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Box type solar cookers with sensible thermal energy storage medium: A comparative experimental investigation and thermodynamic analysis

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ABSTRACT

Box type solar cookers with and without thermal energy storage are experimentally analysed within the scope of this research for characteristic continental climatic conditions of Bayburt, Turkey. For efficient and continuous cooking in such climates, thermal energy storage is required to be considered in solar cookers due to remarkable temperature differences between sunrise and sunset. Bayburt stone, a special natural stone with low density and notably high specific heat capacity, is utilised as a sensible thermal energy storage medium in a box type solar cooker, and thermal performance assessment of Bayburt stone cooker is compared with a conventional cooker without thermal energy storage through a comprehensive experimental research and thermodynamic analysis. For a typical late summer day, solar intensity, ambient temperature, absorber plate temperatures, internal air temperatures, internal and external glass temperatures, water temperatures, energy and exergy efficiencies are determined time-dependently for each solar cooker. The results clearly indicate that absorber plate temperature in conventional solar cooker has a notable decreasing tendency toward sunset, which totally affects the overall thermal performance of the system. On the contrary, Bayburt stone cooker enables an efficient, steady and continuous cooking till late evening owing to sensible thermal energy storage medium. In terms of thermodynamic performance figures, Bayburt stone cooker is observed to have considerably better energy and exergy efficiency. According to the results, energy efficiency of Bayburt stone cooker is determined to be in the range of 35.3–21.7% while it is found to be 27.6–16.9% for conventional solar cooker. On the other hand, exergy efficiency of Bayburt stone cooker is determined to be 21.2–14.1% whereas it is calculated to be 18.0–11.6% for conventional cooker. It can be concluded from the results that Bayburt stone as a thermal energy storage medium remarkably improves the thermal performance figures of box type solar cookers.

1. Introduction

As a consequence of unequivocal stimulation into renewable energy resources over the last two decades (Saxena and Agarwal, 2018) due to limited reserves of fossil fuels (Geddam et al., 2015) and their indisputable hazardous environmental impacts (Belaid and Youssef, 2017), the share of renewables in total final energy consumption and in global electricity production is reported to be 19.3 and 24.5% according to the latest analyses of International Energy Agency (Internal Energy Agency, 2017). Remarkable advances in renewable energy technologies notably in solar energy take place at global scale to mitigate total world energy demand (Nejat et al., 2015) thus to reduce carbon emissions (Cuce and Cuce, 2015a), and solar thermal applications are of significant relevance in this respect. Within a wide range of solar thermal applications available, solar cookers are highly in the centre of interest as they are utilised for multi-functional purposes such as cooking, drying, pasteurisation and sterilisation (Cuce and Cuce, 2015b). Solar cookers are also of vital importance since cooking is reported to be one of the most energy consuming sectors in developing countries (Soria-Verdugo, 2015). Moreover, solar cookers are considered as a decisive solution in developing counties for preventing some serious ecological matters such as deforestation (Saxena et al., 2013) since wood is still widely utilised as primary energy source in urban areas. Solar cookers are proposed to be capable of minimising the demand to fossil fuels for cooking, thus they are considered promising in reducing carbon emissions in most of the developing regions (Toonen, 2009).

Cooking constitutes a significant amount of total energy consumption in rural areas of Africa. People in the said regions usually meet the energy demand for cooking from non-commercial fuels such as agricultural waste, firewood, kerosene and cow dung (Wentzel and Pouris, 2007). A similar scenario takes place in India. About 36% of total primary energy consumption in India belongs to cooking. It is reported by Pohekar et al. (2005) that 90% of Indian households in rural areas still utilise biomass-based energy resources. Dependency on non-

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commercial fuels for cooking demand forces people to collect firewood from forested lands by walking several kilometres every day. On the other hand, firewood is costly for people in urban areas especially for poor families. Besides the financial limitations and hazardous environmental impacts, there are also health-related problems originated from the use of firewood such as eye disorders, burns and lung diseases (Geddam et al., 2015). World Health Organisation (WHO) underlines that 1.6 million deaths per year are reported due to indoor air pollution (World Health Organisation, 2006). In this respect, there is a rising attention and strong stimulation into renewable energy based cooking systems, and solar cookers are of significant relevance since the developing countries are usually blessed with abundant solar energy. Mean daily solar radiation for the said regions is addressed to be 5–7 kWh/m^2, and annual sunny days are reported to be more than 275 (Nahar, 2003), which proves the feasibility of using solar cookers as an alternative to conventional biomass fuels. However, it needs to be reported for the rest 90 days that solar cookers are required to be utilised as a hybrid system for a continuous and sustainable usage. In this respect, other energy resources such as wind, biomass and geothermal can be considered depending on their availability. Besides the unequivocal potential of solar cookers in reducing primary energy consumption levels and carbon emissions, they provide additional advantages. For instance, high nutritional value of food is achieved via solar cooking. Moreover, solar cookers can operate with a stable efficiency over a long lifespan with high durability (Muthusivagami et al., 2010).

