

## EFFECT OF THE PHASE CHANGE MATERIAL IN A SOLAR RECEIVER ON THERMAL PERFORMANCE OF PARABOLIC DISH COLLECTOR

by

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*In this work, the use of phase change material in the circular tank solar receiver is proposed for a 16 m<sup>2</sup> Scheffler parabolic dish solar concentrator to improve the heat transfer in the receiver. Magnesium chloride hexahydrate with melting temperature of 117 °C is selected as the phase change material in the annular space of the receiver with rectangular fins inside the phase change material. Experimental work is carried out to analyze heat transfer from the receiver to heat transfer fluid with and without phase change material in the inner periphery. Energy and exergy efficiency are determined from the measurements of solar radiation intensity, receiver temperature, surroundings temperature, heat transfer fluid inlet and outlet temperatures, storage tank temperature, and wind speed. The experiments were conducted in SRM University, Chennai, India (latitude: 13° 5' N, longitude: 80°16' E) in April 2014. Use of phase change material in receiver periphery increased energy efficiency by 5.62%, exergy efficiency by 12.8% and decreased time to reach the boiling point of water by 20% when compared with the receiver without phase change material.*

**Key words:** *Scheffler parabolic dish, phase change material integrated receiver, exergy efficiency*

### Introduction

Parabolic type solar collectors are used for several applications, ranges from domestic hot water to steam generations with and without integrated collector storage. The Scheffler reflectors are best suited for medium temperature applications, around 100-150 °C [1-3]. This collector is becoming more popular in India for community cooking owing to the increasing cost of fossil fuels and the added harmful pollution caused by burning of fuels. The receiver of Scheffler parabolic dish collector (PDC) is located away from the dish but at its fixed focal point. The ARUN technology is another PDC available in India with larger collector aperture (Fresnel mirrors) with cavity receiver kept at focal point (always above) of the parabolic dish. In ARUN PDC, both reflector and receiver track the Sun but the reflector only tracks the Sun in Scheffler technology [4]. Mehling *et al.* [5] found that adding phase change material (PCM) in the storage tank increased the thermal stratification. Similar to box solar cookers, several researchers added PCM in the domestic hot water tank to improve the effectiveness and productivity [6-8]. Castell *et al.* [9] studied the natural convection heat transfer inside

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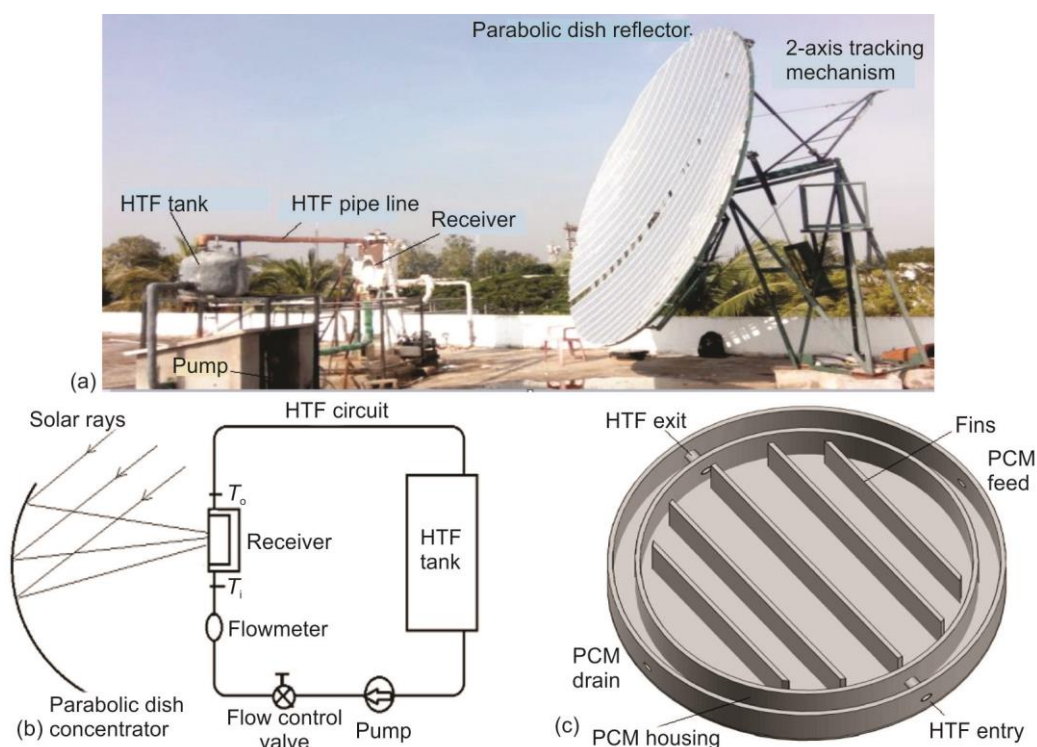
PCM module with vertical fins and found improvement in heat transfer. Sohif *et al.* [10] stated that PCM storage with internal-external fins in latent heat energy storage lessened the PCM melting duration by 43%. Ahmet *et al.* [11] observed an energy efficiency of 45% and exergy efficiency of 2.2% in a solar collector with integral energy storage. El-Sebaili *et al.* [12] found a low subcooling, around 2 °C, for one thousand charging and discharging cycles with  $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$  as a PCM candidate for solar cooking. Wang and Siddiqui [13] simulated the thermal performance of solar parabolic dish receiver system and observed a more dominant effect of aperture and different inlet/outlet configurations of solar receiver than the effect of rim angle. Chee *et al.* [14] built a double dish reflector with the two dishes having a diameter of 1.2 m and 0.31 m, respectively, with a fin heat transfer based energy storage with molten salt  $\text{KNO}_3 \cdot \text{NaNO}_3$  as PCM at the 230-260 °C operating temperatures for cooking purpose.

