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Impact of load variation on the energy and exergy efficiencies of a single vacuum tube based solar cooker

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ABSTRACT

A single vacuum tube based solar cooker has high energy and exergy efficiency, and is capable of achieving cooking temperatures as high as 250 °C. The reason for high energy and exergy efficiencies of this solar cooker is the high achievable concentration ratios of 15–20, which are not possible with multiple vacuum tube based solar cookers. In this paper, a comparative study has been carried out to experimentally determine the impact of varying the load on the various performance measuring parameters. Five experiments have been carried out with 3, 4, 5, 6 and 7 kg of respective water loads. Performance measuring parameters including the energy and exergy efficiencies, heat loss coefficient, quality factor, adjusted quality factor, peak exergy power, and peak exergy power to temperature difference gap product have been determined for each case. It is concluded that the performance measuring parameters have correlation with the load on the solar cooker. Performance parameters indicate average peak exergy power of 51.07 W, while the product of temperature difference gap at half power to that of peak exergy power is about 3000 W K. The highest value of the quality factor was found to be 0.0506 with 6 kg of water load.

1. Introduction

Cooking is one of the primary energy applications for people all over the world and a vast majority of the world population lives in regions with abundant solar resource. Under the current scenario of increasing global population and depleting energy reserves, it is quite natural to develop feasible technologies for the harnessing of solar energy to its fullest extent for cooking as well as other applications [1–3]. Solar cooking offers advantages like no recurring costs, energy independence and high nutritional value of food [4].

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.

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, acting as heat sink, inside a chamber. The cooking pan was placed directly over the oven plate. This cooker attained a maximum cooking temperature of 203 °C in about 3.5 h [8,9]. With further experiments, the size of the vacuum tube panel was doubled to house twelve vacuum tubes instead of six. The maximum oil temperature of 231 °C was reached with the double-stage vacuum tube system.

Another vacuum tube based community solar pressure cooker was experimented and performance evaluated by Kumar et al., in 2001 [10]. The optimum cooking temperature was established at 120 °C according to the pressure cooker specifications. M. Esen tested a solar cooker in 2004 with similar configurations as that of

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Balzar et al., but with three different refrigerants and water, filled inside the heat pipes [11]. The maximum temperature achieved in the cooking chamber was 175 °C in 3.5 h with 7 L of edible oil. Sharma et al. carried out experiments with the same type of evacuated tube solar collector as that of Balzar et al., in 2005, with a phase change material (PCM) [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.

A single vacuum tube based solar cooker was reported recently [13]. It utilized a 1.77 m^2 linear Freznel collector bed containing laser aligned plain mirror strips, capable of focusing the solar radiation onto a fixed absorber vacuum tube mounted over the collector at a height. A secondary curved reflector mounted over the absorber tube reflected back any leaked radiation to it, as illustrated in Fig. 1.

The cooking chamber was connected to the top end of the vacuum tube, and was well insulated from outside to minimize thermal losses, as shown in schematic Fig. 2. Along with the vacuum tube, the cooking chamber was half filled with a high boiling point thermal fluid, such as thermal or vegetable oil. The thermal fluid circulated between the vacuum tube and the cooking chamber through natural thermal siphoning. A frame supported the cooking chamber above the vacuum tube. A cooking pot containing the stuff to be cooked, was placed inside the cooking chamber, as shown in Fig. 3. As per desire, this configuration permitted frequent interaction with the food, during the cooking process, which is not permissible in the conventional solar cookers.

The cooker utilized a one dimensional solar tracker. The overall thermal power transfer efficiency was measured to be between 20 and 30%, while temperatures of up to 250 °C were achieved. Experimental results of this cooker indicated more than five times greater heat absorption capacity compared to a 60 cm × 60 cm conventional box type solar cooker. The average power consumption of the tracking circuit and motor was 4 W, as it was operated for 10 s after 50 s intervals, through a timer. The energy and exergy efficiencies of the cooker were also determined with 5 kg of water load [14]. In this paper, the effect of variation of load from 3 to 7 kg of water on the energy and exergy efficiencies of the cooker has been experimentally investigated.

