EFFECT OF EXTENDED GEOMETRIES ON CHARGING AND DISCHARGING BEHAVIOR OF PCM USING FLAT PLATE COLLECTOR FOR VARIOUS RENEWABLE ENERGY APPLICATIONS

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ABSTRACT

The objective of this study is to investigate the charging and discharging characteristics of phase change materials (PCM) utilizing solar energy, with the intention of assessing their suitability for diverse renewable energy applications. Two distinct geometrically similar models of flat plate collectors were utilized to evaluate the characteristics of PCM. Experimental investigations were conducted during the high-temperature summer season in Moradabad City, situated in India. In order to assess the impact of a fin on the charging and discharging characteristics of phase change material (PCM), two solar flat plate collectors were constructed and tested. The collectors were identical, with the only difference being the absorber plate used. Both collectors were filled with the same volume of PCM beneath the absorber plate. The study's findings indicate that the utilization of fins results in a reduction of approximately 1.5 – 2 hours in the charging and discharging time of phase change material (PCM) compared to scenarios where fins are not employed. An increase in the quantity of fins positioned beneath the absorber plate leads to a reduction in the time required for the phase change material (PCM) to charge. The developed system is well-suited for applications that necessitate moderate temperatures outside of daylight hours. These applications encompass agricultural drying, space heating, and water heating, among others.

KEYWORDS: *PCM, Extended geometry, Thermal performance, solar air heater*

ABBREVIATIONS USED: *SAH(s), solar air heater(s); SWH, Solar water heater; FPSC, Flat plate solar collector; LHS, latent heat storage; PCM(s), Phase Change Material(s).*

1. INTRODUCTION

The global community is currently facing two imminent challenges of significant magnitude: a pronounced scarcity of energy resources and an accelerated and dynamic alteration of the Earth's climate. Collectively, these entities present a significant risk to the accomplishments of human civilization. The resolution of both concerns can be achieved through the simultaneous implementation of strategies aimed at diversifying the fuel supply and adopting environmentally sustainable methods for energy production. Fortunately, a wide range of clean and diverse alternatives is emerging. Nevertheless, the acceptance of these technologies faces various societal obstacles, particularly in less developed nations. Solar energy is an inexhaustible and perpetual source of energy. Renewable energy has gained significant recognition as a prominent source of power on a global scale, exhibiting an average annual growth rate of 35 percent in recent times. India's progress in the development of solar energy has been comparatively sluggish in comparison to other nations that are actively pursuing harnessing the sun's energy. Significant advancements have been observed solely in the domain of SWH, while the realm of solar energy in food processing industries holds immense untapped potential. In the year 2005, the total installed capacity of solar photovoltaic systems in India remained constant at approximately 16 megawatts peak (MWP), whereas solar thermal concentrating technology did not generate any electricity. Efficiently addressing the food crisis in developing countries can be achieved through the implementation of two distinct approaches: (i) there has been an increase in the availability of food materials. (ii) The challenge of aligning population growth with food production. According to a scholarly source, the global population had reached a total of 6.47 billion individuals by the year 2005, with projections indicating that it will surpass 9 billion by the year 2050 [1].

Solar energy possesses significant potential to meet the rising demands for energy [2]. In recent years, there has been a notable scholarly and industrial emphasis on the investigation of solar energy conversion through both thermal and photovoltaic means [3]. The primary objective of the implemented initiatives is to enhance performance and reduce costs [4]. SWH have received a substantial amount of attention as a potential choice for filling the growing demand for hot water around the world [5]. At present, the market offers a range of solar water heater designs at progressively reduced prices [6]. At a global scale, the cumulative installed size of 410.2 GWth was achieved, analogous to an area of 586 million square meters covered by solar collectors [7]. Passive thermo-syphonic solar water heaters (SWH) are frequently favored for residential hot water production in urban areas [8]. On the other hand, it can be argued that active solar water heating systems (SWH) that utilize circulating pumps are better suited for larger-scale commercial and industrial purposes [9]. The utilization of combined collector storage can fulfill a significant portion of the hot water requirements for low-income communities residing in rural areas [10]. The increasing popularity of these systems can be attributed to their enhanced reliability, streamlined designs, and reduced costs. Consequently, these systems may exhibit greater suitability for rural areas that possess a higher abundance of solar energy resources [11]. One significant limitation of these systems pertains to their substantial losses of heat during nocturnal stages. Numerous research endeavors were undertaken to address this issue, resulting in the proposal of various modified designs.

