Conference Proceedings

Solar World Congress 2015
Daegu, Korea, 08 – 12 November 2015

STEAM BASED CHARGING-DISCHARGING OF A PCM HEAT STORAGE

Asfafaw H. Tesfay[1], Mulu B. Kahsay[1] and Ole J. Nydal[2]

[1] School of Mechanical and Industrial Engineering, Ethiopian Institute of Technology-Mekelle, Mekelle University P.O.box 231, Mekelle, Ethiopia

[2] Department of Energy and Process Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway

Abstract

Latent heat storage and efficient heat transport technology helps to utilize the intermittent solar energy for continuous and near isothermal applications. Nonetheless, latent heat storages face challenges of storage charging, heat retaining, and discharging the stored heat. The focus point of solar concentrators is the ideal position to collect maximum thermal power; however, this place is not convenient. Therefore, it is important to transport the concentrated heat from the focus to some place efficiently in order to utilize it safely. This paper addresses the challenges of heat transportation and storage charging-discharging issues. The heat transportation from the receiver over some distance is carried out with a pipe lines and water as heat transfer fluids. However, the charging-discharging process was carried by pipe less method with the help of fins. In addition, the stored heat was retained for a couple of days by using appropriate insulation material. The latent heat is stored in a phase change material (PCM) of nitrate salt (mixture of 60%NaNO3 and 40%KNO3), which melts at 222ºC and has 109 J/g specific heat of fusion. The storage was designed to supply nearly isothermal heat during the liquid-solid phase transition and the sensible heat stored in the solid and liquid form is used to perform additional applications that do not require uniform heat. The low thermal conductivity of the PCM is improved by using extended fins, which enhance the thermal conductivity within the storage. In this article, two-phase loop thermosyphon of steam was used to manage long distance heat transportation between the receiver and the storage. The steam in the thermosyphon flow was restricted to a maximum working temperature of 250ºC. Steam is selected for its highest heat capacity, easily availability and stable nature. The steam carries the heat from the collector focus point and condenses in a coiled pipe imbedded in aluminum plate placed on top of the storage. Many fins have solidly attached to this plate to conduct this heat down to the PCM inside the storage during charging. This design configuration avoids pressure development inside the PCM storage. The charging-discharging temperature of the storage is recorded in three zones (top, middle and bottom) of the storage. The experimental and numerical results show the heat transportation, retention and charging-discharging methods are effective.

Keywords: *solar energy, PCM storage, latent heat storage, two-phase thermosyphon,*

1. Introduction

Solar thermal energy can be stored by using sensible heat storage (SHS) or latent heat storage (LHS) using a Phase change material (PCM). The stored heat can be used for different application such as cooking, space heating, hot water supply and etc. Latent heat storage provides higher storage capacity, compact size, and nearly isothermal heat supply. However, SHS such as Rock bed, water, oil etc. are larger storage and have faster temperature decay compared to LHS of the same capacity. These characterstics SHS can be improved by combining PCM material in their design as studied by D. Okello et al. [1].]. Latent heat storage using phase change materials (PCMs) can be designed to have much higher energy storage density than the sensible heat storage [2].

doi:10.18086/swc.2015.02.06 Available at http://proceedings.ises.org

Generally, PCMs have low thermal conductivities and took longer time of charging [3]. A number of methods have been proposed to increase the thermal conductivity of PCMs [4]. The finned tube configuration [4], metal structure insertion into the PCMs [4], and dispersion of thermally conductive nano or micro particles within the PCM matrix [4] are some of the widely studied approaches. In addition to thermal conductivity, mass flow rate and inlet temperature of the heat transfer fluid (HTF) has also affected the charging-discharging process [5]. PCM charging-discharging process can be improved by designing multi stage storages with different thermo physical properties [6]. Furthermore, it can be improved by using fast flowing HTF instead of slow flowing HTF [7]. On the other hand, there is a pressure build-up concern associated with PCMs due to the expansion of air at elevated temperatures and due to volume change of PCMs. The design of this paper has tried to avoid any possible contact between the HTF and PCM and possibilities of pressure buildup by providing a 10% extra volume.

