Experimental Investigation of Thermal energy storage with phase changing material

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Abstract
Solar energy is the most prospective source of energy in recent years. Investigation is going on to utilize the solar energy by various academicians and researchers. The main problem in harnessing and using solar energy is its discontinuous nature. Solar energy is not available continuously for 24 hours. So, there is a need to develop a method to store thermal energy during sunshine and utilise this stored energy as per requirement. Some materials available called phase changing materials (PCMs) which can store large amount of thermal energy in the form of latent heat. This energy can be used to heat the water for domestic purposes during evening hours. In this work, an experiment was carried out on parabolic solar concentrator to check the feasibility of using phase changing material as a solar energy storage medium to heat the water. Two containers were put on the concentrator to heat the same amount of water. One container was with PCM material and the other container was without PCM material. The energy efficiency of the system with pcm storage was greater than the system without pcm storage. It means that the pcm storage system is able to trap more of the incident radiation in the form of thermal energy. The exergy efficiency of the system with pcm storage was also higher than the system without pcm storage.

1. Introduction

It's a fact that civilized society is completely reliant upon fossil fuels for nearly every aspect of its existence. While fossil fuels have been important in the development of most industrial nations, there are a few realities of using them that society needs to come to terms with. There are hundreds of years or just a few decades left of this resource. At some point, fossil fuels are going to either be gone or they are going to become too expensive to realistically use. Fossil fuels account for 85 percent of the United States' energy. If the world was entirely reliant upon solar energy, that would be fine because sunlight is a perpetual resource. Also fossil fuel emissions are contributing greatly to climate change. Every year, power plants in the US alone put more than 2.5 million tons of CO_2, a major greenhouse gas, into the atmosphere. Fossil fuels are also responsible for a significant amount of land, water, and air pollution. On the other hand, solar energy panels and wind turbines generate zero emissions in the generation of electricity. This stands as an even more poignant example of the necessity of renewable energy development.

While renewable energy systems on a large scale are an important step for keeping national and international infrastructures intact, it's also important to understand the scalability of renewable energy solutions. The average person who can't afford his own coal-powered power plant is generally capable of purchasing a home solar array or small wind turbine. When individuals are able to own the equipment that generates their electricity it means that they don't have to rely upon fluctuating prices or shortages from outside energy producers.

Also, renewable energy can often be gathered cleanly and safely in local or regional communities due to the wide availability of the inputs. According to recent Greenpeace estimates, the world could save around $180 billion a year by switching 70% of the planet's electricity production to renewable options.

In this regard we have solar energy as the largest source of renewable energy. More solar energy hits the earth in one hour than all the energy the world consumes in a year. So to solve the energy crisis, we should go to the bank where the energy is kept — the sun. The earth receives 1.25×10^{21} kcal of solar energy annually as a whole. If an economic method could be found to store and utilise the sunlight falling on our roofs, it could easily cover all our domestic energy needs, while the sunlight falling on large open areas could easily run all the wheels of the human industry. India is blessed with good sunshine. The country receives solar radiation amounting to over 5 x1015 kWh per annum [1] with the daily average incident energy varying between 4-7 kWh per m^2 depending on the location [2]. So utilising more and more solar energy will save more and more fuel cost and also it will help in reducing environmental pollution. Energy storage is essential in solar energy utilization to cater for its intermittence.

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There is always a debate going on utilities of renewable energy to balance the energy crisis. But concerns on the utility side of the table are real: intermittency, potential destabilization at the feeder level, non-baseload, and peaks in generation that don't necessarily match demand peaks. Today's power infrastructure involves unpredictability in both supply and demand that is extremely difficult to manage. The choice comes down to two options: over-generate so as to not undersupply, or find ways to better match up supply and demand. To balance the grid and keep it in a stable condition, we need energy storage. It is to be understood that how to integrate energy storage into a variety of applications. As more renewable energy comes into the power mix, high-response energy storage seems imperative.

2.A review on the fabrication techniques of integrating PCM with solar water heating system and its effects

Integration of PCMs with solar water heating systems results in higher energy density. Thus a number of fabrication techniques have been proposed in this regard. B. Kanimozhi [3] designed a PCM storage tank consisting of a number of copper tubes, filled with PCMs as shown in the Fig. 1 and 2. This PCM storage tank was kept in well insulated storage tank.

