THE USE OF PARAFFIN WAX IN A NEW SOLAR COOKER WITH INNER AND OUTER REFLECTORS

by

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Original scientific paper
DOI: 10.2298/TSCI121022031A

The potential use and effectiveness of paraffin wax in a new solar cooker was experimentally investigated during daylight and late evening hours. For these experiments, a cooker having an inner reflecting surface was designed, constructed by filling paraffin wax and metal shavings. The side- and sub-surface temperatures of the paraffin wax in the cooker were measured in the summer months of June and July. The thermal efficiency of the cooker was tested on different conditions. The results show that the optimum angle of the outer reflector is 30°. Here, the peak temperature of the paraffin wax in the solar cooker was 83.4 °C. The average solar radiation reflected makes a contribution of 9.26% to the temperature of paraffin wax with the outer reflector. The solar cooker with the outer reflector angle of 30° receives also reflected radiation from the inner reflectors. Besides, the heating time decreased to approximately one hour. The designed solar cooker can be effectively used with 30.3% daily thermal efficiency and paraffin wax due to the amount of energy stored.

Key words: *solar energy, solar cooker, energy storage, phase change, paraffin wax, inner reflector*

Introduction

Solar energy has long been presented as an answer to the world's energy sources and other environmental problems associated with fuel supply. Among the applications of the solar energy, the solar cookers are used to assist in the effective utilization of thermal energy. Over the last century, many studies have been performed on the development of various types of solar cookers and on the evaluation of the performance and economic aspects of solar cookers. There have also been several attempts to increase the performance and efficiency of cookers in non-tropical regions [1]. The solar energy potential of Turkey is 2624 hours per year with a maximum of 365 hours per month in July and a minimum of 103 hours per month in December [2]. In spite of this energy potential, except for solar collectors, solar cookers are not widely used. Solar cookers are expected to contribute considerably towards meeting the requirements for domestic cooking energy [3]. The different types of solar cookers can be classified into three types, which are box type, direct or concentrating type and indirect or advanced type [4]. Some researchers have investigated on the performance of a solar cooker for possible use in different applications, such as sun non-tracking system [5], outer-inner reflectors [6], different insulating materials [7, 8], various booster mirrors [9], a modified absorber plate [10, 11], a

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modified utensil (apart from a concave shaped-lid) [12], a wind shield [13], a hybrid solar system [14, 15], a cylindrical shaped box [16], two axes tracking system [17], and a microcontroller-based system [18]. Recently, some studies have been performed concerning the use of phase change materials (PCM) integrated with solar cookers. For this purpose, magnesium nitrate hexahydrate [19], stearic acid [19, 20], acetamide [21], acetanilide [22], erythritol [23] materials, hydrated salts [24] and engine oil [25] have been used as a PCM storage medium. A theoretical investigation on the performance of PCM (magnesium nitrate hexahydrate, stearic acid, acetamide, acetanilide, and erythritol) has also been conducted by Chen *et al*. [26]. Also, magnesium nitrate hexahydrate is used as PCM inside the indoor cooking unit of a new indirect solar cooker (*i. e.* flat-plate collector solar cooker and evacuated tube collector cookers) [27]. The results show that these applications increase the average efficiency of the cooker. The use of a PCM results in shorter cooking times [23]. It is concluded that, acetanilide is a promising PCM for cooking indoors with aluminum; but it exhibits some corrosion in contact with steel. However, magnesium nitrate hexahydrate is not stable during its thermal cycling due to the phase segregation problem; therefore, it is not recommended as a storage material inside solar cookers for cooking indoors [28]. Also, these PCM are rather expensive when high temperatures are concerned. In addition, Sharma *et al.* [29] found that paraffin wax have shown reasonably good thermal stability in their melting temperature as well as variations in their latent heat of fusion. The ideal PCM to be used for latent heat storage system must meet following requirements: high sensitive heat capacity and heat of fusion, stable composition, high density and heat conductivity, chemical inert, non-toxic and non-inflammable, reasonable, and inexpensive [30]. Paraffins appear particularly well suited for applications related to energy conservation in buildings and solar energy [31]. The evaluation and selection of PCM for solar cooker systems and applications in the field of solar energy are described in detail elsewhere [30-33]. In addition, Yuksel [33] and Yuksel *et al.* [34] proposed a theoretical approach for the prediction of the time and temperature change of the heat stored in the PCM.

