Enhanced performance figures of solar cookers through latent heat storage and low-cost booster reflectors

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Abstract

Solar box cookers draw attention of many researchers across the globe as a promising renewable energy application for cooking purposes. Compared to other types available in literature, solar box cookers are more in the centre of interest owing to their simple and low-cost design, emerging thermodynamic performance figures, high durability and reliable cooking processes without any risk of burning food. On the other hand, cooking power and overall thermal performance of solar box cookers are still somewhat challenging to compete with the conventional cooking systems for the climatic conditions with low solar radiation potential like the Black Sea Region of Turkey. Within the scope of this research, a novel solar box cooker is devised, fabricated and tested to overcome the said shortcomings of traditional solar box cookers through natural and recycled materials. Double-glazed structure having 16-mm-thick air between two 6-mm-thick thermally resistive clear glasses is considered for aperture glazing with an area of 0.16 m^2. The oven area has a depth of 350 mm, and it is entirely painted matte black for maximum solar absorption. The oven body made of stainless steel sheets is encountered by a latent heat storage medium filled by natural beeswax product, waste of propolis. Propolis is a resinous mixture that is used for protection of beehives, from either climatic changes or diseases. Polyphenols rich in balsamic part of the structure is extracted by alcohol than used for many apitherapic purposes. The remaining pulp or waste is not considered. In this study, it is used as green chemistry agents. It is found that water temperature in the cooking pot is kept over 40°C till very late hours as a consequence of latent heat storage. First figure of merit is determined to be 0.08, and the thermal efficiency of the cooker varies from 7.47 to 4.54%.

Keywords: solar box cooker; energy storage; booster reflector; PCM; propolis; thermal performance

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1 INTRODUCTION

Cooking is an essential need that constitutes of a significant part of total world energy consumption [8]. In most areas of developing world like Africa, India and China, non-commercial fuels such as agricultural waste, cow dung, firewood and kerosene are usually used by people to meet the cooking demand [11]. About 36% of primary energy use in India is attributed to cooking, which needs to be noted [7]. It is emphasised by Pohekar et al. [19] that almost 90% of residents in India still make a fire in rural areas to be able to cook their foods. This can be explained with the abundancy of wood in the aforesaid areas. In addition, wood is unequivocally the cheapest energy source in rural areas to meet the cooking demand [9]. However, it needs to be underlined that people are exposed to walk for hours almost every day to collect the firewood that they need to make a fire for cooking [10]. Excessive use of

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firewood and other biomass-related energy resources causes some serious environmental problems such as deforestation and climate change. Burning of such fuels first of all pollutes air and negatively affects human health through eye disorders, lung diseases and burns [13]. Therefore, intensive efforts are made at global scale to develop renewable and sustainable energy solutions to meet the cooking demand of people in both rural and urban areas. Solar cookers are such devices that are energy-efficient, eco-friendly and low-cost as well as not requiring any skill to be operated [21]. In most parts of the world, solar cookers in general have a great potential to reduce total world energy consumption and greenhouse gas emissions owing to the solar radiation potential. Moreover, solar cookers are ideal systems for high nutritional value of food, high durability and almost stable efficiency range over their long lifetimes [16].

In a typical solar cooker, incoming solar radiation is converted into thermal power, which is then utilised to cook food [23]. Besides their known function of cooking, solar cookers can be considered for some important processes such as sterilisation and pasteurisation. The overall thermal performance of solar cookers greatly depends on the solar radiation potential of the region. Solar radiation falling on the transparent aperture glazing transmits into the oven area and is absorbed by a surface that is usually made of metallic materials and painted matte black to maximise solar absorption. Material, colour and surface properties are of vital importance for the effectiveness of solar absorption. Foods are put in the cooking pots that are usually made of copper and aluminium, and they are placed on the absorber surface. Through the heat transfer mechanisms of natural convection, conduction and partially thermal radiation, cooking process takes place in solar cookers usually from 1 to 6 h depending on food. Solar cookers have a wide range of types and applications in market, and they are improved year after year in terms of different performance merits. In other words, classification of solar cookers is a challenge in most cases. However, splitting them into three groups as solar panel cookers, solar box cookers and solar dish/parabolic cookers is approved by most of the researchers.