This fabricated PCM storage tank received hot water from solar tank which was integrated with evacuated glass tubes collector. During charging process heat energy could be stored in PCMs inside copper tubes and this energy could be recovered during discharging process by applying cold water. The line diagram of the experimental set-up is as shown by figure 3:

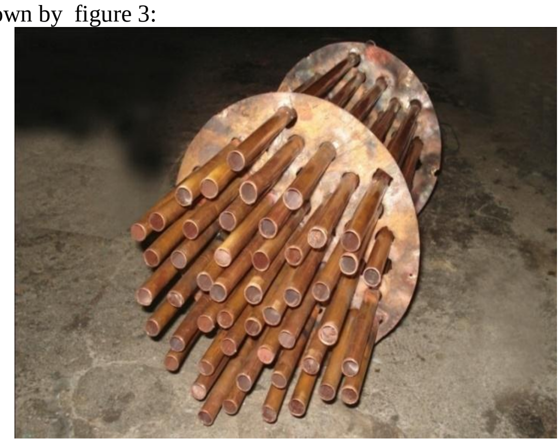


Fig.1: Copper tube arrangements [3]

Fig.2: Fabricated PCM storage tank [3]

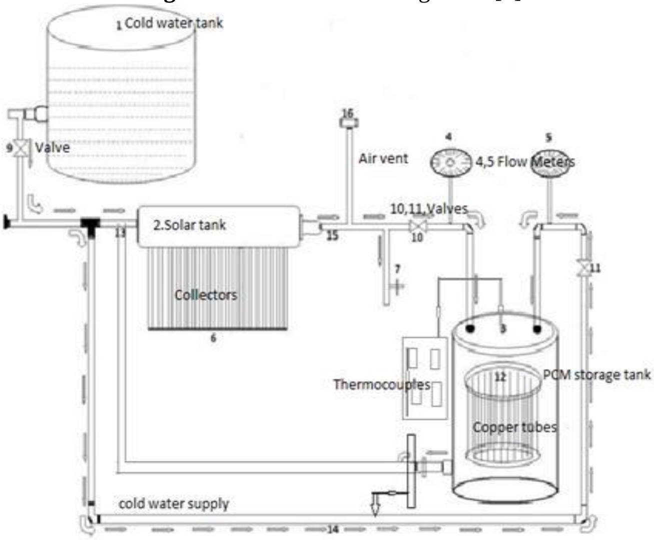


Fig. 3: Line Diagram of the Experimental setup [3]

It was concluded from the experimental results that the enhancement of thermal energy stored could be achieved by changing the number of copper tubes in the fabricated storage tank, the smaller diameter of copper tubes could effectively enhance the heat transfer from the HTF to the PCM as well as from the PCM to the HTF during charging and discharging processes.

Padmaraju [4] in his work studied the feasibility of storing solar energy using phase changing materials and utilising this energy to heat water for domestic applications during night time. The storage system, as shown in Fig. 4 consisted of two simultaneously functioning heat absorbing units. One was a solar water heater and other was heat storage unit consisting of PCM. The storage unit utilised small cylinders made of aluminium filled with paraffin as PCM and integrated with a solar collector to absorb solar energy the performance of this PCM based thermal energy storage system was compared with conventional heat energy storage system.

Fig. 4: Photographic view of Experimental Setup [4]

It was observed that the heat stored in the LHS (latent heat storage) system was far more than that stored in the SHS (sensible heat storage) system of the same size and volume of the storage tank.

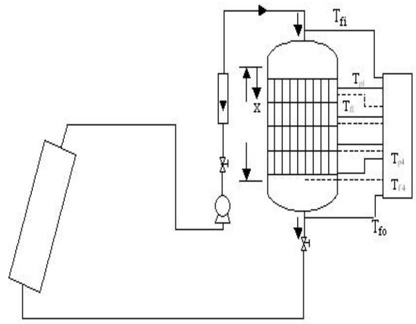


Fig. 5: Schematic of Experimental Setup [4]

1. Solar flat plate collector; 2. Pump 3 & 4. Flow control valves; 5. Flow meter; 6. TES tank 7. PCM capsules 8. Temperature indicator, TP & Tf - Temperature sensors.