The objective of this paper was to develop thermal energy storage to store the surplus solar energy during the day and keep it for later use by supplying nearly isothermal heat during discharging. To realize this, two-phase closed loop thermosyphon based heat transfer was used to charge the PCM storage. This design provides threshold height difference between evaporator and condenser of the thermosyphon loop to initiate natural circulation by density difference. Two-phase closed loop thermosyphon was selected because it is capable of transferring heat from a heat source to a separate heat sink over some distance [8]. This heat transfer mechanism is used in many applications such as nuclear cooling and electronic cooling [9]. However, this method of charging thermal storage has rarely employed in small-scale applications such as cooking. The prime objective of this study has focused to give solutions to the alarming deforestation, energy poverty, and related ecological impacts of developing countries associated with cooking. The cooking application experiment of this paper's design has documented in an accompanied paper submitted and presented in parallel by the authors.

2. Materials and Methodology

The methodology followed in this study includes identification of appropriate PCM material that has a solid-liquid phase transition temperature of 222ºC, storage design, thermal analysis, modeling and simulation, prototype development and test.

2.1. Phase change material

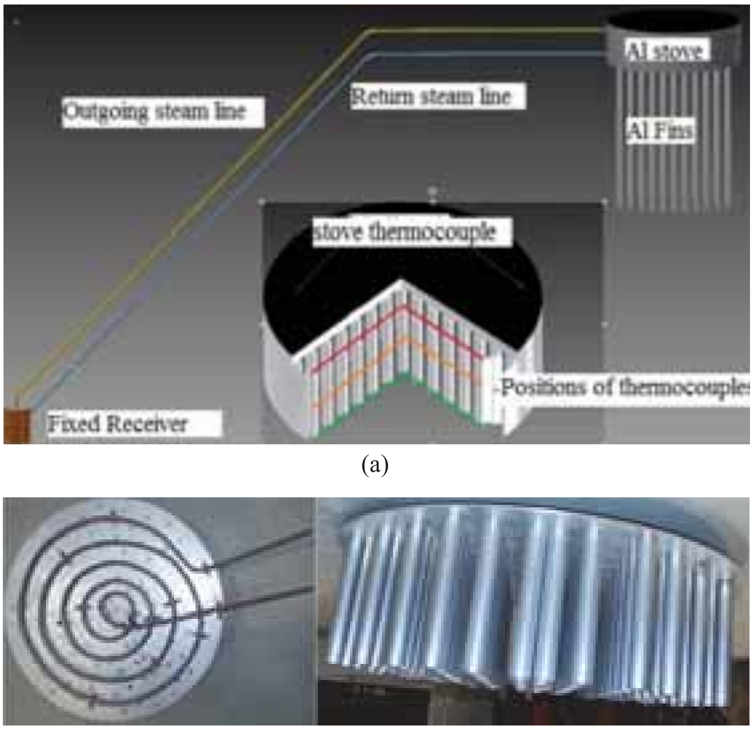
The PCM used in the experiment of this study was 20 kg of solar salt (nitrate salt mixture 40% KNO_3 and 60% $NaKO_3$). For computational simplicity, the latent heat was described in terms of an effective heat capacity in a narrow temperature range of melting [10].

$$Q = \int_{T_i}^{T_f} mC_p \mathrm{dT} \qquad (1)$$

$$C_P[kJ/kg] = \begin{cases} 0.75 & T < 110^0C \\ 4.2 & 110^0C \le T \le 120^0C \\ 1.4 & 120^0C < T < 210^0C \\ 12 & 210^0C \le T \le 220^0C \\ 1.6 & T > 220^0C \end{cases} \qquad (2)$$

2.2. Storage design

The PCM storage is designed to be charged by a two-phase self-circulatig closed loop heat carrier, a polar mounted parabolic dish with sun tracker, a fixed receiver was designed to act as an evaporator and an aluminum casted plate with extruded fins down to the PCM was placed on top of the storage. The heat transfer fluid used was water and the receiver converts this water in to steam. Figure 1 shows a schematic and actual picture of the system.



