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Performance assessment of a solar domestic cooking unit integrated with thermal energy storage system

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ABSTRACT

The performance evaluation of a newly developed double walled cooking unit (tava type) suitable for an indirect type solar cooking application integrated with thermal energy storage system is presented. The experimental set-up consists of a cooking unit, a storage tank and a positive displacement pump. Therminol 55 and D-Mannitol are used as the heat transfer fluid (HTF) and storage medium respectively. During the cooking experiment the maximum temperature reached by the olive oil in the cooking unit was 152 °C within a duration of 15 min which is comparatively lesser than the time taken by a conventional LPG stove in simmering mode. A heat balance for the developed cooking unit was prepared to account for the heat input and the distribution pattern. An experiment was also conducted to evaluate the average heat loss encountered in the system under no load condition and it was found that there was considerable heat loss in the flow circuit during the discharging process. The results of the present study will be very useful for the design of solar based indoor cooking units.

1. Introduction

In developing countries, 730 million tonnes of biomass is burned each year for cooking, amounting to more than 1 billion tonnes of CO_2 build-up in the atmosphere [1]. Unfortunately there are still millions of people whose deaths are attributed to diseases resulting from smoke inhalation from open cooking fires [2–4]. Moreover the cutting of firewood for cooking causes deforestation, leading to desertification. Hence, the 'Cook without Wood' i.e. solar cooking is considered the best solution to not only reduce public health risks, but also curtail global warming.

Owing to the importance of solar cooking, several types of solar cookers have been developed over the years. Though different types of classification of solar cookers are reported in literature [5–8], they are broadly categorised into two types, the box type and the concentration type. In the box type solar cookers, the solar radiation enters directly through the glass window for cooking the food. In concentration type of solar cookers, parabolic or spheroid reflectors are used with the cooking pot placed at the focal point, where the sun rays are focussed.Though concentration type solar cookers deliver higher temperature for cooking as compared to box type solar cookers, the user has to constantly adjust them to track the sun. Hence an indirect type solar cooker is preferred for indoor cooking, where cooking is carried out in the shade or inside a building [9,10]. In this arrangement, the pot/cooking unit is physically displaced from the collector and a heat-transfer medium is required to transfer the heat to the cooking pot. In India, the use of indirect type solar cooker has become popular in places like hostels, schools, temples and other community level organizations where mass cooking is undertaken [11]. In these systems solar energy is directly used for cooking without storage as the cooking is required only in the afternoon hours. However, the success of solar cooking in household applications is possible only if the energy for cooking is made available even during non-sunshine hours. Therefore, solar cookers require energy storage to provide energy during the night and overcast periods [12–19]. The collective information on solar cookers with energy storage system has been presented [20,21]. In addition, one of the major requirements of using solar energy for cooking application is the development of a suitable cooking unit, which should be fast and energy efficient [11]. Detailed surveys of various designs of cooking equipments, their behaviour and energy efficiencies were carried out [22–24]. The cooking time was appreciably reduced when suitable modifications were made to the shape of the cooking vessel and it was reported that more heat was transferred to the food through the pot walls due to the changes in such configurations [25–28].

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Nomenclature

HTF	Heat transfer fluid
LPG	Liquefied petroleum gas
PTC	Parabolic trough collector
TES	Thermal energy storage tank
PCM	Phase change material
MS	Mild steel
Q	Heat, W
U_{loss}	Overall heat loss coefficient (W/m^2K)
Q_{loss}	Tank heat loss (W)
d_o	Outer diameter of TES tank (m)
H	Height of TES tank (m)
LMTD	Logarithmic mean temperature difference (K)
$\dot{m}$	Mass flow rate (kg/s)
c_p	Specific heat capacity (J/kg K)
T	Time, s
T_1	Average temperature of HTF after time interval t (K)
T_2	Average temperature of PCM after time interval t (K)
$T\alpha$	Ambient temperature (K)
Q_{del}	Instantaneous heat supply (W)
T_{out}	Temperature at outlet of TES tank (K)
T_{in}	Temperature at inlet of TES tank (K)
Q_{gain}	Instantaneous heat gain (W)
$Q_{loss,pipe}$	Instantaneous pipe heat loss (W)
$Q_{loss,tank}$	Instantaneous TES tank heat loss (W)
$Q_{del,ave}$	Average rate of heat delivered from the TES tank (W)
N	Total number of measurements
$Q_{tava,ave}$	Average rate of heat delivered from the tava (W)
$Q_{gainave,olive}$	Average rate of heat gain by the olive oil (W)
T_{final}	Final temperature of olive oil (W)
$T_{initial}$	Initial temperature of olive oil (W)
$Q_{lossave,pipe}$	Average rate of heat loss by pipe (W)
$T_{tankout}$	Temperature of HTF at the outlet of TES tank (K)
T_{tankin}	Temperature of HTF at the inlet of TES tank (K)
$T_{tavaout}$	Temperature of HTF at the outlet of tava (K)
T_{tavain}	Temperature of HTF at the inlet of tava (K)
$Q_{lossave,tank}$	Average rate of heat loss by TES tank (W)
$Q_{lossave,tava}$	Average rate of heat loss by tava (W)
$Q_{un\text{-}acc}$	Unaccounted heat loss (W)
$\eta_{overall}$	Overall efficiency (%)
η_{tava}	Tava efficiency (%)