The literature clearly indicates that the investigations deal with the PCM used in the solar cooker. However, no investigation is reported in the literature on preparation and comprehensive characterization of a solar cooker with two concurrent features: (1) solar cookers filled with PCM paraffin wax, and (2) solar cookers having reflectors designs at different angles. In this article, a new box-type solar cooker with two inner reflector surfaces is designed, constructed, and tested. The inner reflectors are arranged in a three-step fashion at different inclinations with respect to the horizontal plane. The thermal performance of the new cooker is investigated for the outer reflectors at different angles. In city of Bursa, Turkey, the temperature behaviour of paraffin wax was measured during clear and cloudy days, as well as in the late evening hours.

Description of the solar cooker

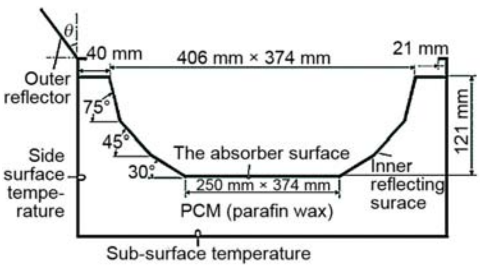

Figure 1. Schematic diagram of the box-type solar cooker with inner and outer reflectors

The new box type solar cooker with three-step inner reflectors consists of an outer box, an inner box and the outer reflectors. The solar cooker stores heat from solar energy collected throughout the day and use it for cooking any time after. The cross-section schematic of the cooker is shown in fig. 1. The rectangular solar cooker has 643 mm × 520 mm × 290 mm outer dimensions and 406 mm × 374 mm × 121 mm inner dimensions. In this design, the outer box is an insulated box with a double glazed cover. The outer box is made of 10 mm thick wood, as shown in fig. 2. The inner box is placed in the centre of the outer box. The inner box consists of the inner reflector surfaces, the absorber surface and the other (sub-side) surfaces. These surfaces are made from two aluminum sheet of 3 mm thickness. As distinct from the model [19, 35], only two of the inner surfaces are arranged at the angles of 30°, 45°, and 75°, as shown in figs. 1 and 2. Also, the space between the two aluminum sheets is filled with 5 kg of the PCM and 3.5 kg of the metal shavings. However, the space behind inner reflectors was filled with insulation material [19, 35]. In this study, metal shavings are used to ensure the homogeneous distribution of paraffin wax, and to make thermal contact with the inner absorber surface. The inner reflector surface is polished to minimize the heat absorption. The inner surface area is 0.151844 m^2. The thermophysical properties of the paraffin wax that is used as the PCM can be found elsewhere [30-34]. Sharma *et al.* [30] reported that the values of the melting point and latent heat of fusion of paraffin wax are 58-60 °C and 189 kJ/kg, respectively. The gap between the inner box and the outer box is filled with 8 mm thick glass wool to minimize heat loss of the solar cooker (fig. 2). Also, the box type solar cooker is closed with 18 mm thick double glass covers. Such a glass material is commercially available 3.5 mm thick tempered glass.

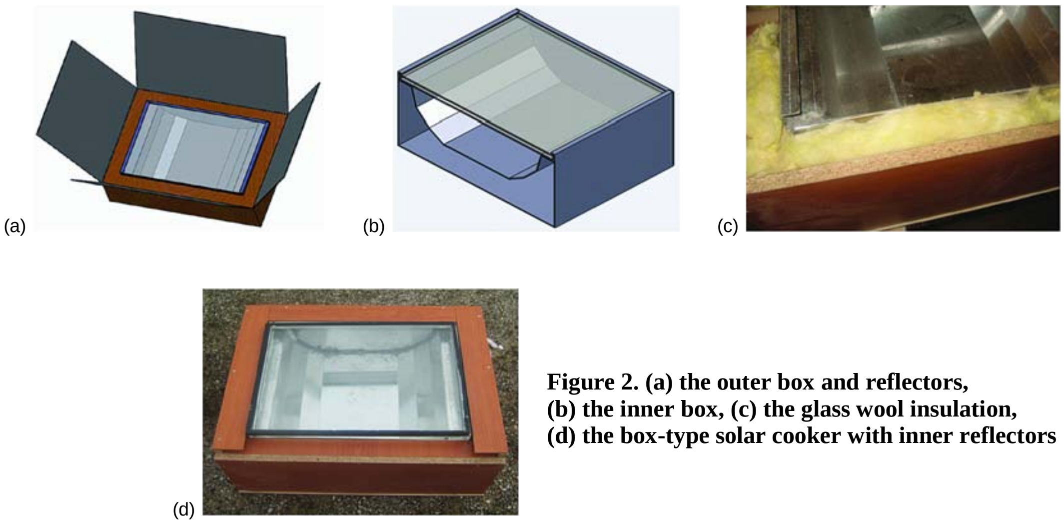

Figure 2. (a) the outer box and reflectors, (b) the inner box, (c) the glass wool insulation, (d) the box-type solar cooker with inner reflectors

