International Journal on Emerging Technologies **1**(2): 125-132(2010)

ISSN No. (Print): 0975-8364

High Performance Solar Energy Latent Heat Thermal Storage system

Jairam Rajak
Lecturer in Electrical Engineering,
Government Polytechnic College, Shahdol (M.P.), India.

(Received 04 May 2010 Accepted 29 July, 2010)

ABSTRACT: In This Paper presents Latent heat storage is one of the most efficient ways of storing thermal energy. Unlike the sensible heat storage method, the latent heat storage method provides much higher storage density, with a smaller temperature difference between storing and releasing heat. This work on latent heat storage and provides an insight to recent efforts to develop new classes of phase change materials (PCMs) for use in energy storage. Three aspects have been the focus of this PCM materials, encapsulation and applications. There are large numbers of phase change materials that melt and solidify at a wide range of temperatures, making them attractive in a number of applications. Paraffin waxes are cheap and have moderate thermal energy storage density but low thermal conductivity and, hence, require large surface area. Hydrated salts have larger energy storage density and higher thermal conductivity but experience super cooling and phase segregation, and hence, their application requires the use of some nucleating and thickening agents. The main advantages of PCM encapsulation are providing large heat transfer area, reduction of the PCMs reactivity towards the outside environment and controlling the changes in volume of the storage materials as phase change occurs. The different applications in which the phase change method of heat storage can be applied are also reviewed. The problems associated with the application of PCMs with regards to the material and the methods used to contain them are also discussed. All rights reserved. Finally, based on the, a more detailed design of the device is proposed.

Keywords: High-temperature thermal energy storage; Thermocline storage; Packed bed; Industrial scale design; Concentrated solar power.

I. INTRODUCTION

A suitable phase change temperature and a large melting enthalpy are two obvious requirements on a phase change material. They 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 grouped into physical, technical, and economic requirements [1]. Physical requirements, regarding the storage and release of heat Suitable phase change temperature to assure storage and release of heat in an application with given temperatures for heat source and heat sink. Large phase change enthalpy pch to achieve high storage density compared to sensible heat storage. Reproducible phase change, also called cycling stability to use the storage material as many times for storage and release of heat as required by an application. The number of cycles varies from only one, when the PCM is used for heat protection in the case of a fire, to several thousand cycles when used for heating or cooling of buildings. One of the main problems of cycling stability is phase separation. When a PCM consists of several components, phases with different compositions can form upon cycling. Phase separation is the effect that phases with different composition are separated from each other macroscopically [2]. The phases with a composition different from the correct initial composition optimized for heat storage then show a significantly lower capacity to store heat. Little sub cooling to assure that melting and solidification can proceed in a narrow temperature range. Good thermal conductivity to be able to store or release the latent heat in a given volume of the storage material in a short time, that is with sufficient heating or cooling power [3, 4]. If a good thermal conductivity is necessary strongly depends on the application and the design of the storage. Technical requirements, regarding the construction of a storage Low vapor pressure to reduce requirements of mechanical stability and tightness on a vessel containing the PCM Small volume change to reduce requirements of mechanical stability on a vessel containing the PCM Chemical stability of the PCM to assure long lifetime of the PCM if it is exposed to higher temperatures, radiation, gases Compatibility of the PCM with other materials to assure long lifetime of the vessel that contains the PCM, and of the surrounding materials in the case of leakage of the PCM This includes destructive effects as for example the corrosively of the PCM with respect to other materials, but also other effects that significantly reduce or stop important functions of another material [5].

