7

Design and Development of Low Cost Solar Energy Based Charger for Charging of Heat Packs in Extreme Conditions

7.1 INTRODUCTION

The extreme low environmental temperature at high altitude areas, creates difficulties for survivability of inhabitants and also take a toll on the health such as hypothermia, frostbites, and physiological changes in the vital body organs. The ordinary environmental conditions are essential to elude such difficulties and generally heating sources such as fossil fuels and electricity, are commonly used for such uses. The geographical conditions at high altitude make difficult to utilize these heating sources. Latent heat based thermal energy storage systems, such as phase change materials (PCMs) based reusable heating packs, may offer an alternate to overcome such difficulties [Kapralis *et al.*, 1990; Zalba *et al.*, 2003; Sandnes and Rekstad, 2006; Wei and Ohsasa, 2010]. These PCM based heat packs can be utilized to provide instantaneous heat for comfort in the cold climatic conditions and heat treatment for arthritis, frost bite, backache, sprains, hypothermia and sports injury related heath applications. The benefits of such PCM heat packs include reusability for large thermal cycling, significant high thermal energy storage density, heat storage at low environmental temperature conditions (< 0 ^{o}C) for longer time durations, instantaneous heat discharge at human body soothing temperature, non-toxicity, portable, economical and ecofriendly [Sandnes and Rekstad, 2006]. The aqueous sodium acetate solution is being used in PCM based heat packs to store heat [Ulman and Valentin, 1983; Araki *et al.*, 1995]. It melts at ~ 58 ^{o}C and can persist in the metastable supercooled liquid state even at very low environmental temperature conditions [Kapralis *et al.*, 1990; Wei and Ohsasa, 2010]. This property of aqueous sodium acetate makes it appropriate to accumulate and discharge instantaneous heat in extreme low environmental temperature conditions. PCM based heat packs can be used to accumulate heat at the time of heat source accessibility and deliver heat on demand. However, such systems have to be charged after discharging heat for further probable applications. Stringent geographical circumstances of high altitude areas make situations difficult and challenging to utilize energy sources such as electrical energy, fossil fuels, etc. because of their less accessibility and also higher transportation cost. It compels to explore alternative methods for low cost charging of PCM based heat packs, not depending on the conventional energy resources but depends on renewable energy resources. The high altitude areas are mostly blessed with intense, clean, and ample solar energy, which can be utilized for PCM based heat packs. Generally, hot water is used to charge such heat packs, which can be obtained from parabolic solar energy dish concentrator. The parabolic dish concentrators have been used for hot water and cooking applications [Kumar *et al.*; 1993; Hosny and Ziyan, 1998; Budhi *et al.*, 2003; Pohekar and Ramachandran, 2004 and 2006; Akter, et. al., 2017]. The parabolic dish has several advantages compared to non-concentrating systems, such as (i) better efficiency (ii) requirement of small area and portability and (iii) most prominently the low cost and easy installation at high altitude areas. Mullic *et al.* 1991 provided a thermal test procedure for a paraboloid type concentrator solar cooker. Funk, 2000 suggested standard testing procedures to test the performance for solar cookers. Huseyin, 2004 measured experimentally the energy and exergy efficiency of a parabolic solar cooker. Petela, 2005 conducted exergy analysis for cylindrical solar parabolic cooker. Schwarzer *et al.* 2008 has provided characterization and design methodologies for solar cookers. El-Ouederni *et al.*, 2009 carried out experimental work on parabolic concentrator with opening diameter 2.2 m. Chandak *et al.*, 2011 conducted comparative study on Prince-15 and SK-14 solar energy concentrator and concluded that the Prince-15 have better efficiency as compared to that of SK-14. Mohammed, 2013 has designed and developed a dish type solar thermal cooker with 180 cm diameter, 29 cm depth and 69.8 cm focal length as geometrical parameters. Yahya, 2013 determined the heat losses from parabolic solar cooker. Andrianaivo *et al.*, 2014 investigated the life cycle and environmental effect on SK 14 solar cooker in Madagascar.