(a)

(b)

Figure 1: Design and development process of a PCM storage

The Al plate has an embedded stainless steel (SS) steam pipe that acts as heating element. The heat storage was coupled to parabolic dish filmed with 5cm glass tiles. The polar mounted technique of the concentrator's design gave a suitable platform for the fixed receiver. This concentrator is coupled to PCM storage with a thermosyphon loop. The system was tested on a real sun and artificial heating to charge the storage. In this experiment mainly K-type thermocouples, pressure gage, and photo sensors were used to measure temperature distribution, regulate steam pressure and control the tracking mechanisms of the system respectively.the complete list of items is given in Table 1.

Table 1: system instruments and sensors

Label	Description	Label	Description
A			
	Pressure relief valve	F	Inlet, out let and directional control valves
B	Pressure gauge	G	DC Power regulator
C	Tracking sensor	H	Parabolic dish reflector
D	Sprocket and chain drive	I	Data logger
E	DC motor	J	Thermocouples

2.3. Heat transfer mechanisms

PCM storage charging with hot water or oil utilizes the medium's sensible heat capacity, in which the amount of energy released per unit volume is relatively small. However, charging with saturated steam employs the latent heat released during its phase change. The condensate exits the PCM storage at temperatures close to the inlet steam temperature. The thermosyphon loop was first flushed to free any trapped air and filled 2/3 of its volume with water. There is no expansion tank in this loop design. A boiling-condensing mode of heat transfer technique was followed to transport the heat from the receiver to the storage. Theoretically, the mass flow rate of the fluid circulating in the loop can be found by conducting a momentum balance around the loop [11] and the heat transfer in the imbedded pipe is treated as film condensation in nearly horizontal pipes.

The mode of heat transfer between the stainless steel pipe and aluminum block is treated as a pure conduction between composite solids as shown in Figure 2. This heat was analyzed using Fourier's conduction equations (3-5).

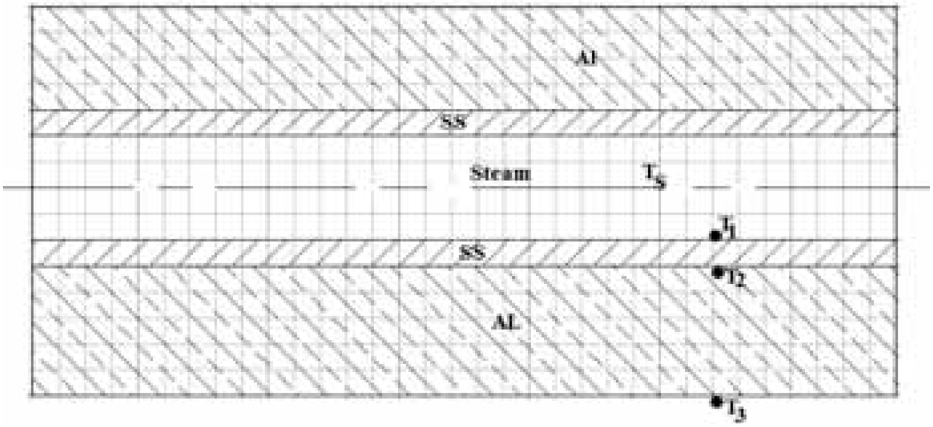


Figure 2: Composite materials of aluminum and SS

Assuming small pipe wall thickness (L) compared to pipe diameter:

