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RESEARCH ARTICLE

Performance Evaluation of Thermal Storage Unit based on Parabolic Dish Collector for Indoor Cooking Application

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Abstract

In this study, a thermal storage unit (TSU) having phase change material (PCM) to store energy is studied on a concentrated parabolic dish collector. The stored thermal energy is utilized for indoor cooking. Acetanilide was used as a latent heat storage material. The thermal storage unit with fins on the outer surface of inner cylinder was used. The finned cooking pot was used instead of the conventional cooking pot and it was found that two batches of indoor cooking were possible with this thermal storage unit. The cooking performance was studied under variety of operating and climatic conditions. The payback period of the cooker was found to be 6.11 and 3.67 months for LPG and electricity respectively.

Keywords: Thermal storage unit, phase change material, acetanilide, indoor cooking, climatic conditions.

Introduction

Solar energy is the most promising renewable source of energy and the solar cookers are the tool for harnessing this energy for cooking purpose. India is gifted around 300 sunny days in a year (Khalifa *et al.,* 1984), which is an ideal condition for the functioning of solar cookers. The importance of cooking was felt from the fact that in developing countries like India, energy requirement for cooking is 36% of primary energy consumption and 70% of its population residing in rural areas are dependent on fire wood, dung cake, kerosene oil, agricultural waste for cooking application (Sharma *et al.,* 2009). This is hitting the greenery and causes pollution which results in ecological imbalance. Solar cookers are one of the possible solutions to handle this situation. But they are unable to perform afternoon and evening cooking in indoors where there is no sunlight. So the need of developing thermal storage unit was felt. The emphasis is laid on indoor cooking because it is unhygienic to cook in open and it is inconvenient for user to stand nearby the solar cooker in sunshine during cooking.

Many researchers developed solar cookers which are able to perform indoor cooking operations. Generally all of them used Phase Change Material for storing solar energy in the form of thermal energy for performing afternoon and evening cooking in indoors. Domanski *et al*. (1995) used stearic acid and magnesium nitrate hexa-hydrate for energy storage in box solar cooker. They experimentally evaluated the thermal performance of solar cooker for charging and discharging times of phase change materials. The overall efficiency of about 82% was achieved and maximum temperature inside the cooker was in between 78-84°C. The results obtained are satisfactory which opened the way for further research on PCMs. Buddhi and Sahoo (1997) designed and experimentally tested the solar cooker with latent heat storage materials. They used commercial grade stearic acid (melting point-55.1°C, latent heat of fusion-160 kJ/kg) as PCM. They concluded that night cooking was possible by using stearic acid but at a slow rate because melting point of stearic acid is low compared to cooking temperature of food which is around 90°C. So to avoid such discrepancy, melting point of phase change material should be 100°C or more and latent heat of fusion should be high enough. Sharma *et al*. (2005) designed, developed and calculated the thermal performance of box solar cooker having latent heat storage unit and used commercial grade acetamide (melting point-82°C, latent heat of fusion-263 kJ/kg) as PCM. They designed concentric cylindrical vessel for energy storage unit. The void space was filled with PCM. The performance of the cooker was compared with the standard solar cooker. The testing was performed at different loading conditions. They evaluated that evening cooking was possible by this cooker. Buddhi *et al.* (2003) calculated the thermal performance of box solar cooker with latent heat storage unit, having three reflectors. This time they used commercial grade acetanilide (melting point-118°C, latent of heat fusion-222 kJ/kg) as PCM for energy storage. They experimentally tested the cooker under different loading conditions and loading times and concluded that it had much better thermal performance than their previously developed solar cooker. Sharma *et al*. (2005) designed and experimentally tested evacuated tube solar cooker having storage unit. They used erythritol (melting point-118°C, latent heat of fusion-339 kJ/kg) as PCM for energy storage.