Solar box cookers, among the three types, can be asserted as the most improved solar cooking devices in terms of thermodynamic performance parameters. Solar box cookers usually have a box shape either cylindrical or prismatic. Aperture glazing that is placed on the top of solar cooker welcomes solar radiation, and transmitted radiative energy is absorbed by a metallic absorber that is painted matte black. Cooking pots are put on the absorber surface directly. Box edges are usually well insulated to minimise heat losses across the body material, and booster reflectors are considered to enhance the solar intensity thus the efficiency figures [6]. Solar box cookers usually have a lifetime more than 20 years, and thermal performance figures of solar box cookers are promising (good range for energy and exergy efficiency, adequate cooking power for most foods, notably shorter cooking times compared to solar panel cookers) and continuously improved. However, it needs to be noted that solar box cookers have some shortcomings as well especially for hard-to-cook foods. In regions with fair solar radiation potential, solar box cookers might not be sufficient enough for a successful cooking process, and to overcome this handicap, several solutions are considered. Some of them can be listed as improving thermal insulation feature of body, improving incoming radiative power via booster reflectors, enhancing solar absorption effectiveness of absorber surfaces and considering thermal energy storage medium within the body.

Enhancing thermal performance figures of solar box cookers via sensible and latent heat storage materials is in the centre of interest worldwide especially over the last two decades [17]. Especially phase change material (PCM) utilisation in solar box cookers to provide late evening cooking draws attention of many researchers, and there are various attempts in this respect conducted with different PCMs. The experimental study carried out by Choudhari and Shende investigates the potential improvements in a solar cooker using PCM [4]. The solar cooker system consists of a parabolic dish collector and a cooking pot with PCM. Acetanilide is utilised as PCM and its latent heat value is reported to be 222 kJ/kg. Based on the results, the energy efficiency of the cooker is in the range of 6–8%, and the cooker temperature during the evening period is found to be 78°C in case of using PCM. Another research based on a parabolic trough collector with PCM (acetanilide) is conducted to investigate the thermal performance of a solar cooker [20]. The system comprises of absorber tubes, solar cooker and thermosiphon in which thermal energy is transferred from tube to cooking unit. In this experimental setup, water and thermal oil are utilised as working fluids. The findings show that the foods can be cooked two times in a day by using latent heat storage medium, and the rate of cooking belonging to the evening time is higher than noon cooking. Compared to water, using thermal oil as a working fluid leads to an increase in the amount of energy stored by PCM in the range of 20–31%. The research conducted by Petela investigated the changes in energy and exergy efficiency of solar cookers having parabolic shapes [18]. Findings of the experimental research indicate that the maximum energy efficiency of the solar cooker is about 19%, and the exergy efficiency is nearly 1%. Pyramid solar box cookers are evaluated in another research in terms of several performance figures [14]. Depending on the results, the coefficient of heat loss, quality factor and the maximum exergy are found to be 4.09 W/m^{2}K, 0.15 and 7.124 W respectively.

The effective utilisation of PCMs in solar cookers require researchers to have at least fundamental knowledge about latent heat storage materials. PCMs can be split into two groups as organic and inorganic materials. The melting temperatures of organic PCMs are lower than 120°C, and it is accepted that this figure is insufficient to cook the foods properly. For greater temperatures over 200°C, nitrate salts are usually considered that are more suitable to be considered in solar cookers as a PCM. According to the numerical and experimental works conducted with PCMs with a melting point lower than 120°C, acetamide and stearic acid are found to be providing better thermal performance than the other options [3]. It is also reported that acetamide is more convenient for aluminium containers than other alternative PCMs like magnesium chloride hexahydrate [12]. Coccia et al. conduct an experimental study to observe performance of a