Upon reviewing the available literature, it is evident that the primary focus of research efforts has revolved around the enhancement of methodologies aimed at optimizing energy harvesting and heat retention [12]. In previous research, various studies have introduced triangular and rectangular integrated circuit solar water heaters (ICSSWHs) that incorporate transparent insulation [13, 14]. Several authors [15, 16, 17] have conducted experimental studies investigating the application of phase change materials (PCMs) in SWHs. Table 1 presents a complete overview of different flat plate solar collectors that incorporate phase change materials (PCM).

Table. 1. Summary of Computational and Experimental Studies FPSC using PCM.

Reference	**Energy Storage Material**	**Type**	**Examination type**	**Conclusion**
Saw et al. [18]	Paraffin wax & nano-enhanced	FPSC with PCM	Experimental	The collection efficiency was improved by 6.9% when PCM was used, and by 8.4% when PCM was nano-enhanced. (NEPCM)
Narayanan et al. [19]	Three PCM, 1.Paraffin	Solar water heater	Experimental	The findings of the study indicate that the utilization of phase change material (PCM)

	2.Eutectic gel PCM 3.Eutectic gel PCM nanocomposite			nanocomposites in solar water heating (SWH) systems leads to an improved charging rate of PCM, while simultaneously reducing the rate at which PCM releases heat into the water. This enhancement in efficiency contributes to the optimization of the SWH system's performance and the maximization of solar energy utilization.
Hamed et al. [20]	A new variety of PCM packed beds with various melting points	Pure PCM layer that is integrated beneath the absorber	Theoretical model	Nighttime heating requirements rise with increasing water inlet temperature, PCM melting temperature, PCM thickness, and decreasing mass flow rates in the LHS-based system.
Allouhi et al. [21]	N-eicosane ($C_{20}H_{42}$)	Integrated type SAW by incorporating a layer of phase change material (PCM) on their underside.	Numerical	The system's overall quality is influenced by climatic conditions, the specific phase change material (PCM) employed, the thickness of the PCM layer, and the flow rate of water within the system. Optimal outcomes can be achieved by employing a mass flow rate of 0.0015 kg/s, a phase change material (PCM) thickness of 0.01 m, and maintaining a temperature of 313 K.
Koyuncu et al. [22]	Paraffin wax	304 stainless steel chromium FPSC with PCM inside	Experimental	In PCM-enhanced collector 12.5% enhancement is seen is when the fluid is stationary and increases to 62.0% when the fluid is in motion.
Serale et al. [23]	Slurry PCM	The heat transfer medium utilized in the Fluidized Bed Solar Power Concentrator (FPSC) is known as Phase Change Slurry (PCS).	Numerical analysis	The potential for enhancing the utilization of solar energy can be notably augmented through the utilization of Phase Change Materials (PCMs) as a heat transfer medium, contingent upon the prevailing conditions. In regions with colder climates, this advantage can be fully realized.
Bilardo et al. [24]	PCM	The integrated circuit system (ICS) is equipped	Experimental and Numerical	The study yielded an average solar fraction of 56% and an

		with a storage cavity that houses phase change memory (PCM).		overall productivity of 402.2 kW h/m2.
Serale et al. [25]	Slurry PCM	The use of Phase Change Material (PCM) slurry as the primary heat carrier in a Fluidized Bed Solar Power Concentrator (FPSC) system is being investigated.	Numerical analysis	The increase in instantaneous efficiency during the winter season is observed to be between 20% and 40%, whereas during the summer season, the rise is typically between 5% and 10%.
Al-Kayiem et al. [26]	Paraffin wax	Built-in PCM-TES unit	Experimental	Flat plate collectors are considered to be the most efficient collectors, exhibiting an efficiency of 47.6% in the absence of phase change material (PCM). However, when PCM is incorporated, the efficiency increases to 51.1%. Furthermore, the utilization of a Cu-PCM nanocomposite further enhances the efficiency to 52%. The measurement of efficiency is conducted at a scale of 10 microns.
Chen et al. [27]	Paraffin wax	PCM with Aluminum foams	Two temperature Numerical model	The inclusion of aluminium foams within paraffin exhibits a notable impact on the melting rate of paraffin as well as its thermal conductivity. The inclusion of aluminium foams in paraffin leads to a higher degree of thermal stability in the temperature distribution compared to paraffin without aluminium foams.
Tyagi et al. [28]	Hytherm oil & Paraffin wax	The integration of evacuated tubes filled with phase change material (PCM) is observed in a FPSAH.	An experimental	An increase in the thermodynamic efficiency, denoted as η therm, was observed, rising from 20% to 53%.
Aissa et al. [29]	Granite stone storage material	The proposed system is a flat plate solar air	An experimental and Numerical	10-15 ^{o}C Increment in T_o