The insulated stainless steel tube was used to transfer hot water from evacuated tubes to the PCM storage unit. They concluded that erythritol achieved the temperature of 130°C and it was able to cook food twice a day easily. Hussein *et al*. (2008) experimentally tested indirect solar cooker with indoor PCM thermal storage unit and used magnesium nitrate hexa-hydrate (melting point-89°C and latent heat of fusion-134 kJ/kg) as PCM for energy storage. This system consists of flat plate collector with two reflectors. Solar cooker was of elliptical cross-section and wickless heat pipe was used. Experiments were conducted on solar cooker with no load and with different load at different loading times. The experimental results concluded that this cooker was able to cook different kinds of food at noon, afternoon and evening times. It was also used for keeping food hot at night and early morning. Storage unit consisted of integrated cooking pots around which PCM was filled. Condensing coils are used around them to transfer energy to PCM which stores it.

Foong *et al*. (2011) investigated small scale double reflector solar concentrating system with mixture of nitrates as heat storage material. The mixture consists of $NaNO_3$ and KNO_3 in 60:40 mole percent ratios. Thermal behavior of salts was studied with differential scanning calorimeter (DSC). The melting temperature of mixture of salts was about 220°C; which was suitable for cooking and baking. They used cooper fins to enhance heat transfer from salts to top plate. Salts were completely melted within 2-2.5 h. This system was simulated with the help of finite element method; simulation was based on effective heat capacity method. Chaudhary *et al*. (2013) designed and experimentally evaluated thermal performance of parabolic dish solar cooker with latent heat storage unit. They used acetanilide (melting point-118°C, latent of heat fusion-222 kJ/kg) as PCM for energy storage. They considered three cases for enhancing thermal performance of solar cooker. These cases were: ordinary solar cooker, solar cooker with outer surface painted black and solar cooker with outer surface painted black with glazing. They found that solar cooker with outer surface painted black with glazing was the most efficient and stored 32.3% more heat in contrast to PCM in ordinary solar cooker. Very few research groups have worked on parabolic dish collector integrated with thermal storage unit (TSU) incorporating PCM. To the best of author’s knowledge no work has been performed using finned cooking pot (which is inserted in TSU) for cooking purpose. The objectives of this study are:

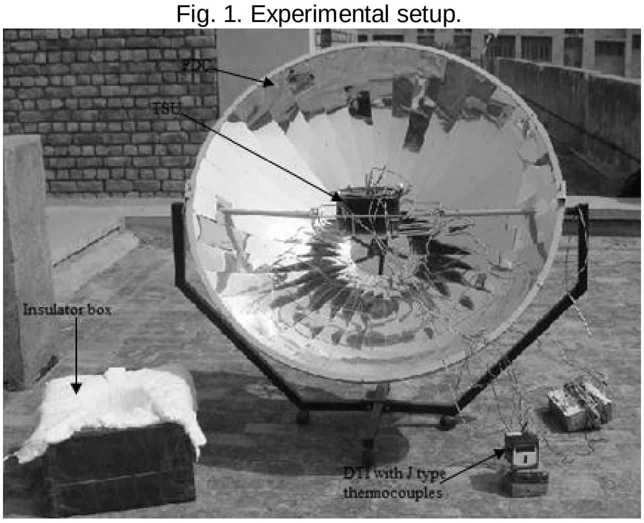
1. To test the feasibility of indoor afternoon cooking by TSU; using water and rice as the cooking medium.
2. To test the feasibility of indoor evening cooking by TSU; using water and rice as the cooking medium.
3. Comparative analysis of various performance parameters which include energy storage by PCM and heating (cooking) power of TSU.

Materials and methods

Experimental setup: Experimental setup was designed and fabricated to investigate the feasibility of afternoon and evening indoor cooking with the help of solar energy stored by PCM in the form of thermal energy. The experimental setup is installed at Dept. of Mechanical Engineering, GJUSandT, Hisar (29.15°North and 75.70°East), India as shown in Fig. 1. The main components of experimental setup are:

1. Parabolic dish collector (PDC)
2. Thermal storage unit (TSU) containing PCM
3. Cooking pot
4. Insulator box

Fig. 1. Experimental setup.