The solar cooker is exposed to the solar radiation both directly and from the outer reflectors used. The outer four reflectors are mounted at all sides of the cooker, as shown in fig. 2. The four reflectors are rectangular in shape, having dimensions of 520 mm × 950 mm and 643 mm × 950 mm. The outer reflectors are made of the paperboard and the surfaces are covered with aluminum foil chosen as a reflector material due to its good reflectivity. Also, the corners and edges of the solar cooker are welded and covered with silicone sealant to prevent any air leakage.

Experimental results and discussion

The new solar cooker was tested during summer conditions in the city of Bursa. The cooker was placed facing directly south and towards the Sun. But, the cooker's position was not changed, which did not follow the Sun's movement during the day. Four reflectors were arranged at different angles on different days. The angle of the outer reflector can be varied between 0° and 90° with respect to the vertical axis. By adjusting these angles, efforts are made to keep the reflected solar radiation on the absorber surface. Hence, the variation in the local solar radiation was measured by a weather station (Davis Vantage Pro2, Davis 92 Instruments Corp., USA) and readings were taken at intervals of approximately 10 min. The sub- and the side-surface temperatures of the paraffin wax and the mean ambient temperature were recorded, and the results were discussed. The time-wise temperatures of paraffin wax were determined using thermocouples connected to a multi channel digital data recorder (Cole-Parmer Digi-Sense model 92000-05). As shown in fig. 1, two K type thermocouples are positioned in different locations. All experiments were conducted in an outdoor environment during June and July 2011 to evaluate the effect of paraffin wax on the cooker performance. For this purpose, a series of experiments with and without the outer reflectors were performed on the double glazed box type cooker filled with paraffin wax. The experiments were carried out for approximately one month. The experiments began at midnight on June 16th. For the solar cooker without insulation, the measurements were continued for five days. Over the next five days, the top aperture of the solar cooker was covered with 5 cm thick polyurethane foam for thermal insulation and additional insulation was applied between 18:00 p. m. and 08:00 a. m. Then, four reflectors were added to the solar cooker for the next thirteen days. The reflectors angles were set to 30°, 60°, and 45°, respectively. According to the experimental measurements, the temperature variation of the paraffin wax in the cooker with and without insulation is shown in figs. 3 and 4. For reflector angles of 30°, 60°, and 45°, figs. 5, 6, and 7 show the temperature variation of the paraffin wax in the solar cooker depending on certain days of the summer. Otherwise, the variations in the ground reflected solar radiation *vs* time of day for different types are shown in figs. 3, 4, 5, 6, and 7.

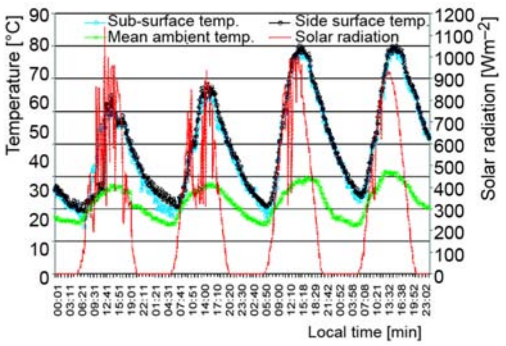

Figure 3. The sub- and side-surface temperature curve of the paraffin wax in the cooker without insulation and the solar radiation intensity for the region on June 17-20, 2011
(for color image see journal web-site)

