Journal of Material Science and Mechanical Engineering (JMSME)
Print ISSN : 2339-9095; Online ISSN : 2393-9109; Volume 2, Number 6; April – June, 2015 pp 9 – 12
Krishi Sanskriti Publications
http://www.krishisanskriti.org/jmsme.html

Thermal Analysis of a Solar Cooker with Sensible Heat Storage unit

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Abstract—*In this article, the thermal analysis of sensible heat storage units (sand, stone pebbles, iron grits and iron balls) in a solar cooker based on parabolic dish type solar collector for late evening cooking is theoretically investigated. In the theoretical analysis the heat input and output to the system was calculated using the thermodynamics equations. The various losses in the system were measured. The theoretical data obtained were compared to the experimental data and relative error was calculated. The efficiency of the system for different cases was calculated theoretically and experimentally and was found to be in range of 4 to 9%.*

Keywords: *Parabolic dish type collector, sensible heat storage units, solar cooker, thermal analysis*

1. INTRODUCTION

Solar cooking is better substitute for cooking by fuel or wood in India. Solar energy has become one of the most promising alternative energy resources because it is free, environmental friendly and available in abundance. From the last few decades, solar energy is utilized in the field of cooking using different types of collector 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 solar cooker with thermal storage.

Sharma et al. [1] 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. Acetamide was used as PCM and experimental results showed that the melting temperature of PCM should be in the range of 105°C to 110°C for evening cooking. Schwarzer and Silva [2] tested a solar cooking system with or without heat storage in different countries of the world. The system presented many interesting features such as possibility of indoor and night cooking, heat flow control in the pots, modularity and the possibility of further adjustments to incorporate a baking oven. Sharma et al. [3] investigated the thermal performance of a prototype solar cooker based on an evacuated tube collector with 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. Chaudhary et al. [4] investigated a solar cooker based on parabolic dish collector with phase change material. It was observed that solar cooker with phase change material having outer surface painted black along with glazing stores 32.3% more heat as compared to PCM in ordinary solar cooker. Lecuona et al. [5] simulated a parabolic type solar cooker by using finite difference method. A numerical model was used to study its transient behavior with two different types of PCMs: Paraffin and Erythritol. Erythritol is an advantage for fast cooking due to high melting temperature and conductivity. Farooqui Suhail [6] presented a solar cooker based on fresnel lens type collector. The maximum temperature attained in the experiment was 250°C. Heat absorption capacity of this collector was five times more than conventional box type solar cooker. Saini et al. [7] experimentally investigated the thermal performance of a solar cooker with acteamide as PCM based on parabolic trough collector with vacuum tube receiver. It was observed the rate of evening cooking was found to be approximately 1.63 to 4.44 times faster as compared to noon cooking.

Many researchers have worked on solar cooker based on 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 solar cooker based on parabolic dish collector with sensible heat storage unit. The objective of this paper is to investigate the thermal analysis of the solar cooker using different sensible heat storage units. Finally, the energy formulations are applied to the experimental unit using the data collected during a typical operation of the unit. The results are presented in tabular form and discussed.

2. EXPERIMENTAL SETUP

The test section of solar cooker is based on parabolic dish type collector. This system consists of parabolic dish collector and solar cooker.

2.1 Parabolic dish collector

The solar dish is a point focusing collector. At the focus of parabolic dish collector, a holding tray is provided upon which cooker is to be placed as shown in Fig. 1. The tracking of parabolic dish collector is done manually after 30 minutes.

Specifications of the parabolic dish collector are shown in Table 1.