Parabolic dish collector: PDC is the main constituent of experimental setup. The schematic diagram of it is shown in Fig. 2. It is a point focused solar device which concentrates the solar radiations at a point. It constitutes of anodized aluminum strips mounted on the circular parabolic frame which acts as a reflector. The reflector is used to reflect the incident radiations on the receiver. The receiver is the focus point of PDC where all the incident energy is concentrated. Tracking screws are used to track it with respect to sun. With the help of tracking screws, it is aligned normal to sun by reducing the shadow of screws to zero. The design specifications of PDC used in the experimental setup are listed in Table 1.

Fig. 2. Schematic diagram of parabolic dish collector.

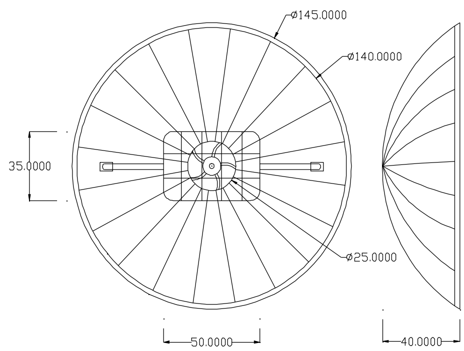


Table 1. Design specifications of parabolic dish collector.

Aperture dia	1.4 m
Focal length	0.2 m
Aperture area	1.539 m^2
Concentration ratio	33
Dish rim angle	120.5°
Optical efficiency	80%

Thermal storage unit containing phase change material: TSU provides facility for indoor afternoon and evening cooking by stored solar energy. This unit consists of two coaxial cylindrical vessels having void space in between them, which is filled by acetanilide (melting point-118°C, latent of heat fusion-222 kJ/kg). Seven U shaped fins are attached to the outer surface of inner cylindrical vessel for enhancing heat transfer rate as shown in Fig. 3. The storage unit and fins are made up of aluminum. The outer surface of thermal storage unit is painted black so that it can absorb large amount of heat. The design specifications of TSU and fins attached to it are shown in Table 2.

Fig. 3. Thermal storage unit.

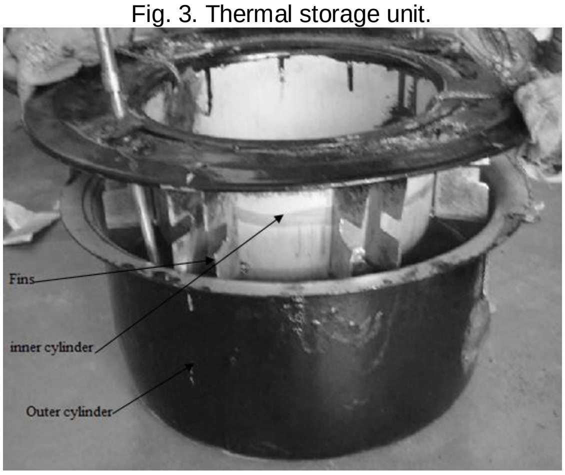


Table 2. Design specifications of thermal storage unit.

Thermal storage unit	
Dia of external cylinder	0.245 m
Height of external cylinder	0.135 m
Dia of internal cylinder	0.175 m
Height of internal cylinder	0.095 m
Thickness of cylinder	0.001 m
Mass of storage unit	1.386 kg
Volume of void space	0.004079 m^3
Fins	
Number of fins	7
Height of fins	0.06 m
Length of fins	0.03 m

Cooking pot: It is cylindrically shaped vessel made up of aluminum in which actual cooking occurs. It is inserted in the cavity of TSU for cooking purpose. It has 'U' shaped fins on its lateral surface for enhancing cooking rate. Figure 4 shows the photograph of finned cooking pot and conventional one having identical dimensions and material properties. The design description of cooking pot and fins attached to it is listed in Table 3.

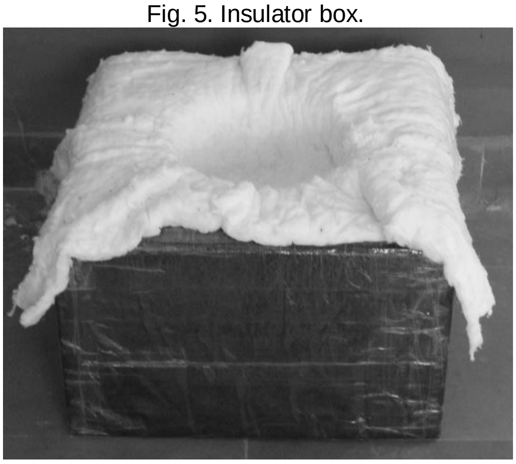
Fig. 4. Conventional and finned cooking pot.

