A NOVEL INDIRECT PARABOLIC SOLAR COOKER

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Abstract

The continuous increase in global demand and cost of electricity are some of the major reasons why solar cooking have received so much attention recently. Other factors such as global campaign against climate change through the use of fossil fuel and deforestation resulting from the continuous use of wood for cooking have also contributed to the global acceptance of solar cookers. Various types of solar cookers are currently in existence ranging from box to panel and parabolic. While some are directly used under the sun, others have been modified to be used indirectly. However, most of the cookers pose the same challenges, exposure of users to sun, inability to function at night or when there is no sunshine, low utilisation efficiency and technical complexities.

This report presents an indirect parabolic cooker that is effective and eliminates the solar cooker challenges identified. The cooker uses a parabolic dish covered with aluminium foil to focus the sun rays to a frustum shaped closed conical receiver which was placed at its focus. The cooker has a cooking system made into a 50 litres heat storage tank insulated with ceramic wool and separated from the dish and cavity receiver system. The heat transfer fluid was distributed through the system by high temperature flexible hose.

Several cooking test were done including boiling water and pancake baking and an extensive analysis of indoor parabolic cooking based on the international testing procedures for solar cookers were performed. The result from the analysis shows that the solar cooker had utilisation efficiency of 39 %, the average characteristic boiling time from the experiment was approximately 13 minutes/kg while the overall calculated exergy efficiency was approximately 0.05 %. The system can be used for family cooking and it has the capability of been scaled up for industrial usage.

Keywords: Parabolic dish; cavity receiver; indoor cooking; utilisation efficiency.

1. Introduction

There are various types of energy sources which has been used for cooking at various locations on earth. While most rural areas in in sub-Saharan Africa have relied predominantly on wood for cooking [1], other major places like South Africa have relied on electricity as the major source of energy for cooking as shown in Figure 1 below where electricity was found to be the major source of heat for cooking in South Africa.

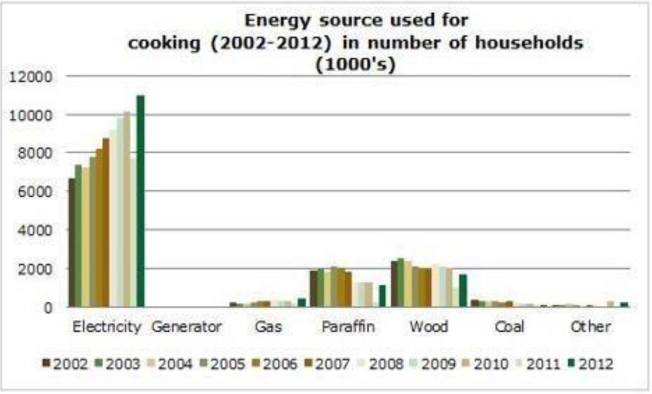

Fig. 1: Energy sources for cooking in South Africa [2]

While the former method in sub-Saharan Africa leads to deforestation, the latter which is high dependence on electricity has contributed to increase in the demand for electricity thereby leading to insufficient supply. The call to find other sources of cooking has therefore been on the rise and solar energy is a realistic option [2].

Solar energy is the most abundant of all the renewable energy as all other energy generates their power from the sun. Because it is free and always available, if all the power from the sun can be harnessed, then all of the human energy need would be met. An important method in which direct energy from the sun is being used is through solar cooking technology which ranges from very simple technologies to very sophisticated ones [3]. Any system that makes use of solar energy to boil or pasteurize water or cook food can be referred to as a solar cooker [4]. The existing solar cookers have been classified based on their shape, reflection techniques or their cooking methods. Panwar *et al*. [5] presented a comprehensive classification based on shape and reflection technique as shown in Figure 2.

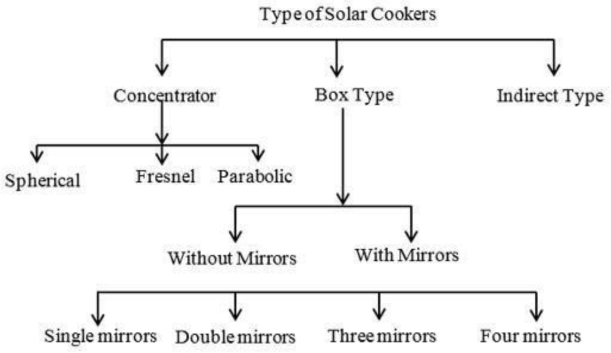

Fig. 2: Classification of solar cookers [5]

While direct solar cookers are the one that works with the cooker and the food directly exposed to sunshine, indirect solar cookers are the types that eliminates the exposure of users to the sun. In indirect solar cooking, the solar collector that receives direct solar radiation is separated from the cooking section. The heat is often transferred between the two parts using heat transfer mediums ranging from steam, paraffin to various types of oil [4]. Some types of these cookers are available commercially but the adoption and deployment has been low due to complexities, low efficiencies and cost. Some of the commercially existing ones have been based on either siphon technology using glass or evacuator tube technology as seen in Figure 3a and 3b respectively.