The heat stored per unit volume was found to be 0.234 kJ/cc for the LHS system and was 0.144 kJ/cc for the SHS system. It was thus concluded that the LHS systems could provide a substantial decrease in the storage volumes for the same heat stored, when compared to SHS systems. It was observed that the SHS system charged to the maximum temperature of 70°C, 40 minutes sooner than the LHS system. On an average, the charging time in SHS systems was quicker than the LHS systems by 30-60 minutes depending on the flow rates. On the other hand, heat transfer between the HTF and PCM in the Latent heat system reduced the temperature gradient of the HTF and increased the charging time. It was also observed that the efficiency of SHS system is fluctuating over various periods of time, while the efficiency of the LHS system was constant over the phase transition temperatures and that it also showed a higher efficiency. Hence the LHS system was more efficient.

B. K. Gond [5] designed two box type solar water heater. One had conventional tube-in-sheet flat plate collector and another was modified by using Phase Change Material (PCM) as short term heat storage media. Many practices were tried to fill and seal the PCM to maintain effective thermal contact of water with tube. The prototype was developed and tested for indoor as well as outdoor climatic condition of Gwalior city India. It was observed that water could be heated to 90°C by mid afternoon in simple water heater where as PCM filled collector kept water warm even after sun-set. It was found that 40° C temperature of water was available till 10 pm in winter conditions. It was concluded that a ½ kg of PCM with some pipe work in the flat plate collector could improve the efficiency as well as dependability of cloudy or short-term Sun off period. It's fabrication is shown in the Fig. 6.

Fig.6: Step-by-step fabrication of PCM filled flat plate collector has been shown [5]

Present experimental study is an attempt to investigate the performance of solar water heating system with latent heat storage using exergy and energy analysis. In conventional sensible heat storage systems water is directly put in a steel container having black absorptive coating while in the pcm storage system water is kept in a copper vessel and the copper vessel is kept inside the steel container and the copper vessel is surrounded by a layer of paraffin wax.

The experiment was performed for five days in the typical climatic conditions of Lucknow, India on the roof of the Baba Bhimrao Ambedkar University, Lucknow..

3. Description of the experiment

In this work, an experiment was carried out on parabolic solar cooker to check the performance of phase changing materials in storing heat. Two identical copper containers were put on the parabolic solar cooker; both were used to heat the water of same quantity. One of the containers was put inside a steel box having black absorptive coating, the space between the copper container and the steel box was filled with paraffin wax (phase changing material). The holes were made to insert the thermometers to take the temperatures of the paraffin wax and the water in both the containers, at the interval of 30 minutes. The holes were properly sealed to avoid losses of heat through the holes. The amount of water heated was 102 ml and the amount of the paraffin wax used was 419 gm.

Fig. 7: Steel container with water and paraffin wax

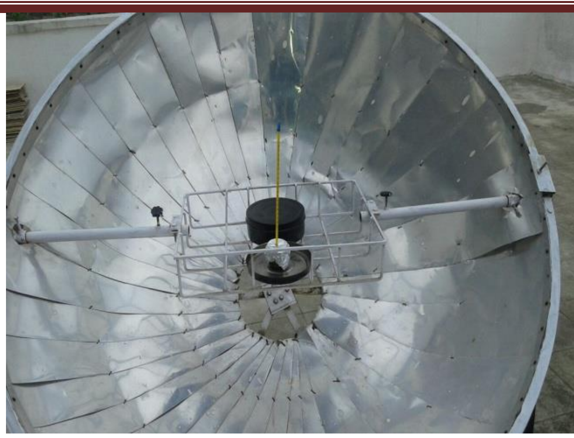


Fig. 8 Experimental arrangement

4. Exergy and energy analysis for the charging period

Performance of engineering systems is generally measured using efficiency as defined by first law of thermodynamics. Efficiency as defined by first law uses energy for its quantification. Second law efficiency or exergetic efficiency is an analogous parameter defined using availability. Energy and exergy analysis were carried out to evaluate the efficiency of the solar water heating system with PCM.

4.1 Energy analysis

The energy analysis is based on the first law of thermodynamics and the corresponding first law efficiency has been calculated. The energy incident on the system is given by

$$Q_i = AI_s \quad (1)$$

Where A is the surface area of the containers, I_s is the intensity of the solar radiation at any particular site.