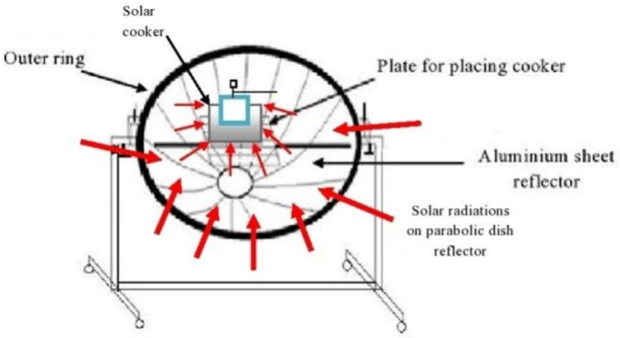

Fig. 1: Schematic diagram of parabolic dish collector

Table 1: Specifications of Dish Collector

Diameter of outer ring	1.4 m
Focal length of dish	0.2 m
Dish rim angle	120.5°
Aperture area of dish	1.539 m^2
Concentration ratio of dish	33

2.2 Cooker with Sensible heat storage unit (Solar cooker)

Solar cooker is made up of hollow concentric cylindrical pot of aluminum and a pressure cooker placed at their centre. The diameter and height of pot is 0.285 m and 0.14 m respectively while the pressure cooker has diameter 0.13 m and height as 0.11 m as shown in Fig. 2. In experiment 1, 2, 3 and 4 the space of cooker is filled with sand, stone pebbles, iron grits and iron balls respectively. Thermo physical properties of these units which are used to store heat are given in Table 2.

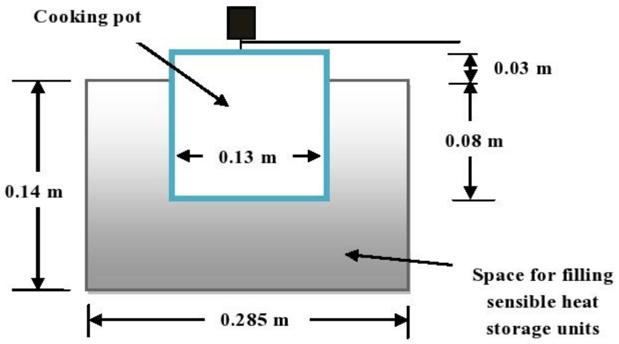

Fig. 2: Section view of solar cooker

Table 2: Thermophysical Properties of Sensible Heat Storage Unit

Materials / Properties	Sand	Stone pebbles	Iron grits	Iron balls
Mass (kg)	12.78	14.39	12.46	26
Specific heat (kJ/kg °C)	0.8	0.88	0.46	0.45

3. THERMAL ANALYSIS

The solar cooker is placed on the plate of dish collector and the system is exposed to solar radiations from 13:00 hr to 16:00 hr. During this period energy is stored in the sensible heat storage material and this is known as charging time. At 16:00 hr the solar cooker is lifted from the dish collector and placed in the insulator box and loaded for evening cooking.

The solar radiations received at the aperture area (see table 1) of the parabolic dish reflector is calculated by the formula:

$$I_D = I \times A$$

In the above equation average solar intensity during charging time is taken.

The radiations after falling on solar dish are reflected at the receiver plate of dish. Highly reflective aluminium sheets with reflectivity of 80% are used. The solar radiation reflected by the dish is given as:

$$I_{RD} = I_D \times \rho_D$$

The radiations after reflecting from solar dish are received by the solar cooker. But, there are some losses of radiations as few radiations could not reach the solar cooker because area of solar cooker is less as compared to absorber area of solar dish. In this case, there are approximately 30% of radiations losses. The system has radiation receiving factor of 0.7. Radiations received at the solar cooker:

$$I_{SC} = I_{RD} \times RRF$$

The solar cooker is made up of aluminium material of absorptivity 75%. Radiations absorbed by solar cooker:

$$I_{abs} = I_{sc} \times \alpha_{SC}$$

Energy absorbed by solar cooker in charging time of 3 hours i.e. from 13:00 hr to 16:00 hr is given as:

$$Q_{abs} = I_{abs} \times t_{ch}$$

During charging time the system is exposed to the atmospheric conditions. There will be convection losses calculated by:

$$C_l = hA_{sc}\Delta T$$

Every body which has temperature above 0K radiates energy from them. There will be radiation losses which are calculated by:

$$R_l = \sigma A_{sc}T^4$$

Energy left after convection and radiation losses:

$$Q_{left} = Q_{abs} - (C_l + R_l)$$

Now this energy is left with the sensible heat storage material. This energy will be used for cooking during evening time. The energy can also be equated as follows:

$$Q_{left} = mC(T_{max} - T_{amb})$$

From the above equation, the maximum temperature of the sensible heat storage material can be calculated. The value of mass and specific heat of materials are shown in table 2.

