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# Improvement of thermal energy storage density of parabolic dish solar absorber with organic phase change materials

**Ramalingam Senthil * and Palanichamy Sundaram**

Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, India

*Corresponding author: senthil.r@ktr.srmuniv.ac.in

**Abstract.** The enhancement of the thermal storage capacity of the solar absorber using phase change material was investigated in this work. A 16 $m^2$ paraboloidal dish concentrator was employed to concentrate the solar rays on the absorber. Erythritol and D-Mannitol are selected based on the temperature region of the absorber during the outdoor testing at the test site (Chennai; 13°N, 80°E). The mass flow rate of heat transfer fluid was in the range of 25-150 kg/h. The solar absorber with phase change material will ensure a uniform thermal output during a sudden discontinuity of solar radiation, for a few to several minutes. The absorber is ensured with the uniform temperature. PCM solar absorbers will act as a thermal battery for later use in thermal applications with proper insulation of the absorber.

**Key words.** Solar absorber, Parabolic dish collector, Outdoor testing, Integrated PCM, Solar thermal battery

## 1. Introduction

Utilization of renewable energy and energy conservation are entertained in each country regarding the environmental pollution. Especially, solar energy has the greatest potential and increasing deployment all over the world. The optical properties of solar absorber is important to convert more incident solar energy into useful energy. Various solar absorbers in concentrating collectors were researched extensively in past decades. The addition of more metal fins may provide more uniform temperature inside. However, it increases the mass and cost. The parabolic dish collector (PDC) with integrated storage at its focus was numerically studied using Ray-tracing method by Tao *et al.* [1]. The solar absorber consisted of many heat transfer tubes. HTF flowed through tubes. The shell side was filled with PCM.

The non-uniform heat flux on absorber tube surface resulted in a non-uniform temperature distribution on the inner surface of PDC. Ashmore and Simeon [2] investigated the performance of a dish solar concentrator using energy and exergy efficiencies. Exergy analysis is used to add more meaningful discussions. Ricardo *et al.* [3] studied a PDC consisting of a heat collection element composed of a stainless-steel tube. A selective absorber tube surface was covered by an evacuated glass cover to prevent oxidation and heat losses.

Sunil et al. [4] used paraffin wax in the solar box cooker to keep the the cooked food in hot condition for 3-4 hours. The thermal storage capacity of the cooker was improved. Non-uniform temperature distribution observed on the solar absorber of PDC [5]. A modified **heat trnasfer fluid** (HTF) path also suggested for heat absorption. Further, the effect of PCM in the the receiver with improvement in exergetic performance was determined [6-10]. Ahmet *et al.* [11] tested six building composite PCMs with expanded graphite and observed with a good thermal stability. A comprehensive model for evacuated tube solar collector was presented by Jafarkazemi *et al.* [12].

The exergetic performance of collector increases with increase in inlet temperature and decrease in the mass flow of water. Vinod *et al.* [13] determined convection heat loss from a cavity absorber. The energy and exergy analysis of organic Rankine cycle driven by waste heat were analysed by Cihan and Kavasogullari [14]. Nation et al. [15] modelled a novel Electrical Energy Storage Receiver for solar parabolic trough collector. The presented a conceptual design and mathematical models are describing the operation of the receiver along with important results of model validation. At adiabatic conditions, the results were found to be consistent. Fleming et al. [16] proposed a general model to analyze the thermal performance of multi-cavity CSP receivers. An optimal aperture flux maximizes the local efficiency. The constraint is the maximum receiver temperature. The thermal efficiency, receiver and fluid temperature were determined through optimized flux.

The thermal storage density of the absorber with PCM was not much addressed in literature for compensating a short time unavailability of radiation and improved heat flux inside the absorber. Thermal storage density is useful for all applications requiring uniform heat supply like solar cooking, preheating of fuels, heat treatment. It was found that sugar alcohols are promising PCM candidates with their high energy density and melting temperature range of 100-170°C. Erythritol and D-Mannitol were selected for the absorber temperature zones at 120°C and 180°C respectively. PCM is aimed to achieve output temperature around 100°C during short time cloudy conditions. The enhancement of thermal storage density using multiple PCMs are investigated in outdoor testing and the improvements are reported in this study.