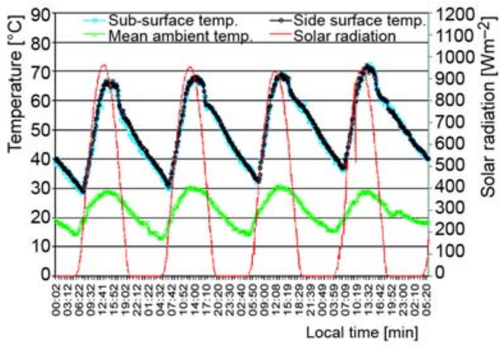

Figure 4. The sub- and side-surface temperature curve of the paraffin wax in the cooker with insulation and the solar radiation intensity for the region on June 22-26, 2011
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From all the figures, the temperature variations in the paraffin wax have the same value in both the side surface and the sub-surface, due to the use of metal shavings. This mixing characteristic leads to a homogeneous distribution of local heat transfer. The solar cooker's heat losses also decrease with the use of additional polyurethane insulation. Therefore, the stored energy during the daylight hours is preserved as effectively as possible until the morning. The minimum temperature of the paraffin wax of the solar cooker with insulation is higher than that of the solar cooker without insulation at 7:00-8:00 a. m. Here, a net energy

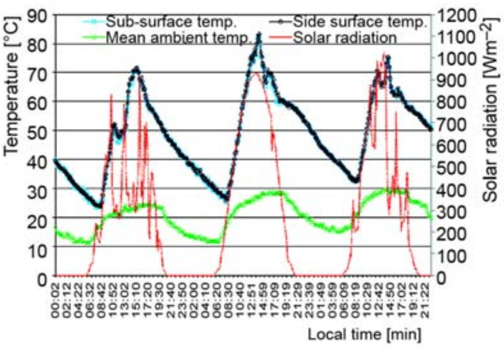

Figure 5. The sub- and side-surface temperature curve of the paraffin wax in the cooker with a reflector angle of 30° and the solar radiation intensity for the region on June 29-July 1, 2011
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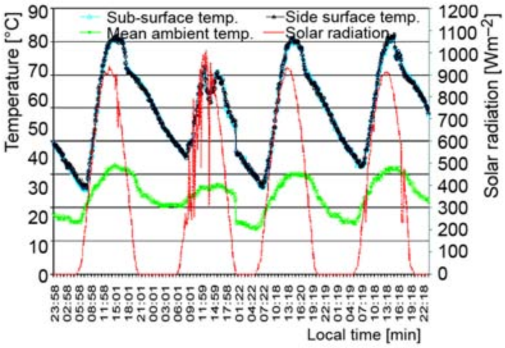

Figure 6. The sub- and side-surface temperature curve of the paraffin wax in the cooker with a reflector angle of 60° and the solar radiation intensity for the region on July 3-6, 2011
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gain is achieved in the heat discharge. From the result of fig. 3, it can be seen that the intensity of the total energy gain over day is less, since the minimum temperatures of the paraffin wax in the cooker without insulation are lower than that of cooker with insulation.

The temperatures of the paraffin wax are affected by the reflector angle and the solar radiation. It is clear from figs. 5, 6, and 7 that the maximum temperature of the paraffin wax increases with the reflector angle of 30°. From the results of figs. 6 and 7, the maximum temperatures of the paraffin wax are same or close to same. However, the minimum temperatures of the paraffin wax become higher, when the reflector angle is 45°. These differences are due to city of Bursa latitude angle of 40.22°. With the reflector angle of 30°, the solar cooker receives also reflected radiation from the inner reflectors. The maximum temperature of the paraffin wax decreases with an increase of the reflector angle of 30°. From the all figures, the reflected radiation makes a maximum contribution of 9.26% to the temperature of the paraffin wax. Also, a reflector angle of 30° significantly affects the heating time. When the temperature of the paraffin wax achieved a maximum value, the heating time decreased to approximately one hour. From the result of fig. 5, it can be seen that the intensity of the total solar radiation over day is less, when the reflector angle is 30°. Here, the maximum temperatures of the paraffin wax are 71.6 °C, 83.4 °C, and 75.5 °C, respectively. For a reflector angle of 60° and 45°, the maximum temperature of the paraffin wax is in the range of 69.4 °C to 74.5 °C. Also, it is observed that the intensity of the solar radiation is less during cloudy days (June 16, 17, 18, 29, July 4 and June 26 was a rainy day). Because of this, the peak temperature variation in the paraffin wax is affected on June 29 (as shown in fig. 5) and July 4 (as shown in fig. 6). The peak temperature can be assumed to be higher than the present temperature of paraffin wax. In addition, the absorber surface temperature can be assumed to

