1. INTRODUCTION

Cooking is a prime necessity for all people across the world. About 75% of people living in rural India fulfill their cooking energy needs from noncommercial fuels like wood from the forest which contributes to deforestation and greenhouse effect. However, the price of liquefied petroleum gas (LPG) in India, which is another major source of energy for cooking, has risen around 30% in the last year. Due to this, cooking by using renewable energy sources is a burning issue. Fortunately, India is blessed with an ample amount of solar radiation. This offers solar cooking as one of the most attractive options. Successful application of solar energy depends to a large extent on the method of energy storage. Energy storage not only provides a bridge between
supply and demand, but also improves the performance and reliability of the system. Thermal energy storage (TES) systems can substantially reduce the total energy consumption and conserve the indigenous fossil fuels. Different types of thermal energy storage system may involve only sensible heat storage (storing of energy by heating or cooling), latent heat storage (by melting or vaporizing or solidifying or liquefying), or a combination of both. If solar cookers are provided with the thermal storage unit, then there is the possibility of cooking food during the off-sunshine hours. For the last few decades, solar energy has been utilized in the field of cooking with different types of collectors such as box-type solar cooker, parabolic dish collector, parabolic trough collector, and evacuated tube collector.

Several efforts were made for day and evening cooking using a box-type solar cooker with thermal storage [1–4]. Domanski et al. [1] experimentally investigated the possibility of cooking during off-sunshine hours using phase change materials as storage media. Stearic acid or magnesium nitrate hexahydrate was used as phase change material (PCM). A solar simulator was used to provide the desired solar radiations and they found that the parameters such as solar intensity, mass of cooking medium, and the thermophysical properties of the PCM have a strong effect on cooker performance. Buddhi and Sahoo [2] designed and fabricated a solar cooker with latent heat storage for Indian climate conditions. They found that late evening cooking was possible with a solar cooker having a thermal storage unit and also compared the experimental results with those of a conventional solar cooker. Sharma et al. [3] designed and developed a cylindrical PCM storage unit for a solar cooker with two reflectors and compared the performance of this solar cooker with a standard solar cooker. Commercial grade acetamide was used as PCM and experimental results showed that the melting temperature of PCM should be in the range of $105^\circ C$ to $110^\circ C$ for evening cooking. Buddhi et al. [4] designed and developed a PCM storage

<table>
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<tr>
<th>NOMENCLATURE</th>
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<tbody>
<tr>
<td>$C_{PCM}$</td>
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<tr>
<td>$C_{sand}$</td>
</tr>
<tr>
<td>$L$</td>
</tr>
<tr>
<td>$m_{PCM}$</td>
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<tr>
<td>$m_{sand}$</td>
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<tr>
<td>$Q_{PCM}$</td>
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<tr>
<td>$Q_{sand}$</td>
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<td>$T_i$</td>
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<td>$T_m$</td>
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<tr>
<td>$T_{PCM,max}$</td>
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<tr>
<td>$T_{sand,max}$</td>
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</table>
Solar Cooker with Dual Thermal Storage Unit

unit for a box-type solar cooker having three reflectors to store energy during sunshine hours. They used commercial grade acetanilide as a latent heat storage material. The experimental results demonstrated that late evening cooking is possible in a solar cooker with reflectors and a latent heat storage unit.

The cooking was also carried out with a flat plate collector with a latent heat storage unit [5–8]. Schwarzer and Silva [5] tested a solar cooking system with or without heat storage in different countries of the world. The system presented many interesting features such as the possibility of indoor and night cooking, heat flow control in the pots, modularity, and the possibility of further adjustments to incorporate a baking oven. Mettawee and Assassa [6] experimentally investigated the performance of a compact PCM solar collector. Solar energy was stored in PCM (paraffin wax) and was discharged to cold water flowing in pipes located inside the wax. Results showed that during the charging process, the average heat transfer coefficient is very small at the start of the melting process, which indicates that the heat is mainly transferred by conduction. The rate of heat transfer increases with time because the natural convection currents grow in the melted layer. During the discharging process, the useful heat gain was found to increase as the water mass flow rate increases from 8.3 to 21.7 kg/h. Nallusamy et al. [7] experimentally studied the TES with integrated constant/varying temperature source. Paraffin-filled spherical capsules were filled in an insulated cylindrical storage unit of TES. They concluded that at a constant inlet fluid temperature, mass flow rate has a small effect on the rate of charging and, with an increase in inlet temperature of heat transfer fluid, the rate of heat transfer increases in direct proportion. Hussein et al. [8] presented a novel indirect solar cooker based on a flat plate solar collector with magnesium nitrate hexa-hydrate as a PCM thermal storage unit. The solar cooker was of elliptical cross section and wickless heat pipes were used. The results showed the feasibility of elliptical cross section, wickless heat pipes, and PCM in an indirect solar cooker for use in evening cooking and to warm the food during off-sunshine hours.