## 2. Materials and Methods

A 16 $m^2$ paraboloidal dish concentrator with hardened steel in an elliptical frame of 3.8 m x 5.3 m axes with around 850 solar grade mirrors of 0.9 reflectivity (made by Thermax Ltd, Pune, India) was used. The solar tracking of the PDC is a two-way axis mechanism. The specifications of the paraboloidal dish have been explained in the authors' earlier work [5].

The external diameter and width of the absorber were 406 mm and 100 mm respectively. The cylindrical tank type absorber was fabricated with 5 mm thick mild steel plate. The actual concentration ratio was around ninety. The absorber was fixed at a focal distance of 2.5 m from the dish. An absorber with multiple PCMs was tested for the effect of thermal storage capacity.

Figure 1 and 2 show the photographic view and schematic layout of the PDC experimental test setup respectively. The absorber was halved with 30 mm thick glass wool insulation. The insulation between the two absorbers was made to avoid heat interaction between the sections. Rectangular thin fins of 90 mm length and 2.5 mm thickness were fixed on the incident surface. The thickness of PCM around fins and absorber plate was 25 mm thickness. The HTF was allowed to flow at a uniform rate over the PCM housings in PCM side and directly over the fins on another side.

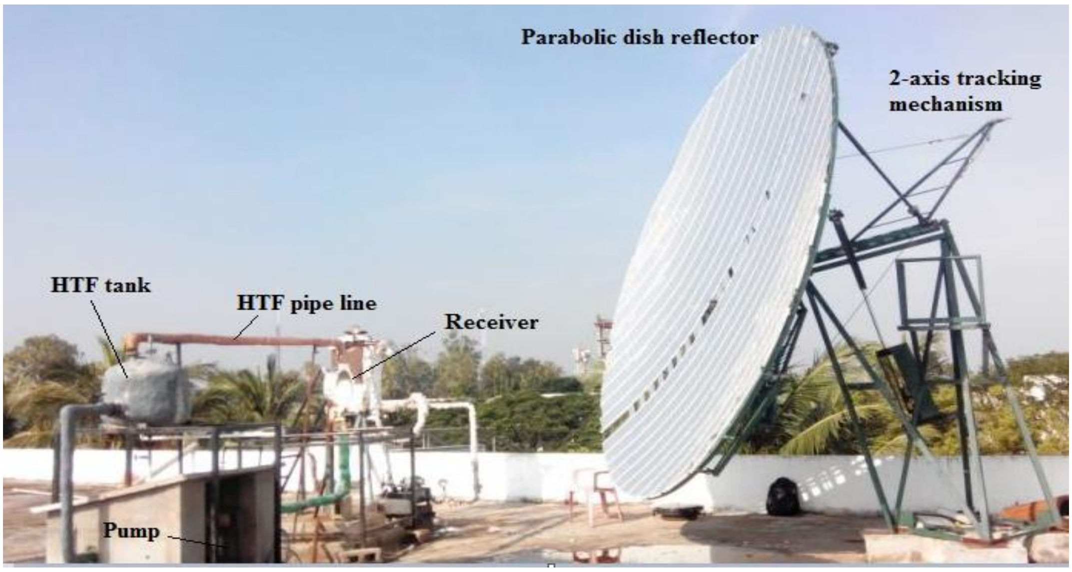


**Figure 1.** Photographic view of parabolic dish collector and absorber

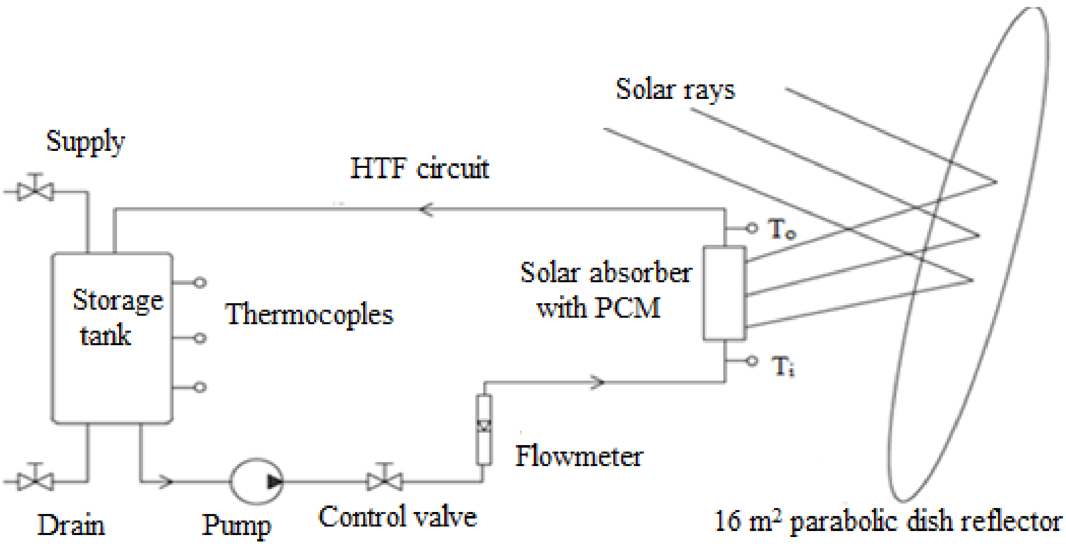


**Figure 2.** Schematic layout of parabolic dish collector and absorber

The sectional views of the absorber is shown in fig. 3. In the second absorber settings, two PCMs were employed. HTF enters the absorber radially inward and leaves axially outward. An increase in temperature from both the sides was observed. The concentration ration was maintained by two-way tracking of PDC. The operating parameters of HTF flow rate, inlet and outlet