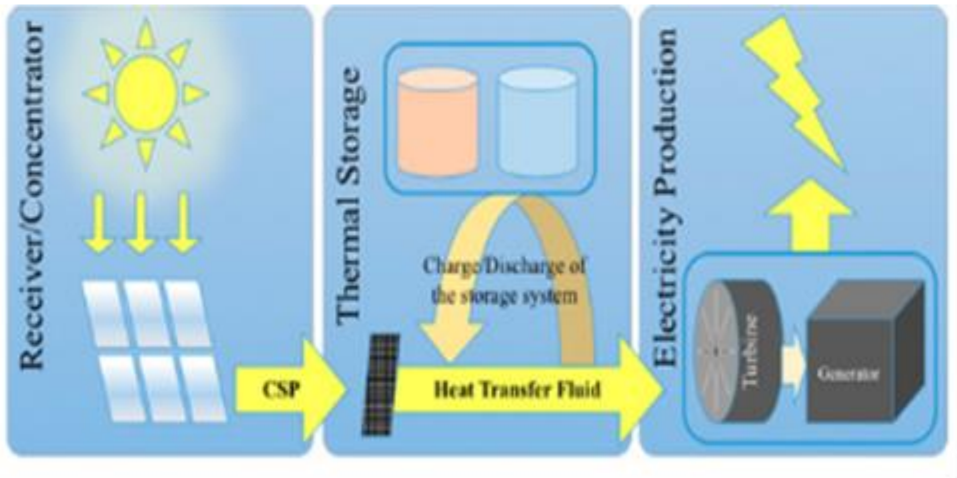

Fig. 1. Schematic of proposed integrated thermochemical storage system.

Safety constraints the construction of a storage can be restricted by laws that require the use of non-toxic, non-flammable materials. Other environmental and safety consideration can apply additionally.

Integrated Thermochemical Storage System

In combination with renewable energy sources, such as solar heat and waste heat, thermochemical sorption reactions can supply required space heating, cooling and domestic hot water the objective of the work for the past years was and is to develop, demonstrate and evaluate a compact seasonal thermochemical heat storage system based on novel high-density materials. An initial test reactor was built using the sorption pair zeolite-water for vacuum operation. The focus was to study the behaviour of a small thermochemical storage system as well as components and material stability in the range of 10-130 °C in an evacuated system. Both loading and unloading of the thermal store is tested thoroughly, yielding information on temperature levels required and obtained, storage capacity, energy density and output power, as well as on possible heat and mass-transfer limitations [6]. The model is a semi-physical model with a few parameters that have to be determined with parameter identification from measured data. These parameters are the UA-values for the heat exchangers (adsorber and evaporator/condenser) and a UA-value for the sensible heat losses from the sorption storage tank to ambient. Otherwise it is based on energy and mass balances and the physical properties of the sorption material. The main assumptions of the model are. It is a single node model and there is no time dependency of adsorption and desorption processes How accurate these assumptions are depends very much on the used heat exchanger that brings in the heat to the reactor and takes out heat. The tested store contained a spiral heat exchanger consisting of sheet copper and pipes soldered to it [7]. The distance between the sheet copper layers was approximately Laboratory measurements have shown that the assumptions mentioned above are reasonable for this setup. Therefore, it is assumed that the simulated store contains a heat exchanger with a similar setup to the one tested. However, up and downscaling cannot be done easily because the UA-values of the heat exchangers and for the store heat losses have to be derived from measurements. For the simulations presented in this assumptions have been made but this is a major limitation of the model. Energy storage technologies have long been a subject of great interest to both academia and industry [7]. The aim of this project is to develop a novel, cost effective and high performance Latent Heat Thermal Energy Storage System (LHTESS) for seasonal accumulation of solar energy in increased quantities. The major barrier for currently used Phase Change Materials (PCMs, organic and hydrated salts) is their very low heat conduction coefficient, low density, chemical instability and tendency to sub-cooling. Such inferior thermo-physical properties large dimensions and not having a capacity to provide the necessary rate of heat re-charge and discharge, even with highly developed heat exchangers [8]. The new approach to overcome the above issues is the deployment of low grade, eutectic low melting temperature metallic alloys (ELMTAs). The ELMTAs are currently produced for application in other areas and have not been actively considered for the thermal energy accumulation with the exception of very limited studies. Their heat conduction is two orders of magnitude greater than that of conventional PCMs, they are stable and provide the thermal storage capacity which is 2-3 times greater per unit of volume. The project consists of both theoretical and experimental investigations. A range of low grade ELMTAs for application in LHTESS will be selected and Differential Scanning Calorimetry will be used to measure their thermal properties. Thermal cycling tests of such alloys will be conducted.