		heater featuring a singular glass glazing.		
Krishnananth & Murugavel [30]	Paraffin wax in Al capsules	Multi pass Hybrid Flat Plate Solar air heater	An experimental	$T_{o, Max}$ 58° C
Yadav et al. [31]	Desert sand Single-glazed	Hybrid type FPSAH	An experimental	47% to 69% Improvement seen.
Saxena et al. [32]	Granular carbon powder	Single-glazed hybrid Flat Plate Solar air heater	An experimental	43% to 73% Improvement seen.
Singh A.K. et al. [33]	PCM	Single pass flat plate cylindrical extended absorber	An experimental	η_{energy} was varied between 66%, at mass flow of 0.03 kg/s
Singh A.K. et al. [34]	Paraffin wax storage	Single pass serrated plate absorber	An experimental	63%, at 0.03 kg/s
Bouadila et al., [35]	Packed bed	A standard greenhouse structure, commonly referred to as a solar-assisted greenhouse (SAH)	An experimental	To was around 7 degrees Celsius warmer than Ti all night long.
Kabeel at al.[36]	flat and v-corrugated	V-corrugated FPSAH	An experimental	When compared to employing a flat plate without PCM, efficiency was raised by 21.3%.
Khadraoui at al [37]	Paraffin wax	A latent storage unit commonly adopts a rectangular configuration and is filled with paraffin wax.	An experimental	Phase change material (PCM) helped the solar air heater (SAH) raise its nighttime air temperature. PCM increased operational efficiency by 16%.

So far, PCM have been used in various applications in solar water heating, air heating etc. but none has used to check the effect of incorporating fins below the absorber plate of solar collector to check the behavior of PCM melting and solidification. So in this experimental analysis effect of use of fins on melting and solidification of PCM are analyzed and presented.

2. Experimental Methodology and Materials

2.1. Setup for experimentation:

This study aims to analyze the melting and solidification behavior of a latent heat storage material for various applications utilizing solar energy. Two solar collectors with geometric similarity have been prepared. The first collector is constructed utilizing a flat plate absorber, while the second collector incorporates a flat plate with a cylindrical extended geometric absorber. The absorber plate was coated with a black paint in order to optimize the absorption of solar radiation in both collectors. Figure 1(a) & (b) shows a sectional view of both the collectors. Paraffin wax is used as a latent heat storage material.