Table 3. Design specification of cooking pot and fins attached to it.

Cooking pot	
Dia	0.145 m
Height	0.095 m
Thickness	0.001 m
Mass of cooking pot	0.238 kg
Fins	
Number of fins	7
Height of fins	0.06 m
Length of fins	0.015 m

Insulator box: Insulator box is designed to prevent the heat loss from the TSU after charging (means after storing solar energy in the form of thermal energy) (Fig. 5). It is made up of wood and stainless steel cavity around which glass wool is filled for insulation purpose. Its dimensions (l × b × h) are 0.40 m, 0.40 m and 0.25 m respectively.

Fig. 5. Insulator box.



Measuring devices and instruments: Measuring devices and instruments are the auxiliary part of experimental setup. The parameters which have to be measured for conducting this test include: outer and inner surface temperature of TSU, PCM temperature, ambient and cooking medium temperature and intensity of solar radiations. Outer surface temperature of TSU, inner surface temperature of TSU, PCM temperature, ambient temperature, cooking medium temperature are measured with J type thermocouples which are connected with digital temperature indicator having temperature range up to 600°C and has an accuracy of ±1°C.

Intensity of solar radiations is measured with the help of solar power meter. The instrument used is of WACO 206 series having range up to 1999 W/m^2 with accuracy of ±10 W/m^2.

System operation: System operation consists of two processes which include: charging and discharging process. During charging process TSU is placed on the receiver of PDC which is exposed to solar radiations. Charging process means storing of energy by acetanilide due to phase transition. Solar radiations impinging on the TSU raises the temperature of acetanilide and changes its phase (solid to liquid). Thermocouples are attached to the surface of TSU and kept in contact of acetanilide for measuring temperature. The observations are taken regularly at an interval of 30 min each during charging process. After charging of TSU, it is removed from the PDC and placed in the insulator box. The cooking pot having load is inserted in the cavity of TSU for cooking purpose. This leads to fall in the temperature of acetanilide which is called discharging process. The observations are taken after an interval of 10 min each during discharging process. The same procedure is adopted to conduct indoor afternoon and evening cooking.

Analysis of experimental data: The following terms and equations are used to analyze the experimental data. Energy stored by PCM is given by Sharma *et al*. (2000):

$$Q_{PCM} = m_{PCM}[C_{PCM}(T_m - T_1) + L_{PCM} + C_{PCM}(T_2 - T_m)] \quad (1)$$

The expression for energy stored by TSU containing PCM is derived by modifying the above equation.

$$Q_{TSU} = [(m_C.C_C + m_{PCM}.C_{PCM}).(T_m - T_1) + m_{PCM}.L_{PCM} + (m_C.C_C + m_{PCM}.C_{PCM}).(T_2 - T_m)] \quad (2)$$

Cooking power of TSU

$$P = \frac{(m_{cp}.C_{cp} + m_w C_w).(T_{w2} - T_{w1})}{\tau} \quad (3)$$

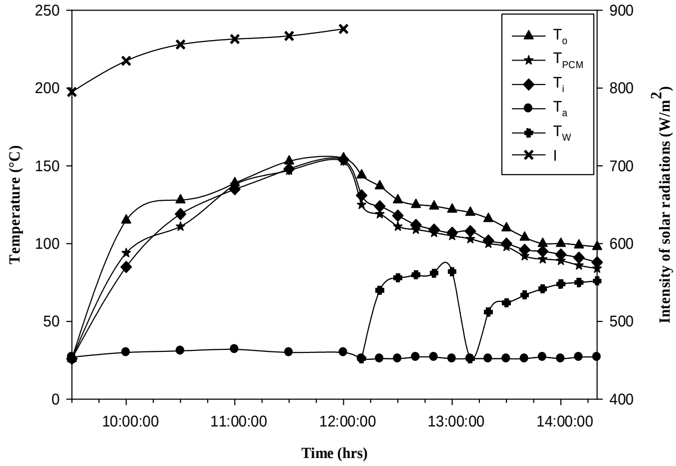
Results and discussion

The experimental setup is designed for making indoor cooking possible both at afternoon and evening time. The testing of experimental setup is performed during the clear sunny days of March and April.

