Experimental investigation of Latent Heat Storage System using Phase Change Material

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Abstract— Thermal energy storage (TES) is becoming a growing concern in modern technology and it has number of applications. In order to avoid the gap between energy supply and demand thermal energy storage system plays an important role in concentrated solar power plants. The objective of present work is to investigate experimentally the behavior of latent heat thermal energy storage system (LHTES) using Phase Change Material (PCM) in removing fluctuation from heat transfer fluid (HTF) temperature and maintaining it at constant temperature (~170 ^{0}C). The PCM has the advantage of having high storage density and the isothermal nature of the storage process. Due to this volume of material reduces and hence the cost of the system. In this experiment Hytherm 600 is used as heat transfer fluid (HTF) and A164 (organic) as PCM whose melting point is 168.7 ^{0}C. The fluctuation is simulated using a charging and a discharging cycle. In the charging cycle, HTF is allowed to enter the LHTES at ~180 ^{0}C and during discharging period, the HTF inlet temperature is ~156 ^{0}C. Hytherm 600, which is a thermic oil, is used as Heat Transfer Fluid.

***Keywords*:**Thermal Energy storage, Phase change material, Solar Energy, Heat Transfer Enhancement, Solar thermal plant

I. INTRODUCTION

Due to unpredictable and unstable nature of solar radiation, it becomes very difficult to satisfy the gap between supply and demand of electricity. The only solution to this problem is to have storage in the system which can satisfy the demand regardless of unavailability of radiation. In storage, the extra energy that is not required, is collected and used it during hours when sunlight is not ample to satisfy the demand. Thermal storage can also be used for process application where a waste heat can be stored in thermal storage and used when it is required. The advantages of using thermal energy storage in solar thermal power plant are given below(F. Dinter and D. M. Gonzalez, 2014)

- Possibility of 24-hour power generation and shifting of power generation to peak period.
- Generation of power independent of weather condition and time.
- Support to other renewable energy sources.
- Improved economics, payback time is reduced due to more hours of power generation.
- Completely remove the problem of fluctuations because due to thermal storage, constant power generation is there.
- Support for power quality

II. LITERATURE REVIEW

2.1 Thermal energy storage methods

There are many ways to store thermal energy. They can be divided into:
(1) Sensible heat storage
(2) Latent heat storage
(3) Thermochemical storage

2.1.1 Sensible heat storage

In sensible heat storage, the thermal energy is stored due to increase in temperature of storedmedium. The amount of energy stored depends on the specific heat, the change in temperature and mass of the material.

Q = $\int_{T_1}^{T_2} mC_p\,dT$

Sensible heat storage can be differentiated on the basis of storage media, *viz. (i)* liquids such as oil, water and molten salt, and (ii) solids such as rocks and metals.

2.1.2 Latent heat storage

Latent heat storage system (LHS) uses the energy released or absorbed in the phase change region. When the material reaches the phase change temperature it absorbs or releases a huge amount of energy to carry out the phase change which is known as the latent heat of fusion or evaporation depending on the state and in this way the energy is stored. The materials used are known as phase change materials (PCM). They have very high energy density and hence they reduce the volume and hence the cost. Figure 1 explains the energy storage mechanism of a PCM. When a solid is heated, its temperature rises up to its melting temperature. After this point the temperature come to an end to increases and the phase change occurs. After the PCM has completely melted, the temperature rises again up till it reaches the boiling temperature. After this the temperature remains constant till everything is evaporated. In PCM application one can give and extract the energy within the phase change region and therefore without changing the temperature.

$Q = \int_{T_1}^{T_m} mC_{p\_solid}\, dT + mL_m + \int_{T_m}^{T_f} mC_{p\_liquid}\, dT$

(1) The 1st term represents the increase in sensible energy stored by the increase in temperature of material from initial temperature to melting temperature.
(2) The 2nd term represents the latent energy stored in the material by phase change.
(3) The 3rd term represents the sensible energy stored by increase in temperature.

