Effect Of Heat Transfer Fluid Flow Through A Cylindrical Containers With Phase Change Material In The Annular Region

R. Senthil

Abstract—The main objective of the study is to propose thermal energy storage for medium temperature solar systems. The selection of TES is also concerned about the feasibility and effectiveness of the phase change material followed by the design considerations of the storage tank. The storage process focus is to determine the charging and discharging of heat by the latent heat or sensible heat storage for the entire day. By providing the design configuration in a satisfying aspect can provide the information on the charging and discharging process according to the melting and solidification criteria of specific phase change material used in the system. The precise examination of the parameters of solar receiver and the design characteristic features of the storage compartment provides the exact details on the charging and discharging of the phase change materials used for TES system. Heat transfer fluid flow rate of 120, 150 and 180 kg/h used to charge the TES. The fluid flow rate during the discharge process is 25 kg/h. Energy analysis of the receiver is performed to have an effective thermal performance and reduction in heat losses from the system. The peak collector efficiency is 57% and the overall system efficiency including TES is 75% for the HTF flow rate of 180 kg/h.

Index Terms— Phase change material, Process heating, Sensible heating, Parabolic dish, Solar absorber, Thermal energy storage.

1 INTRODUCTION

Solar energy one of the promising renewable energy candidates for our thermal as well as electrical energy needs for its eco-friendliness. A large amount of energy being used for domestic and industrial purposes. There are many thermal energy storage (TES) materials available which mostly work based on sensible and latent heat principle. The present work focuses on the latent heat TES system which can be used for various applications like water heating, cooking, steam generation, air dryer, space heating etc. Developed a physical model and analyzed in finite element analysis where a tube was surrounded by PCM storage in which fluid flows through the inner tube and exchanges heat with the PCM along its path.

Daabo et al. [1] examined the effect of receiver geometry on the optical performance of a small-scale solar cavity receiver for parabolic dish applications by analyzing three different geometries viz., cylindrical, spherical and conical cavity receivers not only on the optical efficiency aspect, but also the flux distribution in respective geometries. The relation between the flux distribution and the optical efficiency of the receivers is obtained as the result from this study. The conical receiver found to have good absorption and high reflective flux energy. The shape of the receiver and receiver absorptivity decides the focal point location criteria. Finally, the experimental results are compared with numerical models. Zhao et al. [2] studied the cyclic thermal characterization of a molten-salt packed bed TES for concentrating solar power.

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Molten-salt packed-bed thermocline thermal energy storage was found to be the cost competitive thermal energy storage type concentrated solar plant. The simulations were done by a one-dimensional enthalpy method dispersed-concentric model. The thermal performance of the introduced partial charge cycles and subsequent full charge cycles are evaluated in ideal operating conditions. The partial charge effect is obtained by making variations in thermocline development and energy storage or release capacity. Encapsulated PCMs containing configurations are of greater resistance and stronger recoverability to the variation in energy storage or release capacity. And the strong performance of the packed-bed storage depends on the thermal behavior of the storage mediums within the region.

Riahi et al. [3] studied the impact of a periodic flow reversal of heat transfer fluid on the melting and solidification processes in latent heat shell and tube storage system. Riahi et al. [4] undergone a comparative study of melting and solidification processes in different configurations of shell and tube high temperature latent heat storage system.

Chen et al. [5] studied the characteristics of the mixed convection heat transfer of molten salts in horizontal square tubes. Different sets of side heating conditions are done both experimentally and numerically to study the performance of mixed convection heat transfer of salts in the tubes placed horizontally. The experimental study on the bottom side heating is done and its correlation is predicted on comparison with the experimental data. Experimentally it was found that there is an increase in pump frequency when the molten salt flow rate and the Reynolds number increases. The numerical examinations are also performed in two-side heating conditions.

The enthalpy formulation during the charging process the conduction plays a major role and during the discharging process convection plays a major role. Parabolic dish solar collector (PDSC) is most beneficial to produce the medium temperature working fluids. Few studies carried out to effectively utilize the heat storage at the focus of the solar receiver [6-10]. Molten salt and thermochemical energy storage are investigated by several authors [11-15].

