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A review of vacuum tube based solar cookers with the experimental determination of energy and exergy efficiencies of a single vacuum tube based prototype

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ABSTRACT

Solar cookers may be generally classified into direct and indirect types. The direct types include the box type and parabolic type, while the indirect types include the vacuum tube based cookers. This paper reviews the gradual progress made in the second type. The energy and exergy analysis of a single vacuum tube based prototype has been carried out experimentally. Performance parameters indicate a high peak exergy power of 55.6 W, while the temperature difference gap at half power is 38.75 K and the quality factor is 0.042. The energy efficiency of the cooker is 20–30%, while the exergy efficiency is 4–6%. These results make this compact single family solar cooker comparable in performance to large community based Scheffer type solar cookers. Results have been compared to a number of other solar cooker types.

Contents

1. Introduction

Though there is a history for solar cooking since 1650, the first patent of a solar cooker was acquired by W. Adams in 1876 in India, who developed an octagonal oven with eight mirrors which cooked rations for seven soldiers in 2 h [1]. Cooking is one of the primary energy applications for people all over the world. For the strained economies of the developing countries, its share of energy consumption is even more [2]. Further, due to the growing realization of the environmental hazards of the use of fossil fuels and the impact of forest cutting on the ecological balance of the Earth, there is an ever greater necessity to develop more user and environment friendly cooking technologies [3]. The modern solar cookers were mainly developed after 1950s [4].

A vast majority of the world population lives in regions with abundant solar resource. It is well known that the total global energy demand is less than 0.01% of the solar radiation energy intercepted by Earth. It is therefore quite natural to develop feasible technologies for the harnessing of solar energy to its fullest extent. In addition to the addressing of the above mentioned issues, solar cooking offers other advantages like no recurring costs, energy independence and high nutritional value

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of food. Still, the public adaptation of solar cookers is substantially lower than their potential. The main reasons are lack of trust by the public, intermittent nature of sunshine and inconvenience in the usage of many types of solar cookers. The solar cooking technology is yet not fully mature as far as the user convenience is concerned, and requires modifications in their life styles and energy usage habits. For this reason, not only a lot of further work is required to make these technologies more user friendly, but also promotional schemes and public demonstrations are required for the successful commercialization of solar cookers as a substitute for conventional cooking devices [3].

Fundamentally, there are three broad classes of solar cookers—the box type, parabolic type and the vacuum tube based type. The box type is the simplest, cheapest and slowest type as it utilizes the green house effect to trap the solar radiation energy inside an airtight box. They typically require two dimensional solar tracking every 20–30 min. The maximum achievable temperatures fluctuate around 120–130 °C, and therefore they are suitable only for water based cooking [5,6]. The parabolic types acquire the highest operating temperatures and are fastest in cooking, but require two dimensional solar tracking every 4–5 min. Reflection of high intensity solar radiation from the parabola may cause discomfort to the users. Their larger sizes are prone to wind caused damages. The vacuum tube based solar cookers either require one dimensional solar tracking or no tracking at all. Their operating temperatures and efficiencies are high, and they are relatively more user friendly. In this paper, a review has been carried out on the development of these types of solar cookers. Further, experimental determination of the energy and exergy efficiency of a recently proposed single vacuum tube based prototype has been carried out, and results are compared with the other major types.

2. Vacuum tube based solar cookers—An overview

While all the above mentioned types of solar cookers may be effectively used for the cooking of food when there is ample sun, vacuum tube based cookers have the special advantage that either they do not require solar tracking or they require only one-dimensional tracking and they attain higher cooking temperatures more quickly.

The first vacuum tube based solar cooker was reported by Balzar et al. [7] in 1996. Their system consisted of six double walled evacuated tubes mounted in parallel over successively curved aluminum reflectors. A long integrated copper heat pipe was inserted inside each vacuum tube. All the heat pipes were eventually connected to an aluminum plate. The plate that acted as heat sink in this case, was inserted inside a well insulated box that acted as the cooking chamber. A lid was provided at the top of this chamber to place any cooking pan directly over the oven plate. This cooker attained a maximum cooking temperature of 203 °C in about 3.5 h, while the maximum temperature attained with solar tracking and addition of booster mirrors was 252 °C in slightly less than 3 h. The effects of the reflector designs and material properties on the efficiency of this cooker were investigated in 1997 [8].