Most of the PCM suffer from a constraint of low thermal conductivity of around 0.2 and 0.5 W/mK for paraffin and inorganic salts respectively.

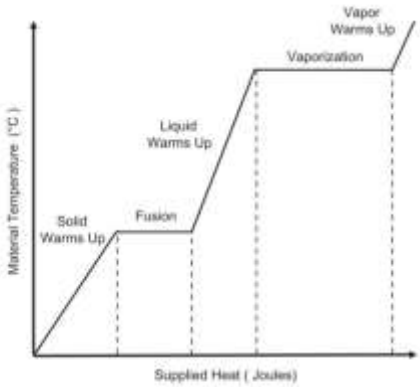

Fig.1: Temperature profile of a PCM with heat supply

2.1.3 Thermochemical heat storage

This is the most underdeveloped method of thermal energy storage. It contains the use of endothermic chemical reactions. When heat is supplied to an appropriate material, it is utilised in breaking the chemical bonds of the compound. Later all of this energy is recovered when the reaction takes place. This technology offers various advantages but it is in the early stages of development. The different types of PCMs are classified in figure 2.

2.2 Classification of PCM

The materials used in latent heat application are known as phase change material (PCM). They may undergo the following transformations:
(1) Solid-solid (Ex. Cellulose diacetate)
(2) Solid-liquid (Ex. Paraffin)
(3) Liquid-gas (Ex. Water)

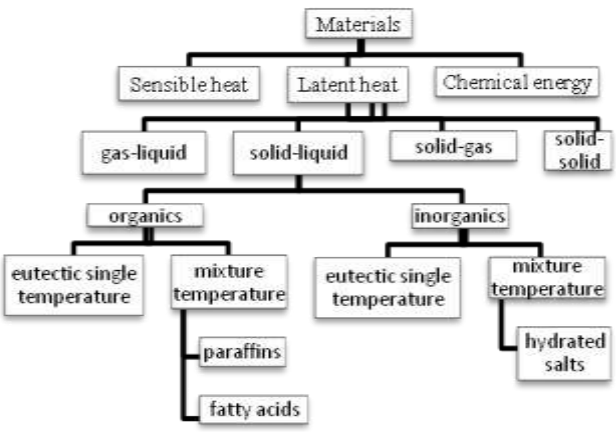

Fig.2: Classification of TES materials (Sharma A., et, al, 2009)

2.2.1 Solid-solid PCM

Solid-solid PCM materials transform their crystalline structure at a particular temperature. The transformation energy is comparable to the best solid to liquid PCMs. They are very easy to handle and cost effective because the absence of liquid state eliminates the problem of leakage and need for encapsulation. Research is going on for developing steel alloy for such application (T. Nomura, et, al, 2010).

2.2.2 Liquid-gas latent heat storage

The transformation from liquid to gaseous state requires the highest amount of energy. But due to enormous amount of change in volume, the economic and practical feasibility becomes very difficult. Also, not much information is available on the gaseous state of materials.

2.2.3 Solid-liquid latent heat storage

The transition of materials from solid to liquid is studied and used widely in latent heat storage applications. Even though they have several times less latent heat compared to liquid-gas PCMs, they are acceptable as they do not present technical and economic difficulties of expansion. Normally their expansion is less than 10% of their original volume.
There are many problems associated with the use of solid-liquid PCM such as the complexity of the container, phase segregation and subcooling. But, the biggest hurdle to its application is the low thermal conductivity. It restricts the extraction and storage of the energy in a limited time period and also leads to wastage of PCM material by remaining unused.