In the present work, the efforts are made to provide low cost renewable energy based solution for charging of PCM heat packs at stringent geographical conditions such as high altitude area. This includes: (i) design and fabrication of parabolic dish type solar energy based charger; (ii) performance assessment of charger; (iii) generation of performance characteristic curve to predict its performance at different ambient temperatures and solar insolations; and (iv) charging and discharging studies of PCM heat packs

7.2 EXPERIMENTAL DETAILS

A parabolic dish solar energy concentrator having 1.4 m diameter and 0.38 m depth was designed and fabricated for charging of PCM heat packs using solar energy. A total of 24 highly reflecting (> 90% reflectance) aluminum sheets (0.4 mm thickness) (make ALANOS GmbH & Co. KG, Germany) are utilized to fabricate parabolic dish for concentration of solar energy at its focal point. The schematic design and photograph of real parabolic of dish concentrator is shown in Figure 7.1. The frame structure of concentrator was made of stainless steel. The aluminum sheets are fixed with frame using screws. In order to focus the solar radiation, a manual rotation and shadow mechanisms are combined with the parabolic dish soar concentrator for tracking Sun and the container is kept at the focal point, as shown in Figure 7.1. The depth (h) and diameter (D) of parabolic dish are used to compute the aperture area $(A_{ap} = \pi D^2/4)$, focal length $(f = D^2/16.h)$ and solar energy collecting surface area $A_t = 8\pi f^2/3 \lfloor\{1 + (D/4f)^2\}^{3/2} - 1\rfloor$, where, A_{ap}, f, and A_t are aperture area, focal length and surface area of dish respectively [Ouederni *et. al*, 2009]. The values of A_{ap}, f, and A_t are 1.54 m^2, 0.32 m, and 3.69 m^2, respectively for the designed parabolic dish concentrator.

We used a container (5 liter cooker) at the focal area of dish to store the concentrated solar energy. The diameter and height of the container are 0.22 m and 0.18 m, respectively. These container dimensions are sufficient to cover the total light focal spot of ~ 0.2 m diameter. The container's total surface area (A_{pot}) is 0.2 m^2.The exterior part of container is coated with black paint for maximum solar energy absorption. The dish was kept facing east in the morning and after that it was manually tilted as per Sun angles throughout the measurements.

The aqueous sodium acetate solution with 3 wt% ethylene glycol was used as heat storing material in heat packs. PVC packs of size 145 mm X 80 mm containing ~ 150 g PCM were prepared for charging and discharging studies.

Figure 7.1: Schematic scheme (left) and real photograph (right) of dish solar energy concentrator with a container painted by black paint and kept at the focal point of dish. The rightmost photograph represents the arrangement of shadow mechanism to keep parabolic dish in normal direction to the Sun

7.3 RESULTS AND DISCUSSION

7.3.1 Thermal Performance Analysis of Parabolic Dish

The thermal test procedure proposed by Mullic at al., 1991 is followed to investigate thermal performance of parabolic dish. A mild steel (MS) plate was used to measure stagnation temperature at focal spot of dish concentrator using without load stagnation temperature test. The temperature of the plate surface was measured using K-type thermocouples. The first figure of merit (ratio of optical efficiency to the heat loss factor) of dish concentrator was investigated from this no load test [Chandak *et al.*, 2011]. The heat loss ($F'U_L$) and optical efficiency factor ($F'\eta_0$) of dish concentrator are determined using water heating and cooling experiments [Mullic *et al.*, 1991]. The maximum theoretical upper limit of the overall efficiency of parabolic dish concentrator is represented by optical efficiency factor.

7.3.1.1 No load Test Measurement

A no load test was carried out to investigate the parabolic dish concentrator's first figure of merit. A MS plate (diameter 0.25 m) was retained at parabolic dish focal point and sheet's stagnation temperature was measured using K- type thermocouple. Voltcraft pyranometer (model PL-110SM) was used to measure solar radiation flux density. The values of stagnation temperature, average ambient temperature and average solar insolation used are 505 ºC, 40 ºC, and 720 W m^{-2}, respectively for the investigated experimental duration. The first figure of merit (F_1) of parabolic dish is defined as