Energy stored in the container with pcm is given by:

$$Q_{tp} = m_p c_{ps}\Delta T + m_p L_P + m_p c_{pl}\Delta T + m_w c_w \Delta T \quad (2)$$

Energy stored in the container without pcm is given as:

$$Q_t = m_w c_w \Delta T \quad (3)$$

Where m_p is the mass of the paraffin wax, c_p is the specific heat of the paraffin wax, ΔT is the temperature difference, L_P is the latent heat of melting of the paraffin wax, m_w is the mass of the water, c_w is the specific heat of the water.

There are also losses of heat in the system due to conduction and convection. It is assumed that these losses are negligible as in this work area of interest is the amount of heat stored in the two systems.

The following equation is used to calculate energy efficiency of the system:

$$\eta = \frac{stored\ useful\ heat}{solar\ energy\ input} \quad (4)$$

It can be formulated as:

$$\eta = \frac{Q_t}{Q_i} \quad (5)$$

4.2 Exergy analysis

Exergy is the tool, which indicates how far the system is from equilibrium state. The concept of exergy was put forward by Gibbs in 1878. It was further developed by Rant in 1957.

Exergy uses the conservation of mass and energy principles together with the second law of thermodynamics for the design and analysis of energy systems. An analysis of exergy can reveal whether or not and by how much amount it is possible to design more efficient systems by reducing the limitations in existing systems [6].

The exergetic efficiency or second law efficiency (ε) can be defined as:

$$\varepsilon = \frac{availability\ output}{availability\ input} \quad (6)$$

$$availability\ input = Q_i\left(1 - \frac{T_o}{T_{sun}}\right) \quad (7)$$

Where Q_i is the incident solar radiation, T_o is the temperature of the surroundings, T_{sun} is the temperature of the sun.

Availability output in case of container with PCM is given as:

$$availability\ output = dQ_s\left(1 - \frac{T_o}{T}\right) \quad (8)$$

$$availability\ output = (m_p c_{ps} dT + m_p L_P + m_p c_{pl} dT + m_w c_w dT)\left(1 - \frac{T_o}{T}\right) \quad (9)$$

$$availability\ output = m_p c_{ps}(T_2 - T_1) - m_p c_{ps} T_o ln\frac{T_2}{T_1} + m_p L_P - m_p L_P \frac{T_o}{T} + m_p c_{pl}(T_2 - T_1) - m_p c_{pl} T_o ln\frac{T_2}{T_1} + m_w c_w (T_2 - T_1) - m_w c_w T_o ln\frac{T_2}{T_1} \quad (10)$$

Availability output in case of container without PCM is given as:

$$availability\ output = m_w c_w (T_2 - T_1) - m_w c_w T_o ln\frac{T_2}{T_1} \quad (11)$$

Thermal properties of water:

Density	1000 gm/L
Boiling point	100° C
Latent heat of melting	334 kJ/kg
Latent heat of evaporation	2,270 kJ/kg
Specific heat water	4.187 kJ/kgK
Specific heat water vapour	1.996 kJ/kgK

Thermal properties of paraffin wax:

Density	900 kg/m³
Specific heat (solid)	2.9 kJ/kgK
Specific heat (liquid)	2.13 kJ/kgK
Melting point	53° C
Latent heat of melting	147 kJ/kg
Thermal conductivity	0.25 W/mK

5. Results and discussion

The experiment was carried out to check the feasibility of using phase changing materials as heat storage medium. Thus the parabolic solar cooker was used to heat the water in two ways- 1) conventionally, i.e., without PCM 2) with PCM. The readings were taken for 5 days. The time interval between each reading was set to be 30 minutes. The graph was plotted between time and the temperatures of the PCM, water (with PCM), water (without PCM). The trend thus obtained is shown in the following graph. The graph shows that the rate of temperature rise is greater in case of PCM container. It is noted that the difference between the temperature of water with PCM and water without PCM is quite high. The normal water comes to the ambient temperature at 7:30 pm but the temperature of the water with PCM remains 6 degrees higher for two more hours. The maximum temperature reached in the water with pcm storage is 100° C while the maximum temperature reached in the water without pcm storage is just 66 °C. The fluctuation in temperature is seen due to the fluctuation in the irradiation and due to the effects of the wind velocity. The angle of the parabolic concentrator had to be set according to the angle of the sunlight as the angle of the sun changes by 15 degrees every hour.

