCM Micro– encapsulation.
b. PCM Macro– encapsulation.
c. PCM in tank, immersed heat exchanger (bulk storage).

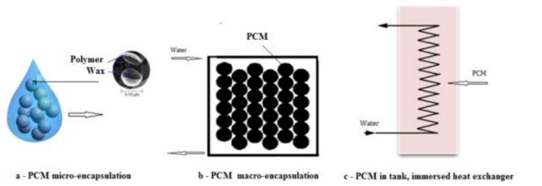



Fig. 1.7: Integration of phase change materials into (TES), [12].

### *1.2.1. Paraffins*

Paraffins are an organic materials, which include congruent melting means melt and freeze repeatedly without phase segregation and consequent degradation of their latent heat of fusion, self-nucleation means they crystallize with little or no supercooling [13].

Paraffins are used for thermal storage as latent heat with high volumetric energy densities and characterized by several advantages: Chemical and thermal stability, Suffer little or no supercooling, non-corrosives, non-toxic, high heat of fusion and low vapour pressure, but on the other hand it has some disadvantages which are: low thermal conductivity, high changes in volumes on phase change, inflammability, lower phase change enthalpy [14-15].

The normal paraffins of type $CnH_{2n+2}$ are a family of saturated hydrocarbons with very similar properties. Paraffins between $C_5$ and $C_{15}$ are liquids, and the rest are waxy solids. Paraffin wax is the most-used commercial organic heat storage PCM. It consists of mainly straight chain hydrocarbons that have melting temperatures ranging from 23 to 67 $^{O}$C [16].

Paraffin wax typically contains primarily linear alkanes in the C20 to C40 range. It is microcrystalline, hard, brittle, and has a low affinity for oil. It melts in the range of 46-68 $^{O}$C [17].

Thermal conductivity of the candidate PCM composite is of utmost importance to system performance, particularly when using low conductivity paraffin –based PCM`s. Heat storage rate as well as material charge and recharge dependent on thermal conductivity.

The ability of a material to absorb and release energy determines the activeness of the PCM and the TES system as a whole [18].

For improvement of charging and discharging processes of the storage, two parameters have to be optimized, which are:

1. The inner surface between the heat transfer medium and the PCM.
2. The thermal conductivity of the PCM during melting and solidification processes [19].

## 2. ENCAPSULATION OF PCM's

There are two types of PCM-encapsulation: micro-encapsulation and macro-encapsulation. Encapsulation serves as heat transfer surface, prevents PCM from reacting with outside environment, and adds mechanical strength to the structure.

Micro-encapsulation is the process by which individual particles or droplets of solid or liquid material (the core) are surrounded or coated with a continuous film of polymeric material (the shell) to produce capsules in 1 μm to millimeter diameter range, known as microcapsules [20,21]. A large improvement in the heat transfer rate was obtained by encapsulating the PCM in small plastic spheres to form a packed bed storage unit figure (2.1). However, the expected high pressure drop through the initial cost may be major drawbacks of such units [22].

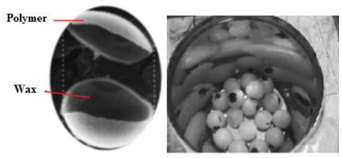



Fig. 2.1: PCM Microcapsule [8,5]

According to the core material and the deposition process of the shell, the morphology of microcapsules can be described and classified into three types as shown in figure (2.2) [23]:

1- Mononuclear (core-shell) microcapsules contain the shell around the core.
2- Polynuclear capsules have many cores enclosed within the shell.
3- Matrix encapsulation in which the core material is distributed homogeneously into the shell material.

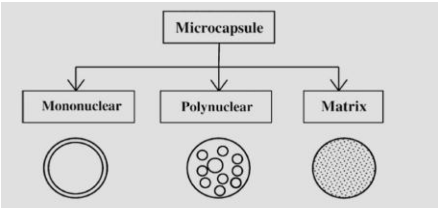



Fig. 2.2: Morphology of Microcapsules

Macro-encapsulation means filling the PCM in a macroscopic containment that fit amounts from several ml up to several liters. These are often containers and bags made of metal or plastic [20]. The advantage of the macro-encapsulation is that the possibility to apply with both liquid and air as heat transfer fluids and easier to ship and handle [22].