Despite the lack of consistency and reliability of solar power, the government of many tropical countries, their scientists, and researchers are taking several efforts to make solar power more affordable and efficient for different applications including cooking [29–31]. Though in recent years, different types of solar collectors, box type cooking units and other integrated direct type collector have been successfully developed, the associated units like the thermal storage system, and cooking devices that use the stored energy have not been given enough attention, and hence, solar cookers have not been able to fully replace other conventional modes of cooking. The objective of the present work is to efficiently make use of available solar energy for cooking application by the introduction of a newly developed double walled tava type cooking unit that transfers the heat energy from the storage system to the foodstuff in the cooking unit. In the present work, the thermal performance of the overall system and the efficiency of the tava cooking unit are studied experimentally. Further an experiment is conducted to study the average heat loss encountered in the flow circuit under no load condition and the results are reported.

2. Experimental setup

The system description and details about the HTF and storage medium identified in the present work are discussed in this section.

2.1. System description

The experimental setup as shown in Fig. 1 consisted of a parabolic trough collector (PTC), a thermal energy storage (TES) tank, double walled cooking unit (tava type) and a positive displacement pump. The newly developed indirect type solar domestic cooking unit integrated with PTC and storage tank was installed on the rooftop of the Institute for Energy Studies building at Anna University, Chennai, a city located in the southern part of India. The PTC was installed on the open terrace, while the TES tank and the cooking unit were installed in a closed room constructed near the PTC on the rooftop of the building and they were interconnected through the piping system.

The PTC had a total aperture area of 7.5 m^2 which concentrated the incoming solar radiation to the absorber tube. The PTC received the solar radiation to heat the HTF in the circuit that transferred its energy to the phase change material (PCM) in closed loop. A cylindrical thermal energy storage (TES) tank having a diameter of 550 mm (d_o) and 1100 mm (h) length made of 5 mm thick mild steel (MS) plate was kept vertically, with two plenum chambers on the top and bottom of the tank, and a perforated distributor plate was provided at the bottom of the tank to achieve a uniform HTF

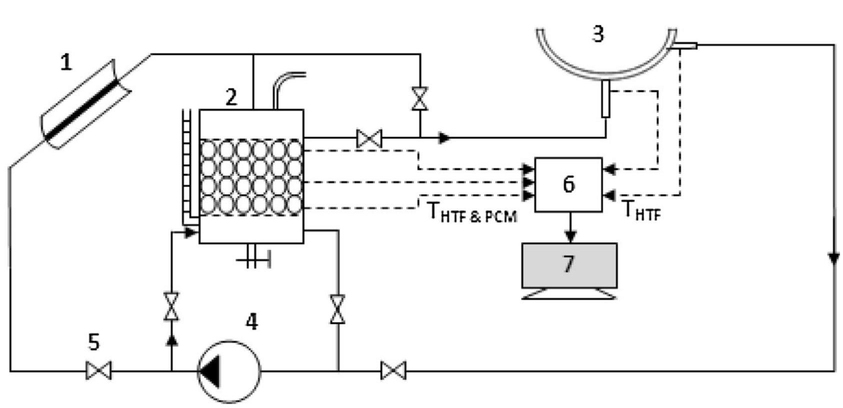

Fig. 1. Schematic of the experimental setup: (1) parabolic trough collector (2) TES tank (3) cooking unit (4) positive displacement pump (5) valve(6) data acquisition unit (7) computer and $T_{HTF\&PCM}$ – temperature sensors for HTF and PCM.