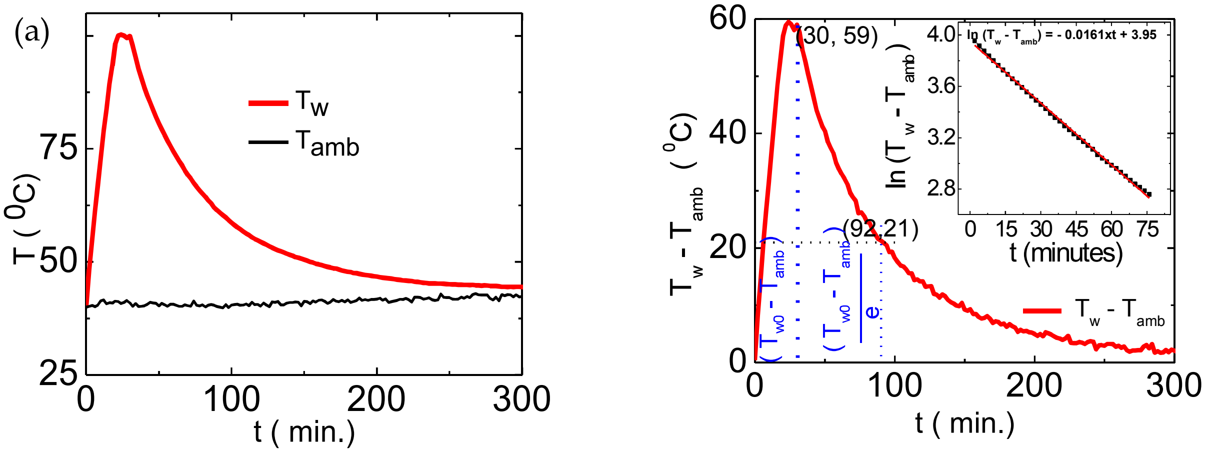
$$F_1 = \eta_0/U_L = (T_{stag} - T_{amb})/I_b \tag{7.1}$$

Where, U_L, η_0, T_{amb}, T_{stag}, and I_b are heat loss factor for plate, optical efficiency, average ambient temperature, stagnation temperature of plate, and solar radiation flux density [Chandak *et al.*, 2011]. Using these numerical values, the observed that figure of merit F_1 is ~ 0.368 for fabricated dish.

7.3.1.2 Load Test Measurements

2.5 kg deionized water was filled in container and kept at focal point of the dish concentrator. The heating profile of deionized water was measured by immersing K type thermocouple at the center of container under clear sun shine ambient conditions. The heating experiments were carried out from 12:00 to 13:00 hours [Funk, 2000]. The parabolic dish was tilted manually at every 5 minutes time interval as per Sun angles following Sun path to accumulate the maximum solar thermal energy.

The cooling profile of heated water was recorded under Sun shading conditions at normal ambient temperature. Ambient and water temperatures were measured using K-type thermocouples at every 2 minutes time interval. Thermocouple tip was submerged up to the center of water for temperature measurements. The thermocouples were attached to Agilent data logger (Model 34980) and recorded temperature data were stored in the computer. Solar radiation flux density data were recorded after every 5 minutes time interval. The heating and cooling response of water is shown in Figure 7.2.



(a) (b)

Figure 7.2: (a) Heating and cooling response of 2.5 kg water and respective ambient temperature and (b) variation of water and ambient temperature difference with time, with semi log plot (inset)

The water temperature increased from 40.3 °C to 100 °C in 21 minutes and cooled down to 44 °C in 304 minutes, Figure 7.2(a). We assumed that ambient temperature (T_{amb}) and heat loss factor (U_L) for container remain constant during whole cooling experiment. Under these assumptions, the time (τ) required to reduce water temperature from $T_{w,i}$ to $T_{w,f}$ is estimated using following Eq.(7.2)

$$\tau = -\frac{(M_w.C_{p,w}) + (M_{pot}.C_{p,pot})}{A_{pot}F'U_L}\ ln\left|\frac{(T_{w,f} - T_{amb})}{(T_{w,i} - T_{amb})}\right| \tag{7.2}$$

where, M_w, M_{pot}, $C_{p,w}$, $C_{p,pot}$, F' and A_{pot}, are water mass, container mass, specific heat of water, specific heat of container, heat exchange efficiency factor and container surface area respectively [Mullic *et al.*, 1991]. After reorganizing Eq. (7.2), we get

$$(T_{w,f} - T_{amb}) = (T_{w,i} - T_{amb})\ e^{\tau/\tau_0} \tag{7.3}$$

Where,

$$\tau_0 = \{(M_w.C_{p,w}) + (M_{pot}.C_{p,pot})\}/A_{pot}\ F'U_L \tag{7.4}$$

Here, τ_0 is cooling time constant and defined as time required reducing the difference of water and ambient temperature (T_w-T_{amb}) to 36.8% of its initial value. The τ_0 was estimated by semi log plot, inset Figure 7.2(b) and it is ~ 62 minutes. The heat loss factor $F'U_L$ for container is estimated by following Eq.