Chandrashekara and Avadhesh [16] conducted an experimental study of exfoliated graphite solar thermal coating on a receiver with a Scheffler dish and latent heat storage for desalination processes. The desalination system powered by solar power uses the EG coating on the receiver with Scheffler dish is developed for water production and it is compared to the system without EG coating. It was found that the productivity is enhanced and of about 13% is achieved in comparison to the receiver without EG coating. The receiver coating with Scheffler possess high thermal stability of 420ºC.

Anwar, et al. [17] constructed a thermal battery mimicking a concentrated volumetric solar receiver. The thermal battery uses metallic (Aluminium) meshes and PCM (LiNO3) in the energy storage medium. Uniform heating is provided by the rotation of the receiver (Symmetric axis). Thermal analysis related to TES is analyzed for the improvement of heat diffusion in the energy storage media and Aluminium mesh and $LiNO_3$ are incorporated in the receiver. The thermal and flow field in the receiver is simulated by Finite element code. Temperature remains high in the close region of the solar irradiation on the receiver.

Carlos et al. [18] performed a comparison between a group of thermal conductivity enhancement methodology in phase change material for thermal storage application. The thermal conductivity enhancement methods are employed in the literature such as conductive foams and finned pipes and applied on the system composed by a vertical pipe surrounded by the storage material. In order to obtain the comparative result, the PCM is kept at constant for all the cases. Specific fin pattern is more efficient than the transmission of heat than simple fin configurations. Aluminium fins have better performance than carbon steel ones and the sizing approach explains the opening new branch of fins are profitable than increasing the thickness.

Hassab et al. [19] analyzed the effect of volume expansion on the melting process's thermal behavior. The study of the influence of density change of PCM during the melting process on the heat transfer characteristics of the process at different boundary conditions. The two different models for the PCM melting process has been conducted. The step change in density has been taken into account to have the behavior of melting process characteristics and time. An enthalpy-porosity technique is used in Ansys-Fluent for modelling the process. Uniform heating process does not improve the natural convection of wax melting it leads to very high stratification.

Takahiro et al. [20] experimented microencapsulated phase change materials with high heat capacity and high cyclic durability for high temperature. Ibrahim et al. [21] done a critical review on the heat transfer enhancement of phase change materials for TES applications. In this paper various techniques of heat transfer enhancement in the latent heat TES system were discussed. The enhancement techniques may be achieved through either geometric configuration or thermal conductivity enhancement. The techniques for heat transfer enhancement are enhanced with fins, application of heat pipes, Multiple PCMs. Thermal conductivity is enhanced by dispersion of nanoparticles/high conductivity materials, dispersion of low-density materials.

John et al. [22] studied the cost optimization of dish solar concentrators for improved scalability decisions. A simple, cost model in which the structural problem is modelled mathematically and optimized for the minimum cost subject to wind-load resistance constraints. Pavlovic et al. [23] undergone an experimental investigation and parametric analysis of a solar thermal dish collector with spiral absorber. Solar collectors need some important considerations such as manufacturing costs, complexity, efficiency of the collector, uniform flux distribution and heat transfer fluid selection. The collector dish is designed at low cost and simple in structure with spiral absorber. By employing water as the working fluid, volumetric flow rate, inlet, outlet and ambient temperatures are measured.

Micheal et al. [24] undergone some investigations on thermochemical energy storage based on technical grade manganese-iron oxide in lab scale packed bed reactor. A packed bed granular manganese-iron oxide storage material in accordance to the heat and transport effects of mass in connection with chemical reaction is analyzed by using the experimental test rig. The material preparations are done in a good-mannered ratio, which should be a surplus and cost effective in nature. In experimental studies, thermal properties and kinetic properties of the redox reactions decides the development of the typical temperature profiles along the height of the bed. The process proceedings of the redox reactions during charging and discharging periods proves the stabilized temperature of the bed.