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \tag{3}$$

$$\frac{\dot{Q}}{A}\int_0^L dx = -\int_{T_1}^{T_2} kdT \tag{4}$$

If the small variation of k is ignored the equation simplifies in to:

$$\dot{Q} = \frac{kA}{L}(T_1 - T_2) \tag{5}$$

Where $\frac{L}{kA}$ is the thermal resistance of the material

The overall thermal resistances of composite wall are treated in the same way as total series resistance of electric circuit. Assuming 2D geometry for simplicity: the fin and the plate temperature progress is the same and change in area (A) and thermal conductivity (k) with temperature is negligible, T_3 (fin temperature) was then calculated by:

$$T_3 - T_1 = \dot{Q}\left(\frac{L_{SS}}{k_{SS}A} + \frac{L_{Al}}{k_{Al}A}\right) \tag{6}$$

In a heating plate temperature-time profile, the analysis of the heat transfer rate from the heating plate (frying pan) to the fins and from the fins to the PCM was analyzed using eq. (7 and 8) respectively [11].

$$\dot{Q}_{p,f} = \frac{T_p - T_f}{R_{P,f}} \tag{7}$$

$$\dot{Q}_{f,PCM} = \frac{T_f - T_{PCM}}{R_{f,PCM}} \tag{8}$$

Theoretically, the temperature development of the fin is found by using eq. (9) and the heat transfer rate from the fin at temperature,T_f, to the PCM at temperature,T_{hp} , in the storage must equal to the heat transfer rate from the plate to the fin as shown in eq. (10).

$$\frac{dT_f}{dt} = \frac{\dot{Q}_{\mathrm{P},f} - \dot{Q}_{f,Pcm}}{m_f c_{v,f}} \tag{9}$$

$$\dot{Q}_{f,\mathrm{PCM}} = \frac{T_f - T_{PCM}}{R_{f,PCM}} = \dot{Q}_{\mathrm{P},f} = \frac{T_P - T_f}{R_{P,f}} \tag{10}$$

On rearranging of eq. (10), the PCM temperature simplifies to eq. (11). Figure 3 shows the COMSOL mesh of the PCM material adjacent to the fin.

$$T_{PCM} = \frac{T_f R_{PCM,f} + T_f R_{f,\mathrm{PCM,}}}{R_{P,f} + R_{f,PCM}} \tag{11}$$

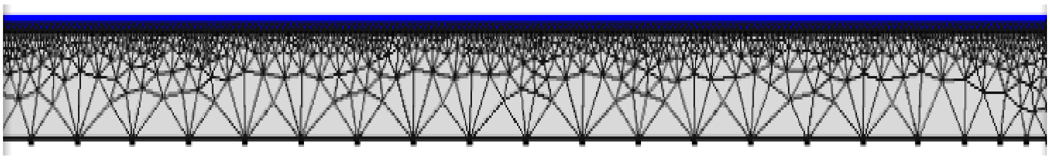


Figure 3: Mesh of PCM material during conduction charging

2.4. Thermal performance

The thermal performance of the system is given by the ratio of the useful energy stored to the energy incident at the concentrator's aperture. The storage energy is the sum of the energy stored in the PCM and in the aluminum fin. Therefore, the thermal efficiency of the system is computed by:

$$\eta_{th} = \frac{c_{Al} m_{Al}(T_f - T_i) + m\int_{T_i}^{T_f} C_p dT}{A_a I_B} \tag{12}$$

Where cp is the effective heat capacity of the PCM (eq.2)

Both normal and diffuse radiation enters the aperture area of any solar collectors. However, in concentrating collectors only the direct radiation can be focused on the receiver. In this paper, the thermal analysis of the system was performed only for its solid phase sensible heat-storing ability as it was not fully charged. The systems developed here reached 157°C of maximum temperature during the experiments of this study. Therefore, the thermal performance during these days was calculated 19%. The performance of the system was affected mainly by the heat loss from the receiver.

2.5. Insulation

Aerogel and Rockwool insulations were used to insulate the storage and the steam pipelines respectively. Although the insulations maximum working temperature is about 650°C, the maximum working temperature of the systems' was set to 250°C (by adjusting the pressure relief valve) and the design thickness of the insulation is 25mm for the storage and 50mm for the pipeline. The insulations thermal conductivity is 0.03W/Km and 0.07 W/Km respectively and they have the same surface emissivity of 0.05.