The macro-encapsulation is characterized by the possibility to serve directly as heat exchangers, to be incorporated in building products, possibility of using different PCM's in one tank and availability of a wide range of temperatures [24]. On other hand, it requirements for a high heat transfer rate, which means that the modules should be as small as possible and / or improvement of the thermal conductivity.

Macro-encapsulation may be achieved by a myriad techniques: ball capsules, spherical capsules, cylindrical capsules, stripe capsules, bag capsules, profiles with fins, flat and tube containers, and plates [22,25], as shown in some examples in figure (2.3).

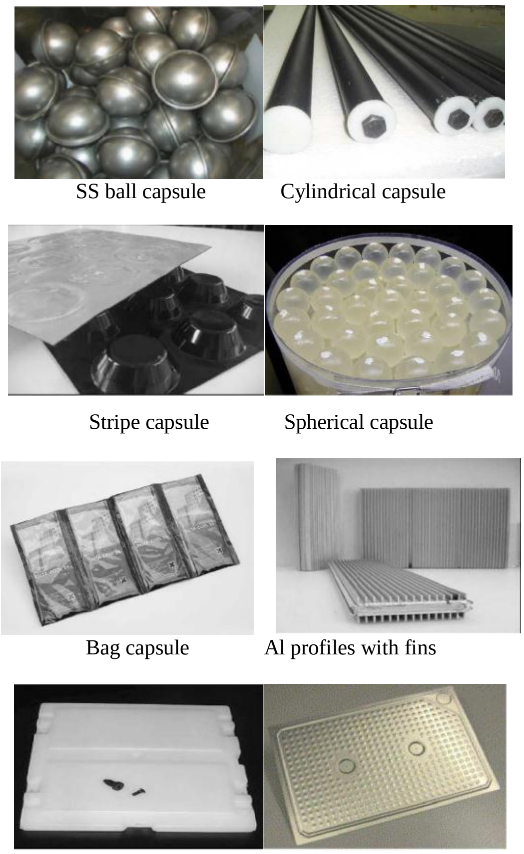



Fig. 2.3: Photographs of macro-encapsulation of various geometry [22].

### *2.1. Ceramic Particles with Paraffin*

Various kinds of nanoparticles of ceramic materials such as cupric oxide (CuO), alumina ($Al_2O_3$), titania ($TiO_2$), zinc oxide (ZnO) and silica ($SiO_2$) are added to PCM (paraffin) in the solar latent heat storage unit to produce nanocomposite-enhanced phase-change materials (NEPCMs). Using of (NEPCMs) aims to enhance the heat conduction and thermal storage of PCM. Also to improve the performance of the PCM like charging and discharging time and the melting process.

By mixing paraffin with alumina ($Al_2O_3$), titania ($TiO_2$), silica ($SiO_2$), and zinc oxide (ZnO) as the experimental samples and through heat conduction and differential scanning calorimeter experiments to evaluate the effects of varying concentrations of the nano-additives on the heat conduction performance and thermal storage characteristics of NEPCMs, their feasibility for use in thermal storage was determined, the experimental results demonstrate that $TiO_2$ is more effective than the other additives in enhancing both the heat conduction and thermal storage performance of paraffin for most of the experimental parameters. Furthermore, $TiO_2$ reduces the melting onset temperature and increases the solidification onset temperature of paraffin [26].

Cupric oxide (CuO) nano-material was used for improvement of thermal conductivity and performance of low temperature energy storage system of solar pond. They proved enhancement of thermal conductivity of the PCM. Also the performance of the PCM like charging and discharging time and the melting process are improved. It is also observed that there is almost 50% reduction in charging time and discharging time of the PCM for a volume concentration of 0.16% and for all the three constant heat flux (flow rate of hot water). Further, there is a scope to determine the correct proportion of mixing the nano particle to the PCM and also there is scope to determine the better nano particle that can be dispersed with a particular type of PCM [27].

### *2.2. Metal Foams in Paraffin Storage Unit*

In the last two decades, another kind of material have been under increasing development and commercial utilization in different sectors of the economy such as building and architecture, mechanical, chemical industries: cellular metallic materials. These materials are highly porous, with relative density lower than 0.3, and present an interesting combination of properties, as low weight, high impact absorption, damping properties, sound and thermal insulation, etc. [28-29].