Figure 3a is an outdoor cooker made by Schwarzer *et al*. [6] for a primary school in Northern Chile. The heat transfer medium is groundnut oil which operates in a cycle. The pot is fixed therefore making cleaning difficult and thus compromising the hygiene standards for cooking. The cooker also does not function well in the absence of direct sunshine. Figure 3b was reported by Muthusivagami *et al*. [7] to have been manufactured by Balzar. It uses sets of heat pipes placed in a vacuum tube as heat transfer medium and the cooking is done in an insulated oven done on the right side. This technique for solar cooking was welcomed because it required no solar tracking. But the fact that it is fragile, expensive and high-tech halted its wide distribution.

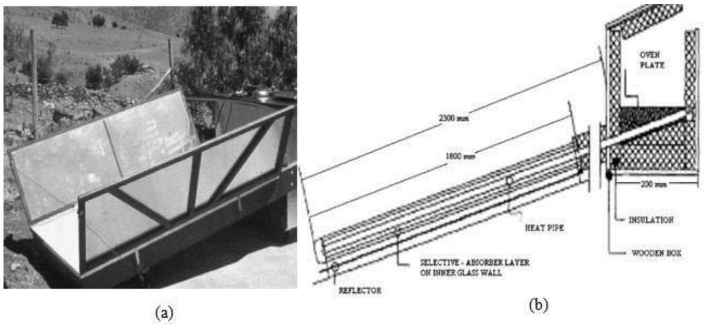

Fig. 3: Indirect solar cookers: flat plate in Chile [6] (a); Evacuated tube [7], (b)

2. Theory and design

The design under consideration in this report uses an indirect parabolic dish technology. The concentrator used was a 2 m parabolic shaped satellite dish which was covered with aluminium foil. The maximum desired output temperature was 220 ℃, the system was an active one as it uses a refurbished motor car pump to circulate the heat-transfer fluid through the whole system.

A tracking system was developed as a modification to the model by Roth *et al*. [8], using the automatic positioner of Prinsloo and Dobson [9]. The error calculations and actual parabolic reflections determination were done using equations developed by Stine and Geyer [10].

It was assumed in this design that the rays of the sun are parallel to the collector dish in accordance with the model developed by Stine and Geyer [10] for error analysis, and the error equations were developed in terms of rim angles. The developed equations were used to find the slope errors in the sun's rays, and this was solved simultaneously with tracking errors to analyse the spread of the reflected rays of the sun on the focus of the dish. The result of this analysis shows the size of image formed at the focus of the dish and then used that to determine the minimum and maximum size of the receiver aperture. A step by step analysis developed by Craig [4] shown in Figure 4 was followed.

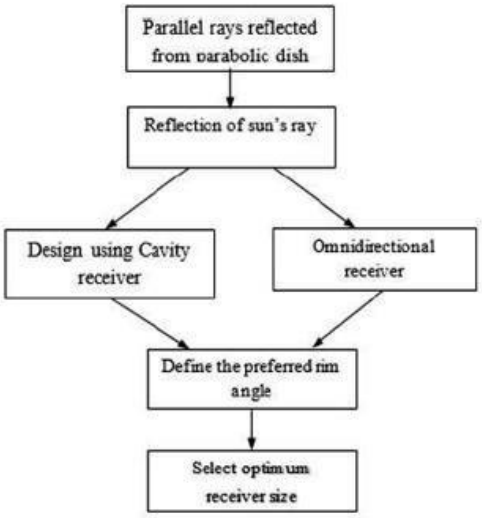

Fig. 4: Parabolic reflector optical analysis [4]

The minimum entry aperture width for the receiver was then determined using the procedure shown in in Figure 4 and modified Equation becomes

$$W_n = 2\,p\,\left(\mathrm{n}\,\frac{\sigma_{total}}{2}\right)\cos\varphi \qquad (1)$$

Where W_n is the width of the receiver aperture, σ_{total} is the total tracking error while φ is the rim angle, n is the number of days from January and p is the parabolic radius of the reflector dish. A frustum shaped conical receiver was then manufactured based on Equation 1 with copper tube of 40 m length and 10 mm diameter covered with a bucket of stainless steel with ceramic wool as insulator as shown in Figure 5.