Numerical investigations of heat transfer and flow in the LHTESS with ELMTAs will be performed. Experimental studies of heat transfer and flow in a laboratory prototype of the LHTESS with ELMTAs will be conducted [9]. As outcomes of investigations, dimensionless heat transfer correlations will be derived and design recommendations for a practical solar energy seasonal LHTESS with the low grade ELMTA will be produced for project industrial partner In recent years, where the world is straying away from harmful and environmentally damaging methods of harvesting energy such as fossil fuels, there has been a lot of development on renewable technologies [10]. Many of these, including for instance wind and solar energy systems, are intermittent and volatile in nature In order to exploit the true potential of these energy collection methods, it is necessary to pair them with other existing technologies that enable their further usage and availability, while mitigating the gap that exists between the consumers and the providers. Out of all the available storage solutions, this paper discusses the use of Thermal Energy Storage (TES) to balance the disarray.

B. MATERIALS AND METHODS

In this paper, hypothetical TES materials were studied in order to evaluate the effect of individual thermal properties on charging heating dynamics. Water was selected as the heat transfer fluid (HTF) due to its well-known and favorable thermal properties (low cost, high specific heat, thermal conductivity etc. and its effectiveness with the system's operating temperature range. The system consists of a packed bed containing PCM in encapsulated spheres and the analysis focuses on the charging aspect and influence of specific material parameters on the system performance. Thermal energy storage (TES) system is the most eminent storage method that aids in the power generation. Latent heat storage (LHS) is on the rapid mark-up that fosters the TES with the utilization of the phase transition of a material to store the heat. Typically the phase change materials (PCM) are used in the LHS system to store the energy. During the material's phase transition, thermal energy is stored and released. Nevertheless, the low thermal conductivity of the PCM in the LHS is susceptible to deteriorate the charging and discharging of the thermal energy. Hence there is a necessity to enhance the thermal performance of the LHS system, on which various studies have been done. Therefore this paper aims in providing a review on the enhancements of the LHS system with improved heat transfer rate and heat transfer enhancement techniques in the PCM for better efficiency. A comprehensive review on the LHS system component is provided to make an emphasis on the heat transfer enhancement rate and storage time. Various characterizations and categories of the PCM are provided to intensify the outcomes of the review as PCMs are most viable materials for storing thermal energy. In addition the recent researches on the integration of PCM with other materials are also discussed that help in the improvements of the thermal conductivity of the PCM. The selection parameters of the PCM materials are also discussed in brief to avoid the poor performance of the PCMs [11]. The heat transfer analysis methods are analyzed to improve the efficiency and reduce the heat loss. Finally, advancements in the future trends for the enhancement of heat transfer is provided. In this study, experiments were conducted on a cylindrical-shaped Thermal Energy Storage (TES) system for a novel Concentrating Solar Power (CSP) falling particle receiver system. The TES is to be used for storing heated solid particles. The main objective of the study was to evaluate the thermal performance of some candidate materials of construction for the walls of TES Hot-bin. In particular, emphasis was on the calculation of the rate of heat loss over a prescribed period of time, since this parameter was critical to the overall performance of a high-temperature solar energy plant. The construction materials were selected in order to have low thermal conductivity and the ability to withstand cyclic high temperatures without failure. An experiment was continuously run in which the temperature was maintained at about 300 °C, 500 °C, and 700 °C respectively, allowing steady state conditions to be achieved for sustained period of time. To simulate the presence of a high temperature storage material, a heater inserted in the center line of the interior of the Hot-bin, and the thermocouples were installed to measure the temperatures at various locations throughout the composite that the thermal conductivity of insulating firebrick remains low (approximately 0.22 W/m·K) at an average layer temperature as high as 640 °C, but it was evident that the addition of mortar had an impact on its effective thermal conductivity. Results also show that the thermal conductivity of perlite concrete is very low, approximately (0.15 W/m·K) at an average layer temperature of 360 °C. This is evident by the large temperature drop that occurs across the perlite concrete layer. Due to the large daily ambient temperature swing, a measurement of the thermal conductivity of reinforced concrete was estimated by applying a 3D model of the reinforced concrete layer. Thermal conductivity of the reinforced concrete layer is about 1.936 W/m·K at ann average temperature 52.5 °C. Based on the estimated thermal conductivity values of layers, heat loss was found to be 1.39%, 2.58% and 4.59% at 300 °C, 500 °C and 700 °C respectively. Furthermore, inspection of the materials used to construct the TES system showed that they remained intact and did not show signs of cracking or wearing [12].