Safa *et al.* [15] compared the energy reaching the focal point of the absorber with different types of absorbers. Ashmore and Taole [16] made a common experimental set-up for testing different receivers for PDC to compare the energy efficiency and exergy efficiency. Tyagi *et al.* [17] conducted an exergy analysis and parametric study on concentrating solar collectors. The optimization of latent heat thermal energy storage (LHTES) using exergy based study is vital when compared to the energy based optimization. Jagadheeswaran *et al.* [18] reviewed the exergy based evaluations of LHTES. The exergy increased when the LHTES working temperature deviated from its surroundings. Kaushik and Gupta [19] determined the energy and exergy efficiency of community solar cookers. Mohseni-Languri *et al.* [20] determined optimum mass flow rate of air for maximum exergy of a solar air heater using second law efficiency. Uniform heat supply is an important cooking parameter for taste and quality of food. A few minutes of absence of solar energy due to cloud cover leads to a drop or discontinuity in the useful output of the receiver. Several Scheffler to dishes can be connected in series and parallel configuration suitably to produce higher thermal energy. Thermal analysis of PCM energy storage, solar collectors, and PCM integrated collector storage were reported extensively in the literature. However, the effect of PCM inside the solar receiver of parabolic dish concentrating collectors for thermal performance enhancement was detailed in the literatures. In this work, the thermal performance of PCM integrated solar receiver was investigated and also reported with a considerable improvement in thermal performance of the receiver with PCM.

### Materials and methods

The parabolic dish reflector is fitted with around 800 multifaceted flat high-grade solar mirrors (Model: Metalia G031, Saint Gobain, Courbevoie, France) onto the elliptical hardened steel frame of 3.8 m major axis and 1.8 m minor axis. The mirrors are 180 mm long, 100 mm wide, and of 3 mm thickness with high reflective coatings (reflectivity = 0.9) on the front side and anticorrosive coatings on the backside of the mirrors. The PDC with tracking mechanism weighs around 480 kg. The 16 m<sup>2</sup> PDC (Model: SolPac 160) is built by Thermax Ltd, Pune, India. Figure 1 illustrates the photographic view of the experimental set-up, schematics of experimental set-up and receiver without back cover. The effective aperture area of the reflector varies from 9-12 m<sup>2</sup> based on the seasonal orientation of the Sun. The speed of daily tracking is at 15° per hour and seasonal tracking is done once in three days. Circular tank type dish receiver is preferred for its simplicity in construction, low cost, and maintenance. The receiver consists of 406 mm diameter mild steel plate with thickness of 5 mm and the periphery is welded with a rectangular mild steel plate of 1276 mm length by 100 mm wide, having thickness of 5 mm. One of the circular surfaces of the receiver is prepared with