2.3 Parameters for selection of PCM

Some points should be taken care while selecting a PCM for appropriate application (F. Agyenim, et, al, 2010), which are as follows:
(1) Melting temperature near our requirement
(2) High latent heat of fusion
(3) Low specific heat
(4) High thermal conductivity in solid state, so that the heat is diffused in lesser time
(5) Low thermal expansion coefficient so that design becomes easier and cheaper materials can be used for containing it
(6) Low or zero subcooling during freezing
(7) Non-poisonous, non-explosive and non-flammable
(8) Cheap and easily available

2.4 PCM container

After the PCM has been selected, the factors to consider are:
1. Design of the PCM container
2. The thermal and geometric parameters of the container required for a given amount of PCM

These factors have great role in influencing the parameters of heat transfer. PCMs are kept in long thin heat pipes (B. Horbaniuc, et, al 1999), cylindrical containers (E. Papanicolaou and V. Belessiotis2002), (F. Agyenim, et, al, 2009) or rectangular containers (P. D. Silva, et, al, 2002), (K.Ermis, A., et, al, 2007) as shown in figure 3. Rectangular and cylindrical containers are the most common shapes of container. Among them shell and tube system is the most commonly used one, which accounts for more than 70%.

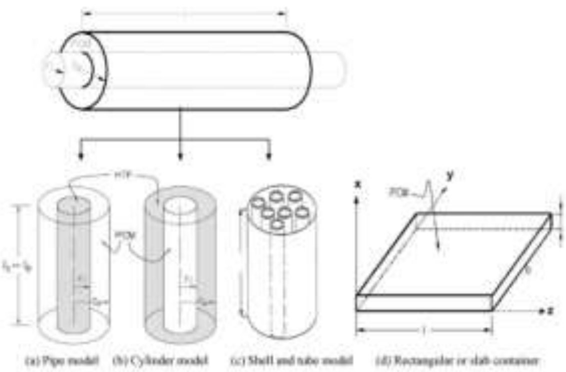

Fig.3: Commonly used PCM containers (F. Agyenim, et, al, 2010)

The cylindrical PCM container can be used in the following ways:
(1) In the 1st configuration, the PCM is on the shell side and heat transfer fluid flows inside the tube(M. Esen, et, al, 1998)

(2) In the 2nd configuration, the PCM is in the tube and the HTF flows on the shell side. According to Esen et al.(M. Esen, et, al, 1998), the pipe model is better because it took less time to melt.
(3) The 3rd model is the shell and tube system. It is commonly used to improve heat transfer in PCMs. Agyenim conducted experiments with horizontal shell and tube heat exchanger (4 tubes) and a pipe model (F. Agyenim, et, al, 2010). Heat transfer in the shell and tube system was better. The reason for this was found to be multiple convective heat transfer.

2.5 Comparison of counter-current and parallel heat transfer fluid (HTF) flow directions

In a cylindrical assembly, the HTF can flow in two directions during charging and discharging of the PCM, viz. (a) hot and cold streams are entered from same direction, and (b) hot and cold streams are entered from opposite direction. Gong and Mujumdar (Z.X. Gong and A. S. Mujumdar 1997) conducted numerical simulations to find the effect of the parallel and counter-current flow modes. They found that parallel flow increases the energy charge/discharge rate by 5% more than counter-current flow.

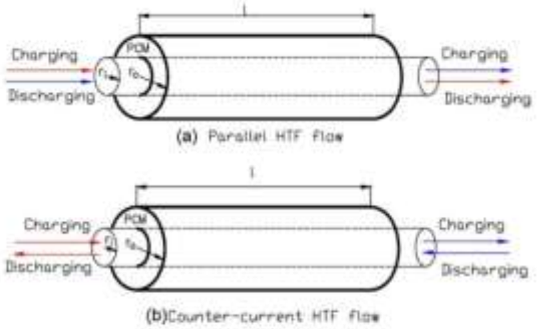

Fig.4: Comparison of parallel and counter flow (F. Agyenim, et, al, 2010)

2.6 Heat transfer enhancement techniques

Most of the PCM suffers from low thermal conductivity which leads to very poor heat transfer coefficient. In order to overcome this problem, heat transfer enhancement techniques are used as shown in figure 5, such as,
(1) Finned tubes
(2) Bubble agitation
(3) Insertion of a metal matrix in the PCM
(4) PCM dispersed with high conductivity particles
(5) Micro-encapsulation of the PCM
(6) Shell and tube