These that the high-temperature TES systems can be constructed of readily available materials and yet meet the heat loss requirements for a falling particle receiver system, thereby contributing to reducing the overall cost of concentrating solar power systems. An important secondary outcome of this study is building a database for the thermal conductivity of some masonry materials at high temperatures be useful for future studies, especially those that focus on numerical modelling of TES bins. The conversion efficiency of a photovoltaic (PV) cell, or solar cell, is the percentage of the solar energy shining on a PV device that is converted into usable electricity [13]. Improving this conversion efficiency is a key goal of research and helps make PV technologies cost-competitive with conventional sources of energy.

Factors Affecting Conversion Efficiency

Not all of the sunlight that reaches a PV cell is converted into electricity. In fact, most of it is lost. Multiple factors in solar cell design play roles in limiting a cell's ability to convert the sunlight it receives. Designing with these factors in mind is how higher efficiencies can be achieved.

Wavelength—Light is composed of photons—or packets of energy—that have a wide range of wavelengths and energies. The sunlight that reaches the earth's surface has wavelengths from ultraviolet, through the visible range, to infrared. When light strikes the surface of a solar cell, some photons are reflected, while others pass right through. Some of the absorbed photons have their energy turned into heat. The remainder have the right amount of energy to separate electrons from their atomic bonds to produce charge carriers and electric current.

Recombination—One way for electric current to flow in a semiconductor is for a "charge carrier," such as a negatively-charged electron, to flow across the material. Another such charge carrier is known as a "hole," which represents the absence of an electron within the material and acts like a positive charge carrier. When an electron encounters a hole, they may recombine and therefore cancel out their contributions to the electrical current. Direct recombination, in which light-generated electrons and holes encounter each other, recombine, and emit a photon, reverses the process from which electricity is generated in a solar cell [14]. It is one of the fundamental factors that limits efficiency. Indirect recombination is a process in which the electrons or holes encounter an impurity, a defect in the crystal structure, or interface that makes it easier for them to recombine and release their energy as heat.

Temperature—Solar cells generally work best at low temperatures. Higher temperatures cause the semiconductor properties to shift, resulting in a slight increase in current, but a much larger decrease in voltage. Extreme increases in temperature can also damage the cell and other module materials, leading to shorter operating lifetimes. Since much of the sunlight shining on cells becomes heat, proper thermal management improves both efficiency and lifetime.

Reflection—A cell's efficiency can be increased by minimizing the amount of light reflected away from the cell's surface. For example, untreated silicon reflects more than 30% of incident light. Anti-reflection coatings and textured surfaces help decrease reflection. A high-efficiency cell will appear dark blue or black.

Determining Conversion Efficiency

Researchers measure the performance of a PV device to predict the power the cell will produce. Electrical power is the product of current and voltage. Current-voltage relationships measure the electrical characteristics of PV devices. If a certain "load" resistance is connected to the two terminals of a cell or module, the current and voltage being produced will adjust according to Ohm's law (the current through a conductor between two points is directly proportional to the potential difference across the two points). Efficiencies are obtained by exposing the cell to a constant, standard level of light while maintaining a constant cell temperature, and measuring the current and voltage that are produced for different load resistances. The perlite concrete layer, whose thermal performance is least known in the literature, exhibited superior thermal performance, with its thermal conductivity being as low as 0.15 W/m•K, even at an average layer temperature of more than 350 °C. While thermal conductivity of reinforced concrete estimated from 3-D simulation model due to large variation of ambient temperature at average temperature 52.2 °C.