absorptive black chrome coating and all the other sides are insulated with glass wool of 28 mm thickness. Receiver is welded with five vertical mild steel fins (thermal conductivity, 16.27 W/mK) of 2.5 mm thickness to increase the heat transfer from the incident surface to heat transfer fluid (HTF) through conduction and convection. The absorptivity and emissivity of receiver surface are 0.85 and 0.15, respectively. The receiver is kept at a focal distance of 2.5 m.



**Figure 1. Parabolic dish collector; (a) photographic view, (b) schematic layout, (c) schematic of receiver with PCM housing and fins without back cover**

The concentrated energy on the receiver surface is transferred to HTF through the attached rectangular fins (mild steel) as shown in fig. 1(c). The capacity of the receiver is 7 liters. The PCM housing is an annulus area with outer diameter of 396 mm and 376 mm. On the PCM side 12 mild steel fins of 90 mm length, 15 mm width, and 2.5 mm thickness are provided to increase the contact surface area of the PCM. The K-type thermocouples are fitted in the inlet/outlet of HTF pipes and storage tank. The receiver is kept at 13.5°, inclined south from the vertical axis as the optimized position for the seasonal variation of Sun's position. Piping consists of mild steel tube of diameter 0.0125 m, length 9 m, and a storage tank capacity of 110 liters. The piping and the receiver are insulated with glass wool (thermal conductivity 0.04 W/mK and thickness 28 mm). Sensible and latent heat of 2 kg of PCM is supplied by the concentrated solar energy and the PCM wall gives extended heating surface to the HTF. Convection dominated heat transfer occurs in the liquid PCM during melting and conduction dominated heat transfer occurs in the PCM during solidification. Free space of 12% is provided in the PCM housing for the volumetric expansion during the phase change process. The PCM integrated receiver is always operated with circulation of HTF through the receiver in

order to avoid the degradation/mass loss of PCM due to overheating of PCM by concentrated rays. The thermal capacity of the solar PDC is up to 5.5 kW<sub>th</sub> output as steam at a pressure of 10 bar and temperature of 150 °C. The thermophysical properties of the selected PCM, magnesium chloride hexahydrate are given in tab. 1.

**Table 1. Thermophysical properties of magnesium chloride hexahydrate [12]**

Properties	Values
Chemical formula	MgCl <sub>2</sub> ·6H <sub>2</sub> O
Melting temperature [°C]	117
Enthalpy [kJkg <sup>-1</sup> ]	167
Thermal conductivity [Wm <sup>-1</sup> K <sup>-1</sup> ]	0.704 (solid at 110 °C), 0.570 (liquid at 120 °C)
Density [kgm <sup>-3</sup> ]	1570 (solid at 20 °C), 1450 (liquid at 120 °C)
Volumetric expansion	10%
Specific heat capacity [kJkg <sup>-1</sup> K <sup>-1</sup> ]	0.704 (solid at 110 °C), 0.570 (liquid at 120 °C)

### Thermal analysis

Exergy analysis is considered as an important aspect to optimize the system for finding the possibilities of improving the energy utilization along with normal energy analysis. The solar incident energy entering the parabolic dish concentrator is dependent on the solar beam radiation,  $I_b$ , and aperture area of the concentrator,  $A_c$ , and is given by the following relation:

$$Q_i = A_c I_b \quad (1)$$

The solar receiver is kept at a fixed focal distance of 2.5 m away from the parabolic dish. The shading of receiver on the reflector is not possible so that the factor of intercept,  $\gamma$ , and incidence angle are unity ( $\theta = 0^\circ$ , due to continuous tracking of dish towards the Sun). The simplified optical efficiency formulae of dish concentrator depend on the optical properties of dish reflector material like reflectivity,  $\rho$ , transmittance,  $\tau$ , and absorptivity,  $\alpha$ , of receiver [15] is given in the following equation:

