Performance Analysis of Thermal Energy Storage Device using Phase Change Material

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Abstract—In thermal energy storage, the useful energy from the collector is transferred to the storage medium where it is transformed into an internal energy. This may occur in the form of latent heat, sensible heat, or both. Latent heat storage is more attractive than sensible heat storage because of its high storage density with smaller temperature swing. This research work deals with a latent heat storage system using Phase Change Materials (PCM) as an effective way of storing thermal energy (solar energy, off-peak electricity, and industrial waste heat). It has the advantages of high storage density and the isothermal nature of the storage process. This research will show performance analysis of thermal energy storage using PCM for various purposes with ways to enhance the heat transfer, and it will show a designs to store the heat using PCMs for different applications, i.e. space heating and cooling, solar cooking, greenhouses, solar water heating and waste heat recovery systems. It will also help to find the suitable PCM for heat exchanger with ways to enhance the heat transfer and provide the various designs to store the heat using PCM for different applications. It will also show the comparative study of the performance conventional system and system with thermal energy storage with PCM.

Key words: Heat Exchanger, Internal Energy, Latent Heat, Phase Change Materials (PCM), Thermal Energy Storage, Sensible Heat

I. INTRODUCTION

Renewable energy supplies are steadily gaining increasing importance in all the countries. In particular, solar energy, being non-polluting, clean and inexhaustible, has received wide attention among scientists and engineers. Though there are many advantages, an important factor is that solar energy is time dependent energy source with an intermittent character. Hence some form of thermal energy storage (TES) is necessary for the most effective utilization of this energy source. Most of the TES systems in use rely on the specific heat or sensible heat of the storage material, such as water, oil and rock beds and they are known as sensible heat storage (SHS) systems. The main disadvantage of SHS systems is low heat storage capacity per unit volume of the storage medium. On the other hand, latent heat storage (LHS) concept, which involves storing and recovering heat through the solid-liquid phase change process, has advantages of high heat storage capacity and isothermal behaviour during charging (heat storage) and discharging (heat release) processes[1].

II. LITERATURE REVIEW

Thermal energy storage using the latent heat of PCMs has received considerable attention in the past two decades only. Several investigators have studied, theoretically and experimentally, the performance of thermal energy storage employing phase-change material in a wide variety of geometries.

Fouda et. al. [1984][2] studied the characteristics of Glauber’s salt as a LHS medium in solar storage system. The effect of several variables was studied over many complete cycles of the unit, including variable HTF flow rate and inlet temperature, wall thickness etc.

Saitoh and Hirose [1986][3] performed theoretical and experimental investigation of the transient thermal characteristics of a phase-change thermal energy storage unit using spherical capsules. The effects of variation in the capsule diameter, the flow rate of the heat transfer fluid, the inlet temperature difference, the capsule material, and the PCM on the thermal performance of this storage unit were studied in detail using computer simulation and compared with the experimental results of a prototype LHS unit with a capacity of 300 liters.

Anantharayanan et. al. [1987][4] developed a computer model for the estimation of temperature profiles of the solid and the fluid along the length of the packed bed of self-encapsulated Al-Si PCM shots as functions of distance along the bed and time during a series of heat storage and utilization cycles. Air was used as heat transfer fluid in their study.

Beasley et. al. [1989][5] developed a computational model to study the transient thermal response of a packed bed of spheres containing a phase change material using one dimensional separate phases formulation. Results from the model were compared with the experimental results of a commercial size thermal storage bed packed with polypropylene spheres containing paraffin wax for both the energy storage and recovery periods using air as heat transfer fluid.

Esen et. al. [1998][6] made numerical investigation on the thermal performance of solar water heating systems integrated with cylindrical LHS unit using various PCMs.

Ismail and Henriquez [2002][7] presented a numerical model to simulate the process of heat transfer (charging and discharging) in a LHS system of packed bed of spherical capsules filled with PCM (Water). The effect of heat transfer fluid (ethylene glycol) entry temperature, the mass flow rate and material of the spherical capsule on the performance of the storage unit were investigated both by numerically and experimentally.

Mehling et. al. [2003][8] presented the experimental and numerical simulation results of energy storage density of solar hot water system using different cylindrical PCM modules. Their results show that adding PCM modules at the top of the water tank would give the system higher storage density and compensate heat loss in the top layer.