Sharma et al. [9] investigated the thermal performance of a prototype solar cooker based on an evacuated tube collector with a PCM storage unit. The system achieved high temperatures up to 130°C without tracking when erythritol was used as a PCM, which was sufficient to cook food during late evening.

Literature discussed until now was based on a nonconcentrating-type collector. Generally, to achieve high temperature ranges, concentrating type of collectors are used. More developments have been made in recent years. The concentrating type of collectors can be categorized into two groups based upon their applications, first achieving the high temperature range up to 300–400°C in solar power plants and second, in industrial process heat applications where the temperature range required is 150–250°C. The parabolic dish-type concentrator has a high collector efficiency so it is widely used in the area of solar cooking [10–12]. Foong et al. [10] studied a small-scale double-reflector solar concentrating system with high-temperature heat storage.
medium (NaNO₃ and KNO₃) and a finite element model was used to numerically analyze the latent heat storage unit. The experimental results demonstrated that the melting of PCM occurred in 2 to 2.5 h and reached a temperature range of 230–260°C, suitable for cooking and baking purposes. Chaudhary et al. [11] investigated a solar cooker based on a parabolic dish collector with PCM. It was observed that a solar cooker with PCM having an outer surface painted black along with glazing stores 32.3% more heat as compared to PCM in an ordinary solar cooker. Lecuona et al. [12] simulated a portable solar cooker of parabolic type using a one-dimensional (1D) finite difference method. A numerical model was used to study its transient behavior with two different types of PCMs: paraffin and erythritol. High melting heat and conductivity of a PCM like erythritol is an advantage for fast cooking.

Farooqui [13] presented a solar cooker based on the Fresnel lens-type collector. The proposed cooker consists of rectangular glass mirror strips mounted on a wooden frame and requires 1D solar tracking. The maximum temperature attained in the experiment was 250°C. The heat absorption capacity of this collector was five times more than a conventional box-type solar cooker.

With the development in the field of solar energy, the parabolic trough collector was also used for solar cooking [14–16]. Umanand and Prasanna [14] modeled and designed the solar thermal system with a parabolic collector for hybrid cooking. The system is modeled using the band graph approach. They compared the results of the simulated modeled system with experimental results at different flow rates. At optimal flow rate, there is about 6% increase in efficiency as compared to the thermosyphon flow rate. Velraj et al. [15] studied the performance of a solar parabolic trough collector with a thermal energy storage system and took therminol-55 as heat transfer fluid. Various performance parameters like useful heat gain and thermal efficiency of individual components were evaluated. Mussard and Nydal [16] used two different types of heat storage units with a solar parabolic trough. The latent heat storage unit contained nitrate mixtures (salt) and oil was used as the heat transfer fluid which self-circulates in the loop connecting the collector and storage unit. Storage based on thermal oil is much more efficient than an aluminum-based storage unit as it reduces thermal losses in the pipe and absorber. Saini et al. [17] experimentally investigated the thermal performance of a solar cooker with acteamide as PCM based on a parabolic trough collector with vacuum tube receiver. They used two different heat transfer fluids separately, for heat circulation through a natural phenomenon called thermosyphon. It was observed that by using thermal oil as heat transfer fluid, the quantity of heat stored by PCM was increased by an amount of 26.66% to 67.49% as compared to water as heat transfer fluid.

Many researchers have worked on solar cookers based on the box-type collector, evacuated tube solar collector, parabolic dish collector, and parabolic trough collector with phase change thermal storage unit, but none of them worked on a solar cooker based on a parabolic dish collector with a dual thermal storage unit, i.e., combined
sensible and latent heat thermal storage system. The objective of this paper is to study the thermal performance of a solar cooker based on a parabolic dish collector with acetamide and sand as a dual thermal storage unit for noon and evening cooking in Indian climatic conditions. The experimental setup is installed at NIT Kurukshetra, India [29°58’ (latitude) North and 76°53’ (longitude) East].