$$\eta_{\text{optical}} = \rho(\tau\alpha) \cos \theta \quad (2)$$

The energy reaching the receiver surface is the combined effect of energy incident on the concentrator and optical efficiency ( $\eta_{\text{optical}}$ ) and expressed:

$$Q_r = \eta_{\text{optical}} Q_i \quad (3)$$

Heat absorbed by the HTF is dependent on liquid specific heat,  $C_p$ , HTF flow rate,  $\dot{m}$ , and temperature gain of fluid ( $T_o - T_i$ ). According to Duffie and Beckman [21], the useful heat gain by the HTF in the receiver is expressed:

$$Q_u = \dot{m} C_p (T_o - T_i) \quad (4)$$

The energy stored by the PCM through its specific heat value, temperature range, and latent heat effect can be written:

$$Q_{st} = \dot{m}_{pcm} \left[ \int_{T_i}^{T_m} C_{ps} dT + H + \int_{T_m}^{T_f} C_{pl} dT \right] \quad (5)$$

The convective heat losses are dependent on the use of glass cover, inclination angle and orientation of receiver, magnitude and direction of wind, and receiver surface temperature and ambient temperature. The receiver surface temperature, sky temperature, emissivity of surface, and surface area are the parameters affecting the radiation heat losses. The major heat loss from the dish receiver can be calculated using the following formula:

$$Q_l = h_w A_r (T_r - T_a) + \sigma A_r \varepsilon (T_r^4 - T_{sky}^4) \quad (6)$$

Wind heat transfer coefficient is given by Hottel and Woertz [22] equation:

$$h_w = 5.67 + 3.8V \quad (7)$$

Sky temperature according to Forristal [23] equation is given:

$$T_{sky} = T_a - 8 \quad (8)$$

Thermal efficiency of the receiver is defined as the ratio of useful heat gained by the HTF to the incident solar energy on the PDC and given in eq. (9):

$$\eta = \frac{Q_u}{A_c I_b} \quad (9)$$

The assumptions made for exergy analysis are steady-state, steady flow energy equation, negligible potential, and kinetic energy effects, no internal heat generation as well as no chemical or nuclear reactions. The exergy efficiency calculation for the solar receiver is determined based on, inlet and outlet temperature of HTF ( $T_i$  and  $T_o$ ).

Solar radiation exergy input to the PDC can be calculated based on solar energy input to the parabolic dish,  $Q_i$ , ambient temperature,  $T_a$  [K], and Sun's surface temperature ( $T_{Sun} = 5762$  K) is expressed based on Patela's [24] expression:

$$Ex_s = Q_i \left[ 1 - \frac{4}{3} \frac{T_a}{T_{Sun}} + \frac{1}{3} \left( \frac{T_a}{T_{Sun}} \right)^4 \right] \quad (10)$$

The exergy at inlet and outlet of the receiver of the receiver ( $Ex_i$  and  $Ex_o$ ) can be calculated based on the inlet/outlet temperatures, ambient temperature, specific heat of HTF, and mass flow rate of HTF [25] and expressed in the following equations:

$$Ex_i = \dot{m} C_p \left[ (T_i - T_a) - T_a \ln \frac{T_i}{T_a} \right] \quad (11)$$

$$Ex_o = \dot{m} C_p \left[ (T_o - T_a) - T_a \ln \frac{T_o}{T_a} \right] \quad (12)$$

Exergy gained by the HTF (exergy output) is expressed as the difference in exergy of water before and after the receiver in eq. (13):

$$Ex_u = Ex_o - Ex_i = \dot{m} C_p \left[ (T_o - T_i) - T_a \ln \frac{T_o}{T_i} \right] \quad (13)$$