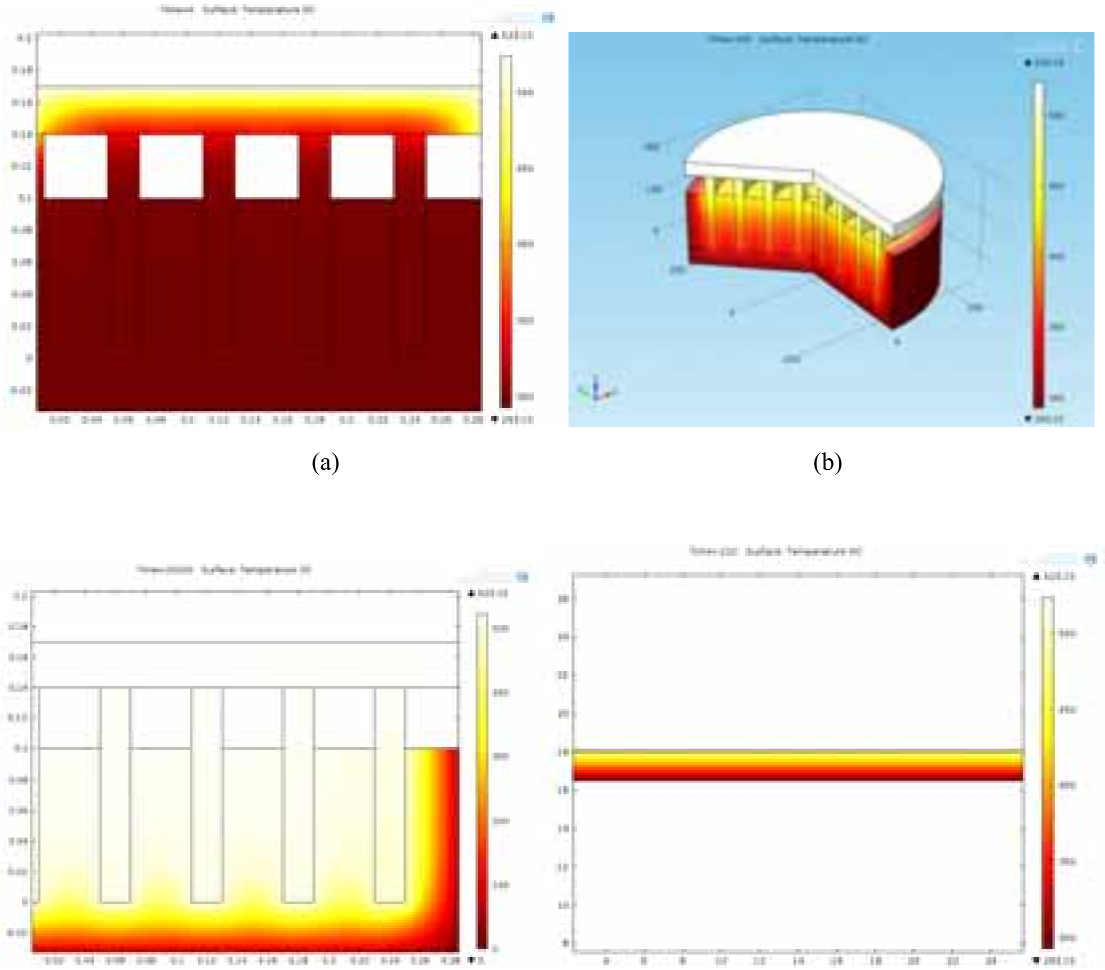
2.6. Pipe lines

The size of the steam pipeline was 10mm and 8mm with 1mm thickness. The SS pipe is used as a pipeline in the heat transfer loop and as a heating element of the Al plate respectively. The pipe has 100bar design pressure and was used for 40bar working pressure. The pipeline used Swagelok connectors and valves. A pressure gage is used to measure the pressure of the steam and regulated with the help of a safety valve that reliefs the pressure when it passed the pre-set value (40bar). The pipeline was flashed before the beginning of experiment to avoid air inclusion.