Testing the feasibility of indoor afternoon cooking by TSU
Case 1–Water as cooking medium: The feasibility of indoor afternoon cooking by TSU with water as cooking medium is checked on 18th March, 2014. The TSU is kept on PDC at 9:30 h and removed it from at 12 h and placed in the insulator box. The average intensity of solar radiations during charging process was 849 W/m^2. The first batch of cooking medium (1 kg water) was loaded on TSU placed in insulator box at 12:10 h and removed after 50 min. After 10 min, 2nd batch of cooking medium (1 kg water) was loaded on TSU.

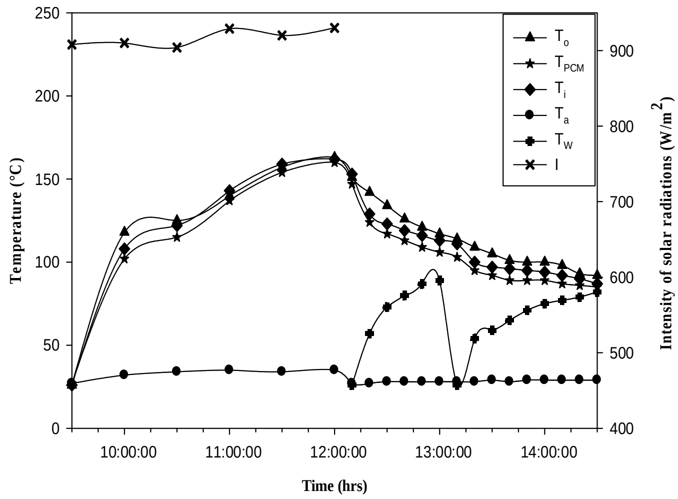
The behavior of TSU during charging process was observed regularly at an interval of 30 min each. The discharging behavior of TSU during 1st and 2nd batch cooking was observed at a regular interval of 10 min each. From the experimental observations, it was evaluated that TSU is capable of cooking two batches of food when charged completely. Figure 6 shows the charging and discharging behavior of TSU with water as cooking medium.

Fig. 6. Temperature variations during afternoon indoor cooking with water as cooking load.



Case 2–Rice as cooking load: The feasibility of indoor afternoon cooking by TSU for cooking rice was tested on 31st March, 2014. The testing procedure used was same as discussed above for case 1. The average intensity of solar radiations during charging period was 909 W/m^2. Figure 7 shows the charging and discharging behavior during 1st and 2nd batch cooking with rice (300 g rice + 600 g water) as cooking medium.

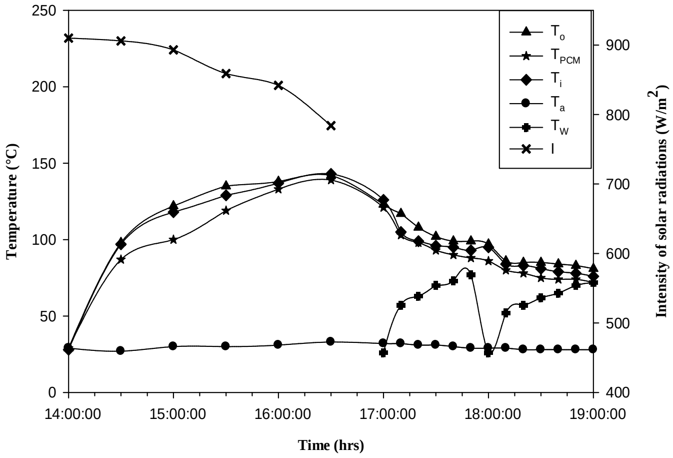
Fig. 7. Temperature variations during afternoon indoor cooking with rice as cooking load.