Exergy efficiency is the ratio of exergy gained by HTF in the solar receiver to solar radiation exergy input and expressed:

$$\eta_x = \frac{Ex_u}{Ex_i} \cdot 100 \quad (14)$$

## Results and discussion

The outdoor experiments were conducted on clear sunny days in the receiver with and without PCM, in April 2014. The solar radiation intensity,  $I_b$ , ambient temperature,  $T_a$ , wind speed, HTF temperatures at inlet,  $T_i$ , outlet of the receiver,  $T_o$ , receiver surface temperature,  $T_w$ , and storage tank temperature were recorded during the test periods with shaded ring pyranometer, cup anemometer, and K-type thermocouples, respectively. The re-circulation of HTF was allowed up to the boiling point of HTF and this restriction was made to avoid a complex two-phase heat transfer phenomenon inside the receiver. The experiment of particular HTF flow rate was repeated on three sunny days to ensure the repeatability of experimental readings. From the observations, it was seen that the thermal gain followed a similar trend for the particular HTF flow rate. For simplicity, one observation graph for each flow rate was shown in figs. 2-5.

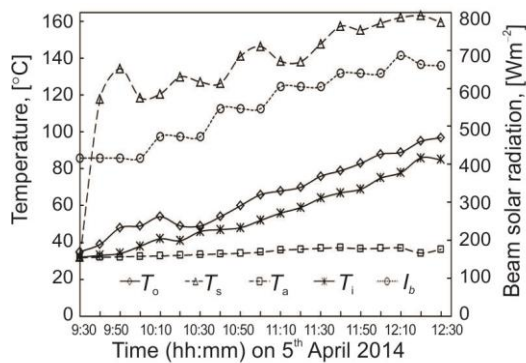


Figure 2. Effect of solar radiation on HTF temperatures for 72 Lph without PCM

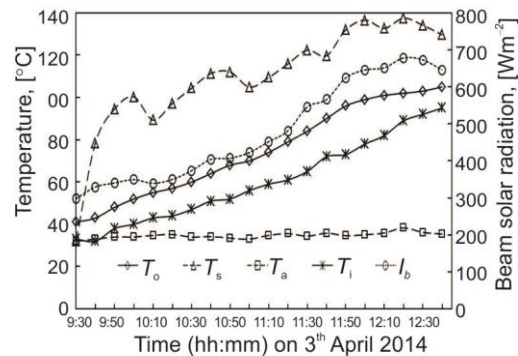


Figure 3. Effect of solar radiation on HTF temperatures for 72 Lph with PCM

Figures 2 and 3 shows the effect of solar radiation on the various temperatures at the receiver. The comparisons of the receiver with and without PCM were analyzed as per thermodynamic laws. The peak solar beam radiation observed during the test period was  $725 \text{ W/m}^2$  and the lowest was  $265 \text{ W/m}^2$ . The average wind speed never exceeded 2 m/s. The ambient temperature varied between 306 K and 310 K during test periods. Receiver surface temperature varied from 100-160 °C. The outlet temperature of HTF increased throughout because of recirculation of HTF.

Reference to figs. 2 and 3, the peak receiver wall temperature of receiver with PCM is around 20 °C lesser than the receiver without PCM which is due to the effective heat absorption by the PCM in the receiver. The PCM housing provides an additional surface of heating to the HTF. From fig. 5, it is clear that the receiver wall temperature lies between 100 °C and 145 °C. The peak receiver wall temperature is around 25 °C lesser than the receiver without PCM. The average temperature of PCM is 5-10 °C higher for the lower HTF flow rate 72 Lph than flow rate of 90 Lph. The higher flow rate absorbs more heat from the receiver sur-

face and the lower HTF flow rate of HTF results in increased PCM temperature during the testing periods.