Erez et al. [25] examined the thermo-electro-chemical storage (TECS) of solar energy. By the thermal regenerative battery concept, a new approach for electricity generation and storage based on solar is proposed. The charging of the external thermo-chemical of the flow battery is by concentrating sunlight and the conventional electro-chemical discharge of the battery produces electricity. In commercially concentrated solar power plants (CSP) which leads to high conversion efficiency is that the steam turbine is replaced by battery. The discussion of the proposal is studied on the aspects of technical and economic feasibility.

Thibut et al. [26] have reviewed the experience feedback and numerical modelling of packed-bed TES systems and design, performance and operation characteristics were summarized. The importance of thermal stratification and storage systems controlling ability was studied in the first part and different numerical models for the system is reviewed in the second part. Finally, the necessary correlations involved in calculating the heat transfer coefficients between fluid-solid and fluid-wall followed by a pressure drop and the effective thermal conductivity in the storage system.

Moran et al. [27] analyzed and undergone optimization of melting temperature span for a multiple-PCM latent heat TES unit. In this the arrangement of PCM is in cascade form, internal melting of PCM takes place in the tube and the heat transfer fluid can flow across the tubes in the system. The parameters are examined based on the effect and they are velocity at the inlet, heat transfer fluid temperature, rows of PCM tube, count of materials and the time taken by the PCM to melt.

Taha et al. [28] compared the Single-PCM and Multiple-PCM TES design and predicted the better performance. Phase change material of different thermo-physical properties are filled in the capsules and made a bed of packed capsules placed in different sections because of PCM melting temperature. The increased rate of charging and discharging is obtained by the utilization of Multiple-PCM and the latent heat TES dynamic performance is improved simultaneously. The sections are utilized on different configurations by having a single type of PCM capsules and the next is followed by the division of the bed into two and different PCM of different melting temperature is used. Finally, the bed is divided into three sections and the PCM capsules with different melting points are arranged from high melting to low melting and vice versa in the bed sections.

Bingchen et al. [29] conducted an efficient tank estimation strategy for packed-bed thermocline TES systems for concentrated solar power. In this study, the reduction in the cost of the concentrated solar power plants is by the thermocline storage packed bed and it was found to be the promising technology. The tank size determination is performed to perform the design aspects of the CSP plant without undergoing the parametric analysis. The result is that the tank size estimation depends based on thermal behavior at periodic intervals.

Mehrdad et al. [30] undergone a study on the performance of heat storage and heat release of water storage tank with PCMs and they equipped the water storage tank with two types of PCMs posses different melting points. By simulation calculation, change in thickness of the phase change materials, the performance of the storage tank is increased. The system is arranged with three water storage tanks and for each tank, it is provided with different PCM contents and also proper circulating water system is arranged. The parameters such as storage time and heat release and total amount of heat release are considered in the study and found that the PCM with different melting point reduces the duration of storing heat.

Yantong Li et.al [31] provided an optimal design of the thermal storage tank with PCM and the application for the seasonal conditions and increasing the performance of the storage tank. The optimization of the tank includes specification, decision variables, platform for computer simulation and decision-making process at the end. The volume of the PCM storage tank is minimized by the application of general procedure to the open-air swimming pool. The computer simulation platform was done using MATLAB and TRNSYS for the investigation on decision variables and its effects on the storage tank volume. Case concludes the fact that storage tank volume is reduced without affecting the capacity of the thermal storage.

Reddy et al. [32] have reviewed the latent heat energy storage for the improvement of material stability and load management in an effective manner. The assistance of both economic and environmental benefits in the platform of large-scale energy demand is overwhelmed by the utilization of phase change materials as TES. This article reviews parameters such as functional principle, thermo physical properties and other important material properties. The discussion on the interaction of the storage material with phase change material for long term stabilization was done and techniques such as thermal conductivity and heat transfer to improve the latent TES was done.