For the calculations of the exergy efficiency and energy efficiency of the two systems for their comparison data as recorded on 21st May, 2015 has been used.

The Fig. 9 shows the variation of temperature of pcm, water with pcm and water without pcm with respect to time according to the data recorded on 21st May, 2015.

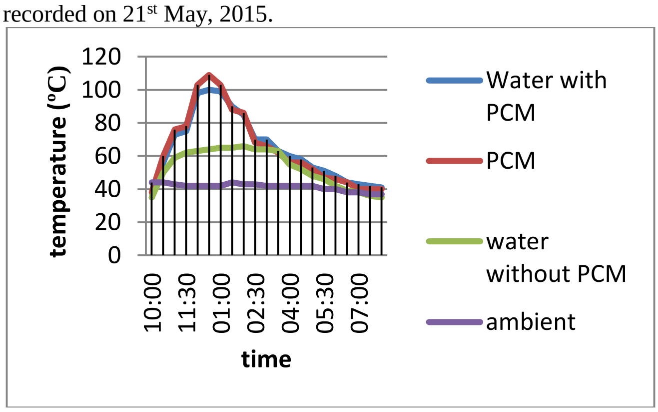


Fig.9: Variation of temperature of PCM and water with time

The Fig.10 shows the variation of the irradiation with time. The measurements of the direct and the reflected irradiation have been taken with the help of the solarimeter. Thus the incident radiation in joule is found out using the equations as:

$$Q = I_s A \Delta t$$

Where I_s is the irradiation or the incident radiation upon a surface per unit time per unit area, A is the surface area of the containers in which the water is kept and Δt is the time interval.

Surface area of the pcm container is

= area of upper surface+area of curved surface+area of lower surface

=0. 02324m²+ 0.0324m²+0.02324m²=0.07888m²

Surface area of the container without pcm

= area of upper surface+area of curved surface+area of lower surface

=0.002463m²+0.008796m²+0.002463m²=0.013716m²

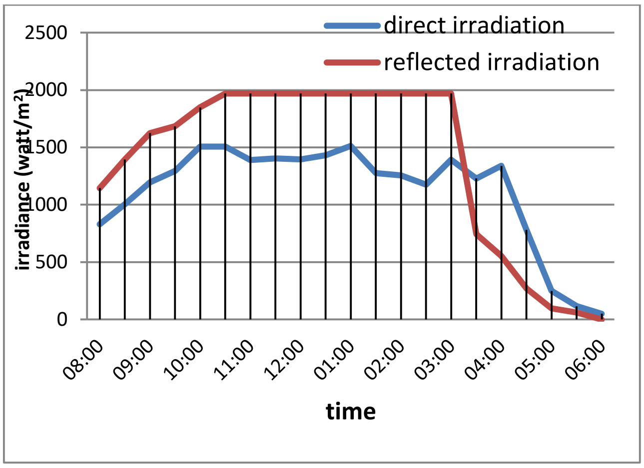


Fig.10: Solar radiation vs. time plot

Figure 11 shows the curve for the heat stored in the water with and without pcm with respect to time. It is observed from the graph that the heat stored in the water with pcm storage is higher than the water without pcm storage for whole of the time.