Efficiency of the system:

$$\eta_{system} = \frac{Q_{output}}{Q_{input}}$$

Where, $$Q_{output} = Q_{left}$$

$$Q_{input} = I_D \times t_{ch}$$

4. RESULTS AND DISCUSSION

The maximum temperature of sensible heat storage materials are theoretically calculated using the equations as described in the paper. Also, the temperatures were measured experimentally and compared to the theoretical data as shown in table 3. The relative error in experimental data compared to theoretical data is calculated.

Table 3: Theoretical and experimental temperature of materials

Material	Maximum temperature theoretically (℃)	Maximum temperature experimentally (℃)	Relative error (%)
Sand	105.3	94.5	10.2
Stone pebbles	98.2	92.7	5.6
Iron grits	108.1	99.1	8.3
Iron balls	91.6	113.6	19.3

The efficiency of the system was calculated using theoretical and experimental data as shown in Fig. 3.

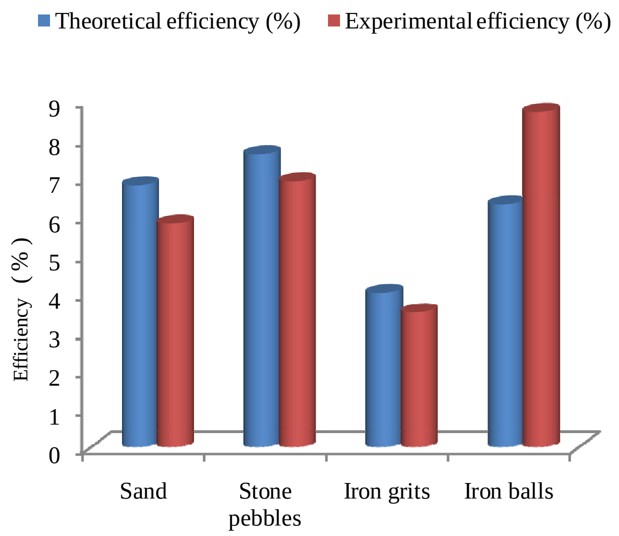

Fig. 3: Efficiency of the system for different cases

Nomenclature

I_D	Solar radiations received at solar dish, W
I	Average solar radiation Intensity, W/m^2
A	Aperture area of solar dish, m^2
I_{RD}	Solar radiations reflected by solar dish, W
ρ_D	Reflectivity of solar dish
I_{SC}	Solar radiations received at solar cooker, W
RRF	Radiation receiving factor
I_{abs}	Solar radiations absorbed by solar cooker, W
α_{SC}	Absorptivity of material of solar cooker
Q_{abs}	Energy absorbed by solar cooker during Charging time, J
t_{ch}	Charging time, hr
C_l	Convection losses, J
h	Convective heat transfer coefficient, W/m^{2}K
A_{sc}	Surface area of solar cooker, m^2
ΔT	Difference between the average temperature of solar cooker and ambient temperature during charging time, ℃
R_l	Radiation losses, J
σ	Stefan Boltzmann's constant, W/m^{2}K^4
T	Average temperature of material during charging time, ℃
Q_{left}	Energy left in the system, J
m	Mass of material, kg
C	Specific heat of material, kJ/kg ℃
T_{max}	Maximum temperature of material, ℃
T_{amb}	Ambient temperature, ℃
η_{system}	Efficiency of the system
Q_{output}	Energy output from the system, J
Q_{input}	Energy input in the system, J

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