Based on the summary of the literature review, the objectives formed, and the experimental methodology was adopted as per the literature. The need of a TES system for solar parabolic dish collector system is proposed. It is observed that due to fluctuation of solar radiation the steam energy produced is not completely utilized, the need of energy does not match with the supply of energy. Hence, a lump sum amount of energy is being wasted daily; one of the ways to meet the demand is to store energy. Solar energy is one of the renewable forms of energy and it is preferred as an alternative energy source for various domestic and industrial applications.

The uniqueness of thermal energy storage (TES) is the easy coupling to the generation of energy through renewable systems with dispatchability. The efficient utilization and energy harnessing process of solar energy is one of the challenges. The selection of solar collectors depends on the application temperature and heat quantity.

2 MATERIALS AND METHODS

Much geometry has been adopted, analyzed and studied in TES systems for solar parabolic dish system having 16 meter-square aperture area with temperatures ranging from 60°C – 120°C. Those methods will be considered while designing the TES system and the best cost effective, efficient TES systems. The TES experimental setup consists of a cylindrical solid aluminum and cylindrical PCM containers inside the receiver.

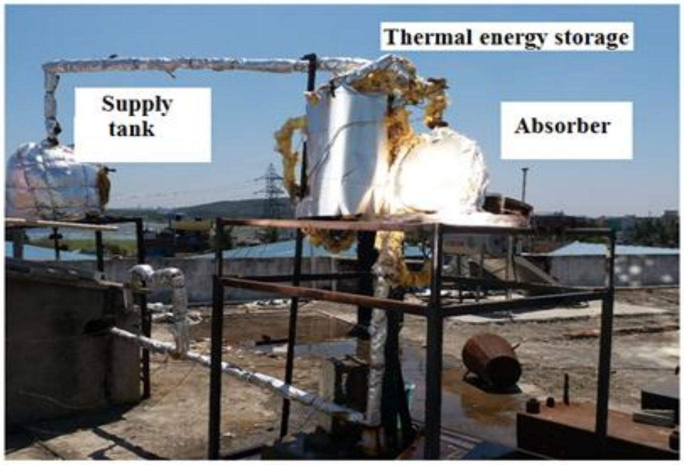

Figure 1. Solar absorber and thermal energy storage

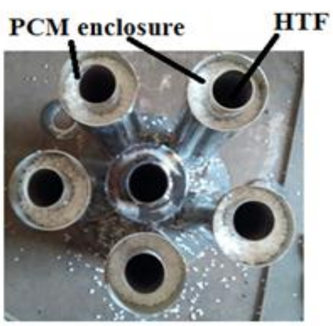

Figure 2. PCM container and HTF tube without outer cover

The heat transfer fluid is supplied to the receiver through the pipelines, supply length is reduced so that the heat loss can be optimized during the transfer of hot HTF from receiver to that of the inlet of the storage tank. The setup is provided with two inlets and outlets for the supply of hot water and cold water along the surface of the cylindrical tank and along the sides of the staggered concentric tubes filled with phase change material. Thermocouples placed in various places of the entire setup for the precise understanding of the heat transfer characteristics and the values are collected by the Data logger. The experiment is followed in different pathways to evaluate the exact storage capacity of the thermal system. The experiment is conducted by different flow rates of 120, 150, 180 kg/h on varied radiation conditions.

Paraffin wax (RT 50) was chosen as the PCM considering the required temperature range of energy storage. Paraffin wax has the melting point around 55°C which favors the conditions of storing heat below the boiling point of water and well above the ambient temperature. During solidification, paraffin does not exhibit any sub cooling effects and during the transition from one phase to another, it has only a negligible volume change. They are stable over a wide range of temperatures and non-corrosive for a very large time period. This allows the selection of paraffin from its wide varieties according to the system specification and requirements.

There is a wide range of paraffins with varying thermodynamic and chemical properties available. The feasibility of paraffin wax in the market and its economic feasibility have favored its preference over other PCMs. Properties of paraffin wax are given in Table 1.

TABLE 1.

