International Journal of Research in Engineering, Science and Management
Volume-2, Issue-3, March-2019
www.ijresm.com | ISSN (Online): 2581-5792

An Investigation of Thermal Performance of PCM Heat Exchanger-Experimental and Simulated Analysis

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***Abstract*: This investigation deals with the Experimental and Simulated analysis of a PCM solar heat exchanger. Phase change material taken is paraffin wax of Type –II with melting point 48oC -50oC. A conventional solar heat collector can extract / transfer only the sensible heat from the solar irradiance into the heat collecting medium, but this system is designed to store the latent heat. Flat plate transfers the heat from the solar irradiance falling on it to the PCM material behind it. The PCM absorbs the heat and rises to its melting point. On reaching the melting state, it continues to store the latent heat. For the analysis, a finned plate-PCM heat exchanger model is designed, fabricated and the results are obtained experimentally. On the review of the literature, the suitable depth of the container is found to be 28 mm. The experiment is conducted for two different seasonal months and the potential results are taken for simulation. The Experimental results for the phase month -I (November- December) show the Partial Melting time to be 135 minutes and the complete Solidification time is 70 minutes. The Experimental results for the phase month -II (March-April) show the Partial Melting/Charging time to be 100 minutes and the complete Solidification/Discharging time is 70 minutes. In this analysis, the simulation is concentrated on the charging phase of the material. For the simulation of the thermal distribution inside the PCM material, three different model systems are taken: 1. Non-finned plate-PCM system, 2. Circular finned plate-PCM system, 3. Rectangular finned plate-PCM system. In addition, how it is affected with fin thickness, fin configuration, plate and fin material configuration is investigated. The simulated results show circular finned system shows better performance than rectangular and non- finned plate - PCM models.**

***Keywords*: charging, PCM heat exchanger, paraffin wax, latent heat storage system.**

1. Introduction

A. Recent Technology in Thermal Storage Systems

In recent advancements, solar towers are installed to extract and store large amounts of heat by using molten salt technology. The molten salt commonly used is a combination of 40% potassium nitrate and 60 % sodium nitrate salt hydrate. It is capable of storing heat at a temperature of 400oC & the molten salt is circulated in the heat exchanger when needed. The heat exchanger transfers the heat from the molten salt to the water and generates steam. This steam is used by the steam power plants to generate electrical power by an alternator. These power plants are used during peak load situations. The environmental concern is these systems are operated by focussed sunlight provided by heliostat (plane mirror). The sunlight on concentration by thousands of heliostat to the solar towers causes accidents/ killing of birds flying across it. Also, large power generation units consume fossil fuel to attain the operating temperature during starting. Though the chance to operate thermal power plant entirely by solar energy is uncommon due to the need for faster energy generation rate, a portion of input heat energy for feed water preheating can be probably provided by solar energy. Solar energy is already been utilized in various applications but the limitation of this source is that it can be utilized only during day times. Thus the necessity to store large amounts of heat and to provide stable energy production, heat from the sun has to be stored.

B. Heat Storage System and Its Components

Heat is stored in two forms, one is sensible heat storage and another is latent heat storage. Sensible heat is responsible for the temperature rise of a substance whereas latent heat is responsible for the phase change. A substance in a particular phase initially extracts sensible heat and rises its temperature. On latent heat storage, the temperature of the substance will be constant for a particular time and then it leads to heat storage during the phase change of the substance

The conventional solar heat collector is a SHSS (sensible heat storage system). It consists of copper tubes arranged in box container carrying water as the heat transfer fluid. It works under the principle of thermosiphon. This conventional system is limited for heat storage due to its simple features. Recently, LHSS (latent heat storage system) gains popularity and more research are undergone to utilize this major quantity of heat. Latent heat stored can be utilized to generate power at peak loads as a standby unit, during cold conditions as heat source etc.