temperature of HTF and absorber temperature were measured experimentally. HTF mass flow rates used were 70 and 90 kg/h for the main inlet. Equal HTF flow rate was allowed to both the sections of the absorber. The PCM selected are based on its melting point, latent heat, thermal stability and non-toxicity. D-Mannitol of 1.1 kg and Erythritol of 3.5 kg. Table 1 shows the thermal properties of PCMs.

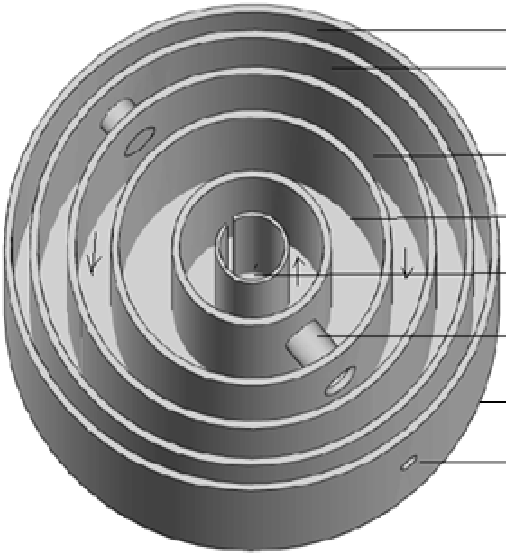


**Figure 3.** Schematic layout of solar absorber with multiple PCMs

**Table 1.** Thermophysical properties of Erythritol and D-Mannitol

| **Properties** | **Erythritol** | **D-Mannitol** |
|---|---|---|
| Melting point, [°C] | 117.7 | 166 |
| Melting enthalpy, [kJ/kg] | 340 | 326 |
| Specific heat, [kJ/kg K] | 1.38 (solid), 2.76 (liquid) | 1.7 (solid), 2.4 (liquid) |
| Thermal conductivity, [W/mK] | 0.733 (solid at 20°C), 0.326 (liquid at 140°C) | 0.279 (solid at 20°C), 0.307 (liquid at 170°C) |
| Density, [kg/m$^3$] | 1480 (solid at 20°C), 1300 (liquid at 140°C) | 1520 (solid at 20°C), 1450 (liquid at 170°C) |

## 3. Performance calculations

The thermal performance calculations are carried out with the experimental readings. The thermal performance includes energy and exergy analysis.
The HTF heat gain ($Q_u$) was given as in eq. (1),

$$Q_u = \dot{m} C_p (T_o - T_i) \tag{1}$$

Where, $C_p$- liquid specific heat, $\dot{m}$ - mass flow rate, $T_i$ and $T_o$- inlet and outlet temperature of HTF.

The dominant heat losses from the absorber surface are radiation and convection losses, the total heat loss is given by eq. (2),

$$Q_l = hA_r(T_w - T_a) + \sigma A_r \varepsilon (T_w{}^4 - T_a{}^4) \tag{2}$$

Where, *h* – combined natural and forced convection heat transfer coefficient, $A_r$ - surface area of the absorber, $T_w$ - average absorber surface temperature, $\sigma$ - Stefan-Boltzmann constant, $\varepsilon$- emissivity of absorber surface and $T_a$ - ambient temperature.