These should be useful for future studies, especially those that focus on numerical modeling of TES bins. Finally, it is worth noting that the thermal mass of the wall construction tested in this study was very high. This is evident from the fact that the time needed to achieve steady-state conditions was one week or more. Given that the operating cycle of a typical CSP plant is 24 h, it is clear that TES bins designed for high temperatures will always operate in a transient mode. literature, exhibited superior thermal performance, with its thermal conductivity being as low as 0.15 W/m•K, even at an average layer temperature of more than 350 °C. While thermal conductivity of reinforced concrete estimated from 3-D simulation model due to large variation of ambient temperature at average temperature 52.2 °C which equal 1.936 W/m•K. These results should be useful for future studies, especially those that focus on numerical modeling of TES bins. Finally, it is worth noting that the thermal mass of the wall construction tested in this study was very high.

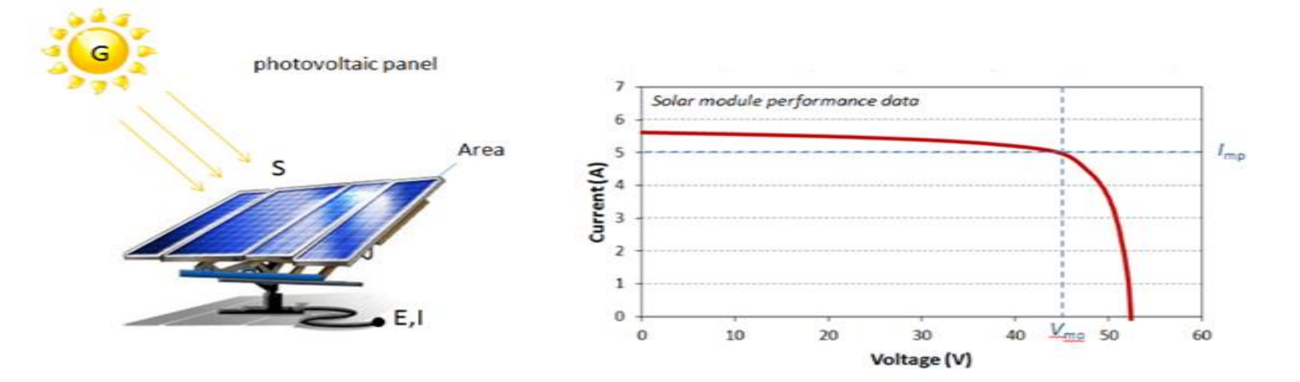

Fig. 2. The connection of efficiency with performance solar module.

This is evident from the fact that the time needed to achieve steady-state conditions was one week or more. Given that the operating cycle of a typical CSP plant is 24 h, it is clear that TESbins designed for high temperatures will always operate in a transient mode. Fossil fuels, increased world energy demand and swelling of environment pollution drive a transition towards renewable energy resources which can deliver 3E objectives (Economic, environmental and energy security). However, the inherent intermittency necessitates efficient energy storage systems to harness the true potential of renewable resources. In this context, high-temperature latent heat storage (LHS) using phase change medium (PCM) can be a promising alternative to address the challenges of the variable renewable energy generation with respect to time and space. Currently, central receiver-based 3rd Gen concentrated solar thermal (CST) plant operating at high-temperatures (800-1000 °C) is the most attractive technology to convert solar energy to heat. Moreover, advanced power-generating cycles such as supercritical CO2 (sCO2) Brayton cycle operating at high-temperature can reduce the Levelized cost of Energy (LCoE) by achieving higher cycle efficiency. Hence, coupling a high-temperature LHS between the central receiver system and sCO2 cycle can have dual benefits: increase in dispatchability of energy and reduction in LCoE. Furthermore, high-temperature LHS can be devised to store high-grade energy such as spillage of energy from Photovoltaic (PV), wind power plant, and waste heat from energy-intensive industries (e.g. glass melting furnace). This article reports a holistic approach to review different components and design aspects of high-temperature LHS with techno-economic challenges to be overcome. A preliminary numerical study has been performed to predict the melting behavior of high-temperature silicon using COMSOL Multiphysics. Based on the review, two configurations of high-temperature LHS have been illustrated to produce continuous and cost-effective electricity.