2. Energy and exergy analysis

An exergy based unified test protocol was presented by Kumar et al. to assess the thermal performance of solar cookers of different geometries [15]. Exergy provides a measure of the potential of a given device to extract heat from its surroundings, as the device moves closer to the equilibrium with its surroundings. It becomes zero as the system reaches a thermal equilibrium with its environment [16,17]. The exergy input to the solar cooker – same as the exergy of solar radiation – can be calculated using available solar radiation flux ($I°A\Delta t$) as [15]:

$$E_{Xi} = I°A\Delta t\cdot[1 + (T_a/T_s)^4\cdot(1/3) - (4/3)\cdot(T_a/T_s)] \quad (1)$$

where T_s is the surface temperature of the sun, T_a is the ambient temperature, $I°$ is the instantaneous solar radiation intensity perpendicular to the collector, Δt is the time interval and A is the aperture area of the solar cooker/collector, whereas the output energy of the system is equal to the energy gained by the material inside the solar cooker as:

$$E_{out} = m\cdot c\cdot\Delta T \quad (2)$$

where c is the specific heat capacity of the material inside the solar cooker, m is its mass, and ΔT is the difference between the initial and final temperatures acquired during the time interval Δt.

For the exergy analysis however, the efficiency of a system also depends upon the ambient temperature. The exergy output of the system is expressible through [16]:

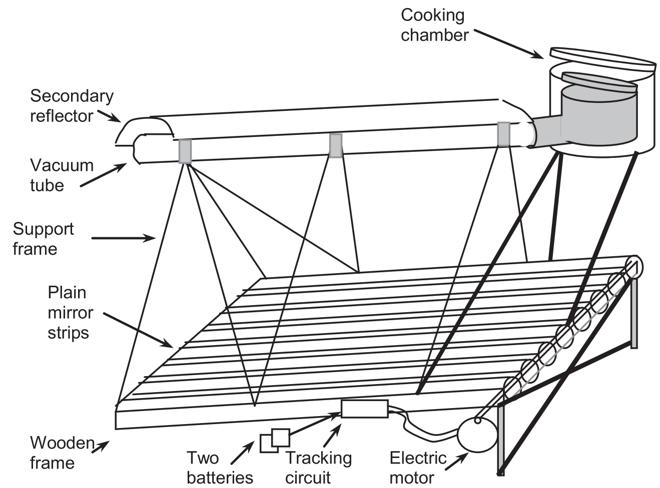

Fig. 2. Schematic diagram of the single vacuum tube based solar cooker using mini Freznel collector.

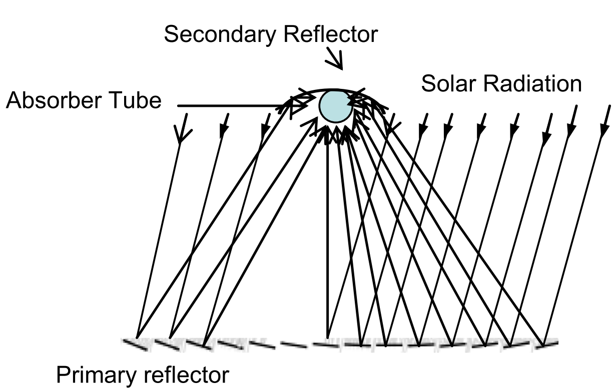

Fig. 1. Cross sectional view of the schematic diagram of a linear Fresnel collector. Laser aligned primary mirrors reflect the incoming light onto the absorber tube. Any leaked radiation strikes the secondary reflector and is reflected back to the tube.

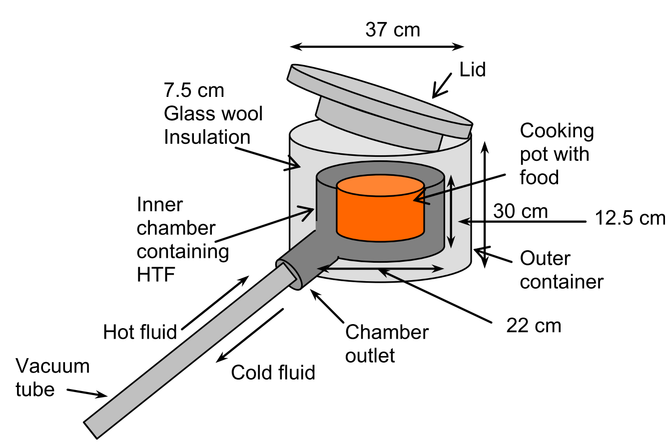

Fig. 3. Schematic diagram of the cooking chamber having outer dimensions (37 cm × 30 cm) and inner dimensions (22 cm × 12.5 cm), with 7.5 cm thick insulation, connected directly to the vacuum tube.