Instantaneous efficiency (η) of the absorber was determined from the HTF heat gain and the incident solar energy on the PDC from eq. (3),

$$\eta = \frac{Q_u}{A_c I_b} \tag{3}$$

Where, $I_b$ - solar irradiance, $A_c$ - reflector aperture area.
Exergy efficiency is defined as the ratio of exergy gained to solar radiation exergy based on Patela [17], McPee and Dincer [18] as written as eq. (4),

$$\eta_{ex} = \left[ \frac{\dot{m} \left[ C_p (T_o - T_i) - T_a C_p \ln \frac{T_o}{T_i} \right]}{Q_i \left[ 1 - \frac{4}{3} \frac{T_a}{T_{sun}} + \left( \frac{T_a}{T_{sun}} \right)^4 \right]} \right] \tag{4}$$

The energy stored by the PCM through its specific heat ($C_p$), temperature range ($dT$) and latent heat ($H$) can be written as:

$$Q_{st} = m_{pcm} \left[ \int_{T_i}^{T_m} C_{p_s} dT + H + \int_{T_m}^{T_f} C_{pl} dT \right] \tag{5}$$

## 4. Results and discussion

During the outdoor experiments, quasi-steady state testing was conducted as per test standards of ASHRAE 93, at clear sky. HTF flow rates were controlled by control valve connected to flow meter for the solar absorber. The liquid phase of HTF was considered as per standard test requirements. Heating of 100 liters water from room temperature to boiling point was considered. The solar beam intensity was observed as 600 – 780 W/m$^2$. The wind speed (0 - 2.5 m/s) and the ambient temperature (32 to 34°C) were measured during the tests. The receiver temperatures and HTF temperatures were logged with a data logger. The absorber surface temperature for both PCM and non-PCM absorber surfaces for different HTF flow rates.

During the recirculation of HTF through both the absorbers, the difference of HTF outlet temperature was significant but after thirty minutes of operation, the difference became negligible. The average beam radiation was around 681 W/m$^2$ and 685 W/m$^2$ for the HTF mass flow rate of 70 kg/h for PCM and non-PCM absorber respectively. Even though the difference in average beam radiation was 4 W/m$^2$, the HTF outlet temperature remains a similar trend. Both the absorbers were suddenly defocused by changing the traction. The heating and cooling test of PCM absorber is shown in Fig. 4. The effect of multiple PCMs in the absorber was studied through response time test and it was shown in fig. 5. The thermal buffering effect was observed for about 15-25 minutes for the absorber with two PCMs. The heating test was found effective within 3 minutes.