$$F'\,U_L = \frac{\{(M_w.\,C_{p,w}) + (M_{pot}.\,C_{p,pot})\}}{A_{pot}\;\tau_0} \tag{7.5}$$

The values of M_w, M_{pot} $C_{p,w}$, $C_{p,pot}$, A_{pot} and τ_0 are 2.5 kg, 1.84 kg, 4200 J kg^{-1}, 920 J kg^{-1} K^{-1}, 0.2 m^2 and 62 minutes respectively. These values are utilized to compute the heat loss factor $F'\,U_L$ using Eq. (7.5) and estimated value is 16.11 W m^{-2} K^{-1}.

Far constant solar insolation and ambient temperature, the heating time τ to raise water temperature from initial temperature T_{w1} to final temperature T_{w2} is given by

$$\tau = -\tau_0\; ln \left[\frac{\left\{ F^{'}\eta_0 - \dfrac{F^{'}U_L(T_{w2} - T_{amb})}{C\,I_b} \right\}}{\left\{ F^{'}\eta_0 - \dfrac{F^{'}U_L(T_{w2} - T_{amb})}{C\,I_b} \right\}} \right] \tag{7.6}$$

Where, C is the ratio of parabolic dish aperture area and water container surface area (A_{ap}/A_{pot}). τ_0 is estimated from water cooling curve. η_0 and I_b are dish optical efficiency and solar radiation flux density on aperture plane, respectively. By rearranging Eq. (7.6) the optical efficiency, $(F'\eta_0)$ is defined as

$$F'\eta_0 = \frac{F'\,U_L}{C} \left[\frac{\left\{ \dfrac{(T_{w2} - T_{amb})}{I_b} - \dfrac{(T_{w1} - T_{amb})\; e^{-\tau/\tau_0}}{I_b} \right\}}{1 - \; e^{-\tau/\tau_0}} \right] \tag{7.7}$$

Eq. (7.7) is used to compute optical efficiency for parabolic dish with $T_{w1} = T_{amb} = 40.5$ °C, $T_{w2} = 98.3$ °C, C = 7.7, $F'U_L$ = 16.11 W m^{-2} K^{-1}, τ_0= 3720 seconds, τ = 1200 seconds and average solar insolation on aperture plane I_b = 722 W m^{-2} and computed value is 0.62. This optical efficiency is in good agreement with other reported literature values under similar constraints.

7.3.1.3 Performance Characteristic Curve

Thermal performance of the system was assessed under 722 W m^{-2} solar insolation and ~ 40 °C ambient temperatures. These operating conditions differ from the high altitude ambient conditions or other climatic conditions. The time required for heating water from initial ambient temperature to final temperature T_f °C can be written as follows

$$\tau_f = -\tau_0\;\; ln \left[1 - \frac{F'\,U_L\;\left(\dfrac{T_f - T_{amb}}{I_b}\right)}{F'\,\eta_0\,C} \right] \tag{7.8}$$

Here, τ_f is required time to heat water up to final temperature T_f °C. The performance characteristic curve was generated for T_f = 100 °C and required time (τ_f) to heat water versus (100-T_{amb})/I_b graph is plotted in Figure 7.3. This graph can be used to estimate the required heating time to heat water in different solar insolation and ambient temperatures conditions.

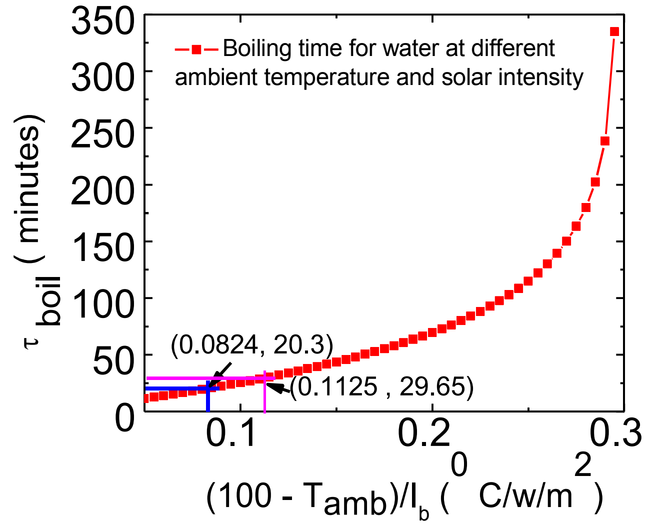


Figure 7.3: Performance parabolic dish characteristic graph for different ambient temperatures and solar insolations for heating water upto 100 °C