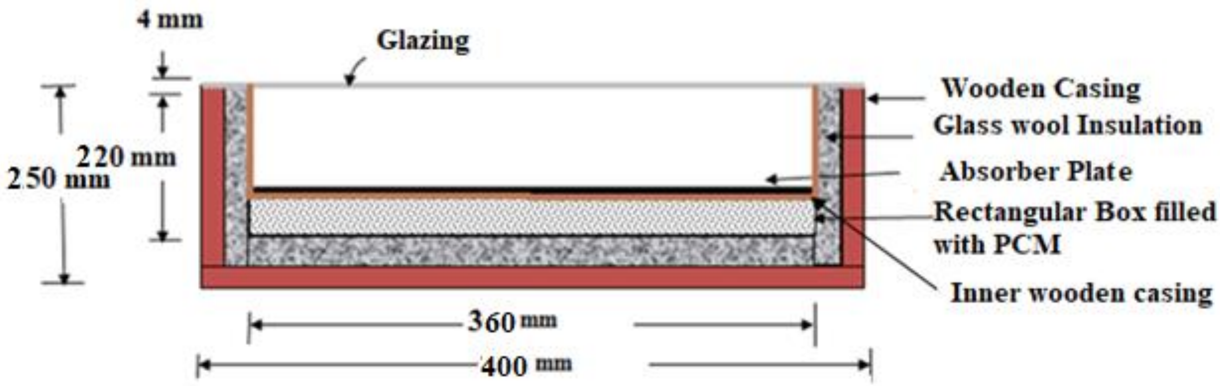

Fig. 1(a). Sectional view of collector-1

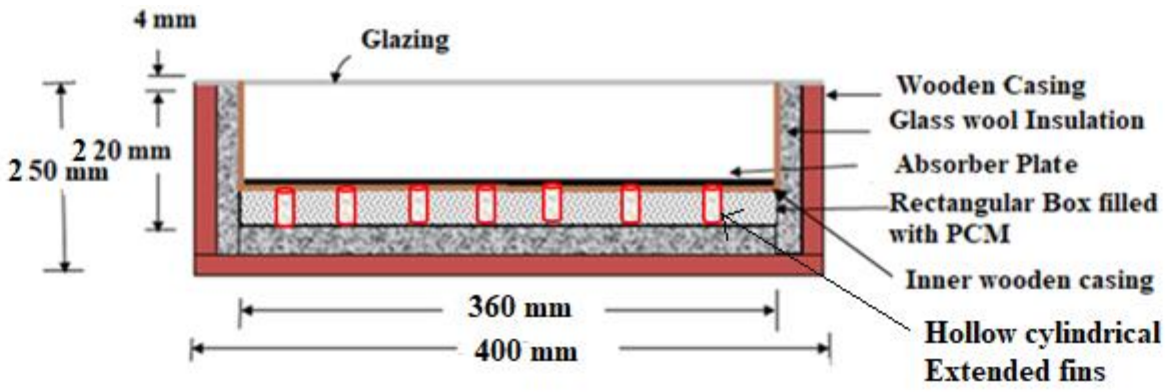

Fig. 1(b). Sectional view of collector-2

Table 2: Thermodynamic properties of energy storage materials used in both configurations [33]:

Properties	Value	Unit
Thermal conductivity	0.21	W/m^{o}C
Heat capacity	2.1	K /kg ^{o}C
Latent heat of melting	190	KJ/kg
PCM melting temperature	54	^{o}C
Solid density	876	Kg/m^3
Liquid density	795	Kg/m^3

The solar collector is positioned at a 43-degree inclination towards the southern direction in order to optimize the absorption of solar irradiation. Since both collectors are geometrically similar, the dimensions of each collector are assumed to be identical. The experimental setup incorporates a collector that possesses a gross collecting area measuring 1680 cm^2. The overall height of the collector measures approximately 250 mm. thin sheet metal and plywood are utilized in the construction of these collectors. A flat plate absorber with a cylindrical extended geometric absorber, consisting of a fins (9, 15, 21 & 27) with an internal diameter of 12 mm and a height of 130 mm, is being fabricated for use in collector-2. The absorbing plate's lower surface and all sides of the collector are effectively coated with insulating material, such as glass wool, to ensure sufficient insulation. This is done to minimize heat loss caused by the temperature difference between the collector and its surroundings. The utilization of a wooden frame is employed to provide structural support for both the sides and the base of the collector, primarily due to its reduced weight and cost-effectiveness. To minimize heat loss in the upward direction, a glass plate with a thickness of 4 mm was affixed onto the collector. Figure 2 depicts the image of various stages of fabrication; the base of the collector, as well as all of its sides, are effectively sealed using a sealant in order to mitigate any leakage.