Metal foams keeping a combination of many advantageous properties of metals with low relative density, are cellular materials containing pores filled with gas. If pores insulated by metal walls from each other is referred to as closed cell metal foam. If pores interconnected with each other is referred to as open cell metal foam or metal sponge [30].

For sponges, the typical applications of these open-cell materials so far are heat exchangers, filter elements, acoustic absorbers, stiffening elements, crash absorbers, metal matrix composites etc., because they have special properties, such as the permeability of the open-cell structure, high porosity and high ratio of surface area to volume etc. [31-32].

In metallic sandwich panels with periodic, open-cell cores are important new structures, enabled by novel fabrication and topology design tools, their open cell structure allows for heat transfer into a coolant fluid, for the storage of electrical energy as a battery [33].

Those materials might be used for an optimization of the charging and discharging behavior of thermal latent heat storages by filling them with PCM's. An advantage especially of open-cell composites structure is that the PCM even in a molten state is fixed by means of capillary forces. As lower the porosity of these materials as higher its resulting effective heat conductivity, but – of course – as lower is the remaining heat capacity [19].

N. dukhan studied the thermal behavior of a small cylindrical shell phase change system. A cylindrical shell of open-cell aluminum foam was filled with Paraffin wax, after it was contained in a solid copper casing. The results showed that the heat transfer rate increased with increasing the airflow rate through the shell. At the maximum flow rate, the average core temperature decayed exponentially with time. Its behavior did not have the typical plateau at the solidification temperature of the wax, rather the behavior of this the core temperature mimicked that of a lumped system but with different slope.

Photograph of Aluminum foam shell

(a) (b)

Photograph of Foam Shell in Copper Casing
(a): Cross-Sectional View, (b): Outside View

A possible explanation of this was the fact that the thickness of the core was relatively small, and that the system included other thermal mass (the copper container) [34].

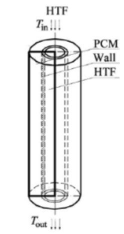
The use of metal foam in thermal energy storage application was evaluated by designing and testing different thermal energy storage systems, with and without copper metal foam. The equivalent thermal conductivity of a foam-wax composite was found to be 3.8 W/mK which was 18 times higher than that of pure paraffin wax (0.21 W/mK). Copper foam reduced the time required to melt approximately the same amount of wax to 36% of that without the use of metal foam. The temperature gradients in TESS (with metal foam) while melting and solidification were significantly lower than that in a pure wax system. The addition of metal foam on the wax side of the TESS helped to significantly increase heat transfer during melting but did not increase heat transfer to air during cooling. Hence, metal foam should be added to both wax and air sides to increase heat recovery by air.

TESS with no Metal Foam

TESS with Metal Foam on wax side

The outlet temperature of air passing through the TESS increases significantly when metal foam is placed on both wax and air sides [35].

High conductivity porosity material-graphite foam was proposed to enhance the phase change materials, paraffin, in order to solve the problem of its low conductivity in the latent heat storage exchanger (LHSE). The LHSE was suggested like shell-and-tube heat exchanger. Paraffin/graphite foam as the PCM filling the shell side and water as HTF circulating inside the tube has been numerical analyzed in this study. Compared with the results of the pure PCM, the phase change heat transfer can be greatly enhanced by using graphite foam in TES.




Schematic of the LHSE

The results showed also that HTF inlet temperature plays a significant role for reducing the melting time and liquid fraction, but the influence of flow velocity on melting process is small although increasing velocity can reduce the melting time [36].

Y. Tian and Y. Zhao investigated the effects of metal foams on heat transfer enhancement in Phase Change Materials (paraffin). The numerical investigation is based on the two-equation non-equilibrium heat transfer model, in which the coupled heat conduction and natural convection are considered at phase transition and liquid zones. They found that heat conduction rate is increased significantly by using metal foams, due to their high thermal conductivities, and that natural convection is suppressed owing to the large flow resistance in metal foams. In spite of this suppression caused by metal foams, the overall heat transfer performance is improved when metal foams are embedded into paraffin; this implies that the enhancement of heat conduction offsets or exceeds the natural convection loss.