We computed heating time required to achieve water temperature 100 °C using the parabolic dish characteristic curve for ambient conditions, T_{amb}= 40.5 °C, and I_b= 722 W m^{-2} and is ~ 20.3 minutes, as marked with blue line in Figure 7.3. This time is in good agreement with measured the experimental values ~ 21 minutes, as shown in Figure 7.2(a). This suggests that the characteristic curves can be utilized to envisage the approximate boiling time for any other values of solar radiation flux density and ambient temperatures. For illustration, at high altitude zone, T_{amb}= 10 °C, I_b= 800 Wm^{-2} and $(100 - T_{amb})/I_b$ = 0.1125, which correspond to 29.65 minutes time for boiling water, as marked with magenta colored line in Figure 7.3. Therefore, such parabolic dish concentrator characteristic curves may help in designing an optimal system suitable for given ambient temperatures and solar insolations.

7.3.1.4 Overall Thermal Efficiency of Dish Concentrator

Thermal performance of parabolic dish solar energy concentrator is characterized by overall thermal efficiency and heat duty for a given system. These thermal performance parameters for a dish concentrator can be determined using water heating measurements. The useful heat stored in container water (Heat duty) kept at the focal point of dish concentrator can be determined using following Eq. (7.9)

$$H.D. = \frac{M_w C_{p,w}(T_{w2} - T_{w1})}{\tau} \qquad (7.9)$$

Thus, the overall thermal efficiency parabolic dish solar concentrator is given as

$$\eta_b = H.D.* \frac{100}{I_b A_{ap}} \qquad (7.10)$$

The heating time (τ) to heat 2.5 kg water from T_{w1}= 40.34 °C to T_{w2}= 89.34 °C is 960 seconds, Figure 7.2 (a). The specific heat of water ($C_{p,w}$) is 4200 J kg^{-1} K^{-1}. The use of Eq.s (7.9) and (7.10), using these values, the measured heat duty and overall efficiency values are 546.9W and 49.2 %, respectively for the designed dish concentrator.

7.3.2 Charging of PCM Heat Packs

The PCM heat packs charging experiments are conducted to understand the charging performance of the designed and fabricated parabolic dish. The cooker, with 2.5 liter water and 16 heat packs, was placed at the focal point of dish concentrator. The average ambient temperature and solar insolation were ~ 39 °C and 715 Wm^{-2} during experimental hours. The temperature rise of water was measured using a K-type thermocouple at every 2 minutes time interval. The water thermal response as a function of time is shown in Figure 7.4. The water temperature raised up to 70 °C in 26 minutes and remained nearly constant for ~ 6 minutes. These results suggest that PCM inside heat packs meted completely during this period. Any further increase in water temperature is attributed to sensible heat storage in PCM above their melting temperatures.

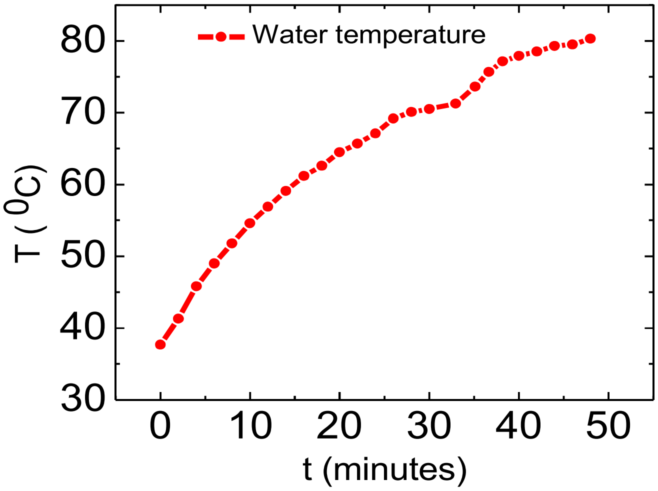


Figure 7.4: Thermal response of water while charging of heat packs using parabolic dish, demonstrating sensible heat storage (solid PCM), latent heat storage (solid-liquid phase chagne) and sensible heat (liquid PCM) heat storage during 0 – 18 minutes, 18 -32 minutes and afte 32 minutes respectively

7.3.3 Discharging of PCM Heat Packs

The discharging behavior of PCM heat packs was studied inside a cooling chamber maintained at -10 °C temperature. The PCM remained in metastable supercooled liquid state at this temperature, suggesting that the heat was stored in the form of latent heat. The metallic triggering disk was pressed to initiate solidification in liquid state. This led to the solidification of PCM in liquid state and transformed into solid state PCM within few seconds (~ 30 seconds). The sequential procedure of nucleation and growth of solid region inside heat packs is presented in Figure 7.5.