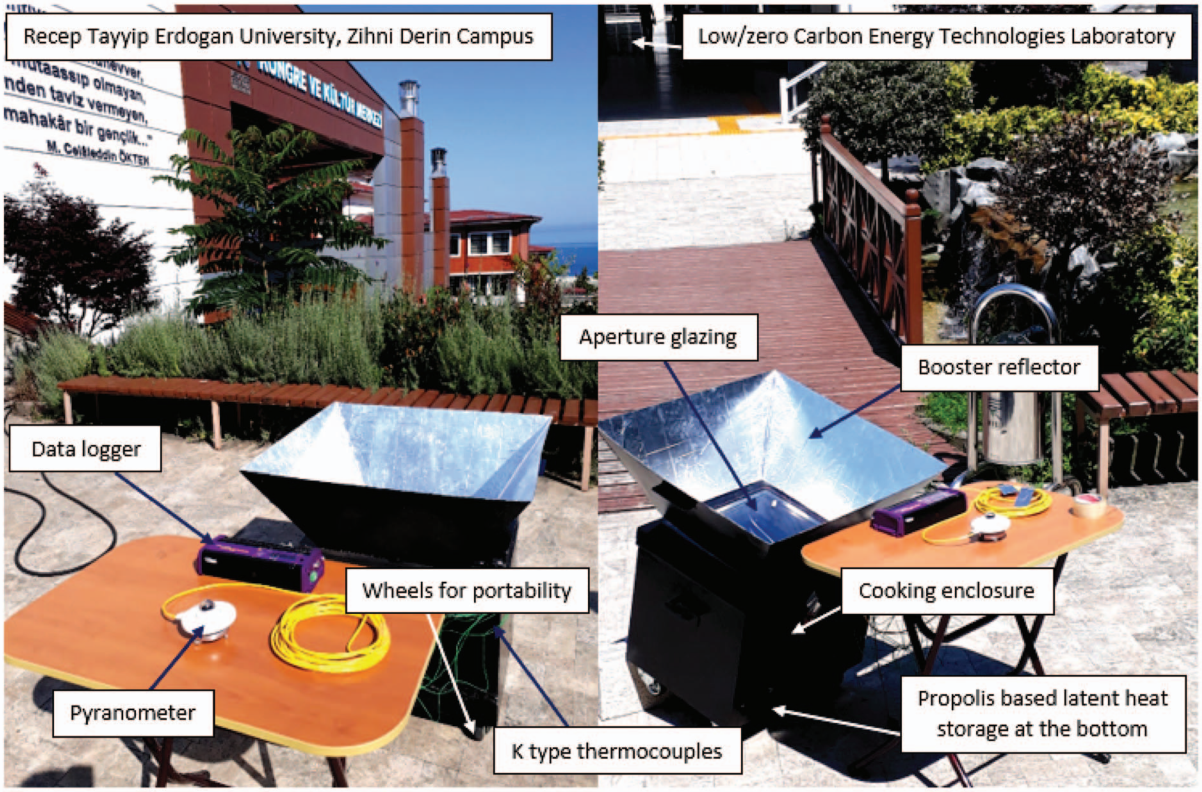

Figure 1. *Experimental setup of solar PCM cooker with the measurement systems.*

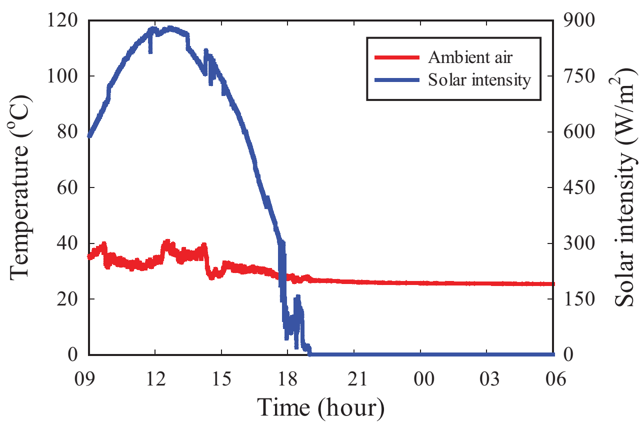

Figure 2. *Solar intensity and ambient temperature during the test period of solar PCM cooker.*