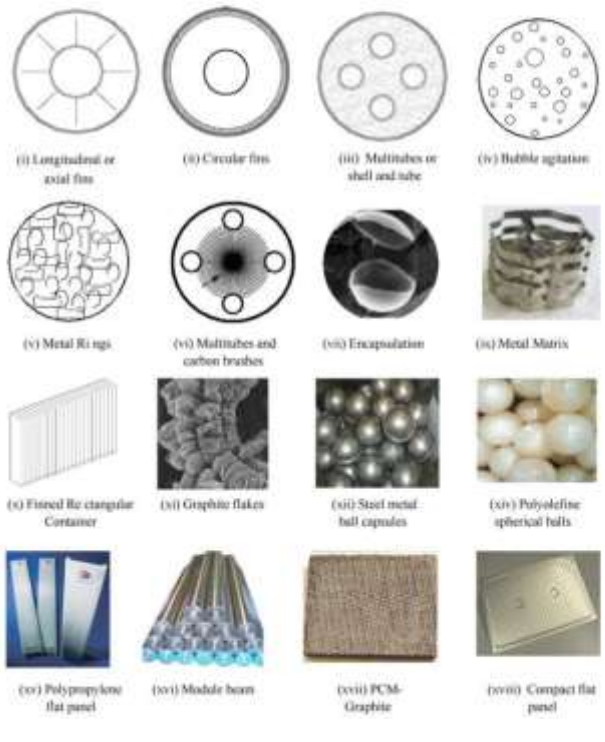

Fig.5: Common heat transfer enhancement technique (F. Agyenim, et, al, 2010)

It should be noted that different researchers used different experimental setups and different materials of PCM and container. Also, researchers used different parameters to assess the heat transfer enhancement in the PCMs. (Velraj*et, al*, 1999)evaluated the performance by calculating the effective thermal conductivity. Horbaniuc et al, evaluated the performance of fins in terms of time taken for complete solidification. (Choi and Kim J. C., et, al, 1992) used the ratio of overall heat transfer coefficient in the finned and unfinned tube systems.

2.6.1 Extended surfaces

Most of the people use fins in PCM as it is simple to manufacture as well as they are cheap. The best improvement in heat transfer was reported by Velraj et al. where the thermal conductivity was improved by 10 times (Velraj*et, al,* 1999).
It was observed that there is no degradation of the material after testing more than 400 h with $NaNO_3$ as PCM (W.D. Steinmann, D. Laing, and R. Tamme2009). Both, aluminium and graphite sheets did not get corroded due to the contact with the galvanized steel of the pipes. Steel fins occupy more volume than graphite fins for same heat transfer. The cost of steel fins is significantly higher because of this.
Mostly encapsulation is used in low temperature materials. It is costly to encapsulate PCM with melting temperatures above 200 ^{0}C. The initial volume of PCM should not be more than 80% of the capsule volume while using a rigid capsule. By doing this, it is ensured that capsule can withstand the pressure exerted.(R. Steinmann and W.D., Tamme2003)

2.6.2 Multiple PCM method

Multiple PCM technique contains more than one PCM having different melting temperatures in the LHS unit. The heat transfer rate is decided by the difference in the temperature of the HTF and the PCM melting point(S. Jegadheeswaran and S. D. Pohekar2009).
If a single PCM is used, heat transfer becomes poor because temperature difference decreases in the flow direction of the HTF. In order to keep a constant temperature difference during the melting process, multiple PCMs should be used in decreasing order by their melting points. This leads to a nearly constant heat flow to the PCM. When HTF is flowed in reverse direction during discharge, the PCMs remain in the increasing order of their melting points, and almost constant heat flow happens from the PCM to the HTF. Figure 6 shows how we can use multiple PCMs in a shell and tube configuration.