Testing the feasibility of indoor evening cooking by TSU

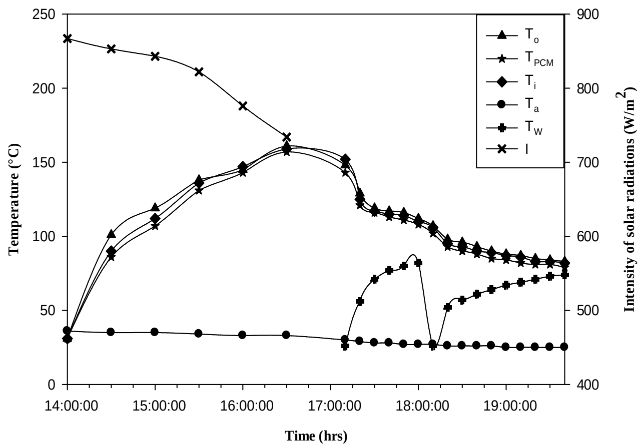
Case 1–Water as cooking medium: For checking the feasibility of indoor evening cooking by TSU, it is placed on PDC at 14 h and removed from it at 16:30 h and kept in the insulator box on 19th March, 2014. This duration of 150 min corresponds to charging process of TSU. The average intensity of solar radiations during this period was 866 W/m^2. After keeping the TSU in insulator box, the 1st batch of cooking medium (1 kg water) is loaded on it at 17 h. TSU performed cooking operation in 50 min for 1st batch cooking medium. Then, 2nd batch of cooking medium was loaded on TSU at 18 h and removed from it at 19 h. The observations related to the charging and discharging behavior of TSU during 1st and 2nd batch cooking are shown in Fig. 8.

Fig. 8. Temperature variations during indoor evening cooking with water as cooking load.



Case 2–Rice as cooking load: The feasibility of indoor evening cooking by TSU with rice (300 g rice + 600 g water) as cooking medium is checked on 1st April, 2014. The same methodology as discussed in the previous case was adopted for carrying out this test. The observations related to charging and discharging process is shown in Fig. 9.

Fig. 9. Temperature variations during indoor evening cooking with rice as cooking load.



Comparative analysis of TSU in terms of various parameters: In this section, comparative analysis of TSU in terms of various parameters is performed for the cases discussed above which is listed in Table 4. This comparison will be helpful in comparing the performance of TSU for indoor afternoon and evening cooking. From this comparison, it is concluded that TSU having high cooking (heating) power for indoor afternoon cooking.

Total cost and payback period of solar cooker: Total cost of solar cooker involves cost of its components. The use of solar cooker depends on its cost effectiveness and payback period. The cost estimation of solar cooker is listed in Table 5. Payback period is amount of time taken by solar cookers to recover its total cost. It is the ratio of total cost of solar cooker to daily savings made by solar cooker. Solar cookers having large payback period for a given application are economically less feasible.

Case 1: Payback period of solar cooker in comparison of LPG

Unsubsidized cost of one LPG cylinder is `1200.

Average running period of 1LPG cylinder for a family of 4 members is 40 d.

Cost per day for cooking considering 1 LPG cylinder = 1200/40 = `30.

Savings made on using solar cooker with TSU instead of LPG is `30.

Payback period = Total cost of solar cooker/savings per day = 5500/30 = 183.33 days = 6.11 months.

Case 2: Payback period of solar cooker in comparison of electricity

Electricity consumed for cooking food for a family of 4 members in a day = 10 kWh.

Cost of 1kWh of energy = `5.

Cost of electricity consumed by a family (4 members) in a single day for cooking = 10×5= `50.

Payback period = Total cost of solar cooker/savings per day = 5500/50 = 110 d = 3.67 months.

Uncertainty analysis: The accuracy of measured data obtained through experimental study is very important which is dependent on the measuring instrument. Uncertainty analysis is performed to prove the extent of accuracy of experimental results which is listed in Table 6. Uncertainty dependent on measuring instrument cannot be removed by number of measurements. The expression for uncertainty in the measured value by an instrument is given by Beckwith *et al*. (1990).

$$\mu = \frac{a}{b_{max}} \times 100 \quad (4)$$

Table 4. Comparative analysis of TSU in terms of various parameters.