3. Results and discussion

3.1. Modelling and simulation

The storage charging process has simulated using COMSOL multiphysics 4.3. The simulation work was run for 2D and 3D models. The simulation results showed the storage is fully charged in about seven hours, when it is heated by a 250°C continuously circulating steam. The simulation considers a constant loss of 15°C from the storage. For model simplicity, the fin in the COMSOL simulation used in Figure 4 (a-c) has considered circularly rolled plate fins instead of the many cylindrical fins in the actual prototype. This fin assumption has an impact on lowering the overall charging time of the storage. The simulation shows the charging of the PCM sanduched between two fins is very quick as shown in Fig. 10(c), however, the PCM adjacent to the storage wall and bottom changes its phase very slowly. This simulation result suggests to half the dimension of the gap between the fin and the storage wall and bottom. Therefore, the PCM thickness between the fin and the wall and between the fin and the bottom should be 20mm. Moreover, it was found rolled plate fins charge the PCM quicker than rod fins. In addition to the PCM charging development, the simulation has also run to show the thermal resistance effect of the SS pipe wall on the Al plate as shown in Fig. 4(d).



(a) (b)

(C) (D)

Figure 4: COMSOL simulation of PCM charging and heat transfer between SS and aluminum wall

3.2. Experimental Test

The polar mounted concept eases the tracking mechanism in the secondary axis and the fixed focus receiver, was found suitable for steam generation. The steam circulates between the evaporator (receiver) and Al plate (condenser) in a closed loop naturally. The steam carries the heat from the receiver and drops it on the aluminum plate. The fins attached to this plate in return carries this energy to the PCM storage. The test unit of this paper is shown in Figure 5.

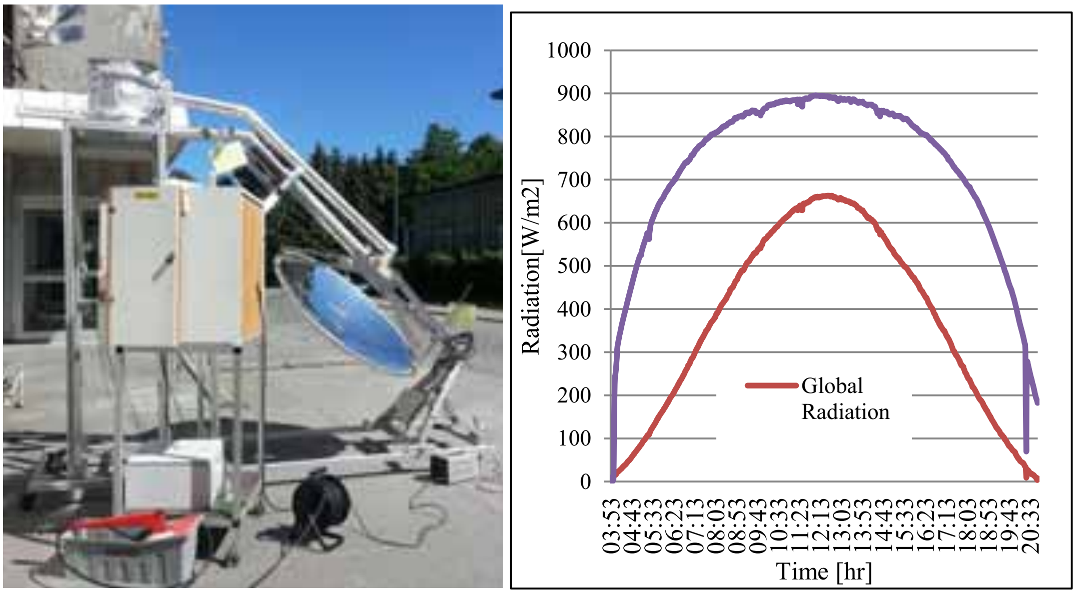


Figure 5: Parabolic dish with PCM storage Trondheim's global and normal beam radiation for 25-07-2013