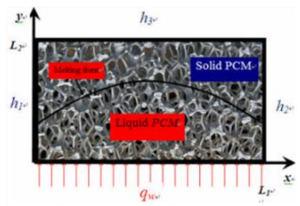



Illustration of PCMs embedded into metal foams

The simulation results also indicated that metal foams with smaller pore size and porosity can achieve better heat transfer performance than those with larger pore size and porosity. In addition, a series of detailed evolutions of velocity and temperature distributions have been obtained; these illustrate clearly the phase change processes of the paraffin wax [37].

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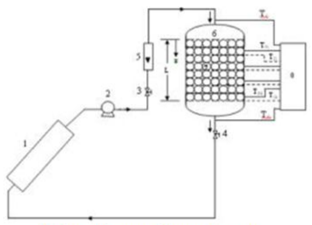
### *2.3. Investigative Review on Macro-encapsulation of Paraffin*

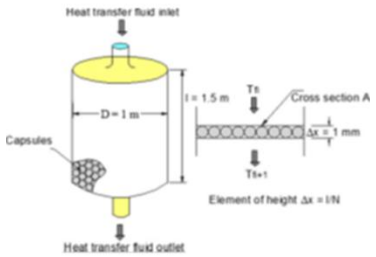
By using TES unit contains paraffin as phase change material (PCM) filled in spherical capsules, which are packed in an insulated cylindrical storage tank in different porosities, and hot water at average temperature of 45 °C for domestic applications as heat transfer fluid (HTF) to transfer heat from the solar collector to the storage tank with various flow rates also acts as sensible heat storage material.



**Schematic experimental setup**

The experimental results demonstrate that the mass flow rate has significant effect on the heat extraction rate from the solar collector, which in turn affects the rate of charging of the TES tank and the packed bed LHS system reduces the size of the storage tank appreciably compared to conventional storage system and that the LHS system employing batchwise discharging of hot water from the TES tank is best suited for applications where the requirement is intermittent [38].

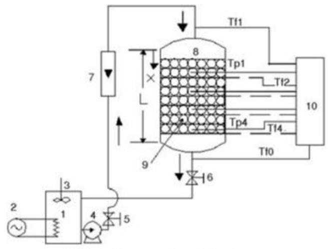
The effects of heat transfer fluid inlet temperature, mass flow rate, phase change temperature range and the radius of the capsule on the dynamic response of a packed bed latent heat thermal energy storage system using spherical capsules filled with paraffin wax as PCM usable with a solar water heating system for both charging and discharging modes have been investigated.




**Layout and details of the storage system**

The results indicated that the complete solidification time is too longer compared to the melting time, higher inlet temperature and the mass flow rate of heat transfer fluid lead to the shorter time for complete charging, capsules of smaller radius have higher charging and discharging rate than those of larger radius, and the phase transition temperature range reduces the complete melting time [39].
In experimental investigation carried out by both Meenakshi and Nallusamy, paraffin and stearic acid were employed as change materials in TES to store the heat as sensible and latent heat also.

In the thermal energy storage system PCM`s are stored in the form of spherical capsules of 38 mm diameter made of high density poly ethylene. Experiments were conducted on the TES unit to study its performance by integrating it with constant heat source. The variables studied include PCM, mass flow rate, and inlet temperature of HTF.

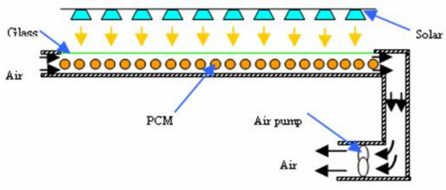


**Schematic experimental set-up**

The results showed that the PCM temperature gradually increased with time and remained constant during the phase change and continued to increase after the phase change before it attained charging temperature. The charging times decreased when increased mass flow rates of HTF. The charging times were reduced when HTF inlet temperature increased. Stearic acid attained maximum temperature faster compared to paraffin [40].
The characteristic of TES in solar system using PCM (paraffin) was investigated. The fabricated PCM storage unit consists of a number of copper tubes filled with paraffin. The PCM storage unit kept in well insulated storage tank. It carries minimum of 45 liters capacity of water with glass wool insulation.
A thermal energy storage system has been developed for the use of hot water at an average temperature of 60ºC, for domestic applications using combined sensible and latent heat storage concept. Mass flow rate had a significant effect of temperature difference between them.