Solar cookers are useful devices to cook food via incoming solar radiation. Besides the cooking function, solar cookers are also utilised for some important processes such as food drying, sterilisation and pasteurisation. In most cases, it is difficult to make an appropriate classification for solar cookers due to their numerous styles in literature. However, it is usually acceptable to split them into three main categories as solar panel cookers, solar parabolic cookers and solar box cookers as shown in Fig. 1. Solar panel cookers are the most common designs owing to the features of low cost, easy-to-construct and high portability. In a typical solar panel cooker, incoming solar radiation is reflected on a cooking vessel enclosed by a clear plastic bag. The design is ideal for people travelling or living alone. However, solar panel cookers usually provide a limited cooking power, which is not appropriate for hard-to-cook foods. In addition, the performance of solar panel cookers is highly dependent on the reflected part of the incoming solar radiation, hence they are not thermally efficient in most cases under cloudy sky conditions (Kimambo, 2007). Parabolic solar cookers differ from the other two types in terms of thermal performance. Owing to the concentrated solar power, remarkably higher temperatures can be reached by parabolic solar cookers. A typical parabolic cooker consists of a parabolic reflector integrated with a cooking vessel on the focal point (Ozturk, 2004). These cookers do not require a special cooking vessel due to the concentrated energy, however there is a risk of burning the food in parabolic solar cookers if they are left unattended. Hence, cooking period needs to controlled entirely by a person, which is a drawback for parabolic solar cookers. Solar box cookers can be considered as the most developed solar cooker type over the last four decades in terms of design and performance parameters. The design basically consists of a well-insulated box in which the cooking takes place, a transparent glazing for thermal insulation and transmission of sunlight into cooking area, and reflective surfaces to maximise incoming solar radiation for better thermal performance (Saxena, 2011). In most cases, solar box cookers provide satisfactory results in terms of thermodynamic performance figures (energy and exergy efficiency), cooking power and cooking time. Owing to their high durability and reliability, they serve over a lifetime of more than 20 years with a stable thermal efficiency. However, their overall performance is highly dependent on the behaviour of solar intensity during the cooking period. Under notable fluctuations in solar intensity values, the overall quality of cooking process gets worse since the cooking power notably depends on absorber plate temperature. Therefore, solar box cookers are usually required to be integrated with thermal energy storage medium for a continuous and efficient cooking.

Thermal energy storage media in solar box cookers enhance the overall thermal performance figures by enabling cooking on a cloudy day or during the night with an almost stable efficiency (Mussard et al., 2013). Energy storage technologies utilised in solar box cookers can be basically split into two main categories as latent and sensible thermal energy storage applications. Especially latent thermal energy storage is widely considered in solar box cookers since the technology is well-documented in literature, and provides reliable and satisfactory results in terms of overall thermal performance (Yadav et al., 2017). Phase change materials (PCMs) are the most commonly used thermal energy storage media in solar box cookers since there are countless types of PCMs available in market with reasonable costs. According to the level of energy storage required, an appropriate PCM is selected by given attention to the phase change temperature, latent heat, thermal conductivity and cost. Numerous works are carried out by researchers on PCM integrated solar box cookers (Saini et al., 2016). Buddhi and Sahoo (Buddhi and Sahoo, 1997) experimentally analyse a solar box cooker with latent heat storage for Indian climatic conditions, and observe that late evening cooking is possible. A similar output is achieved by Sharma et al. (2000) in which the solar cooker is integrated with acetanilide as thermal energy storage medium. They report that the phase change temperature of PCM needs to be in the range of 105–110 °C for the late evening cooking. Mettawee and Assassa (Mettawee and Assassa, 2006) utilise paraffin in their solar cooker, and experimentally analyse the system for different conditions. They show that the overall heat transfer coefficient is highly dependent on the molten layer thickness. An indirect solar cooker supported by a flat plate solar collector with magnesium nitrate hexahydrate as thermal energy storage medium is developed by Hussein et al. (2008). The results indicate that wickless heat pipes and PCM are capable of cooking food at noon and in the evening,

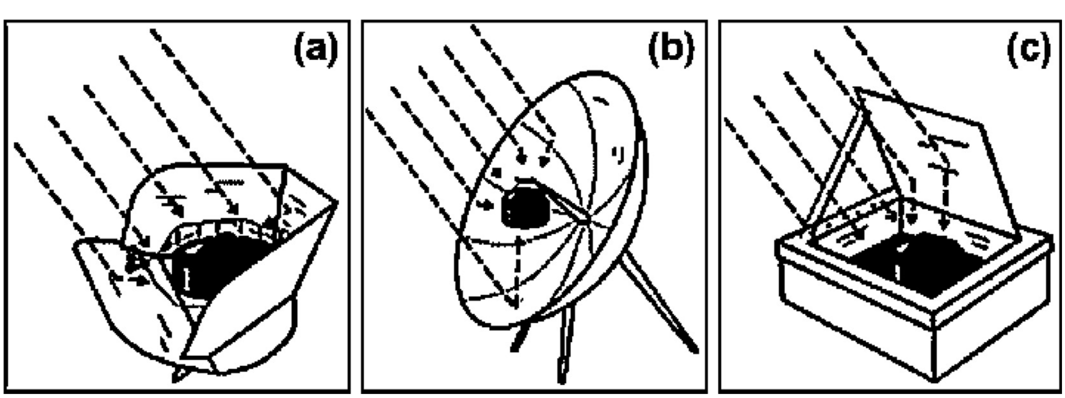

Fig. 1. Classification of solar cookers: (a) solar panel cooker, (b) solar parabolic cooker and (c) solar box cooker (Geddam et al., 2015).