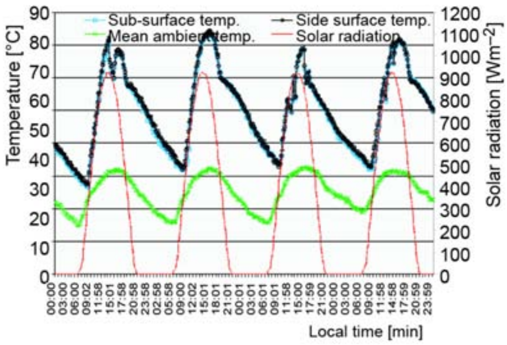

Figure 7. The sub- and side-surface temperature curve of the paraffin wax in the cooker with a reflector angle of 45° and the solar radiation intensity for the region on July 8-11, 2011

be higher than the peak temperature of paraffin wax. Because, the temperature difference between the absorber surface and PCM is about 12 °C [20, 36]. Also, the lowest temperature required for cooking most kinds of foods is about 75 °C [19]. The cooking container temperatures are approximately 89 °C for stearic acid, 101 °C for magnesium nitrate hexahydrate [19]. Despite the differences in designs (the amount and location of PCM and the inner box size) [19, 35], the temperatures are close to each other. Moreover, the solar simulator reported in their study [19] is turned on and adjusted to produce the desired solar radiation intensity. So, the side- and sub- surface temperatures of the paraffin wax are sufficient for the given design conditions, which do not follow the sun's movement during the day. The PCM temperatures of the different cookers were reported as 109 °C for stearic acid [20], 130.6 °C or 142.3 °C for acetamide [21], and 129.8 °C or 137 °C for acetanilide [22]. In this study, the results from the aforementioned papers cannot be used for comparison due to differences in structures and/or climatic conditions. However, higher temperatures can be reached by changing the amount of paraffin wax and solar tracking system, as demonstrated [36]. While the maximum temperature of paraffin wax was 92.6 °C, the temperature was dropped to 56 °C by the next morning [36]. There is a possibility of cooking during cloudy days and in the evening hours and the absorber's surface temperature will increase when choosing the appropriate reflector angle and PCM. Consequently, paraffin wax can be used as the PCM in the inner box of the solar cooker.

The thermal efficiency of solar is determined using the following steps: (1) the solar radiation energy collected on the inner surface and from the four reflectors, and (2) the sensible, latent heat energy occurs in the solar cooker with and without load. In conclusion, the thermal efficiency of the new solar cooker filled with paraffin wax is obtained by the first law of thermodynamic from the relation:

$$Q_{12\text{total}} - W_{12} = \sum m_{2i}u_{2i} - m_{1i}u_{1i} \tag{1}$$

$$(Q_{12} - Q_{\text{loss}}) - W_{12} = m_{ck}C_{ck}(T_2 - T_1) + m_{\text{pcm}}C_{\text{pcm}}(T_2 - T_1) + m_{\text{pcm}}h_f \tag{2}$$

$$Q_{\text{radiation}} = \sum IA\Delta t \tag{3}$$

$$\eta = \frac{m_{ck}Cp_{ck}(T_2 - T_1) + m_{\text{pcm}}Cp_{\text{pcm}}(T_2 - T_1) + m_{\text{pcm}}h_f}{\sum IA\Delta t} \tag{4}$$