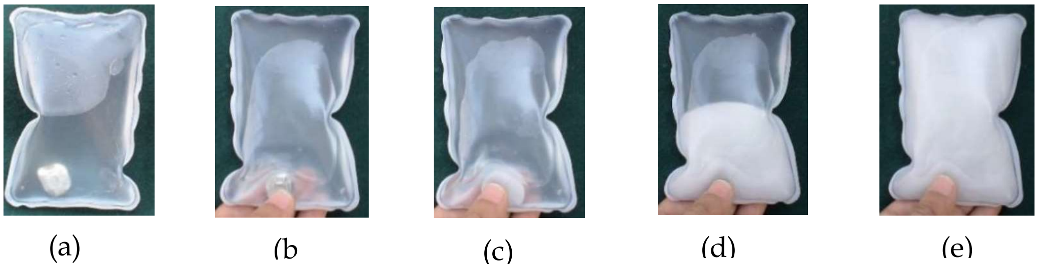

(a) (b (c) (d) (e)

Figure 7.5: Different stages for heat releasing mechanism from heat pack (a) heat pack containing liquid PCM and metallic triggering disk (b) Pressing metallic disc to initiate nucleation in liquid PCM (c) growth of nucleation and solidification (d) movement of solidification in liquid PCM (e) complete solidification of liquid PCM

The temperature of PCM heat pack as a function of temperature was measured at every 10 seconds time interval and data are plotted in Figure (7.6). The temperature of heat pack raised immediately upto 48 °C and took ~ 50 minutes to reach upto 40 °C. These results suggest the use of such PCM heat packs for numerous applications such as medical and comport in cold climatic conditions and similar situations. In addition to such applications, these PCM heat packs can be utilized for generating inventories of solar heat throughout summer seasons and can be used later in winter seasons on demand.

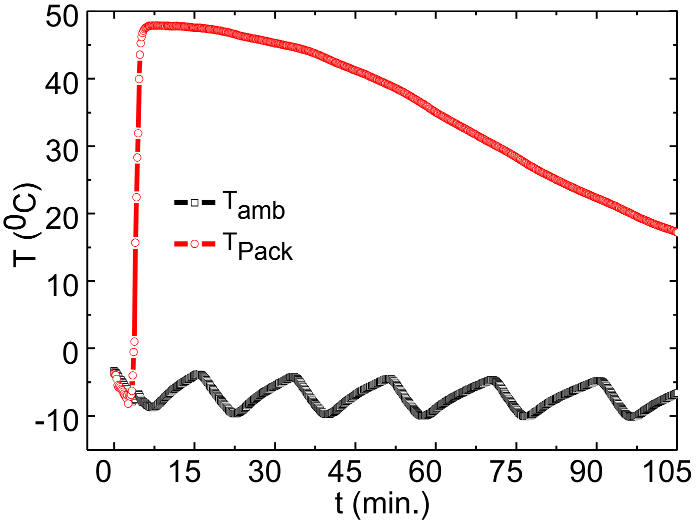


Figure 7.6: Discharging thermal response of PCM heat pack at ambient temperature -10 °C, after starting nucleation.

7.4 CONCLUDING REMARKS

A parabolic dish solar energy concentrator is designed and fabricated to charge PCM heat packs using solar energy for extreme environmental conditions such as high altitude regions. The overall thermal efficiency and heat duty of designed parabolic dish are 49.2% and 546.9 W, respectively. Thermal performance characteristic graph is generated for designed parabolic dish concentrator under different ambient temperatures and solar insolations. This can be used to estimate heating time at different solar insolations and ambient temperatures. The PCM heat packs comprising 2.4 kg PCM are fabricated and used to understand the charging/discharging characteristics using the designed dish concentrator. These heat packs can be charged within ~ 35 minutes using dish concentrator and found that the stored heat can be preserved even at -10 ^{0}C environmental conditions. Thus, findings demonstrate that developed PCM heat packs can be used to store solar heat during sunshine hours for later applications, whenever required.

…