2. EXPERIMENTAL SETUP

The experiment was performed to investigate the thermal performance of a solar cooker with a dual thermal storage unit. The test section of a solar cooker is based on a parabolic dish collector. This system consists of a parabolic dish collector, solar cooker as shown in Fig. 1. The experimental setup consists of the following components:

- Parabolic solar dish collector
- Solar cooker
- Latent heat storage unit
- Sensible heat storage unit
- Insulator box

2.1 Parabolic Solar Dish Collector

The solar parabolic dish collector is a point focusing device which includes a concentrator, a plate for placing the cooker, and a frame (Fig. 2). In this system, 40 segments

FIG. 1: Photograph of the experimental setup
of the anodized aluminum are joined to form the concentrator. The outer ring frame of the parabolic dish collector is made of the mild steel circular channel. At the focal length of the parabolic dish collector, a plate is provided upon which the cooker is to be placed. The tracking of the parabolic dish collector is done manually and for that a tracking screw is provided at the top of the outer ring. The parabolic dish collector is adjusted in such a way that the shadow of the tracking screw is not visible. After setting this position, the parabolic dish collector is locked in that position by the holding screw provided at the bottom of the tracking screw. Wheels are provided at the bottom of the parabolic dish so that the dish can be tracked with the movement of the sun. Specifications of the parabolic dish collector are shown in Table 1.

### 2.2 Solar Cooker

The solar cooker is made up of three hollow concentric cylindrical vessels of aluminum. The diameters of the inner, middle, and outer space are 0.12, 0.18, and 0.22 m, respectively. The inner vessel is used for cooking and a lid is also provided over it. The middle space is filled with 3 kg of commercial grade acetamide (PCM) which is used as a latent heat storage unit. The allowance is considered for volumetric expan-
sion of PCM. The outer space is filled with 6 kg of sand as a sensible heat storage unit. Three ports are provided on the top surface of the solar cooker, two for PCM filling and one for sand filling. These ports also act as safety valves. The cooker is painted black so that it can absorb maximum solar radiation. The side view, top view, and a photo of the solar cooker are shown in Figs. 3(a) and 3(b), respectively.

2.3 Latent Heat Storage Unit

The selection of PCM depends upon its properties such as melting temperature, latent heat of fusion, toxicity, etc. In this paper, commercial grade acetamide is used as a PCM with its thermophysical properties given in Table 2.

2.4 Sensible Heat Storage Unit

Sand is used as a sensible heat storage unit which is filled in the outer space of the solar cooker. A high melting point and availability in abundance made the sand a good option for a sensible heat storage unit. Thermophysical properties of dry sand of coarse nature which is used in this paper are given in Table 3.

<table>
<thead>
<tr>
<th>TABLE 2: Thermophysical properties of commercial grade acetamide</th>
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<tr>
<td>Melting temperature of acetamide (commercial grade)</td>
</tr>
<tr>
<td>Latent heat of fusion of acetamide (commercial grade)</td>
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<tr>
<td>Specific heat of acetamide</td>
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TABLE 3: Thermophysical properties of sand

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Density</td>
<td>1700 kg/m³</td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.26 W/m·K</td>
</tr>
<tr>
<td>Specific heat of sand</td>
<td>0.8 kJ/kg</td>
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</tbody>
</table>

2.5 Insulator Box

A box made up of wood is used for insulation. Its dimensions \((l \times b \times h)\) are 0.375, 0.37, and 0.35 m, respectively, as shown in Figs. 4(a) and 4(b). The box is filled with glass wool for better insulation and in the center of the box a space of diameter 0.26 m is provided for placing the solar cooker. The bottom side of the space is also filled with thermocol. The cover of the insulator box is made up of a GI sheet with a thermocol sheet at the inside surface.

FIG. 4: (a) Schematic diagram of insulator box; (b) photograph of insulator box
3. MEASURING DEVICES AND INSTRUMENTS

Different parameters are measured:

- PCM, sand, and cooking medium temperature
- Ambient temperature
- Solar radiation intensity

PCM, sand, and cooking medium temperature are measured with RTD PT100 thermocouples, which are connected with a digital temperature indicator that shows the temperature with a resolution of 0.1°C.

Dry bulb temperature of ambient air is measured with a sling Psychrometer. The solar radiation intensity is measured during the daytime with a Pyranometer-model CM11, supplied by Kipp and Zonen, Holland.