high-temperature solar box cooker with a solar-salt-based thermal storage unit [5]. They design a storage unit that has a double-walled vessel consisting of two stainless steel cylindrical pots assembled concentrically. Four kilograms of PCM (a mixture of nitrite and nitrate salts) are utilised in the cooking system. It is achieved from the results that PCM thermal storage remarkably enhances the load thermal stabilisation when solar radiation is not available. Saxena et al. conduct an experimental study comparing thermal performance of PCM integrated solar cooker and simple solar cooker [22]. They study some of different phase change materials, but among them, stearic acid (commercial grade) is found to be the best latent heat storage solution that ensures 15 min of lower cooking time in comparison with box type solar cooker without thermal storage. Sharma et al. investigate thermal performance of a solar cooker based on an evacuated tube solar collector with a PCM storage unit [24]. Erythritol is used as a latent heat storage material, and their system includes two separate parts for energy collection and cooking system coupled by a PCM storage unit. Owing to the PCM utilisation, it is observed that evening cooking takes place faster than noon cooking. Chaudhary et al. examine the thermal performance of a solar cooker based on parabolic dish collector with phase change thermal storage unit [2]. In their experimental setup, acetanilide is used as PCM and they compare three different solar cooker models: ordinary solar cooker, solar cooker with outer surface painted black and solar cooker with outer surface painted black along with glazing. The experimental results show that PCM in solar cooker with outer surface painted black can store 26.8% more heat compared to PCM in ordinary solar cooker. Buddhi et al. design a PCM storage unit for a solar cooker, and the system stores energy during sunshine hours [1]. They use acetanilide as a latent heat storage material, and the experiments are conducted with different loads and loading times during the winter season. According to the experimental results, it is possible to cook until 20:00 in the evening by using 4 kg of acetanilide as PCM.

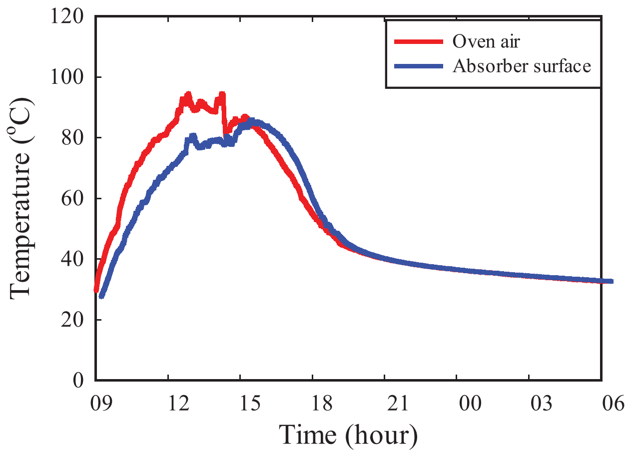

Figure 3. *Oven air and absorber surface temperature during the test period of solar PCM cooker.*

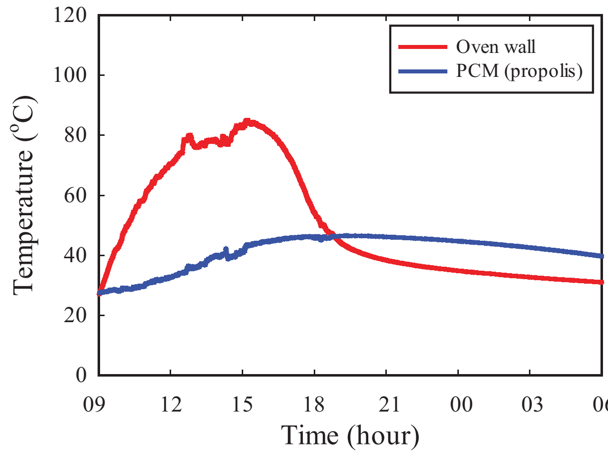

Figure 4. *Oven wall and propolis temperature during the test period of solar PCM cooker.*

It is clear through the previous literature that solar box cookers provide better thermal performance figures when they are integrated with latent heat storage materials. However, it is observed that conventional PCMs are usually considered in the previous works, and alternative natural PCMs are almost ignored. Therefore, in this research, a novel latent heat storage material (propolis) is utilised and its potential impacts on thermal performance parameters of solar box cookers are evaluated. Propolis is a resinous mixture usually utilised to protect beehives, from climatic changes and diseases. Polyphenols rich in balsamic part of the structure is extracted by alcohol than utilised for various apitherapic purposes. The remaining pulp or waste is not used. In this study, it is considered as green chemistry agents.