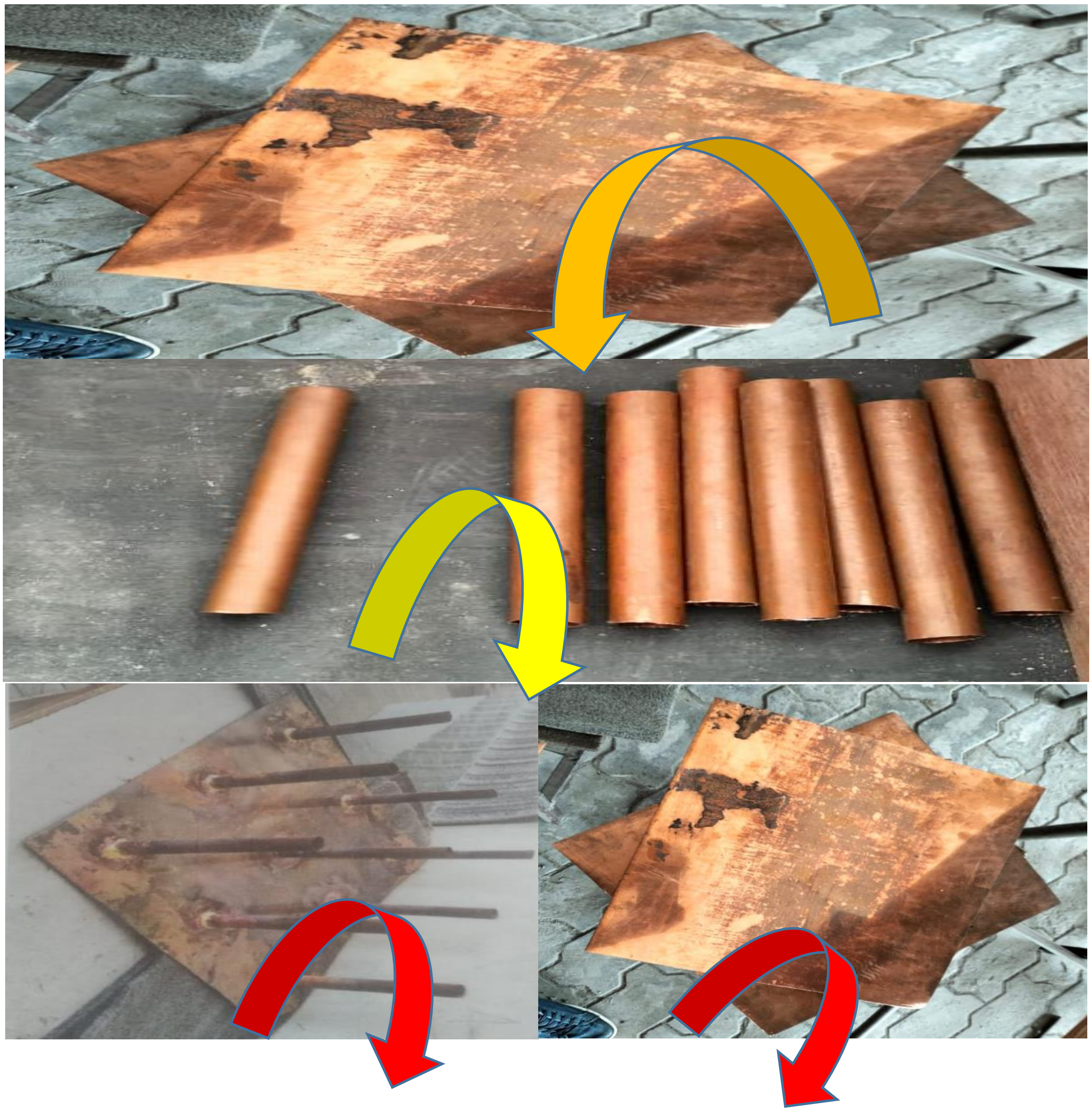

Fig.2 (a) Fabricated Absorber Plate

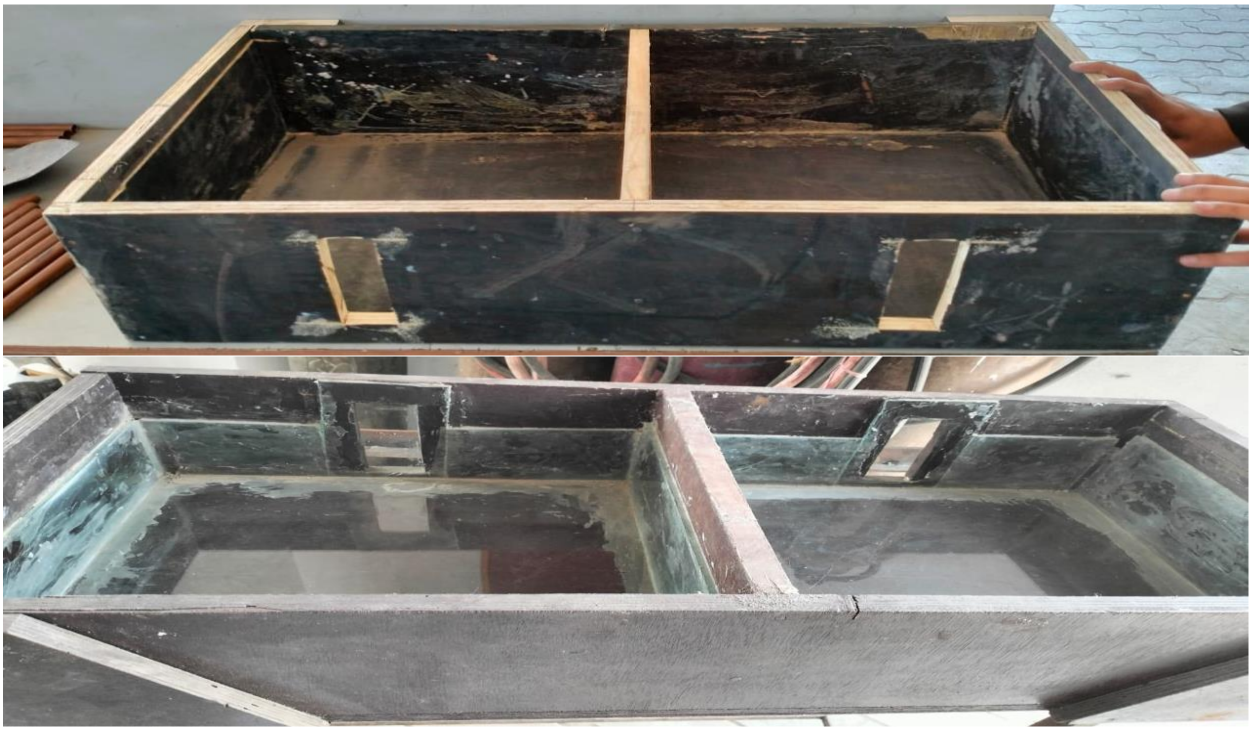

Fig.2. (b) Wooden casing with two separate cabin for fitting absorber plate and PCM.

Fig. 2. Fabricated Experimental Setup

2.2. Experimental procedures

Prior to conducting trials in both collectors, all connections, fittings, and the proper sealing of the PCM are thoroughly tested and verified to ensure there are no leaks. Furthermore, it can be guaranteed that all of the measuring tools are in optimal working condition. The experiments were conducted on various configurations at the MIT campus located in Moradabad, Uttar Pradesh, India, under clear weather conditions.

During the experimental investigations conducted on each collector, measurements were taken to determine the intensity of solar energy as well as the temperatures of the absorber plate and phase change material (PCM) at different stages. During the experimental procedure, a Solar Intensity meter that has been properly calibrated was utilized. This meter has a least count of 20 W/m^2 and possesses an accuracy level of 1.66%. It is capable of accurately measuring intensity values within the range of 0 to 1200 W/m ^{2}. The temperature measuring device utilized in this study had a measured temperature range of 20 ^{O}C to 200 ^{O}C, with an accuracy of 0.5 ^{O}C. These measurements were taken at different locations within the solar collector. In order to determine the mean temperature of the phase change material (PCM) within the collectors, three temperature sensors are strategically positioned at different elevations along the PCM box. Prior to conducting the experiment, the Solarimeter and thermocouple are properly calibrated.