Properties of Paraffin Wax

Properties	Values
Melting temperature	55 °C
Density	900 kg/m^3
Thermal conductivity	0.26 W/m-K
Latent heat	186 J/g
Specific heat	2.05 J/g K

The PCM melting takes place inside the receiver and retains the heat by its phase change. The receiver reaches uniform temperature due to PCM and then the heat transfer fluid (HTF) is passed through the heat transfer tubes, the heat is exchanged from the receiver to the working fluid (air or water). Thus, in the morning the solar energy is utilized as a heat source and it is then self-sustained for integrated heat storage over aluminum cylinder, during night hours, we used as steam boiler to convert water into steam up to Paraffin wax gets solid. By insulating the entire setup, we can store the heat energy within the cylinder itself.

The Collector efficiency of the Scheffler parabolic dish collector is considered as the ratio of the instantaneous heat gain by the HTF and the instantaneous incident beam radiation from the sun (I_b) on the given aperture area (A_c) of the Scheffler collector.

$$\eta = \dot{m}_{HTF} \, C_{p\,HTF} \, (T_o - T_i) / (I_b \, A_c)$$

Where, A_c represents the area of the reflector, T_o and T_i represent the temperature of the HTF at the receiver outlet and inlet measured at any instantaneous time. $\dot{m}_{HTF}$ represents the mass flow rate of the HTF.

3 Results and Discussion

The solar radiation, average wind speed and ambient temperature are laid in the range of 430 – 560 W/m^2, 0 – 1 m/s and 28 – 38 °C respectively for the repeated experiments. The outdoor tests are conducted on Sunny days. The hot water coming out of the solar collector is used to heat the receiver materials. During the outdoor testing, water around 80 °C is used to heat the storage system.

The PCM temperature was observed stable at its melting range. Energy stored in the Al receiver with PCM is the sum of energy stored in Aluminum as sensible heat and energy stored in the PCM. Figure 3 shows the variation of concentration ratio over a year due to the position of the Sun.

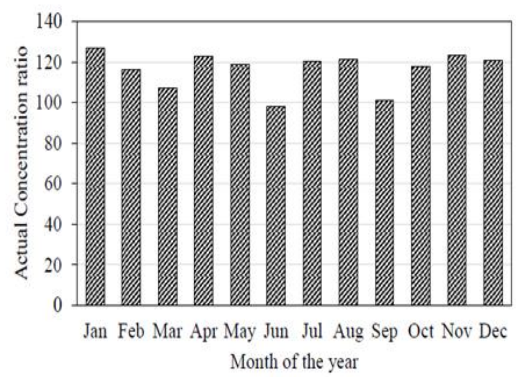

Figure 3. Variation of concentration ratio over ayear

The solar absorber and TES subjected to HTF flow rate of 25 kg/h at a temperature around 80 °C. The discharging of thermal storage was conducted by passing HTF flow rate of 25 kg/h through the receiver. The solar beam radiation was observed using pyranometer in the range of 520 – 850 W/m^2 at the test site. HTF flow rate tested are 120, 150 and 180 kg/h durignthe outdoor tests. The average ambient temperature was around 34.5 °C. The heat transfer flow rate was regulated by a feed water pump and valve arrangement.