2 EXPERIMENTAL ANALYSIS

Thermal performance assessment of solar box cookers with propolis based latent heat storage and low-cost booster reflectors is done through a comprehensive analysis within the scope of this experimental research. A solar box cooker is devised, fabricated and tested in the research for the climatic conditions of Rize, Turkey. The tests are conducted for the typical environmental conditions of July month in the humid temperate climatic conditions. Specifically, one full-day test is carried out in front of Low/Zero Carbon Energy Technologies Laboratory at Zihni Derin Campus of Recep Tayyip Erdogan University as shown in Figure 1. The solar box cooker is equipped with a low-cost booster reflector to maximise incoming solar radiation. Aperture glazing is made of two sheets of clear glass with an air gap of 12 mm. Total entire thickness of aperture glazing is 20 mm, which is appropriate for such applications in terms of visible light transmittance and thermal resistance. The area of aperture glazing is given to be 0.16 m^2. In the system, 8 kg of propolis is utilised for latent heat storage beneath the absorber surface.

Solar intensity is measured by CMP3 pyranometer from Kipp & Zonen company. The aforesaid device is very sensitive and appropriate enough for such solar thermal applications. Thermal performance assessment is done through a time-dependent data triggering that is provided by DT85 Data Logger from DataTaker Company. For the temperature measurements, standard K type thermocouples are utilised. Thermal performance assessment is conducted through temperature measurements that can be listed as ambient air temperature, oven air and absorber surface temperature, oven wall and PCM temperature, internal and external body temperature, internal and external glazing temperature and water temperature. Internal and external surfaces are painted matte black for maximum solar absorption. Total uncertainty of the measurement system is calculated to be below 1%, which is acceptable.

3 RESULTS AND DISCUSSION

The experimental analysis of novel solar box cooker concept with propolis as latent heat storage material starts at 09:00 am in the morning and lasts until the early morning (06:00 am) next day. The propolis utilised inside the solar box cooker has a melting temperature of 47°C, and 8 kg of propolis is placed beneath the absorber surface for the heat storage purpose. The tests are conducted under a clear sky. Solar intensity and ambient air temperature during the test period are illustrated in Figure 2. At 09:00 am, solar intensity is measured to be 588.2 W/m^2, and its variation over the test period has a stable tendency except some negligible fluctuations around the sunset. Maximum solar intensity is determined to be 881.1 W/m^2 during the noontime. The average ambient air temperature during the experiments is observed to be 28.2°C. Oven air and absorber surface temperatures within the solar box cooker are shown in Figure 3. It is firstly understood from the results that oven air temperature rapidly rises compared to absorber surface temperature. This

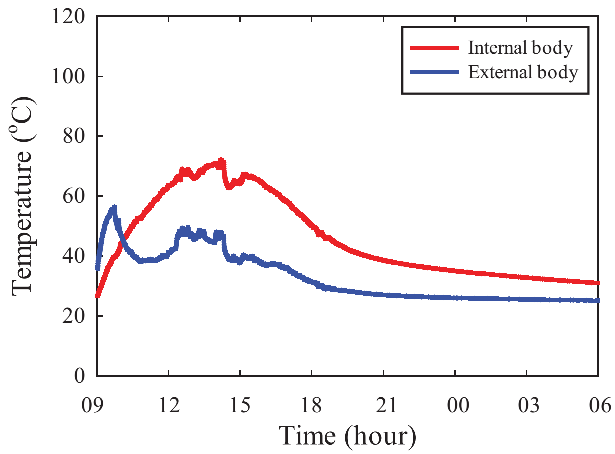

Figure 5. *Internal and external body temperature during the test period of solar PCM cooker.*