Fig. 3. Energy sources, such as wind and solar, emit little to no greenhouse gases, are readily available and in most cases cheaper than coal, oil or gas fossil fuels, increased world energy.

The first layout is high-temperature LHS coupled with 3rd generation (Gen) CST and the second one is a standalone high-temperature LHS device with Thermionic-photovoltaic (TIPV) diode. The demand and supply of energy go hand in hand, however, major consequences of the increasing energy demands are the depletion of fossil fuel reserves and their impact on the environment. In the current scenario, the energy sector is plausibly dependent upon natural resources for minimizing the instability in the market. Among all the renewable energy resources, solar energy is one of the most prominent sources due to its ample availability and use in numerous applications such as thermal comfort in buildings, solar water heating, solar cooking, solar drying and power generation. Due to the intermittent nature of solar energy, it cannot meet a continuous supply and storage of energy becomes essential. Thermal energy storage (TES) acts as a temporary reservoir to store energy and assist the operation of the application system during peak demand. This enables stable grid performance added with a decreased reliance on non-renewable energy resources. Concentrated solar power (CSP) technology integrated with TES is a promising solution to develop a stand-alone renewable power generation system. Thermal energy can be stored by various methods; Sensible, Latent and Thermochemical storage. Among all, latent heat storage (LHS) is the most customary storage technique due to its relatively high energy density and a wide range of operating temperatures. LHS systems use phase change materials (PCMs) which absorb the energy due to phase change for energy storage. The isothermal behaviour of phase change leads to a stable power output delivered by the PCMs. Since the thermal conductivity of most PCMs is generally low (0.1^{-1} W m^{-1} K^{-1}), most of the research works have focused on improving the thermal performance of LHS systems. The present research work explores the high-temperature LHS systems keeping in mind their integration to applications such as CSP and direct steam generation (DSG). The design, development and performance investigations of high-temperature LHS systems have been scarcely reported in the literature. The thesis work focusses on two major objectives; (i) Thermal modelling, design, development and testing of high-temperature shell and multi-tube and fin and non-finned encapsulated PCM LHS systems. (ii) Development of novel LHS system designs to improve the heat transfer rate in conventional high-temperature LHS systems. To conduct the performance investigations of high-temperature LHS systems, we have designed and developed an experimental test facility at the Indian Institute of Technology Guwahati. The system uses air as the heat transfer fluid (HTF) suitable for maximum operating temperatures and flow rates of 450 ºC and 120 m3/h, respectively. Sodium nitrate with a melting temperature of 305 ºC is chosen as the PCM. To study the charging and discharging heat transfer behaviour of the LHS system, experimentally validated 2-dimensional (2D), 2D axi-symmetric and 3D numerical models were developed for different geometries using the commercial modelling software COMSOL Multiphysics. To develop a shell and multi-tube LHS system (storage capacity: ~20 MJ), a 2-dimensional (2D) numerical model was developed to study the heat transfer characteristics of a multi-tube heat exchanger. Three LHS configurations with 13 (1-inch), 17 (3/4-inch) and 25 (1/2-inch) HTF tubes were modelled by fixing the PCM quantity and the HTF tube surface area. The natural convection was neglected for the discharging model. It was found that by increasing the HTF tubes from 13 to 25, the charging and discharging times were reduced by 20% and 48%, respectively. Based on the modelling study, a multi-tube LHS module with 25 HTF tubes was fabricated and experimental investigations were conducted to study the axial/radial temperature distributions, and performance parameters such as charging/discharging time, energy stored/discharged and output power by varying the flow rate and inlet temperature of the air. To test the performance of high-temperature cylindrical PCM encapsulations (storage capacity: ~0.6 MJ), five different designs were fabricated namely; basic annular annular capsule with straight longitudinal fins annular capsule with tapered longitudinal fins having a decreasing height and annular capsule with tapered longitudinal fins having an increasing height and numerical investigations were carried out to compare the charging and discharging performances of basic and annular capsules (capsule with hole). The results show that adding a hole in the basic capsule leads to better surface contact due to an increase in the heat transfer area and improves the flow dynamics of the incoming air. Further, experimental investigations were conducted to estimate the charging and discharging performances of all the Cases 1-5 by varying the air inlet flow rate and temperature during charging and discharging. To improve the charging and discharging heat transfer rates in conventional shell and tube LHS systems, two heat transfer enhancement techniques with simple design modifications such as effective PCM and fin distribution along the length of conventional shell and tube LHS are proposed. In the first enhancement technique, the design of the LHS system is modified from a cylindrical shell to a conical shell LHS system [15]. A numerical model of the 3D geometry was developed to analyze the charging and discharging characteristics of both designs. The system comprises of single HTF tube system with Sodium Nitrate as the PCM in the shell side and air as the HTF. The shell dimensions were varied by changing the cone angle and fixing the total PCM volume (or fixed LHS capacity).