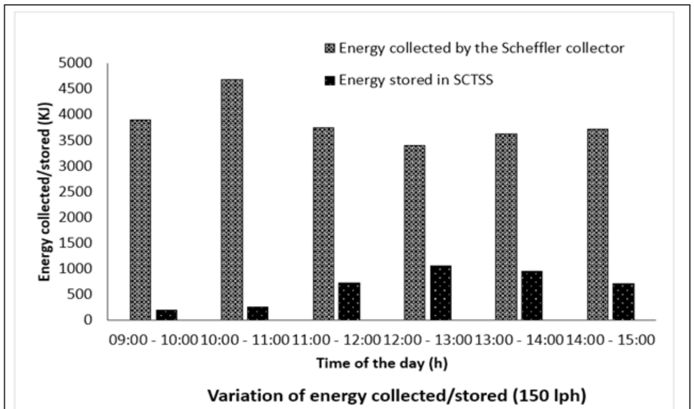

Figure 4. Variation of hourly energy collected/stored for 150lph

Figure 4 shows the energy stored in a sensible and latent form during experimental trials. The energy density is responsible for the heat storage variation in both receiver material and PCM based storage tank. Heat stored in the PCM increases when PCM undergoes a phase change process after two hours of operation. The peak collector efficiency is 57% for the HTF flow rate of 180 kg/h and the overall system efficiency including TES is 75%. The average wind speed during the outdoor testing days. Figure 5 shows the energy efficiency of the overall thermal system with respect to HTF flow rate through the receiver and the storage tank. The storage tank placed near the solar receiver, reduced the heat transport losses.

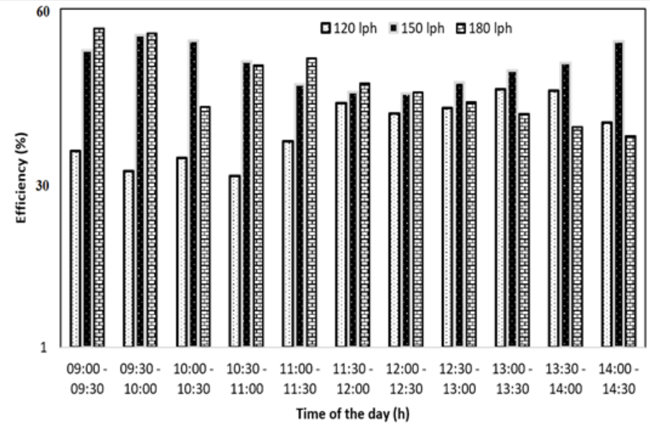

Figure 5. Variation of collector efficiency (120 lph,150 lph, 180 lph)

Figure 6 shows the variation of collector, charging and overall efficiency of the collector-storage system. The overall efficiency is observed more with the PCM. The increase in the amount of energy stored by the PCM in the TES indicates a corresponding increase in the charging efficiency.

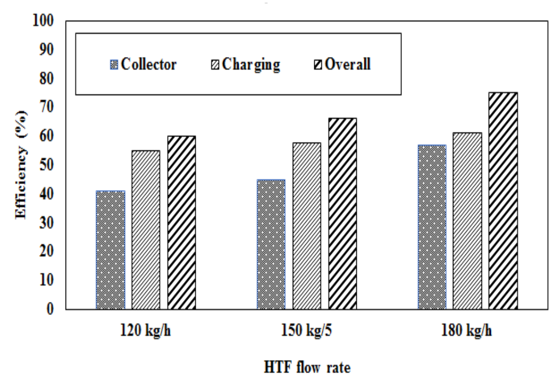

Figure 6. Collector, PCM charging and overall efficiencies

The collector efficiency varies proportionally with the useful heat gain by the Scheffler collector, i.e. The incident beam radiation acts as a major factor influencing the amount of energy collected by the Scheffler collector.

The overall system efficiency is also influenced by the incident beam radiation comparatively more than the volume flow rate. The collector efficiency increases with increase in HTF mass flow rate. The peak collector efficiency is 57% for the HTF flow rate of 180 kg/h and the overall system efficiency including TES is 75%.

Melting and solidification processes in the storage system, depending on various parameters such as flow rate of the heat transfer fluid, selection of PCM, arrangement of the tubes filled with PCM, the initial temperature of the fluid entering the system, melting temperature of the PCM

4 CONCLUSION

The study of the thermal performance of the parabolic dish concentrator by the prediction of the optical effect and evaluated the receiver with and without working fluid and the examination is done to obtain the maximum temperature of the absorber.

The peak collector efficiency is 57% and the overall system efficiency including TES is 75% for the HTF flow rate of 180 kg/h. The outdoor testing of the fabricated thermal storage with the solar collector proved that the latent heat combined thermal storage is useful to store the intermittent solar thermal energy near the solar absorber with a minimum heat transport loss.

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