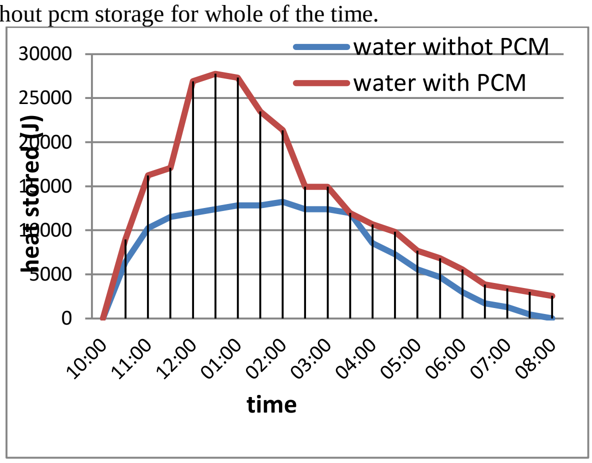
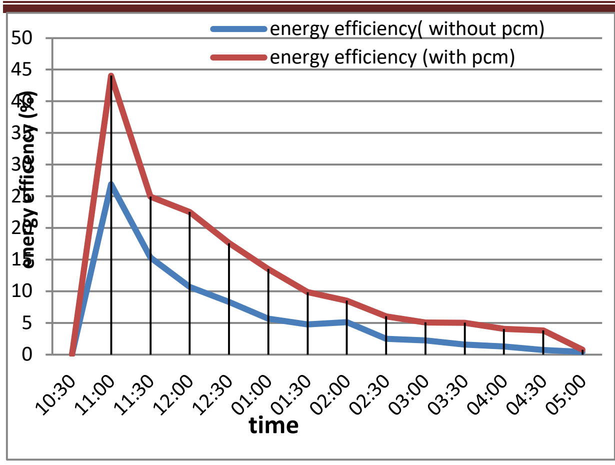


Fig. 11: Instantaneous heat stored vs. time graph

Figure 12 shows the curve for the heat stored in the paraffin wax with respect to time. When this graph is compared with the graph no. 11, it can be observed that the heat absorbed by the paraffin wax is much greater than the water. This large difference in the stored heat is due to the latent heat storage in the paraffin wax, while there is only sensible heat storage in the water. The wax stores heat in the form of sensible heat at first until it reaches its melting temperature and then energy storage is achieved by the melting of the wax at constant temperature, that is, in the form of latent heat. After that the energy is stored as sensible heat in the liquid wax. Wax then transfers this heat to the water in its vicinity. As a result the water with pcm storage has much higher temperature than the water without pcm storage.

Fig. 13 shows the curve for the heat stored in the paraffin wax with respect to time. When this graph is compared with the graph no. 22, it can be observed that the heat absorbed by the paraffin wax is much greater than the water. This large difference in the stored heat is due to the latent heat storage in the paraffin wax, while there is only sensible heat storage in the water. The wax stores heat in the form of sensible heat at first until it reaches its melting temperature and then energy storage is achieved by the melting of the wax at constant temperature, that is, in the form of latent heat. After that the energy is stored as sensible heat in the liquid wax. Wax then transfers this heat to the water in its vicinity. As a result the water with pcm storage has much higher temperature than the water without pcm storage.

Fig. 14 shows the graph between energy efficiency and time. From the graph it can be seen that the efficiency is greatest in the starting because temperature difference is maximum. The efficiency keeps



reducing as the temperature of the system rises because heat storage rate decreases as the temperature of the system increases. Moreover at the latter stages efficiency is very low as storage nearly stops and heat rejection starts which is called the discharging period of the system.