During charging and discharging periods, the experimental data are recorded at an interval of 30 min. The experiments were carried out on mostly clear sky days in the month of March 2014.

4. SYSTEM OPERATION

The main objective of this experimental setup was to cook food twice a day, i.e., in the daytime as well as in the evening time, with a variation in quantity of different cooking loads. In the experimental setup, sand as a sensible heat storage unit is filled in the outer space and acetamide as a latent heat storage unit is filled in the middle space of the solar cooker. The solar cooker is placed on the plate of the dish collector and the system is exposed to solar radiation. Solar radiations are made to concentrate on the solar cooker by the parabolic dish collector. The available heat is absorbed by the solar cooker and is transferred to the sand. During the daytime, heat transfer in the sensible heat storage unit and latent heat storage unit is a twofold process, i.e., these units absorb and also transfer heat to the cooking pot which is loaded with food for the first session of cooking. The dish collector is tracked manually every 15 min with the movement of the sun. At 16:00 h, the solar cooker is lifted from the dish collector with the help of a handle, placed in the insulator box, and loaded for the second session of cooking, i.e., evening cooking. During this process sand acts as insulator, thus preventing heat loss from the PCM to the surrounding. During evening cooking, PCM transfers its stored heat to the cooking pot while sand helps in compensating the loss in heat of PCM, thus maintaining the performance of PCM even at late evening hours.

5. ANALYSIS OF EXPERIMENTAL DATA

Heat stored by the PCM is given by Sharma et al. (2000):

\[ Q_{\text{PCM}} = m_{\text{PCM}}C_{\text{PCM}}(T_m - T_i) + L + C_{\text{PCM}}(T_{\text{PCM},\text{max}} - T_m). \]
It is assumed that the specific heat of solid and liquid phase of PCM is the same. Heat stored by the sand is given as

$$Q_{\text{sand}} = m_{\text{sand}} [C_{\text{sand}}(T_{\text{sand,max}} - T_i)] .$$

6. EXPERIMENTAL RESULTS AND DISCUSSION

In the experimental setup, cooking was conducted in the daytime as well as in the evening time at different cooking loads using a novel design of solar cooker with a dual thermal storage unit based on the parabolic dish-type collector. The performance of the solar cooker was studied under different load conditions at NIT Kurukshetra, India. The experiments were conducted during the month of March 2014. Every day, the solar collector was exposed to solar radiation at 08:30 h and readings were taken from 09:00 h at an every interval of 30 min. Five different cases were studied without load, with variation in load, and with different types of load.

6.1 Solar Cooker without Cooking Load; March 16, 2014

On March 16, the experiment was conducted without any cooking load. During the day, the maximum intensity was 972 W/m² at 15:00 h and the ambient temperature was in the range of 20°C to 31°C. The maximum temperatures of sand and PCM were 152.1°C and 135.8°C, respectively. Figure 5 shows that the sand and PCM were

![Graph showing variation of temperature and solar radiation intensity with time in case of solar cooker without cooking load]

**FIG. 5:** Variation of temperature and solar radiation intensity with time in case of solar cooker without cooking load
charged continuously till 13:30 h and afterward they started discharging the stored energy. The maximum temperature of the surface of the cooking pot reached was 125.5°C at 15:00 h and it was observed that at 20:00 h the pot’s surface temperature was 82.8°C.

### 6.2 Solar Cooker with Water as a Cooking Load; March 20, 2014

On March 20, the solar cooker was loaded with water (600 ml) twice in a day at 10:00 h and 16:00 h. Sand and PCM temperature rise and reach up to maximum values of 118.5°C and 112.7°C, respectively, as shown in Fig. 6. Due to a little bit cloudy day, the maximum temperature achieved in this case was less than the case without loading. Maximum solar intensity was 899 W/m² at 12:00 h and the ambient temperature lies in the range of 20°C to 28°C. In the first session of cooking, water was loaded at 10:00 h. The maximum temperature of water was found to be 99.4°C at 13:00 h. At evening time, the same amount of water was placed at 16:00 h. At 20:00 h the temperature of water was found to be 72.4°C.

