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Development and performance studies of a novel portable solar cooker using a curved Fresnel lens concentrator

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A B S T R A C T

Solar cookers use clean and accessible solar energy to heat food. They provide a new choice for outdoor cooking for users. However, currently available solar cookers now have some weaknesses such as being too big to carry, low heating temperature and overlong cooking time. To overcome these problems, this paper designs a novel portable solar cooker using a curved Fresnel lens as the concentrator. This novel solar cooker can focus sunlight onto an evacuated tube collector to heat the food here. It has a high concentration ratio and allows tracking the sun in both zenith and azimuth angles manually, therefore it is possible to get higher cooking temperature and shorten the cooking time. In this paper, the structure and working principle of the device are introduced. The optical performance of the system is simulated by a software and the heat transfer model of the system is established and presented. Experimental studies have been carried out, and the variation of maximum temperature of the system during the day under no-load condition has been obtained. Moreover, to test the system performance, the theoretical maximum temperatures of the system with no-load condition under different irradiances have been calculated. Results indicate that when direct irradiance is $I = 712\ W/m^2$ the obtained highest average temperature of the system without load can reach at about 361 °C. Besides, the performance of the solar cooker has been tested on four kinds of 0.5 kg representative foods, namely, sweet potato, pork (all lean), yam and radish. Results show that cooking time of pork is the shortest (only 34 min), and radish is the longest (64 min). All cooked food reaches the edible standard.

1. Introduction

The energy consumption for cooking constitutes almost 40% of the total energy consumption in some developing countries, such as India where the cooking energy is about 1.7–2.7 MJ/person/day (Cuce and Cuce, 2013; Indora and Kandpal, 2018; Pohekar et al., 2005). However, with the decline in oil production and the emergence of various environmental problems (air pollution, global warming, etc.) caused by burning conventional fuels, people have gradually turned their eyes into the renewable energy (Herez et al., 2018; Panwar et al., 2011). Therefore, using solar energy to cook food just provides a new and significant choice. Using solar cooker has many advantages, such as decreasing greenhouse gas emissions, saving wood, reducing cooking costs and having long service life (Hager and Morawicki, 2013; Muthusivagami et al., 2010). Thus solar energy, a promising option, has the capability to become the main energy for cooking(Yettou et al., 2014). In fact, it is claimed by the solar cooking international organization that solar cooking has been used in 107 countries (Saxena et al., 2011; Yettou et al., 2014).

Although there are many ways of classifying the solar cookers, they are mainly divided into three categories, namely, solar box cooker, solar parabolic cooker and solar panel cooker. Their general structures are shown in Fig. 1. Solar box cooker is composed of an insulated box with a transparent glass cover and a top reflector on the one side. The inner part of the boxer cooker is painted in black color to increase the heat absorption. When the box cooker works, the sunlight is reflected by the reflector to heat food placed in the cooking vessel (Mahavar et al., 2013; Saxena et al., 2011). As it shows, the structure of the box cooker is not complicated. In addition, the shape of the box cooker looks like a box which makes it easy to be carried out for cooking. However, for this kind of solar cooker, its cooking temperature is not high (around 100 °C) which can only satisfy the requirement of cooking food by boiling. But it hardly cooks food by frying or baking which requires high temperature over 200 °C (Lof, 1963; Yettou et al., 2014). The typical parabolic solar cooker consists of a parabolic reflector, cooking pot placed on the focus point of the reflector and a stand to support the system (Cuce and Cuce, 2013; Kumaresan et al., 2015); besides, some parabolic solar cookers have a tracking system. The

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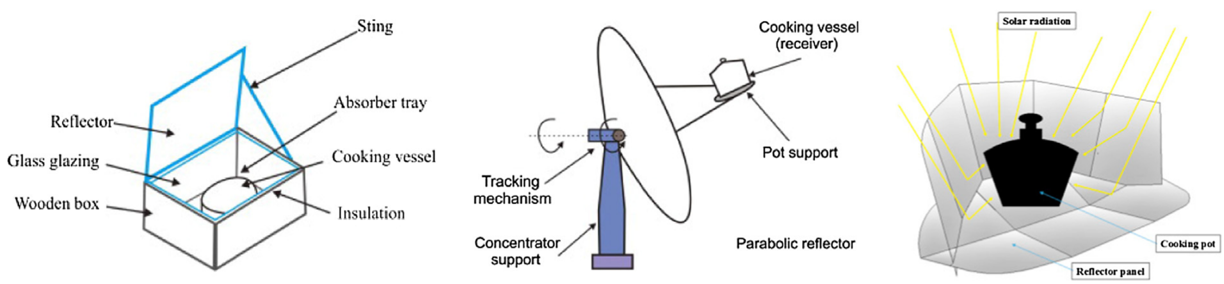
Nomenclature