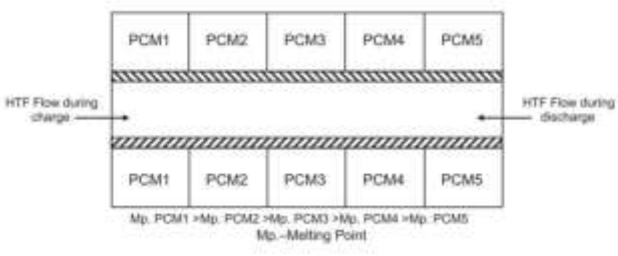

Fig.6: LHS system with multiple PCM (R. V Seeniraj, et, al, 2002)

Farid and Kanzawa(M. M. Faridand A. Kanzawa1989) used 3 PCMs with different melting points in cylindrical capsules. Air was used as HTF. A 10% increase in heat transfer rate was obtained during charging and discharging. Michels and Pitz-Paal(H. Michels and R. Pitz-paal2007)experimented with 3 PCMs on shell side and synthetic oil in the inner tube. Most of the PCM melted during the experiment.
It is necessary to choose right combination of PCMs. For this we require an appropriate difference between the melting points and proper amounts of PCM. Fang and Chen (M. Fang and G. Chen, 2007) performed a numerical study in a shell and tube module to examine the effect of different combinations of PCM. The results showed that it is best to have more melting point difference between the PCMs.
It is best to use multiple PCM along with extended surfaces for even better enhancement(R. V Seeniraj, et, al, 2002). Hence more studies are needed to investigate and find a combination of PCM with even better performance along with extended surfaces.

2.7 Melting process in the PCM

In order to work with PCM, it is very important to understand the process of melting. (Zhang and Bejan1989) together with (Sari and Kaygusuz 2003), (Agyenim et al. 2010) and (Hirata and Nishida 1989) described the melting process in following stages:
(1) Sensible heating at starting increases the temperature of solid PCM. Pure conduction heat transfer occurs during this
(2) After some time a second conduction regime is formed in which heat is purely transferred by conduction from the heated wall to the PCM. Solid-liquid interface is formed when melting had just begun
(3) As the thickness of the melt layer increases transition from conduction to natural convection starts. At the interface, there exists equilibrium between solid body and a pool of its own liquid
(4) A convection regime is formed when most of the solid has been melted and the liquid core temperature distribution depends on height.

III. EXPERIMENTAL SETUP

It consists of following components, *viz.* heater tank, PCM tank with expander and nozzle, canned motor pump, control panel, control and data acquisition system and auxiliary instruments, as shown in figure 7. Auxiliary instruments are used to monitor the experimental setup and measure the desired parameters, and these are Coriolis mass flow meter, pressure indicator, K-type thermocouple, Pumps for cooling canned motor pump and filling the setup.
A set of 22 electrical heaters are used to supply required heat to heat transfer fluid (HTF).
An organic PCM, A164 is used in the storage tank and a thermic fluid, Hytherm 600 is used as HTF. The melting temperature of PCM measured is 168.7 °C.

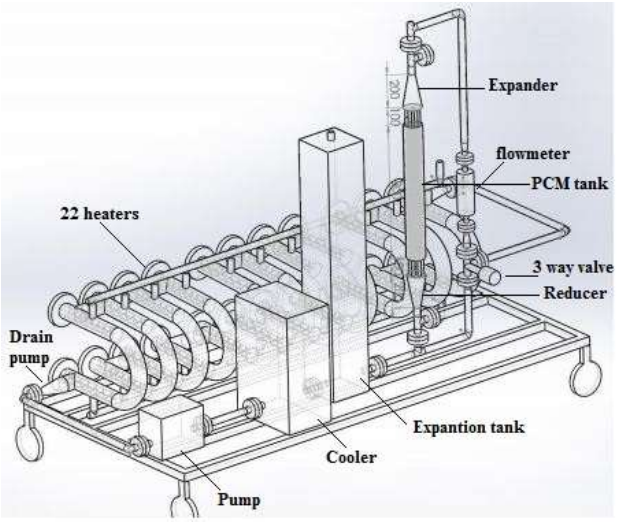

Fig.7 Schematic diagram of experimental setup

IV. RESULTS AND DISCUSSIONS

Inlet temperature, outlet temperature and flow rate are shown below.