### 6.3 Solar Cooker with 100 g Rice as a Cooking Load; March 21, 2014

On March 21, the experiment was conducted with rice as a cooking load (rice 100 g + water 600 ml). On that day, the maximum solar intensity was 944 W/m² at 14:00 h. The melting temperature of PCM is achieved at 10:00 h here, i.e., in 1 h of start of the experiment. The maximum temperature attained by sand and PCM were 117.6°C and 109.1°C, respectively, as shown in Fig. 7. In the first session of cooking, food
was loaded at 10:00 h. Food was checked at 12:00 h and found to be well cooked. The maximum temperature of food was 90.6°C. At evening time, the same load was placed at 16:00 h and it was checked at 17:00 h and found to be well cooked. The maximum temperature of 92°C was attained by food at 17:30 h.

6.4 Solar Cooker with 200 g Rice as a Cooking Load; March 22, 2014

On March 22, the solar cooker was loaded with cooking load (200 g rice + 600 ml water). The maximum solar intensity was 864 W/m². Figure 8 shows that the maximum temperature of sand and PCM were 123.2°C and 108.4°C, respectively. During the day, ambient temperature was in the range of 23.0°C to 32.5°C. In the first session, food was loaded at 10:00 h. The cooker was opened at 12:30 h and food was found to be well cooked. The maximum temperature attained by food was 85.5°C. At evening time, food was loaded at 16:00 h. The status of food was checked at 17:30 h and it was found to be well cooked. The maximum temperature attained by food was 83.7°C. At 20:00 h the temperature of the sand and PCM were found to be 64.2°C and 70.4°C, respectively.

6.5 Solar Cooker with 200 g Pulses as a Cooking Load; March 31, 2014

On March 31, the solar cooker was loaded with cooking load (pulses 200 g + 600 ml water). During the day, the ambient temperature was in the range of 21°C to 30.5°C.
and the maximum intensity was 993 W/m². From Fig. 9 it can be observed that the maximum temperature of sand and PCM were 120.7°C and 107.0°C, respectively. In the first session of cooking, food was loaded at 10:00 h. The food was checked at 12:30 h and it was not properly cooked. Again, it was checked at 13:00 h and found

FIG. 8: Variation of temperature and solar radiation intensity with time in case of solar cooker with 200 g rice as cooking load

FIG. 9: Variation of temperature and solar radiation intensity with time in case of solar cooker with 200 g pulses as cooking load
to be well cooked. The maximum temperature of food was 96.6°C. In the second session of cooking, the solar cooker was loaded at 16:00 h and food was found to be well cooked at 18:00 h. The maximum temperature of food was 81.3°C. At 20:00 h temperature of sand and PCM were found to be 59.0°C and 62.1°C, respectively.

7. HEAT STORED BY SAND AND PCM IN DIFFERENT CASES

In different cases of the experiment performed, it can be seen that the energy stored by PCM during charging process was in the range of 1433.9 to 1266.2 kJ, whereas, the energy stored by sand in different cases was in the range of 610.1 to 444.5 kJ. Overall energy stored by PCM was nearly 2.7 times more as compared to energy stored by sand because of the high specific heat and latent heat of acetamide. Sensible energy stored by sand helps in maintaining the stored heat of PCM, thus keeping the food warm up to late evening hours. Also, it makes the evening cooking much faster as compared to noon cooking.

8. CONCLUSIONS

1. In different cases of the experiments, the maximum temperature range of sensible heat storage unit (sand) and latent heat storage unit (PCM) were found to be 152.1°C to 117.6°C and 135.8°C to 107.0°C, respectively. Thus, both noon and evening cooking were successfully carried out in a day.

2. The average time required by PCM to reach its melting temperature was approximately 2 h.

FIG. 10: Heat stored by sand and PCM for different cases
3. For different cases, the rate of evening cooking was found to be approximately 1.5 to 2 times faster as compared to noon cooking.

4. At 20:00 h, the temperature of cooked food was found in the range of 60.2°C to 70.6°C for different cases. This high temperature of food, even at late evening, was because of the combined sensible heat storage unit and latent heat storage unit. Sensible heat storage unit (sand) not only helps in maintaining the stored energy of PCM during the discharging period by providing its sensible heat, but also acts as an insulator, thus minimizing heat loss to the surroundings.

5. The average energy stored by the sensible heat storage unit and latent heat storage unit were found to be 486.24 and 1310.5 kJ, respectively.

6. The above results show the feasibility of novel design of a solar cooker with a dual thermal storage unit based on a parabolic dish collector for late evening cooking in Indian climatic conditions.

REFERENCES