There is no net exchange of work (W_{12}) between system and the environment. The surface area (A) is the absorber surface area and the visible area of the reflector when viewed from the top. The sensible heat is stored in the aluminum sheets and paraffin wax. For the collected solar radiation energy, the solar cooker (with reflectors and without it) is exposed to solar radiation between the maximum and the minimum temperatures. Therefore, the efficiency of the solar cooker without the reflectors is in the range of 46.20% to 50.80%. For reflector angles of 30°, 60°, and 45°, the thermal efficiencies are approximately 68.70%, 50.10%, and 51.50%, assuming that the outer reflector surface area can be neglected. The minimum contribution of the reflector on the thermal efficiency of the solar cooker is found to be approximately 17.9%. But, the useful thermal efficiencies are approximately 30.30%, 39.70%, 31.10%, and 31.30% at the end of the day (06:00 p. m.). It is also assumed that the temperature of the paraffin wax approaches 40 °C. The maximum thermal efficiency is obtained to be 39.70% for a reflector angle of 30°. In literature, the efficiencies of the solar cookers having PCM were evaluated by testing water and food samples. The efficiencies of the different cookers were reported as 31% [6], 30.5% [8], 24% or 32.4% [19], 28.25% [37], and 27.5% [38]. In this study, the results from the aforementioned papers cannot be used for comparison due to difference in structures and climatic conditions. However, the amounts of heat energy (latent and sensible) stored in the PCM are considered as 416.35 kJ for stearic acid [19], 644.78 kJ for magnesium nitrate hexahydrate [19], 963.648 kJ for stearic acid [20], 913.6 kJ or 957.06 kJ for acetamide [21], 994.5 or 1727.2 kJ for acetanilide [22], 3777.2 kJ for paraffin wax [36], and 1741.4 kJ for paraffin wax (in present study). Accordingly, paraffin as a PCM can be regarded as a high efficiency material due to the amount of energy stored. Cooking trials are also conducted with the egg, pepper, and cake. These foods are cooked for 3, 4, and 6 hours in the new solar cooker with storage, respectively. It is clear from these parameter values that the new box type cooker has a good efficiency and good cooking times for the given design conditions. With the outer reflector angle, the solar cooker receives also reflected radiation from the inner reflectors. The storage rates of thermal energy can be greatly enhanced using nanoPCM, such as paraffin wax with nanoalumina (Al_2O_3) particles [39]. The performance comparison of paraffin wax and stearic acid [40, 41] can be also investigated in solar cookers.

Conclusions

In this paper, a new box type solar cooker with three-step inner reflectors has been designed, constructed, and tested. For the first time, the characteristics of paraffin wax as the PCM in a cooker are investigated using the new designed cooker. Experiments were performed and the influence of the different reflector angles was investigated for each day. From the experimental results of the designed solar cooker the conclusions are as follow:

- The efficiency of the solar cooker and the cooking times are found to depend strongly on the paraffin wax, the reflector angle, insulation, and the solar intensity. The metal shavings are to provide a uniform temperature distribution inside the paraffin wax.
- The available paraffin wax can be used as a storage medium integrated with a solar cooker. It is possible to cook the food in a solar cooker having the paraffin wax, due to the temperature difference in absorber surface and PCM [20, 36]. Moreover, the paraffin as a PCM can be regarded as a high efficiency material due to the amount of energy stored.
- It is found that when the optimum angle of the outer reflector is 30°, the designed solar cooker gives the best performance. The heating time is found to decrease about one hour. In this case, it is obvious that the total solar radiation on the cloudy days is lower than that of the clear days. With the reflector angle of 30°, the solar cooker receives also reflected radiation from the inner reflectors.
- Finally, there is a possibility that the high temperatures can be achieved by changing the amount of paraffin wax and solar tracking system [36]. The paraffin wax is capable to keep PCM temperatures (near 56 °C) by the next morning [36]. We expect that an improvement in the cooker performance is possible with the choice of a storage unit, a PCM, the amount of PCM mass and the amount of radiation received from the solar.

The use of thermal energy storage in solar cookers play a pivotal role in a sustainable energy management based on solar energy as well as for energy conservation. Solar cooking has the potential to reduce fossil fuel use and the release of CO_2 to the environment.

Acknowledgments

The authors are very grateful to Dr. Siddik Cindoruk for his help in the measurements of the local solar radiation for the present study.

Nomenclature

A – surface area, [m^2]
C_p – specific heat, [Jkg^{-1}K^{-1}]
h_f – heat of fusion, [Jkg^{-1}]
I – amount of solar radiation, [Wm^{-2}]
m_{ck} – solar cooker's mass, [kg]
m_{pcm} – phase change material's mass, [kg]
m_{1i}, m_{2i} – initial and final state mass of the components, [kg]
$Q_{12total}$ – total heat transfer of the solar cooker, [J]
Q_{12}, Q_{loss} – heat gain and loss of the solar cooker, [J]
PCM – phase change material, [–]
T_1, T_2 – initial and final temperature, [°C]
u_{1i}, u_{2i} – internal energy of initial and final states of the components, [Jkg^{-1}]
Δt – change in time, [h]

Greek symbols

η – thermal efficiency, [%]
θ – outer reflector angle, [°]

Subscripts and superscripts

ck – solar cooker, [–]
f – latent heat of fusion, [–]
I – radiation, [–]
pcm – phase change material, [–]

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Paper submitted: October 22, 2012
Paper revised: April 8, 2013
Paper accepted: January 13, 2014