2.3. Calculations of heat gain:

The Sensible heat gain by PCM can be analyzed as follows:

$$Q_u = m * C_p * \Delta t$$

(1)

Where, m is the mass of PCM, C_p is specific heat of PCM, and Δt is the difference in temperature after heat gain

The rate of stored thermal energy inside PCM at any instant is given by [38]:

$$Q_s = \frac{m_{pcm}}{\Delta t} c_{p,s} \Delta T_{pcm} \qquad T_{pcm} < T_m \tag{2}$$

$$Q_s = (\frac{m_{pcm}}{\Delta t})_{pcm} \qquad T_{pcm} = T_m \tag{3}$$

$$Q_s = \frac{m_{pcm}}{\Delta t} c_{p,L} \Delta T_{pcm} \qquad T_{pcm} > T_m \tag{4}$$

Total heat absorbed by PCM during charging = Sensible heating + Latent heat of Melting

3. RESULT & DISCUSSION

Two experimental setups were fabricated to be geometrically similar. The area of the absorber plate and the volume of the collector were kept constant in both setups. Both setups were operated simultaneously, and their performance parameters regarding the charging and discharging of phase change material (PCM) were assessed and presented in this study. This study assesses the impact of incorporating cylindrical fins on the charging and discharging characteristics of phase change materials (PCM). Additionally, the influence of the number of fins on the absorber plate is examined and reported in this analysis. Transparent glass is employed in both the collectors to enable the observation of the melting and solidification behavior of phase change materials (PCM).