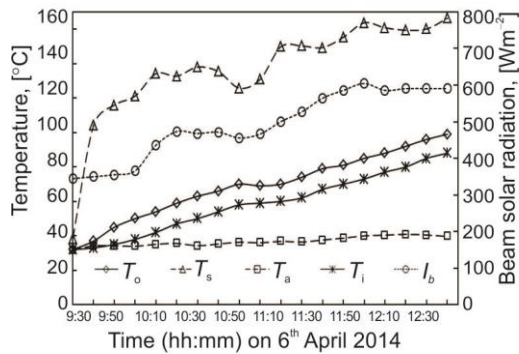


Figure 4. Effect of solar radiation on HTF temperatures for 90 Lph without PCM

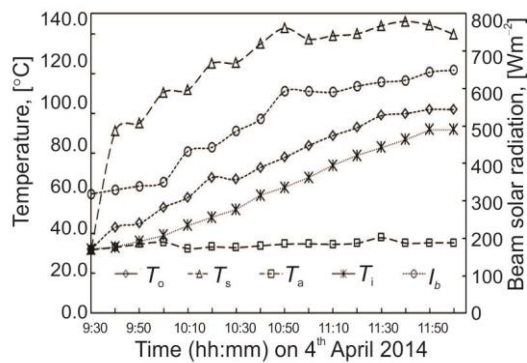


Figure 5. Effect of solar radiation on HTF temperatures for 90 Lph with PCM

From fig. 6, it is seen that the time taken by HTF to reach boiling point for 90 LPH flow rate and 72 Lph with PCM are 130 minutes and 190 minutes, respectively, under similar conditions. If HTF flow rate increases from 72 to 90 Lph, time taken to reach 98 °C decreases by 13.33% and 15.79% for receiver with and without PCM, respectively. This is due to higher heat absorption rate using PCM. The average time reduction for boiling point of water is 20% for the PCM integrated receiver than the receiver without PCM.

Figure 7 shows the variation of energy efficiency with time. Higher efficiency is observed with higher mass flow rate of HTF and PCM integrated receiver produces higher efficiency. The heat is stored as sensible and latent of PCM through the attached rectangular thin fins in the annular outer space of the receiver. The PCM is useful in ensuring a uniform and peak demand heat fluxes inside the receiver. The PCM involves simultaneous charging and discharging processes normally but during a short time absence of solar radiation due to cloud cover, the discharging (heat release) occurs from the PCM. Conduction heat transfer is dominant during solidification and convection during melting of PCM.

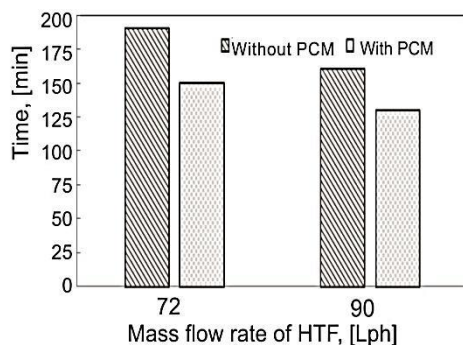


Figure 6. Time of water to reach boiling point with and without PCM in the receiver

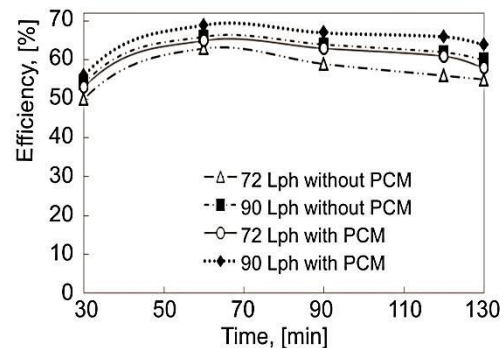


Figure 7. Energy efficiency with and without PCM in the receiver

Energy and exergy efficiency of receiver without and with PCM for selected flow rates are shown in fig. 8. The HTF flow rate of 90 Lph produced collector efficiency of 64.4% and 61.2% with and without PCM in the receiver. The HTF flow rate of 72 Lph produced collector efficiency of 59.41% with PCM integrated receiver and 56.6% for without PCM in the receiver. There is around 5.23% increase in efficiency for HTF flow rate of 90 Lph and around 6% increase in efficiency for 72 Lph. The overall efficiency increases to 63-69% in the first 30 minutes and then it lies between 55% and 67%. The heat loss from the PCM integrated receiver is less due to lower surface temperature of receiver with PCM. The PCM releases the stored heat to the HTF whenever there is a little drop in solar radiation. The repeat-