The conical shell system with a cone angle of 3.4° was found to reduce the charging/discharging times by 17%/28% than the conventional cylindrical shell system. The improvements in the heat transfer rates occur due to the uniform melting and solidification along the system length due to the effective distribution of PCM. Further, the effect of adding straight or tapered fins attached to the HTF tube on the performance of the conical shell system was also analyzed. In the second enhancement technique, a 2D axi-symmetric numerical model of a vertical shell and tube LHS system comprising of three blocks of PCMs having melting point temperatures 360 °C, 335.8 °C and 305.4 °C, respectively, is developed. A non-uniform distribution of fins in three PCM blocks is initially employed to study the performance of the single PCM system (335.8 °C). The effect of inlet HTF temperature on the charging and discharging performances of the single PCM and multiple PCM (m-PCM) systems were analyzed by varying a Stefan number parameter, calculated based on the single PCM system. The charging and discharging times for the m-PCM system are either similar or lesser than the single PCM system for, however, there is an improvement of 21-25% in the specific energy charged and discharged by the m-PCM system for all the values (0.5, 1, 1.5 and 2) considered. By employing a compound enhancement technique, which is a combination of nonuniform fin-distribution and PCM blocks length ratio optimization for the m-PCM system, 30% and 9% reduction in the charging and discharging time, respectively, over the single PCM system is achieved [16]. The work highlights the performance of high-temperature LHS systems. The developed LHS systems can be integrated to high-temperature applications such as CSP and DSG. The important parameters affecting the performance of the LHS system are studied based on experimental and numerical investigations. The research works on high-temperature LHS systems are presently limited and the research output from the present investigations will serve as a benchmark for the development of high-temperature TES devices in the future. The different heat transfer enhancement techniques proposed in the thesis work are simple and can be effectively employed to improve the performances of high-temperature LHS systems.

III. CONCLUSION

This study presents the demand and supply of energy go hand in hand, however, major consequences of the increasing energy demands performed on a TES bin that is primarily designed to work at high temperatures that is compatible with the CSP falling particle heating receiver concepts. The importance of the study stemmed from the need to have a database of the thermal performance of suitable refractory masonry materials at high temperatures by which to construct TES bins. This database would help in modeling similar high-temperature TES systems in larger scale plant applications. This experimental apparatus consisted of a cylindrical-shaped bin that has multi-layered walls consisting of insulating firebrick, perlite concrete, expansion joint, and reinforced concrete, which was meant to validate a full scale TES storage unit to be incorporated into a complete pilot power generation cycle implemented on the RTV tower. For elevated temperature testing, the electric heater was placed at the centreline of the bin, and a multitude of thermocouples are used to take temperature measurements between all layers. The electric heater was set to different power levels that corresponded to pre-selected interior temperatures; namely, 300 °C, 500 °C, and 700 °C. Once steady-state conditions were achieved, the rate of heat loss was calculated across the expansion joint. With this information, the thermal conductivity of the remaining layers was calculated. The thermal conductivity of insulating firebrick is generally low, and it remains low even at an average layer temperature as high as 640 °C (approximately 0.22 W/m·K). However, this value is somewhat higher than the thermal conductivity values cited by the manufacturer, probably due to the addition of mortar.