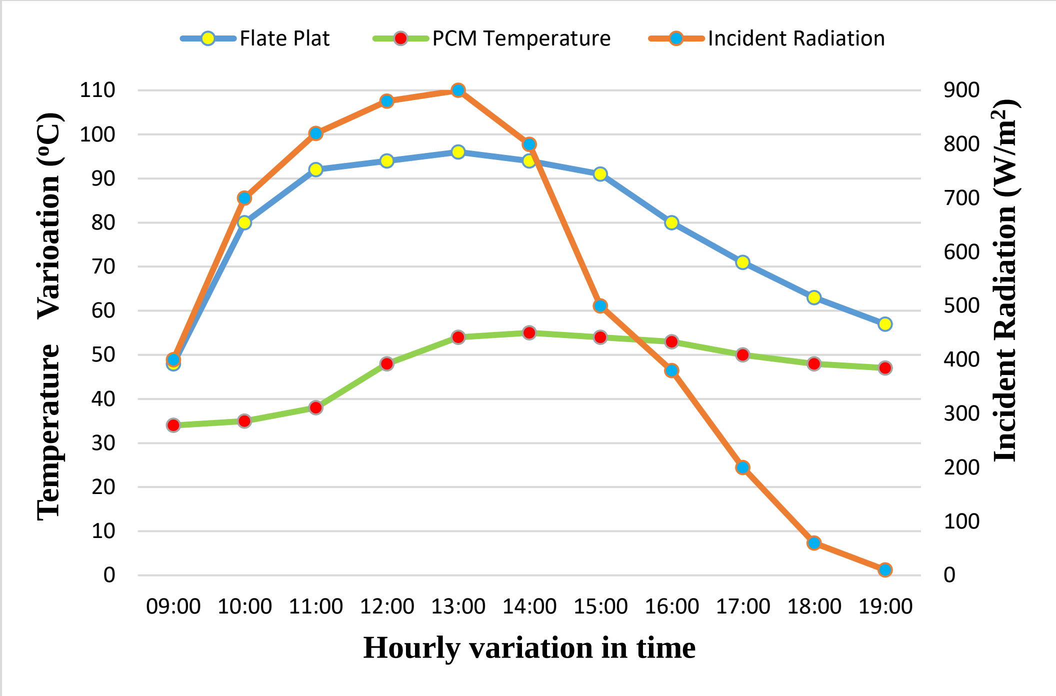

Fig. 3 Variation of PCM & Flat plate absorber temperature

The above figure (Fig.3.) represents the variation in flat plate temperature and PCM temperature along with incident radiation striking on the absorber surface. Temperatures of plate are measured at three different locations and average temperature variation are shown here similarly Temperatures of PCM are measured at three different locations and average temperature variation are presented in the above graph. The above figure shows that, temperature of each elements increases as the intensity increases and reaches its extreme value at 1:00 PM and then declines as the intensity of radiation decreases. Selected PCM has a melting point of 54 ^{o}C, so it is observed from the figure that, in this case PCM starts changing its phase after between 12:30- 1:0 PM. And it stored the latent heat during melting of PCM.