Ajesh Vijayan et. al. [2016][9] Solar water heating systems with PCM shows efficiency variation compared to
the traditional method. In this work the efficiency variation is studied by calculation and also through graphical analysis. In the traditional method without PCMs the efficiency was found to be in the range of 23.4% while in the PCM encapsulated system the efficiency got boosted up to 40%. Also the heat storage capacity showed variation. In the traditional system the energy stored was 3270kJ, while in the PCM nased system it has increased to 4670 kJ. The PCM based technologies may show a great progress in the future and this may be great boon to avoid the energy crisis in the future to some extent.

S. Bharath Subramaniam et. al.[2016] [10] Regardless of the daily operations the Integrated Collector Cum Storage Solar Water Heater (ICSSWH) gives better thermal efficiency for longer period of time by using paraffin wax as PCM. When compared with the solar water heater the integrated PCM storage tank with solar water heater was found to be more efficient and cost effective. During the discharging period, the heat transfer fluid gained enormous amount of heat from the PCM. Hence paraffin wax can be used for solar application from techno economical aspects.

Ettouney et al. [2005] [11] presented a detailed picture of the temperature field inside the PCM encapsulated spherical capsule during melting and solidification processes using paraffin as PCM and air as HTF. The results indicated that the Nusselt number for melting has strong dependence on the sphere diameter, lower dependence on the air temperature and negligible dependence on the air velocity. Works in the related area (i.e. energy storage in spherical capsules) are also reported by Prudhomme et al. (1989) and Cho and Choi (2000). He et al. (2004) used the liquid-solid phase diagram of the binary system of tetradecane and hexadecane to obtain information on the phase transition processes and differential scanning calorimetry to determine the thermo-physical properties of the binary system. They presented a reliable method to incorporate both the heat of phase change and the temperature range of paraffin by combining phase equilibrium.

III. OBJECTIVE OF THE RESEARCH

There has been significant research done on LHESS, however, missing from previous work is an experimental LHESS which can be used to study the simultaneously charging and discharging operating mode.

IV. EXPERIMENTAL SETUP

Fig.4.1. shows the experimental set up. The setup consists of a thermal energy storage (TES) tank. The tank is designed in a horizontal shape and shape made of stainless steel. The cover and support structure of GI is pre-coated with UV stabilized pure polyester powder to resist several damages in the long run. The inner portion of the tank is fabricated in a specific manner in order to provide effective heat transfer. The setup involves a TES tank, temperature indicators, ETC type cold water storage tank, copper tubes filled with paraffin wax as a PCM, flow control valve, the stainless steel tank is of horizontal cylindrical shape dimensions of 580 mm height, 300 mm diameter and 40 mm thickness with PUF as the insulating material. The top and bottom portions are surrounded by water. The middle part consists of 7 number copper tubes of diameter 10 mm. and length 300 mm copper tubes used inside the TES tank filled with paraffin wax of melting point 45±1⁰C through which the heat transfer fluid i.e water flows. The total capacity of the tank is 15 litres. Water is used as the heat transfer fluid (HTF). It also consist cold water storage tank fitted 1.2 meter from TES system which has capacity 50 liter, the water flow from CWST to TES tank through flow control valve. Tap also provided to collect hot water from TES tank.

As a startup procedure, in SWH system using vacuum tubes which are made up of borosilicate glass with special coating to absorb solar radiation are called ETC system. Several experiments are conducted with constant flow rates of HTF. During the experiment, HTF inlet temperature varies in accordance with the solar isolation. The charging of thermal energy storage was done during a day, during a day borosilicate glass absorb solar radiation and transfer heat to the water which flow through inner tube. Water absorb heat and part of the hot water flow through storage unit for charging the PCM tank. During the discharging process PCM releasing latent heat and get converted into solid form that means transformation of LHS. This process continued until the PCM temperature reaches 30⁰C. The mass flow rate of HTF taken 0.14 kg/s according to literature

The subsequent operating conditions of LHS system were:
- Heat transfer fluid (water)
- Maximum inlet temperature of water 26⁰C
- Maximum outlet temperature of water 56 °C
- Test temperature range between26-56 ºC
- Mass flow rate 15 ltr.