Fig. 5: Conical receiver

The top part of the storage tank is shown in Figure 6, the storage tank is a 50 litres cuboidal shape steel with a cylindrical cooking depression made in it and the tank was insulated with ceramics wool up to 60 mm thick. An inside depression was made in the tank to provide a base for the spiral head cooking , and also eliminate the challenge of the cooking pot hygiene experience by Schwarzer et al. [6]. The spiral tube cooking head method was recently confirmed by Craig and Dobson [11] to be a preferred method for cooking when using indirect type solar cooking technology.

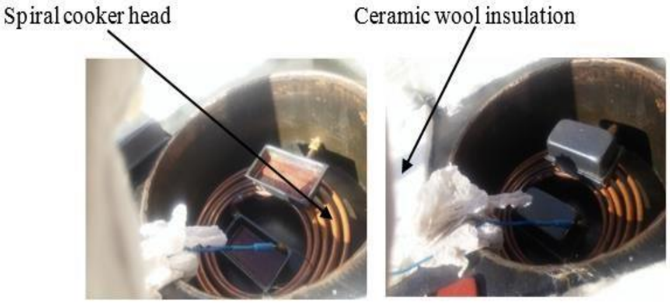

Fig. 6: Storage and cooking system

The receiver with the parabolic dish was then connected to the storage system using a high temperature hose and the heat transfer fluid was shell oil. The system set up was mounted on the heat transfer laboratory roof top at Stellenbosch University 33° paraz55' 41.10" S, 18° 51' 58.80" E and 119 m height above sea level. An overall heat transfer analysis of the system was performed and two parameters by which contributed mostly to the overall useful efficiency were identified as the optical efficiency and receiver losses.

3. Experimental set up

Experiments for this research were set up with the aim of obtaining the parameters by which the system's cooking power and efficiencies could be calculated. Figure 7 shows the solar collection system where the dish with the receiver mounted on the tracker stand is placed outside in the sun and the high temperature flexible hose was used to circulate the heat transfer fluid. The pump circulates the oil throughout the system in cycles.

Fig. 7: Parabolic dish and conical receiver set up

Several cooking experiments were performed to understand the optimal working conditions of the parabolic cooker. The analysis and cooking tests were based on the international testing procedures for solar cookers as reviewed by Funk [12]. The model for the analysis of cooking section was a modification of the combinations of various models presented by ElKassaby [13] based on modifications by Amer [14] and Kimambo [15] with the incorporation of internal energy and heat losses.

4. Experimental Results

The optimal test of performance for a solar cooker is often based on its water boiling characteristics, this is because most types of food involve heating of water during their cooking. Several experiments were performed from April through June, 2015. Figure 8 shows the result of a specific boiling experiment on 12th June with average hourly DNI of 570 W/m^2 during heating of water during cooking which took place between 8 a.m. to 4 p.m. The pot size used for the experiment was 200 x 100 mm holding water of 4 kg mass. The pot was placed on the spiral cooker in the depressed part of the storage tank. The water boiled after 4 hours at around 12.30 pm as shown in Figure 8. The initial oil temperature was at 60 ºC as the storage retained heat from the previous day's experiment. The initial difference between the cooking top temperature T_{ck-top} and the average oil temperature $T_{oil-avg}$ in the tank is as a result of the initial resistance of the spiral cooking head material (copper resistance). T_g is the temperature of the air between the boiled water and the pot covers. It took 3 hours for the average temperature in the tank and the spiral cooking head to reach equilibrium; a high T_g was found to promote high convection. T_{amb} is the ambient temperature and $T_{fd\text{-}water}$ is the water temperature in the pot, while the DNICalc_Avg is the measured hourly direct normal irradiance measured during the experiment.

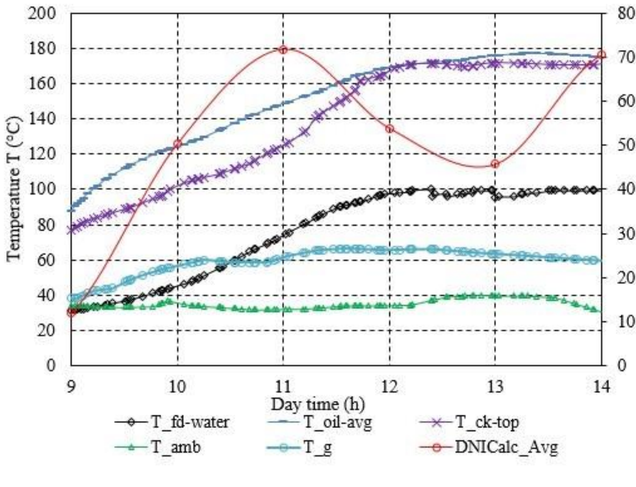

Fig. 8: Boiling of water on 12 June 2015

The experiment proved that the developed parabolic solar cooker could achieve water boiling despite the low DNI available on the winter day that the experiment was carried out. Having confirmed the cooker can boil 4 kg of water in 4 hours, various sensible cooking power analyses were then performed on the cooker to understand the cooking power rating and effectiveness.