Fig. 13: Instantaneous heat stored vs. time graph for paraffin wax

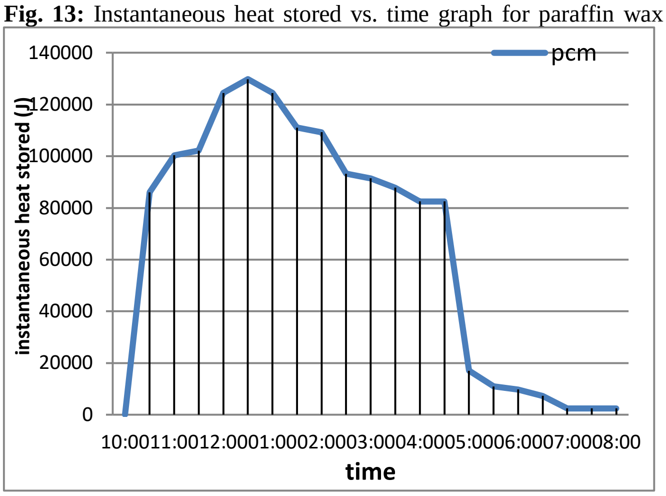


Fig.14: Plot for energy efficiency vs. Time

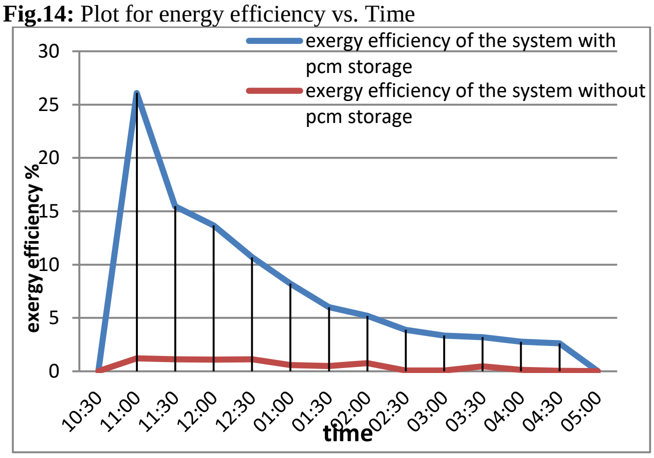


Fig. 15: Plot for exergy efficiency vs. time

The Fig.15 shows the exergy efficiency of the two systems. It can be seen that the exergy efficiency of the system with pcm has higher exergy efficiency than the system without pcm.

The heat transferred in the LHS + SHS unit ranged from 95.032 to 157.55 kJ, whereas the heat stored in the SHS unit was in the range of 6.404–13.23 kJ. The heat stored in the LHS+SHS unit, which was 95.032 kJ at 10:30 am, reached its maximum value (157.55kJ) at 12:30 pm during the experimental period. Fig.16 shows the amount of cumulative thermal exergy stored with time. The thermal exergy stored in the LHS+SHS unit was in the range of 56.12-90.62 kJ. While it only ranged between 0.438-1.862 kJ for the SHS unit. The energy efficiency ranged from 0.403%-26.89% for LHS+SHS unit, while the energy efficiency was in the range of 0.745%–44.06% for the SHS unit. When the energy efficiency is compared with exergy efficiency the following result can be drawn: The energy efficiency was always higher than the exergy efficiency. This is expected because the total energy content of the system is taken into account in order to calculate the energy efficiency. In other words, to calculate the energy efficiency, the quantity of the energy transferred is taken into account, and the quality of the energy transferred is neglected.

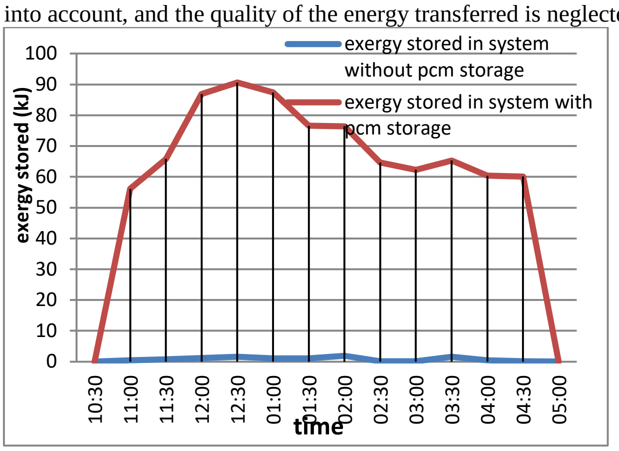


Fig. 16: Plot for exergy stored vs. Time

6. Conclusions

The comparative study based on the first and second law analysis of a water heating system with and without latent heat storage has been done on a parabolic concentrator. The results found from the present experimental study can be summarised as follows:

1) The maximum temperature reached in the case of the system with latent heat storage is much higher than the system without latent heat storage.
2) The heat stored in the system with pcm storage is very high as compared to the system without pcm storage because the paraffin wax stores large amount of heat in the form of latent heat.
3) The wax stores large amount of heat in the form of latent heat and transfers this heat to the water kept in its vicinity. On the other hand, water has a good heat retention capacity and it stores heat for longer duration thus the water keeps the wax warm for longer duration. In this way this combined arrangement of water and wax provides a good storage medium of solar energy.
4) The energy efficiency of the system with pcm storage is greater than the system without pcm storage. It means that the pcm storage system is able to trap more of the incident radiation in the form of thermal energy.
5) The exergy efficiency of the system with pcm storage is also higher than the system without pcm storage.

Acknowledgement

The experiment was performed at Baba Bhimrao Ambedkar University Lucknow.

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