Stumpf, Balzar and others performed further experiments with the above vacuum tube based solar cooker in 2001 [9]. In one experiment, a flat plate collector with double glazed glass sheet (2.18 m^2 absorber area) was used with ten heat pipes, instead of the six vacuum tube panel. In the other experiment, the size of the vacuum tube panel was doubled to house twelve vacuum tubes instead of six. A mathematical model was developed and a comparative study was carried out for all three systems, and it was concluded that the vacuum tube system was most suitable for cooking with 2–3 h of preheating before adding the food stuff to the cooker. The maximum oil temperature of 231 °C was reached with the double-stage and 207 °C with the single stage vacuum tube system. The flat plate system showed a very high thermal conductivity, but reached a maximum temperature of 164 °C in 5 h.

Another vacuum tube based community solar pressure cooker was experimented and performance evaluated by Kumar et al. in 2001 [10]. Their collector contained twelve vacuum tubes mounted over an aluminum cusp rippled reflector, and were directly connected to a heat exchanger. Water was circulated through a pipe connecting a pressure cooker to the heat exchanger. The vacuum tubes were filled with a high boiling point fluid, which got vaporized at high temperatures, rose to the heat exchanger, and transferred its heat to the circulating water. This arrangement was reported to boil 14 kg of water in 140 min, from an initial temperature of 32 °C. The optimum cooking temperature was established at 120 °C according to the pressure cooker specifications. Very good correlation was found between the theoretically predicted and experimentally measured temperatures.

Essen tested a solar cooker in 2004 with similar configurations as that of Balzar et al. but with three different refrigerants and water, filled inside the heat pipes [11]. The refrigerants they used were Freon 22, Freon 122a and Freon 407C. In order to increase the heat transfer area, the coiled heat pipes were embedded in Mobiltherm 605—a thermal fluid, in the condenser section. The thermal fluid also provided a means for heat storage to keeping the food warm in the evenings. The collector panel was covered with a glass sheet and was further evacuated. The maximum temperature achieved in the cooking chamber was 175 °C in 3.5 h with seven liters of edible oil. The performance of refrigerant Freon 407C was reported to be the best amongst the three, due to its lower boiling point of −43.56 °C and higher latent heat of vaporization of 243.8 kJ/kg.

Sharma et al. carried out experiments with the same type of evacuated tube solar collector as that of Balzar et al. [7], with a phase change material (PCM). They used commercial grade erythritol ($C_4H_{10}O_4$) as PCM, having a melting point of 118 °C and latent heat of fusion of 339 kJ/kg [12]. Their experiments showed the possibility of using PCM in conjunction with the evacuated tube solar collectors for late hour cooking after the sun set.

3. A vacuum tube based solar cooker using linear Freznel collector

Another single vacuum tube based solar cooker was recently reported [13]. It utilized a 122 cm × 183 cm linear Freznel collector bed with 17 plain mirror strips. The mirror strips were mounted on square steel pipes, which were fitted inside a wooden frame through bearings, and were rotatable on individual axes, as shown in Fig. 1. Circular Teflon discs were mounted on one end of each of

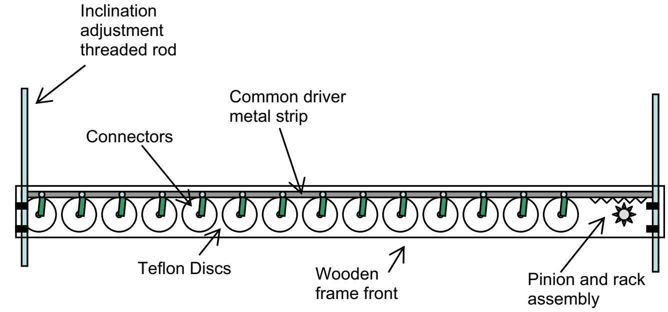

Fig. 1. Schematic cross sectional view of the synchronized tracking system for the primary reflector mirror strips. All the mirrors have to rotate by 0.5° as the sun moves by 1° through the sky. The tracking is performed by a motor connected to a tracking circuit.