I	solar direct irradiance (W/m^2)	T_{F1}	final temperature of the food (K)
R	radius of the curved Fresnel lens (m)	T_p	highest temperature of the working medium without load (K)
d_{max}	maximum thickness of the curved Fresnel lens (m)	T_{th}	theoretical highest temperature of the working medium without load (K)
d_{min}	minimum thickness of the curved Fresnel lens (m)	T_a	upper surface of the inner tube (K)
L	length of the curved Fresnel lens (m)	T_b	lower surface of the inner tube (K)
D	width of the curved Fresnel lens (m)	T_u	top point temperature of the food (K)
f	focal distance of the curved Fresnel lens (m)	T_m	central point temperature of the food (K)
d	focal width of the curved Fresnel lens (m)	T_d	under temperature of the food (K)
c	cooker geometrical concentration ratio	τ_L	transmissivity of the curved Fresnel lens
L_c	length of the evacuated tube collector (m)	α_C	absorptivity of the selective coating
r_1	radius of the inner surface of inner tube (m)	ε_1	emissivity of the selective coating
r_2	radius of the outer surface of outer tube (m)	η_r	light receiving rate (%)
r_3	radius of the outer surface of inner tube (m)	λ_1	conductivity of the glass tube (W/(m·K))
r_4	radius of the inner surface of outer tube (m)	ε_2	emissivity of the outer tube
T_1	temperature of the selective coating (K)	ε_3	emissivity of the cover
T_2	inner surface temperature of outer tube (K)	μ	loss heat factor
T_F	temperature of the working medium in the evacuated tube collector (K)	δ	Stefan–Boltzmann constant
c_F	specific heat capacity of the working medium (J/(kg·K))	λ_2	conductivity of the cover (J/(kg·K))
T_4	outer surface temperature of the cover (K)	h_1	convective heat transfer coefficient between the cover and the environment (W/(m^2·K))
d_g	thickness of the cover (m)	h_2	convective heat transfer coefficient between the outer tube and the environment (W/(m^2·K))
T_0	temperature of the environment (K)	η	energy utilization rate of the whole system (%)
T_3	outer surface temperature of outer tube (K)		
T_{F0}	initial temperature of the food (K)		



(a) box cooker (Yettou et al., 2014) (b) parabolic cooker (Yettou et al., 2014) (c) panel cooker (Herez et al., 2018)

Fig. 1. Three kinds of typical solar cookers.

parabolic solar cooker usually can provide high cooking temperature for frying or baking and shorten cooking time (Stambouli and Koinuma, 2012). However, this kind of cooker also has some disadvantages. Firstly, in order to achieve high temperature, a large aperture paraboloid has to be chosen which makes the system too big and the cooking container be placed at an impractical height above ground. Secondly, the focused light is harmful to eyes and skin when users are not careful (Edmonds, 2018; Valmiki et al., 2011). Finally, the panel cooker focuses the sunlight to heat food by many reflective panels (Geddam et al., 2015; Kimambo, 2007). Because of their ease of construction and low cost material, the solar panel cooker has become the most common type (Kundapur, 1998). However, the panel cooker has poorer performance especially on days with marginal solar radiation or intermittent cloudy conditions; in addition, the panel cooker can only bake bread but not fry food (Geddam et al., 2015; Herez et al., 2018; Kimambo, 2007)

Walking out of the house to get close to nature and enjoy beautiful scenery is becoming popular nowadays. Solar cookers provide a fire-free cooking work in the wild. However, current solar cookers for outdoors still have some shortcomings as follows: (1) low operation temperature; (2) not easy to carry; (3) not easy to assemble. In order to improve performance of solar cooker for more convenient cooking outdoors, many research efforts have been contributed as follows:

For solar box cooker and panel cooker, researchers have tried to improve the cooking temperature and shorten the cooking time. Gianluca Coccia et al. designed a high concentration ratio solar box cooker with multiple reflectors. The cooker composed by two rows of booster mirrors has a cooking chamber with a glass cover on the top and allows an azimuthal and zenithal manual orientation. After a series of tests without load, when solar irradiance I was around 700 W/m^2, the maximum absorber temperature can reach around 300 °C (Coccia et al., 2017). Ian Edmonds designed a low cost solar panel cooker comprised of eight flat reflective panels. It can manually track the sun at the azimuthal and zenithal direction. After a series of tests without load, when solar irradiance I = 738 W/m^2, the maximum absorber temperature can reach around 245 °C (Edmonds, 2018). However, for two kinds of devices, they have quite larger volumes, and It is not easy to bring them together for camping.

In order to make parabolic solar cookers more portable, researchers make efforts as follows: Alberto Regattieria et al. used the cardboard to fold a similar dish shape, and then bond an aluminum foil which forms a parabolic solar cooker to heat the food. Their experiment showed that