REFERENCE

[1]. Bales, C. (2005). “IEA Task 32 Subtask B Report 2: Thermal Properties of Materials for Thermo-chemical Storage of Solar”, http:// www.iea-shc.org.

[2]. Furbo S., Andersen E. and Schultz, J.M. (2006). “Advanced storage concepts for thermal systems in low energy buildings. Slutrapport.” Report no. SR-06-01. Department of Civil Engineering, Technical University of Denmark, can be downloaded from: http://www.byg.dtu.dk/Forskning/hentned.aspx.

[3]. Gantenbein, P. (2006). Adsorption speed and mass transfer zone analysis of water vapour on the solid sorbent materials zeolite and silicagel with the focus on the heat exchanger.

[4]. Hadorn, J.C. (2006). “IEA solar and heating programme task 32: advanced storage concepts for solar and low energy buildings”, Proceedings of Ecostock, Galloway, NJ.

[5]. Hauer, A. (2008). “Sorption Storages for Solar Thermal Energy—Possibilities and Limits”, Proceedings of Eurosun, Lisbon, Portugal.

[6]. Heimrath, R. and Haller, M. (2007). “The Reference Heating System, the Template Solar System of Task 32, a Report of IEA Solar Heating and Cooling programme.

[7]. Adinberg, R. and Epstein, M. (2007). Conception and design of a thermal energy storage system, Proceedings of the 5th IASME/WSEAS Int. Conference on Heat Transfer, Thermal Engineering and Environment, Athens, Greece, August 25-27, 2007.

[8]. Abhat, A. (1983). Low temperature latent heat thermal energy storage – heat storage materials. *Solar Energy*, **30**(4), pp. 313-332.

[9]. Michels, H. and Pitz-Paal, R. (2006). Cascaded latent heat storage for parabolic trough solar power plants. *Solar Energy*, Vol. **81**(6), pp. 829-837.

[10]. Pacheco, J.E. (2002a). Final Test and Evaluation Results from the Solar Two Project, Sandia National Laboratories Report, SAND2002-0120.

[11]. Pacheco, J.E., Showalter, S.K. and Kolb, W.J. (2002b). Development of a molten-salt thermocline thermal storage system for parabolic trough plants. *ASME Journal of Solar Energy Engineering*, Vol. **124**, pp. 153-159.

[12]. Pitz-Paal, European Concentrated Solar Thermal Road-Mapping (ECOSTAR), Roadmap Document. SES-CT-2003-502578.

[13]. Price, H. (2003). Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts, Report, Sargent & Lundy, NREL/SR-550-34440. pts for solar and low energy buildings.

[14]. Py, X., Olives, R., Mauran, S. (2001). Paraffin/porous graphite matrix composite as a high and constant power thermal storage material. *International Journal of Heat and Mass Transfer*, Vol. **44**, pp. 2727.

[15]. Relloso, S., Delgado, E. (2009). Experience with Molten Salt Thermal Storage in a Commercial Parabolic Trough Plant, Proceedings of the Solar Paces Conference, Berlin, Sept. 15-18, 2009.

[16]. Regin, A.F., Solanki, S.C., Saini, J.S. (2008). Heat transfer characteristics of thermal energy storage system using PCM capsules: A review. *Renewable and Sustainable Energy Reviews,* **12**(9), pp. 2438-2458.