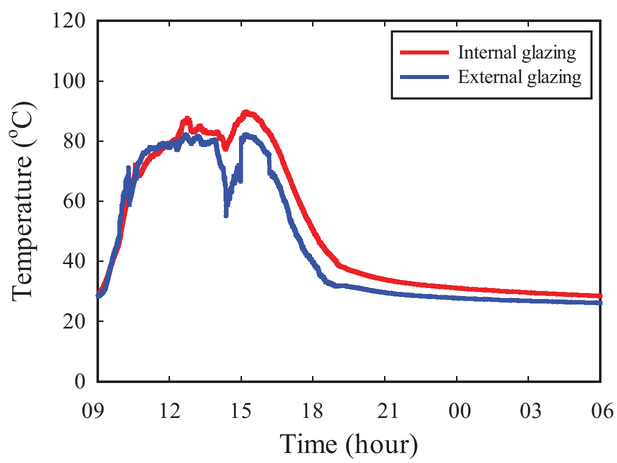

Figure 6. *Internal and external glazing temperature during the test period of solar PCM cooker.*

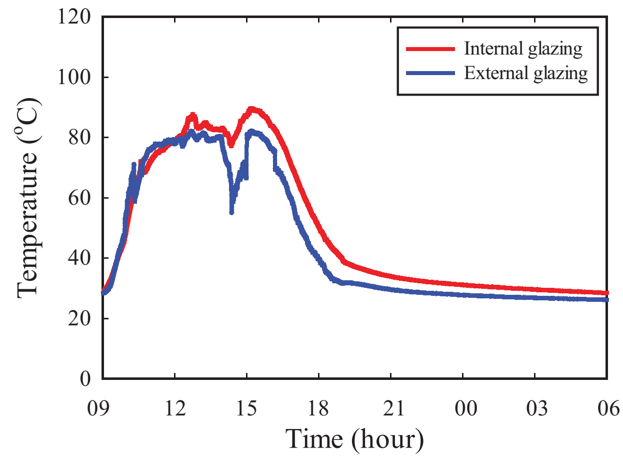

Figure 7. *Water temperature during the test period of solar PCM cooker.*

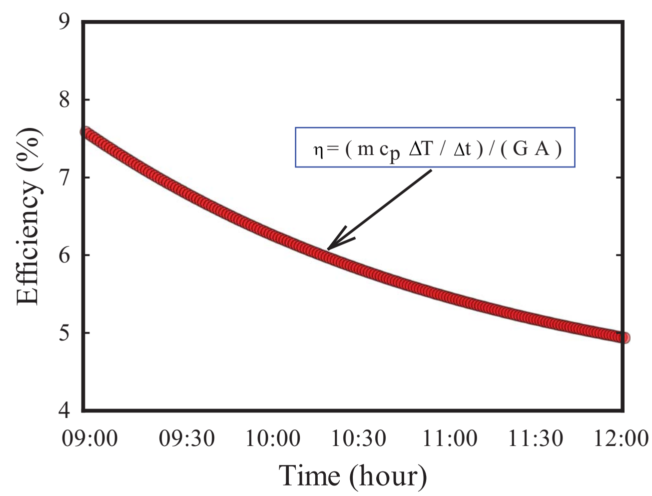

Figure 8. *Thermal efficiency of solar PCM cooker as a function of time.*

is because of the PCM medium beneath the absorber. Greenhouse effect plays a key role in fast increase of oven air temperature. Some part of the absorbed heat is utilised for phase change process within the propolis mass, and this slows down the temperature rise in metallic absorber. A similar tendency is observed between oven wall and oven air temperatures as expected. It is clear from Figure 4 that oven wall temperature is somewhat lower than oven air temperature. Maximum oven air and oven wall temperature are measured to be 94.5 and 85.2°C, respectively. It is also observed from the findings that PCM temperature is still over 40°C at the end of the test period. This finding justifies the thermal energy stored within propolis, which can be utilised to keep the foods warm throughout the night time.