**Cupper tupes arrangements** **Fabricated PCM storage tank**

It is concluded from the experimental results that the enhancement technique were implemented through the numbers of copper tube in the fabricated storage tank, the smaller diameter of copper tubes could effectively enhance the heat transfer between the HTF and the PCM during charging and discharging processes [41].
A phase change material (PCM) consists of paraffin wax with 5% aluminum powder used as a thermal storage compound in a solar air heater, the compound supposed be encapsulated in cylinders as a solar absorber in cross flow of pumped air.
An indoor simulation supposed that the PCM initially heated by solar simulator until liquid phase temperature (50°C) while the pumped air over the cylinders at room temperature (28°C).




Cross section of the solar air collector with PCM cylinders

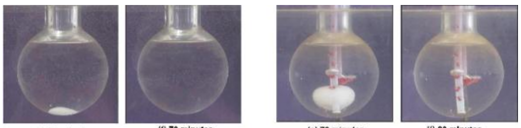
Results show that the air temperature gained due to thermal energy discharge process decreases with increasing of air mass flow rate, and the freezing time for this compound takes long time interval for the lower mass flow rates [42].

A latent heat thermal storage system was designed and fabricated, the PCM storage tank contains PCM storage unit, the storage unit having 90 numbers of copper tube, and the entire setup kept in well insulated stainless steel tank. The PCM has been filled in the tubes. The experimental test unit consists of a cylindrical tank with 600 mm length and diameter of 350mm, inside the tank the number of copper tubes has kept with dimension of length 500mm, 12mm diameter and thickness of 22 gauge.

Copper tubes

Results reveal that, the heat carrying capacity of the solar water heating system is increased by 40%. So, the existing size of the tank is capable of holding added quantity of heat make it more suitable for domestic applications [43].

S. Khot, N. Sane and B. Gawali investigated the constrained and unconstrained melting of PCM inside a spherical capsule using paraffin wax. The experiments are carried out with different HTF temperatures. PCM melting is constrained in spherical capsule using thermocouples used to measure the temperatures in capsule. The thermocouples are mounted inside the Teflon tube to fix up the positions. Under the constrained melting conditions, the melting occurs around the PCM inwards the centre of the capsule. The solid PCM is restricted from sinking by the tube inside the sphere. There is no contact of the solid PCM with the spherical glass. Melting is mainly through the natural convection in the liquid at the top and bottom halves of the solid PCM.



(e) 60 minutes (f) 70 minutes (e) 70 minutes (f) 80 minutes

For the unconstrained melting, the solid PCM sinks to the bottom of the sphere. This is due to heavier density of the solid PCM than the liquid PCM. Under the same experimental condition, unconstrained melting seems to occur at a faster rate than the constrained melting. This is due to larger rate of heat transfer by conduction from the solid PCM to the spherical glass capsule [44].

## 3. CONCLUSION

After review of various literature on macro-encapsulated paraffin, inserting nanoparticles in paraffin and metal foams used in solar latent heat storage unit, also the cellular metal matrix composites reinforced with ceramic nanoparticles, the following conclusions were made:

An addition of an aluminum powder to the paraffin wax leads to increase the thermal conductivity and thermal storage efficiency and reduce the charging time. The freezing time for the compound takes long time interval for the lower mass flow rates of HTF. Heat conductivity, thermal storage performance, specific energy absorption, reduction of the melting onset temperature and increasing of the solidification onset temperature of paraffin can be enhanced by addition an appropriate ceramic particles. By means of inserting a metal foam, such as Al and Cu, can be improved the equivalent thermal conductivity of a foam-wax composite and reduced the time required to melt, also enhanced the temperature gradients in TESS while melting and solidification. Metal foam should be added to both PCM and HTF sides to increase heat transfer to HTF during cooling as it is during the heating. In the packed bed LHS system, the charging time can be reduced with increasing the inlet temperature and the mass flow rate of HTF. The complete melting time can be reduced by the phase transition temperature range. Smaller radius spherical capsules have higher charging and discharging rate than those of larger radius. By reducing the diameter of cylindrical tubes, the heat transfer between HTF and Paraffin during charging and discharging processes can be enhanced. The smaller the thickness of cylindrical tubes the more heat carrying capacity of the solar water heating system. Unconstrained paraffin capsulated in spheres melts faster than those constrained paraffin. This is due to larger rate of heat transfer by conduction from the solid paraffin to the spherical capsules.

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