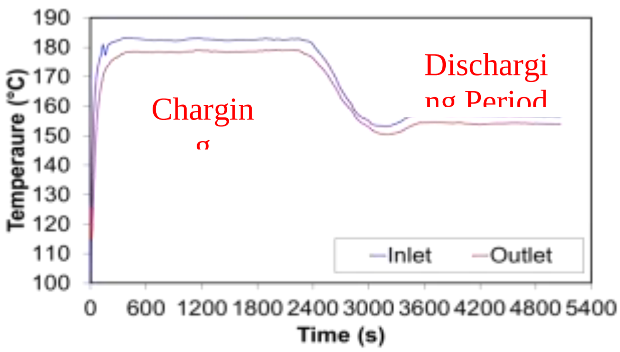

Fig.8 Inlet and Outlet temperature of HTF while Charging and Discharging

During charging inlet temperature of HTF to storage tank is kept ~182 °C. In above readings charging time is ~ 2200 s, transition period is of 800 s and that is up to 3000 s and discharging period is after 3000 s that is up to 5100 s.Flow rate is kept constant at ~8.25 lpm

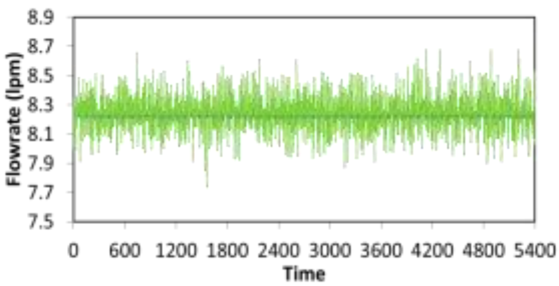

Fig.9 Flow rate variation of HTF with time

V. REPEATABILITY OF EXPERIMENTS

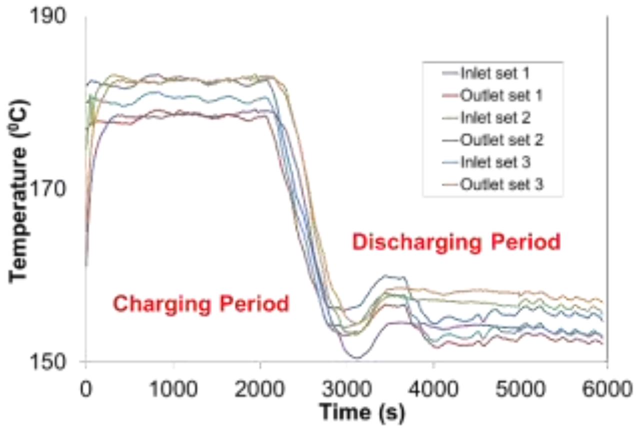

Fig.10 Fluctuations in temperature at constant flow rate

Figure 10 shows 3 sets of readings at constant flow rate of ~8 lpm. The deviation of temperature in the experiment during charging period is ~ 5 ^{0}C and that is during discharging period is ~7 ^{0}C.

VI. CONCLUSIONS

The thermal performance of a thermal energy storage (TES) system using PCM is investigated for the medium temperature application (~ 200 °C) such as ORC based solar thermal power plant. Thermal energy storage (TES) is essential for extending the electricity generation after sunset as there is no sun radiation. Among the different energy storage methods, latent heat storage through phase change material (PCM) is a superior way of storing the energy because of its high energy density.Though PCMs have high energy, it possesses very low thermal conductivity which significantly affects the performance of the unit, so fins are used to increase the heat transfer rate. An organic PCM, A164 (melting temperature 168.7°C) and a HTF, Hytherm 600 are chosen in this study. PCM can be used in more effective way to reduce the fluctuations in the inlet temperature of HTF.

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