Thermal insulation performance of a solar box cooker directly affects the overall performance figures notably energy and exergy efficiency. In this respect, internal and external body temperatures are plotted as shown in Figure 5 to have an understanding about the thermal resistance feature of the present design. At the beginning of the tests, external body temperature gets greater values than the temperature of internal body as it directly absorbs the incoming solar radiation. After a certain period of time, internal body temperature is found to be remarkably higher than external body temperature as expected. Temperature difference is observed to be maximum during the noontime and steadily reduces toward the midnight. Maximum temperature difference is determined to be 27.1°C, which is promising. A similar tendency is obtained for internal and external glazing temperatures. Internal glazing temperature is found to be always greater than external glazing temperature as depicted in Figure 6. Maximum temperature difference is observed to be 21.9°C, which is an acceptable thermal resistance figure. Water temperature is also measured as a function of time as shown in Figure 7. Water mass in the cooking pot is specified to be 0.5 kg. It is clear from the findings that the water temperature reaches 82.5°C within a couple of hours, which is in general an ideal temperature to cook vegetable foods. Water temperature is kept over 40°C till very late hours as a consequence of latent heat storage, which needs to be noted as a characteristic output of the research.

Within the scope of the research, first figure of merit (F_1) and the thermal efficiency of the solar box cooker are also evaluated. The first figure of merit in solar box cookers is defined as follows [15]:

$$F_1 = \frac{T_{as,\max} - \overline{T}_{amb}}{\overline{G}} \quad (1)$$

In Equation (1), $T_{as,\max}$ is the maximum absorber surface temperature, $\overline{T}_{amb}$ is the average ambient temperature and $\overline{G}$ is the average solar intensity. In this research, F_1 is calculated to be 0.08 m^2K/W. It usually takes a value around 0.10 m^2K/W in literature [15]. Thermal efficiency of solar box cookers (η) is given as follows:

$$\eta = \frac{mc_p \Delta T/\Delta t}{GA} \times 100 \quad (2)$$

In Equation (2), m is the water mass in the cooking pot, c_p is the specific heat capacity of water, ΔT is the temperature difference of water, Δt is the time interval, G is the incoming solar intensity and A is the area of aperture glazing. As shown in Figure 8, efficiency of solar box cooker varies from 7.47 to 4.54%. Efficiency values might be considered lower compared to the similar designs in literature without heat storage. Propolis based latent heat storage medium slightly reduces the efficiency but maintains the thermal energy content of oven air till late hours.

4 CONCLUSIONS

A novel solar box cooker integrated with booster reflector and propolis based latent heat storage is devised, fabricated and experimentally analysed for the temperate climatic conditions of Rize, Turkey. It is concluded from the results that propolis, which is a resinous mixture that is used for protection of bee-hives, from either climatic changes or diseases, is also a good PCM solution as a latent heat storage medium. PCM integrated solar box cooker is observed to be thermally resistive enough with 5-cm-thick extruded polystyrene (XPS) foam insulation. Eight kilograms of PCM beneath the absorber surface enables the foods to be kept warm throughout the night. The novel design of solar box cooker can provide late evening cooking with a promising energy and exergy efficiency. Some bullet findings from the research can be listed as follows:

- Aperture glazing is of vital importance in solar cooker performance. Aperture glazing with an air gap of 12 mm can provide a 21.9°C temperature difference, which is promising. However, for high-temperature applications, considering vacuum between clear glass sheets can be much more appropriate for required temperature difference between internal and external glazing surfaces.
- To maintain the thermal energy content of solar box cooker throughout the night, thermal resistance of body material should be as high as possible. In the present case, a temperature difference of 27.1°C between internal and external body is achieved via a 5-mm-thick XPS insulation. XPS has a thermal conductivity of about 0.04 W/mK in practice. However, it loses its thermal and dimensional features at high-temperature applications. Therefore, for the operational temperatures over 120°C, it is much more convenient to consider alternative insulation materials like rock wool or aerogel.
- Booster reflectors are ideal low-cost retrofits to enhance the incoming solar radiation to the aperture glazing of solar box cookers.
- Propolis is a natural product, which is considered as an alternative PCM in this research. Phase change temperature of propolis is determined to be 47°C, and 8 kg of propolis is placed beneath the absorber surface for the heat storage purpose. It is observed that water temperature in the cooking pot is maintained over 40°C till very late hours owing to the use of propolis as a heat storage medium.
- For the present design, maximum water temperature is reported to be 82.5°C, and this is achieved only in a couple of hours.

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