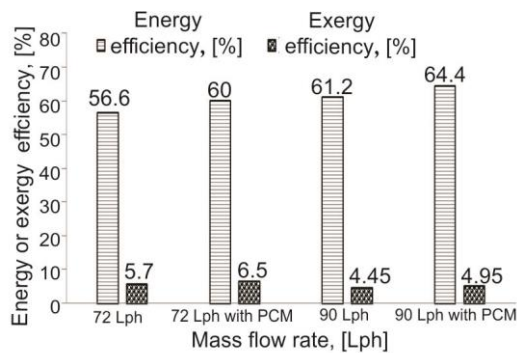


Figure 8. Comparison of energy and exergy efficiency of receiver with and without PCM

ed charging and discharging test cycles of PCM are carried out repeatedly and the reusability is found promising in the solar parabolic dish concentrating collector. Figure 8 shows the energy and exergy efficiencies of solar collector. The uncertainties in the measurement accuracy are as follows: temperature ( $\pm 0.5\%$ ), solar radiation ( $\pm 3\%$ ), wind speed ( $\pm 1\%$ ), receiver surface area measurement ( $\pm 2\%$ ), and flow rate of HTF ( $\pm 1\%$ ). The uncertainty of experimental measurement using root mean square method is  $\pm 4.79\%$  and it indicates that the instruments and measurements are within the sufficient range of reliability.

## Conclusions

The collector efficiency of 16 m<sup>2</sup> Scheffler PDC is 45-58% without PCM in the solar receiver. Integration of PCM in the receiver improved the energy efficiency of parabolic dish solar concentrator is about 60-65%. The PCM housing increases the effective heat transfer area besides the incident circular surface of the receiver and also improves the thermal capacity of the receiver in the absence of solar radiation for few to several minutes. Due to effective heat distribution, PCM integrated receiver increases the collector efficiency by 6% and 5.23% for 72 Lph and 90 Lph, respectively, during water heating experiments.

Exergy efficiency increase by 14.04% and 11.23% with PCM for 72 Lph and 90 Lph, respectively. The variation of exergy efficiency of receiver with PCM is 12.8% higher than the receiver without PCM. Uniform temperature of the receiver improves the safety and life of the receiver because of low temperature gradient. This is useful in receiver design, to the stakeholders of solar collectors for both industrial and domestic applications with better usability and efficiency. In future work, the study will be focused towards the thermal buffering effect of solar receiver with multiple PCM.

## Nomenclatures

$A_c$	– collector surface area, [m <sup>2</sup> ]	$I_b$	– solar beam radiation, [Wm <sup>-2</sup> ]
$A_r$	– surface of the dish receiver, [m <sup>2</sup> ]	$\dot{m}$	– mass flow rate, [lh <sup>-1</sup> ]
$C_p$	– specific heat of water, [Jkg <sup>-1</sup> K <sup>-1</sup> ]	$Q$	– heat transfer, [W]
$dT$	– change in temperature, [K]	$T$	– temperature, [K]
$Ex$	– exergy rate, [W]	$T_m$	– melting point of PCM, [K]
$H$	– latent heat, [kJkg <sup>-1</sup> ]	$V$	– wind velocity, [ms <sup>-1</sup> ]



*Greek symbols*

$\alpha$	– absorptance, [–]
$\gamma$	– intercept factor, [–]
$\varepsilon$	– emissivity, [–]
$\eta$	– energy efficiency, [%]
$\eta_{\text{optical}}$	– optical efficiency, [%]
$\eta_x$	– exergy efficiency, [%]
$\theta$	– inclination angle, [°]
$\rho$	– reflectivity, [–]
$\sigma$	– Stefan-Boltzman constant, [= $5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$ ]
$\tau$	– transmittance, [–]

*Subscripts*

a	– ambient
b	– beam
f	– final
i	– inlet, initial
l	– loss

o	– outlet
pcm	– PCM
r	– receive
Sun	– Sun
s	– surface, supply
sky	– sky
st	– stored
th	– thermal
u	– useful
w	– wind
x	– exergy

*Acronyms*

HTF	– heat transfer fluid
LHTES	– latent heat thermal energy storage
Lph	– liters per hour [ $\text{lh}^{-1}$ ]
PCM	– phase change material
PDC	– parabolic dish collector

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