5. Solar cooker performance analysis

An important criterion for solar cooker performance analysis is the sensible cooking power analysis or power rating or the solar cooker effectiveness measure. It is used to determine the magnitude of power required to boil a particular mass of water over a particular period. The sensible cooking analysis was performed in this study using 4 sets of water boiling experiments on 18th June, 2015 with water of mass 1.5 kg for each set. The experiments were carried out when the storage tank was fully charged (when the spiral cooker head temperature was the same as the average oil temperature) with no further charging (no oil was pumped up to the solar cavity heat receiver for further heating).

As seen in Figure 9, the first water boiling took 13 minutes, the pot was emptied and fresh water was added and the experiment was repeated 3 times. The second, third and final sets of water took 17 minutes, 28 minutes and 38 minutes to boil respectively. The power consumed by each of the experiment equals 1309 W, 915 W, 585 W and 410 W respectively.

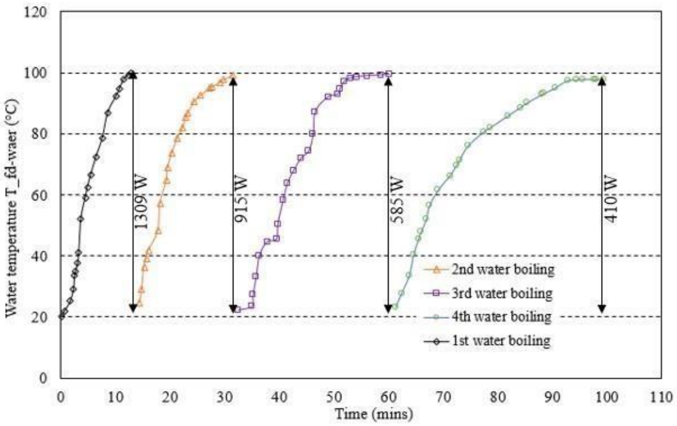

Fig. 9: Water boiling and power rating of the system

Funk [12] developed several other methods to analyse and measure the cooking performance and efficiency of solar cookers. The advantage of these standard cooking test analyses is that the result can be used to compare various cookers under different solar irradiation conditions. Some of the methods include the utilisation efficiency, η_u and characteristic boiling time, t_c. Utilisation efficiency was expressed in terms of solar radiation, I, mass of water, m, the total time taken for water to reach boiling Δt, the solar collector aperture area A.

$$\eta_u = \frac{mc\Delta T}{IA\Delta t} \qquad (2)$$

The results from the experiments were also used to determine the characteristic boiling time of the system. With the reference solar insolation, I_{ref}, of $900\ \mathrm{W/m^2}$ as stated by Khalifa *et al*. (1984) and t^b, specific boiling time. This characteristic is often used as one of the international solar cooker performance analysis

$$t_c = t^b \frac{I_s}{I_{ref}} \tag{3}$$

The specific boiling time can be described in terms of boiling time

$$t^b = \frac{\Delta t A}{m}$$

The average characteristic boiling time for 3 kg water for this parabolic cooker is 3.1 minutes/kg, while the utilisation efficiency is 39 %. These are highly successful figures based on the existing cooking standards. The overall exergy efficiency for the system was also determined to be 0.05 %.

6. Conclusion

The study presented in this paper contributes to the limited existing literatures on indirect parabolic solar cookers, it provides an extensive analysis of indoor parabolic cooking based on the international testing procedures for solar cookers. The solar cooker presented here can cook for a single family but can be scaled up for industrial and communal cooking. The type of receiver design was found to be the effective in increasing utilisation efficiency and reducing heat losses due to convection and radiation. The cooker also eliminated the user's exposure to sunshine.

The ideas from the solar cooker developed in this study can be used by policy-makers to adopt solar cookers for various uses as military camps cooking, refugee camps cooking, communal cooking and many other local uses. The study presented here can also be used to develop some heat energy based industries in rural areas for rural industrialisation. The study identifies the need for simple and cheap solar tracking systems that can be made from local materials as this was the only major reason for the high cost of the design.

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