V. THEORY OF THERMAL ENERGY STORAGE PERFORMANCE

A schematic diagram of the experimental set-up is shown in Figure 5.1. This consists of an insulated cylindrical TES tank, which contains PCM encapsulated cylindrical capsules, solar ETC, flow control valve, cold water storage tank and thermocouples. The stainless steel TES tank has a capacity of 15 liters (300 mm diameter and 480 mm length). There are two plenum chambers on the top and the bottom of the tank and a flow distributor is provided on the top of the tank to make uniform flow of HTF. The storage tank is insulated with glass wool of 40 mm thick. The outer diameter of cylindrical capsules is 11 mm. The total number of capsules in the TES
tank is 7. The PCM capsules occupy 15% of the total volume of storage tank and the remaining volume is occupied by SHS material. The paraffin is used as PCM that has a melting temperature of 45 ± 1°C and latent heat of fusion of 213 kJ/kg. Water is used as both SHS material and HTF.

A cold water tank is provided on top its height 1.2 m is to circulate the HTF through the storage tank. The TES tank is divided into four segments along its axial direction and the thermocouple with an accuracy of ± 0.3°C are placed at the inlet, outlet and three segments of the TES tank to measure the temperatures of HTF. Another one of thermocouple is inserted into the PCM capsules and it is placed at one segments of the TES tank to measure the temperatures of PCM. The position and number of thermocouples are also designated in Fig.5.1. The thermocouples (Resistance temperature detector) are connected to a temperature indicator, which provides instantaneous digital outputs.

Where,  
\[ T_i = \text{inlet temperature of heat transfer fluid} \],  
\[ T_o = \text{outlet temperature of heat transfer fluid} \],  
\[ T_{pcm} = \text{temperature of PCM} \],  
\[ T_{in}, T_{out}, T_{3}, T_{4} = \text{temperatures of HTF at four different points.} \],  
\[ L = \text{length of heat storage tank (mm)} \]  

![Fig. 5.1: Schematic of TES Tank](image)

Having completed the startup procedure, experiment was then carried out in two steps

A. Charging Process

Water the heat transfer fluid and the sensible heat fluid, flows through cylindrical passages surrounded by PCM. During the charging process i.e storing of heat, the HTF transfers the heat to the PCM. At the beginning of the charging process, the temperature of the PCM (\( T_{pcm} \)) inside the tank ranges around 32°C, which is lower than melting temperature. Initially the heat is stored as sensible heat until the PCM reaches its melting temperature. As the charging proceeds, energy is stored by melting the PCM at a constant temperature of 45±1°C. Finally the PCM becomes superheated. The energy is then stored as sensible heat in liquid PCM. The temperature of PCM and HTF at different locations of the TES tank are recorded at an interval of 20 mins. The charging continues until thermal equilibrium is attained between the HTF and PCM. PCM is charged during the day whenever hot water is withdrawn. Other batch of hot water is withdrawn and mixed with cold water to get 15 litres at an average temperature of 45 ±1°C. This process is combined until PCM reaches 32°C.

B. Discharging process

Discharging is done by means of batch wise process. In this method a certain quantity of hot water is withdrawn from the TES tank and mixed with cold water ( at 32°C) to get the required hot water of 15 litres at an average of 45 ±1°C for direct use and the tank is again filled with cold water of quantity equal to the amount of water withdrawn. After an interval of 20 mins, allowing transfer of heat from PCM to water, another batch of hot water is withdrawn and mixed with cold water to get 15 litres at an average temperature of 45 ±1°C. This process is combined until PCM reaches 32°C.

VI. RESULTS & DISCUSSION

The present study investigated the heat transfer process and the convective flow regime during the phase transition period in a PCM. The storage chamber, used during the study was constructed. A thermal energy storage system has been developed for the use of hot water at an average temperature of 45°C for domestic applications using combined sensible and latent heat storage concept. Charging experiments are conducted on the TES unit to study its performance by integrating it with constant heat source. The temperature of water & PCM and energy storage characteristics during charging for copper capsules and PCM (Paraffin and wax) are studied. The use of PCM in solar water heater helps to reduce cooling rate of water, thus it enhance the maximum utilization of solar energy and hence improves efficiency of system. In this research with use of PCM efficiency of solar water heater increase from 25.28% to 32% and also heat storage capacity increase from 1444.17 kJ to 1827.86 kJ. Hence with using PCM material efficiency & heat capacity of solar water heater increases at reduced initial heating rate because PCM take heat to get heated. As PCM based solar water heater store maximum solar energy, it reduces the size of tank and hence can reduce cost of Solar Water Heater. The use of PCM in solar water heater helps to reduce cooling rate of water, thus it enhance the maximum utilization of solar energy and hence improves efficiency of system.

REFERENCES