Compared to a latent heat storage power station, a solar PV cell can convert only a fraction of solar energy into electrical energy. The remaining solar irradiance dissipates to the environment without being utilized. Also the high temperature and dust content on the PV cell layer reduces it efficiency. Hence cooling techniques and consistent maintenance of the system makes it a high economic power generation method. The heat storage process requires primary elements such as heat exchangers (for both heat extraction and heat discharge), Phase change material (in case of latent heat storage) and thermal insulation (to prevent heat loss to surrounding).

1) Heat exchanger

Heat exchangers find greater applications in most of the thermal related areas. Heat energy has to be transferred through a proficient medium either to be converted into another form of energy or to be stored for later use. The heat transfer fluid in the heat exchangers must have good heat extraction/ dissipation capacity to ensure a greater rate of heat transfer. The heat exchangers are classified into various types on the application basis. The common type of heat exchanger used is shell and tube heat exchanger. In a shell and tube heat exchanger, fluids are passed into shell or tube pass. Baffles are provided in the shell side of the heat exchanger to facilitate the fluid flow and to increase the retention time which is needed for the heat to be transferred to/from the tube fluid. The tube spacing as per the TEMA should not be less than 1.25 times the inner diameter of the tube and baffle spacing to be 0.2 to 1 times the inner shell diameter.

2) Phase change material

Phase change materials, shortly as PCM is a valid contender in latent heat storage systems. This PCM exhibits a high heat storage capacity. It melts during heat extraction and solidifies on heat dissipation. It stores and releases large amounts of heat energy. PCMs are classified based on their transition as solid to liquid transition PCMs and liquid to gas transition PCMs. The former classification shows low latent heat storage capabilities but is extensively used due to its minimum change in volume than the later. From the literature, it is found that PCM lacks in its thermal conductivity properties. Therefore, to enhance the effective thermal conductivity of the PCM, two factors are considered (i) by introducing thermal conductivity enhancer (TCE) into the PCM using high thermal conductivity material and (ii) by increasing the surface area for heat transfer (by the use of fins). The more economical method is to use finned surfaces. Also, thinner fins in more numbers are preferable than the thicker fins in less number.

Fig. 1. Paraffin wax chips

3) Thermal insulation

In a heat storage system, thermal insulation is required to reduce the heat loss to the surrounding. Low thermal conductive materials are best suited for thermal insulators. Some of the common thermal insulators are glass wool, polystyrene foam, cellulose, cork. Gases possess low thermal conductivity and specific heat than solid and liquid matter. Hence, air can also be trapped in a spacing to reduce heat transfer. An Increased layer of insulation thickness enhances the insulating capacity of the material. For a cylindrical geometry, the insulation thickness is determined by the critical radius of insulation.

4) Thermocouple and Indicator

Thermocouple is a temperature measuring device. Three thermocouples are used for measuring temperature in flat plate, PCM wax and discharge water. During charging the temperature of PCM rises to its melting point and then the temperature becomes stable storing latent heat in it. The wall temperature of the PCM is noted. During discharging, the inlet and outlet temperature of the heat transfer fluid (water) are noted.

5) Discharge pump with connecting hoses

Tube material is immersed in the PCM material. To discharge heat from the TES, heat transfer fluid is forced circulated through the tube material by discharge pump. The mass flow rate of the HTF is varied to analyze the heat discharge rate. It is done either using a variable speed motor pump or by adjusting the control valve.

2. Selection of operating parameters

A. Selection of Heat Exchanger Material

The application of Heat exchanger in this analysis is for solar heat absorption & transmission to PCM material. To conduct heat faster, e a high thermal conductive material is required. Copper tubes are widely used in conventional systems and so copper is chosen as heat exchanger material. The flat plate (charging) and tube material (discharging) is preferred to be copper.

B. Selection of phase change material

The selected PCM is based on its thermal, chemical, physical properties. Organic PCM's have shown reasonable performance in melting and discharging process and is likely to be durable even for 1000- 2000 cycles of operation. Another desirable property of organic PCM is non- corrosive unlike salt hydrates and eutectics. The phase change material selected in this analysis work is organic paraffin of type II which has a melting point closer to 50^{o}C.