a) Charging of storage on natural sun

When the solar reflector starts focusing the solar radiation on the receiver, the water inside the receiver starts boiling and a vapor at low temperature starts circulating. The stagnation temperature of this unit could not reach the melting point of the PCM. The storage was tried to be charged in successive days using the advantage of the PCM material's heat retention ability. However, this did not help to charge it fully; this was probably due to the losses at the receiver. The maximum temperature attained in the PCM storage had reached a temperature range of 130°C to157°C as shown in Figure 6.

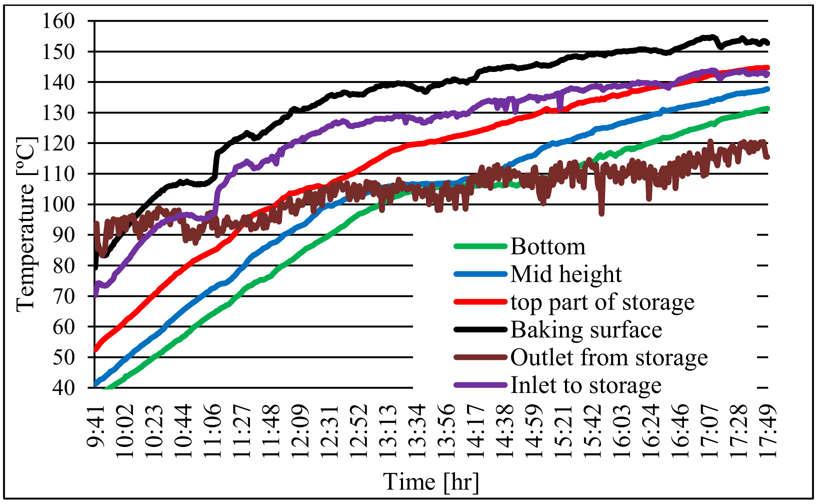


Figure 6: PCM charging practice

b) Charging of PCM storage Artificially

An artificial heating element was coiled around the receiver in order to obtain a regulated temperature at the receiver that is capable of generating steam at elevated temperature, see Figure7(b). The heating element was set to a maximum temperature of 450°C, at which it was delivering an average power of 700W to the receiver.

This power was equivalent to the solar power supply obtained from a 1.2 m parabolic dish concentrator with 80% optical efficiency and $800w/m^2$ average beam radiation. The PCM storage took about eight hours of phase change duration. The temperature development of the steam and the PCM during the charging process are shown in Figure 8.

(a) (b)

Figure 7: Receiver of a parabolic dish collector: (a) solar test and (b) heating element (before insulation)