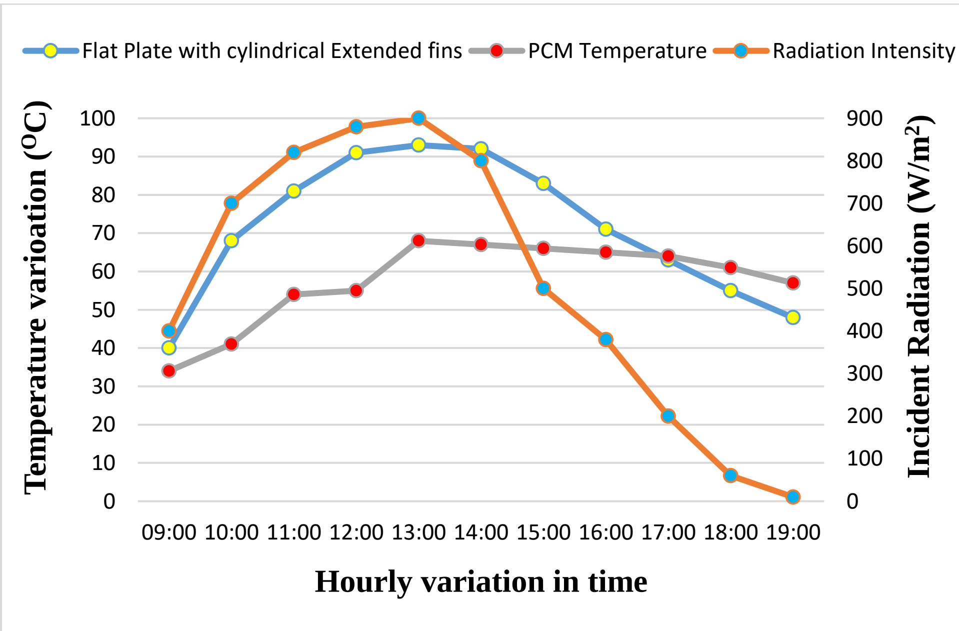

Fig. 4 Variation of PCM and absorber plate with cylindrical fins temperature

The above figure represents the variation in flat plate with cylindrical fin temperature and PCM temperature along with incident radiation striking on the absorber surface. Temperatures of plate are measured at three different locations and average temperature variation are shown here similarly Temperatures of PCM are measured at three different locations and average temperature variation are presented in the above graph. Fig. 4. Shows that, temperature of each elements increases as the intensity increases and reaches its extreme value at 1:00 PM and then declines as the intensity of radiation decreases. Selected PCM has a melting point of 54 °C, so it is observed from the figure that, in this case using fins PCM starts changing its phase after between 10:30- 11:0 AM. And it stored the latent heat during melting of PCM.

Fig. 3.& Fig. 4 also represents that, Using hollow cylindrical fins in flat plate absorber, PCM starts changing its phase approximately 1.5 – 2 hours before without using fins. So it represents that, for same area of collection more latent heat can be stored using extended geometries below the flat plate absorber.

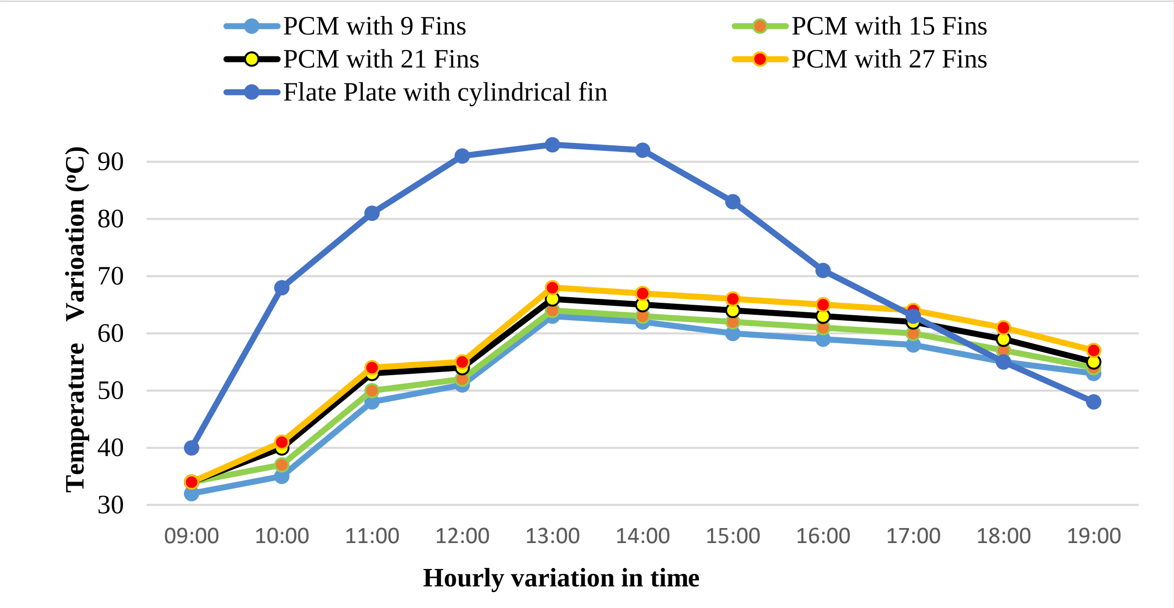

Fig. 5 Effect no increase in Number of Fin on charging behavior of PCM

Fig. 5. Shows the effect of increase in number of fin on the charging behavior of PCM it is detected from the figure that, increase in numbers of fins, PCM starts changing their phase early than less number of fins. So it is concluded that depending upon the size of collector maximum number of fins can be fitted to charge the PCM in minimum time and to store maximum amount of latent heat.

4. Conclusion

This study involves the fabrication and simultaneous analysis of two collectors that are geometrically similar but differ in terms of their absorber plate. The analysis has yielded the following conclusions.

- Experimental observation shows that, charging and discharging of PCM using flat plate collector is slower than flat plate with hollow cylindrical extended collector.
- Using cylindrical extended fins below the flat plate absorber, PCM starts changing its phase approximately 1.5 – 2 hours before without using fins.
- Temperature of each elements increases as the intensity of radiation increases and reaches its peak value at 1:00 PM.
- If number of fins increases below the absorber plate then charging time of PCM decreases.
- For the same area of collection more latent heat can be stored using extended geometries below the flat plate absorber.

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