C. Selection of suitable depth of container

According to Sourav Khanna [5], the suitable depth of the container is chosen to be 28 mm and the most suitable fin height is the one which touches the bottom of the container depth.

3. Physical CAD model

The following figure resembles the container section of 280 * 28 mm in which the PCM is filled and the thermal insulation gap around it.

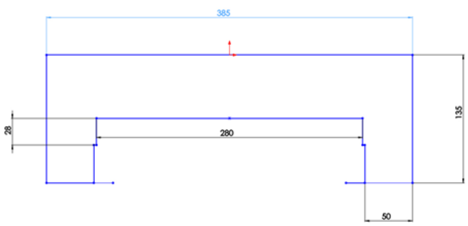

Fig. 2. Top view of the container

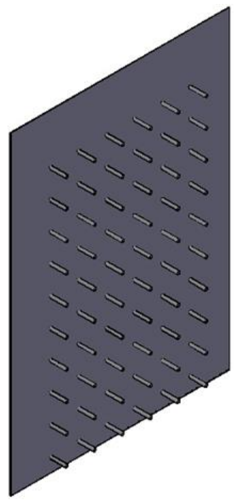

Fig. 3. Isometric view of finned flat plate

4. Block diagram

In the following figure, the red colour section indicates the finned flat plate, yellow colour indicates the PCM material section and magenta colour indicates the thermal insulation material.

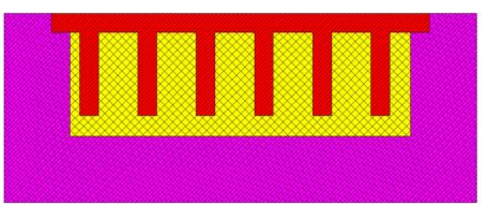

Fig. 4. Model diagram

5. Results & discussion

The experiment is conducted for charging and discharging process for a time interval of 5 minutes. The temperature of flat plate and PCM paraffin are measured using thermocouples during charging process. For discharging, water at a constant mass flow rate of 0.3 Kg/min and room temperature of 28 ^{o}C is used. The charging process is conducted at peak solar radiation timings. The charging and discharging process observations are listed below.

A. *Experimental results*

Table 1
Charging process observation

Time interval	Plate temperature	PCM temperature	Observation of PCM state
13.40	38	25	solid state
13.45	43	30	solid state
13.50	48	33	solid state
13.55	52	36	solid state
14.00	54	40	solid state
14.05	50	48	solid state
14.10	52	43	solid state
14.15	54	44	solid state
14.20	55	43	solid state
14.25	57	43	solid state
14.30	58	44	solid state
14.35	57	44	solid state
14.40	55	45	solid state
14.45	56	44	solid state
14.50	53	45	solid state
14.55	48	50	Melting occurs
15.00	53	50	Melting occurs

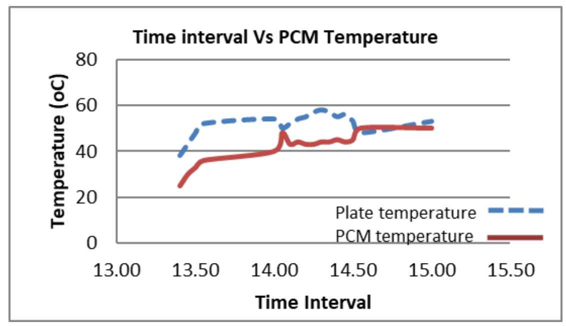

Fig. 5. Time vs PCM temperature (charging process)