	Indoor afternoon cooking		Indoor evening cooking	
	Water	Rice	Water	Rice
	18-03-2014	31-03-2014	19-03-2014	1-04-2014
Q_{PCM}	1666 KJ	1708 KJ	1547 KJ	1659 KJ
Q_{TSU}	1824.42 KJ	1873.90 KJ	1684.21 KJ	1816.17 KJ
I_a	849 W/m^2	909 W/m^2	866 W/m^2	816 W/m^2
P (1st batch cooking)	82.40 W	83.87 W	75.04 W	74.55 W
P (2nd batch cooking)	52.55 W	46.59 W	56.40 W	35.50 W

Table 5. Cost estimation of solar cooker with TSU.

Components	Specification	Cost (`)
Parabolic dish collector	Material–mild steel and anodized aluminium Focal length 0.2 m Dish rim angle 120.5° Aperture area of dish 1.539 m^2 Concentration ratio of dish 33	2500
Cooking pot and TSU	Material–aluminium TSU Inner diameter 0.175 m Outer diameter 0.245 m Height 0.135 m Thickness 0.001 m Cooking pot Diameter 0.145 m Height 0.095 m Thickness 0.001 m	700
Black paint	Dark black colour Quantity used 100 mL	50
Acetanilide	Melting point 118°C Latent heat 222 kJ/kg Specific heat 2 kJ/kg°C Quantity used 3.5 kg	3.5 × 500 = 1750
Insulator box	Material wood Dimensions 0.40 m × 0.40 m × 0.2 5 m (l×b×h)	500
Total cost		5500

Table 6. Uncertainty analysis of measured data.

Name of instrument	Variable measured	Least division of measuring instrument	Max. values measured in experiment	Uncertainty (%)
Thermocouple	Outer surface temperature of TSU	1°C	163°C	0.613
Thermocouple	Inner surface temperature of TSU	1°C	162°C	0.617
Thermocouple	PCM temperature	1°C	160°C	0.625
Thermocouple	Ambient temperature	1°C	36°C	2.778
Thermocouple	Cooking medium temperature	1°C	89°C	1.124
Solar power meter	Intensity of solar radiations	10 W/m^2	930 W/m^2	1.075

Conclusion

The experimental setup is tested under different conditions and the following conclusions can be drawn:

1. The cooking (heating) power of solar cooker equipped with TSU increases on using finned cooking pot in place of conventional one.
2. The solar cooker equipped with TSU can be able to perform indoor afternoon and evening cooking.
3. Fully charged TSU is capable of cooking two batches of food.
4. The cooking (heating) power of solar cooker equipped with TSU is higher for indoor afternoon cooking as compared to indoor evening cooking.
5. The payback period of solar cooker on replacement of LPG and electricity is 6.11 months and 3.67 months respectively.

Nomenclature

Q_{PCM}	Energy stored by PCM, kJ
m_{PCM}	Mass of PCM, kg
C_{PCM}	Specific heat of PCM, kJ/kg°C
L_{PCM}	Latent heat of fusion of PCM, kJ/kg
T_m	Melting point of PCM, °C
T_1, T_2	Initial and final temperature of PCM, °C
Q_{TSU}	Energy stored by TSU, kJ
m_C	Mass of container (TSU), kg
C_C	Specific heat of container (TSU), kJ/kg°C
τ	Time, s
P	Cooking power of TSU
m_{cp}	Mass of cooking pot, kg
C_{cp}	Specific heat of cooking pot, kJ/kg°C
m_w	Mass of cooking medium, kg
C_w	Specific heat of cooking medium, kJ/kg°C
T_{w1}, T_{w2}	Initial and final temperature of cooking medium, °C
I_a	Average intensity of solar radiations (W/m^2)
a	Accuracy of measuring instrument
b_{max}	Maximum measured value of parameter in experiment
T_o	Outer surface temperature of TSU
T_i	Inner surface temperature of TSU
T_{PCM}	Temperature of PCM
T_a	Ambient temperature
T_w	Temperature of cooking medium
I	Intensity of solar radiations

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