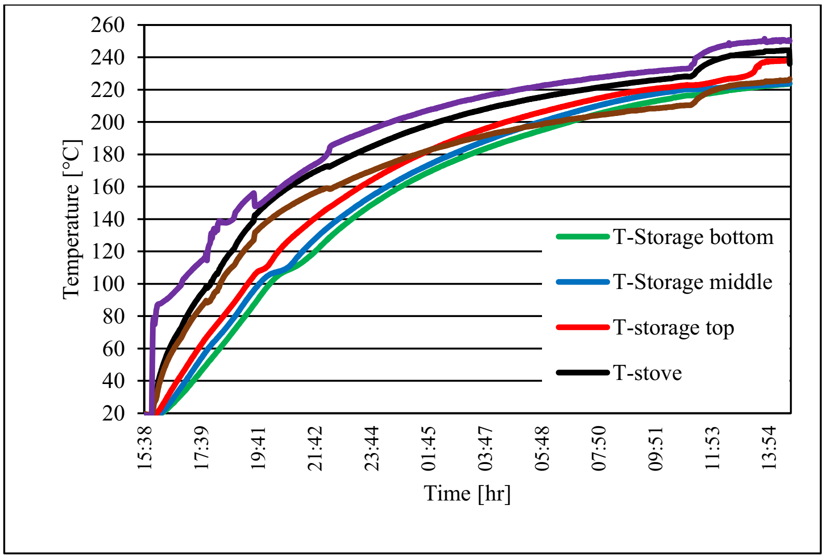


Figure 2: Artificial charging of PCM storage

The experimental result shows a close resemblance to the simulation result of charging time. This indicates the input power at the receiver is small and needs to increase it by using larger aperture area inorder to reduce the charging time.

4. Conclusion

In this paper a concept of steam based heat storage charging by using polar mounted solar concentrator has been developed and demonstrated. Heat is transfer by a thermosyphon principle, with water as the working fluid at about 35-bar pressure. Vapor is generated at the heat absorber in the focus point of the parabolic concentrator and condenses in a coiled tube, which is in Al plate. The plate has heat-conducting rods extending into latent heat storage ("solar salt", Nitrate mixture). A boiling/condensing natural circulation loop (thermosyphon) is feasible with water as the heat transfer fluid. As the water volume is small, the high pressure is manageable but requires high quality pipe and valve components. A boil-off startup procedure is operationally easy. The system can be optimized with respect to losses in the heat transfer loop, in particular at the absorber. The absorber is a spherical boiler in a fixed position, with the solar illuminated area moving from one side to the other during the daily sun tracking

5. References

[1] Denis Okello , Ole J. Nydal and Eldad J.K. Banda, Experimental investigation of thermal de-stratification in rock bed TES systems for high temperature applications, Energy Conversion and Management, vol. 86; pp: 125–131, 2014.

[2] Kuravi S, Trahan J, Goswami DY, Rahman MM, Stefanakos EK. Thermal energy storage technologies and systems for concentrating solar power plants. Prog Energy Combust Sci, Vol.39; pp: 285–319, 2013.

[3] H.M.S. Hussein et al., Experimental investigation of novel indirect solar cooker with indoor PCM thermal storage and cooking unit, Energy Conversion and Management 49 (2008) 2237–2246.

[4] Tanvir E. Alam, Jaspreet S. Dhau, D. Yogi Goswami , Elias Stefanakos, Macroencapsulation and characterization of phase change materials for latent heat thermal energy storage systems, Applied Energy 154 (2015) 92–101

[5] Abduljalil A. Al-Abidi et al., Experimental study of melting and solidification of PCM in a triplextube heat exchanger with fins, Energy and Buildings, Vol. 68; pp: 33–41, 2014.

[6] Taha K. Aldoss and Muhammad M. Rahman, Comparison between the single-PCM and multi-PCM thermal energy storage design, Energy Conversion and Management, vol. 83; pp: 79–87, 2014.

[7] Robynne E. Murray and Dominic Groulx, Experimental study of the phase change and energy characteristics inside a cylindrical latent heat energy storage system: Part 1consecutive charging and discharging, Renewable Energy, vol. 62; pp: 571-581, 2014.

[8] Alessandro Franco and Sauro Filippeschi, Experimental analysis of Closed Loop Two Phase Thermosyphon (CLTPT) for energy systems, Experimental Thermal and Fluid Science, vol. 51; pp: 302–311, 2013.

[9] Liang Zhang et al., An indoor experimental investigation of the thermal performance of a TPLT-based natural circulation steam generator as applied to PTC systems, Applied Thermal Engineering, vol. 62; pp: 330-340, 2014.

[10] Foong Chee Who, Jørgen Løvseth, and Ole Jørgen Nydal, “Heat Capacity Measurements of NaNO3 – KNO3 Binary System”, submitted paper to International journal of Thermophysics, 2011.

[11] R T Dobson and J C Ruppersberg, flow and heat transfer in a closed loop thermosyphon: part I-theoretical simulation, Journal of Energy in South Africa, Vol. 18; pp: 32-80, 2007