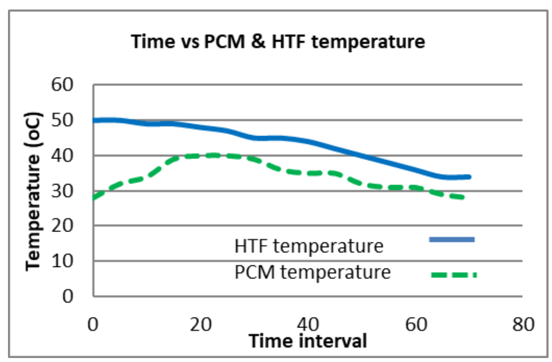

Fig. 6. Time vs PCM temperature (discharging process)

B. *Simulation results*

The temperature distribution inside the paraffin PCM wax material is analysed by varying the parameters: fin configuration, fin thickness and the plate & fin material configuration. The simulation is done using ANSYS 19.1 software. Each geometry is prepared using AutoCAD 3D software and is imported to the ANSYS simulator software. The model is generated and meshed by adaptive size meshing method. The side walls and the bottom of the PCM chamber are assumed to be perfectly insulated. The solar irradiance incident on the plate material is assumed to be uniformly distributed and the PCM chamber is considered to be in good physical contact

Table 2
Discharging process observation

Time interval	HTF outlet temperature	PCM temperature	Observation of PCM state
0	28	50	partial melting
5	32	50	partial melting
10	34	49	partial melting
15	39	49	solid/liquid state
20	40	48	Complete solid
25	40	47	Complete solid
30	39	45	solid state
35	36	45	solid state
40	35	44	solid state
45	35	42	solid state
50	32	40	solid state
55	31	38	solid state
60	31	36	solid state
65	29	34	solid state
70	28	34	solid state

with the plate as well as fin material. The heat transfer plate & fin material specification data is assigned & the solutions are found. The fin height (say 25.4mm) is fixed to a constant maximum value (closer to the depth of the PCM material). For rectangular fin configuration, 2 models are taken: Model 1: length- 3.5 mm, width-2 mm, height- 25.4 mm (same volume as 3 mm dia fin), Model 2: length- 7 mm, width-4 mm, height- 25.4 mm. (same volume as 6 mm dia fin).

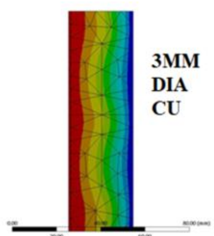

Fig. 7. Effect on temperature distribution by 3mm dia Copper circular fin.

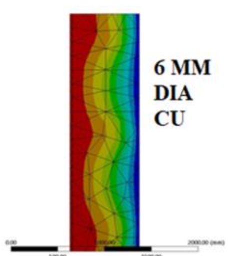

Fig. 8. Effect on temperature distribution by 6mm dia Copper circular fin.

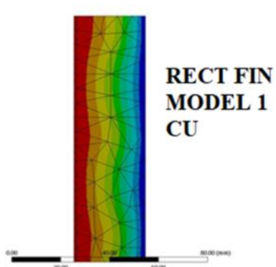

Fig. 9. Effect on temperature distribution by rectangular fin model 1- Copper

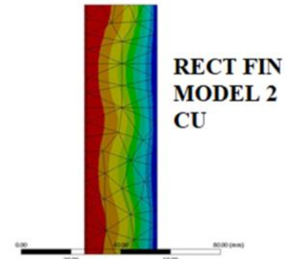

Fig. 10. Effect on temperature distribution by rectangular fin model 2- Copper

6. Conclusion

The experiment was performed to analyze the charging and discharging performance of paraffin PCM. Non concentrated direct sunlight is allowed to heat the flat plate. Water is used in discharging process. From the experimental and simulated results; it is concluded as follows,

- Melting begins in the region close to flat plate and PCM interface.
- The Observed charging time is 100 minutes and discharging time is 70 minutes.
- Based on the circular fin thickness, 6 mm dia fin shows better temperature distribution performance than 3mm fin.
- Based on the rectangular fin thickness, model 2 fin shows better temperature distribution performance than model 1 fin. From the overall results, it is evident that Copper circular fin of 6mm dia shows greater performance compared to other model systems.

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