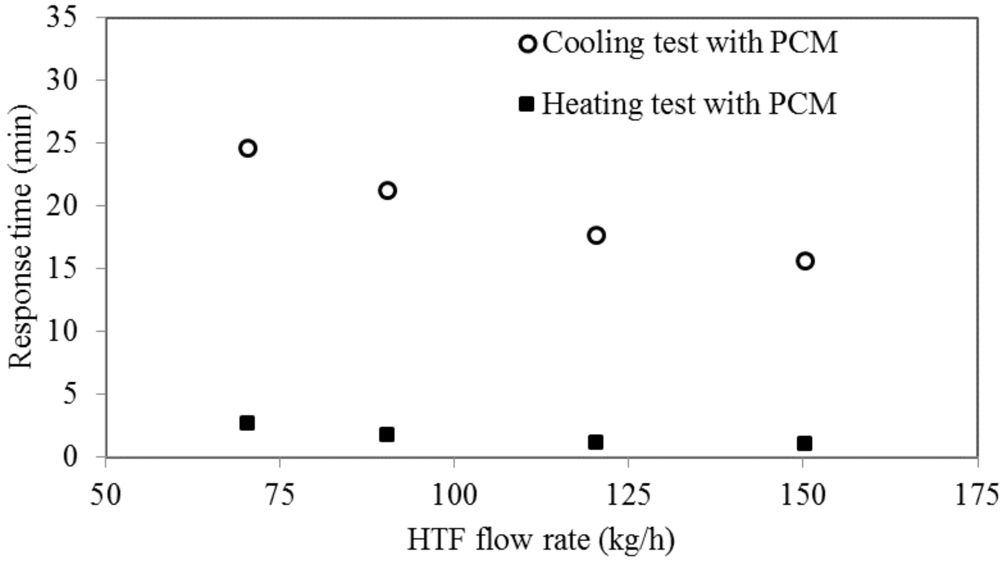


**Figure 4.** The heating and cooling test response time of the receiver with PCM.

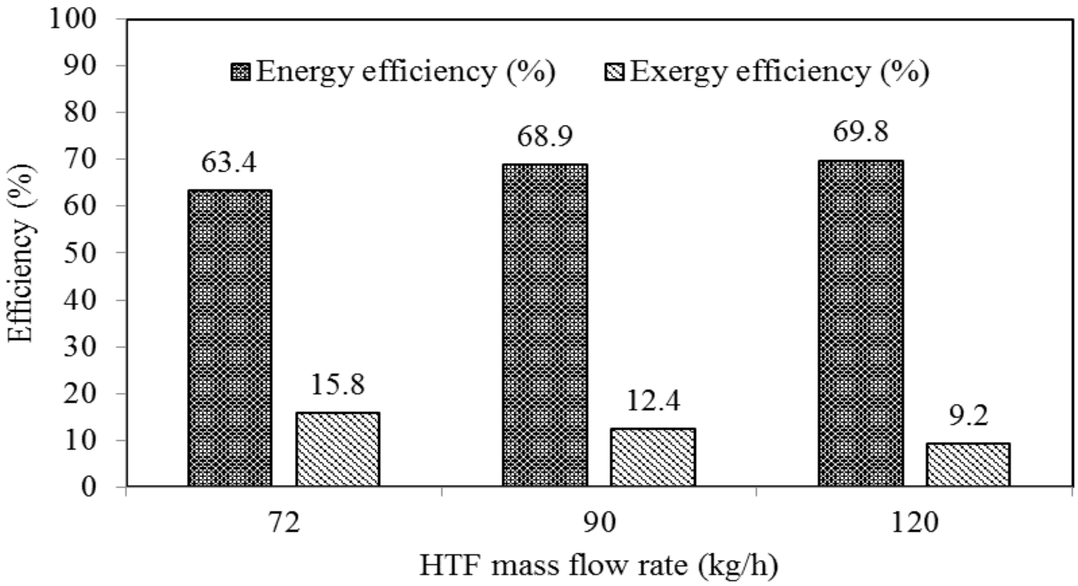


**Figure 5.** Energy and exergy efficiency of solar absorber integrated with multiple PCMs

The exergy efficiency is inversely proportional to the mass flow rate. The peak exergy efficiency of 15.8% at the lower flow rate 72 kg/h and energy efficiency of the absorber is 69.8% at the flow rate of 120 kg/h (fig. 5). The use of PCM in the absorber improves the stored energy. Hence, the absorber may act as a thermal battery for thermal applications. A suitable heat retrieval mechanism is vital for effective use. Table 2 indicates the measurement uncertainties. The uncertainty in thermal efficiency is calculated by the root mean square method. The uncertainty in the experimental energy and exergy efficiency measurement is less than 5% indicating that the instruments.

**Table 2.** Uncertainty analysis

| Property | Uncertainty | Property | Uncertainty |
|---|---|---|---|
| Temperature | ± 1% | Mass flow rate | ± 1% |
| Solar radiation intensity | ± 3% | Aperture | ± 0.5% |
| Wind speed | ± 1% | Mass of PCM | ± 0.5% |

Thus, the testing multiple PCMs in the absorber showed improvements in thermal storage density effect with reduced heat losses. The enhanced short-term thermal storage of the absorber with multiple PCM are highlighted in this study. The thermal management of short time unavailability of solar energy due to passing clouds and the possibility of later use for several heating applications.

## 5. Conclusions

Thermal storage density was enhanced with multiple PCMs in the absorber. Further, the PCM receive is capable of supplying continuous thermal output during the short periods of poor radiation. The effect of passing clouds over the collector is also partly eliminated due to PCM. The uniform heat flux inside the absorber improves the energy storage density of the absorber. The selective PCM should have higher phase change enthalpy and mass energy density to store at high temperature. Such reliable absorbers will act as a thermal battery for later use in thermal applications during the non-solar periods. The use of PCM in the solar absorber may smoothen the thermal output under varying solar radiation. Further, the PCM receiver act as a thermal battery for heating applications.

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