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Parabolic Solar Cooker: Cooking with Heat Pipe VS Direct Spiral Copper Tubes

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Abstract. Cooking with solar energy has been seen by many researchers as a solution to the challenges of poverty and hunger in the world. This is no exception in Africa, as solar coking is viewed as an avenue to eliminate the problem of food insecurity, insufficient energy supply for household and industrial cooking. There are several types of solar cookers that have been manufactured and highlighted in literature. The parabolic types of solar cookers are known to reach higher temperatures and therefore cook faster. These cookers are currently being developed for indoor cooking. This technology has however suffered low cooking efficiency and thus leads to underutilization of the high heat energy captured from the sun in the cooking. This has made parabolic solar cookers unable to compete with other conventional types of cookers. Several methods to maximize heat from the sun for indirect cooking has been developed, and the need to improve on them of utmost urgency. This paper investigates how to optimize the heat collected from the concentrating types of cookers by proposing and comparing two types of cooking sections: the spiral hot plate copper tube and the heat pipe plate. The system uses the concentrating solar parabolic dish technology to focus the sun on a conical cavity of copper tubes and the heat is stored inside an insulated tank which acts both as storage and cooking plate. The use of heat pipes to transfer heat between the oil storage and the cooking pot was compared to the use of a direct natural syphon principle which is achieved using copper tubes in spiral form like electric stove. An accurate theoretical analysis for the heat pipe cooker was achieved by solving the boiling and vaporization in the evaporator side and then balancing it with the condensation and liquid-vapour interaction in the condenser part while correct heat transfer, pressure and height balancing was calculated in the second experiment. The results show and compare the cooking time, boiling characteristics, overall utilisation efficiencies and necessary comparison between the two system and other existing systems. AIP Proceedings article template has many predefined paragraph styles for you to use/apply as you write your paper. To format your abstract, use the Microsoft Word template style.

INTRODUCTION

In order to find an alternative cooking method either as stand-alone [1] or as a hybrid system with other cooking system [2]; authors and manufacturers has designed several types of solar cookers in literature as highlighted by [3] in figure 1

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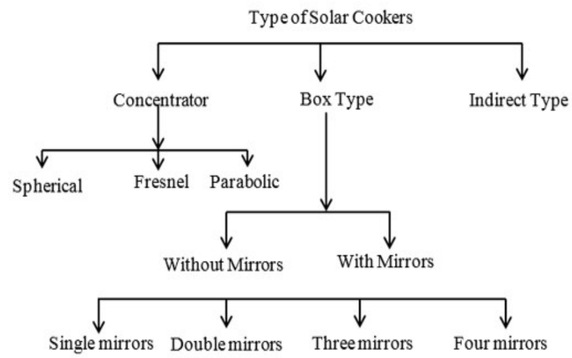

FIGURE 1. Classification of Solar cookers [3]

However, the parabolic solar cookers have been identified to cook faster and can achieve higher temperatures compared to other types [4]–[8]. There are two types of parabolic cookers, the direct cookers where cooking pots are placed in the focus of the parabolic dishes and the second type are the indirect cookers, where the heat is stored and channeled for indoor or night. Concentrating solar cookers can achieve concentrating temperatures up to 700 ℃. While the direct cookers are simple and easy to make, the indirect cookers which can be used for cooking when the sun is not up are still an ongoing technology.

Solar cookers are important because they prevent the user's direct exposure to the sun and also make the technology competitive with other forms of cookers. Parabolic solar cookers have been facing a setback which is low cooking efficiency between 3.05–35.2 % as reported by [8] which is in contrast to their ability to capture high heat from the sun; a much higher cooking efficiency is expected than what they are currently yielding. Various studies on methods to optimize the heat from these cookers for indoor cooking with storage have shown that a lot of heat is lost in transferring the heat energy from the storage to the cooking section. These studies have shown that a lot needs to be done in order to find an appropriate technology or design for the cooking section that will yield cooking efficiency that can be a mirror of the solar energy collection efficiency on the reflector/collector side.

The system presented in this paper investigates how to maximise the heat collected from the concentrating types of cookers by proposing and comparing two types of cooking sections: the hot plate copper tube and the heat pipe plate. The results show and compare the cooking time, boiling characteristics, overall utilisation efficiencies and necessary comparison between using heat pipes to transfer heat between the oil storage and the cooking pot to using a direct natural siphon principle which is achieved using copper tubes in spiral form. The research is still on going.

DATA ACQUISITION

The measurements for the experimental set up in this study were taken at Stellenbosch University Mechanical Engineering heat transfer roof top elevated at 119 m above sea level with coordinates of 33° 55' 41.10" S latitude and 18° 51' 58.08" E longitude with the annual solar radiation over the last 7 years as shown in the figure 2.

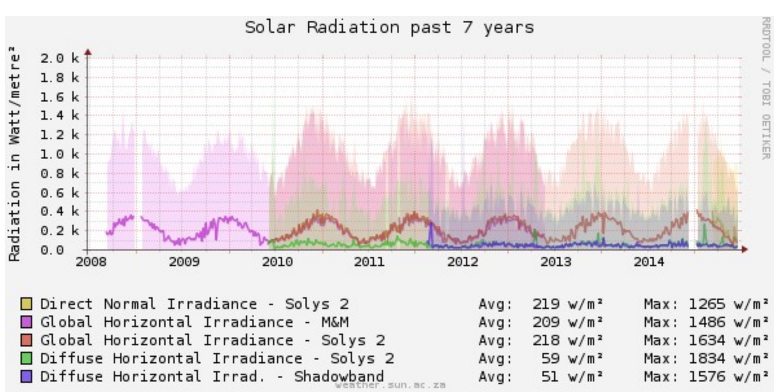

FIGURE 2. Solar Radiation over the year in Stellenbosch University [9]

The graph shows that the site has the ability of receiving an average of more than 220 W/m^2 daily Direct Normal Irradiation (DNI) [9]. The tracking system used for the setup is based on [10].

EXPERIMENTAL SET UP

The experimental set up consists of two sub systems which include the solar energy collection and the storage cooking system as shown in figure 3.

The solar energy collection comprises of a 2 m diameter parabolic dish is an old television satellite dish which serves as the concentrator/reflector. It was covered with aluminium reflecting foil of 0.89 reflectivity, the set-up was placed then placed on a two axis the tracking system.

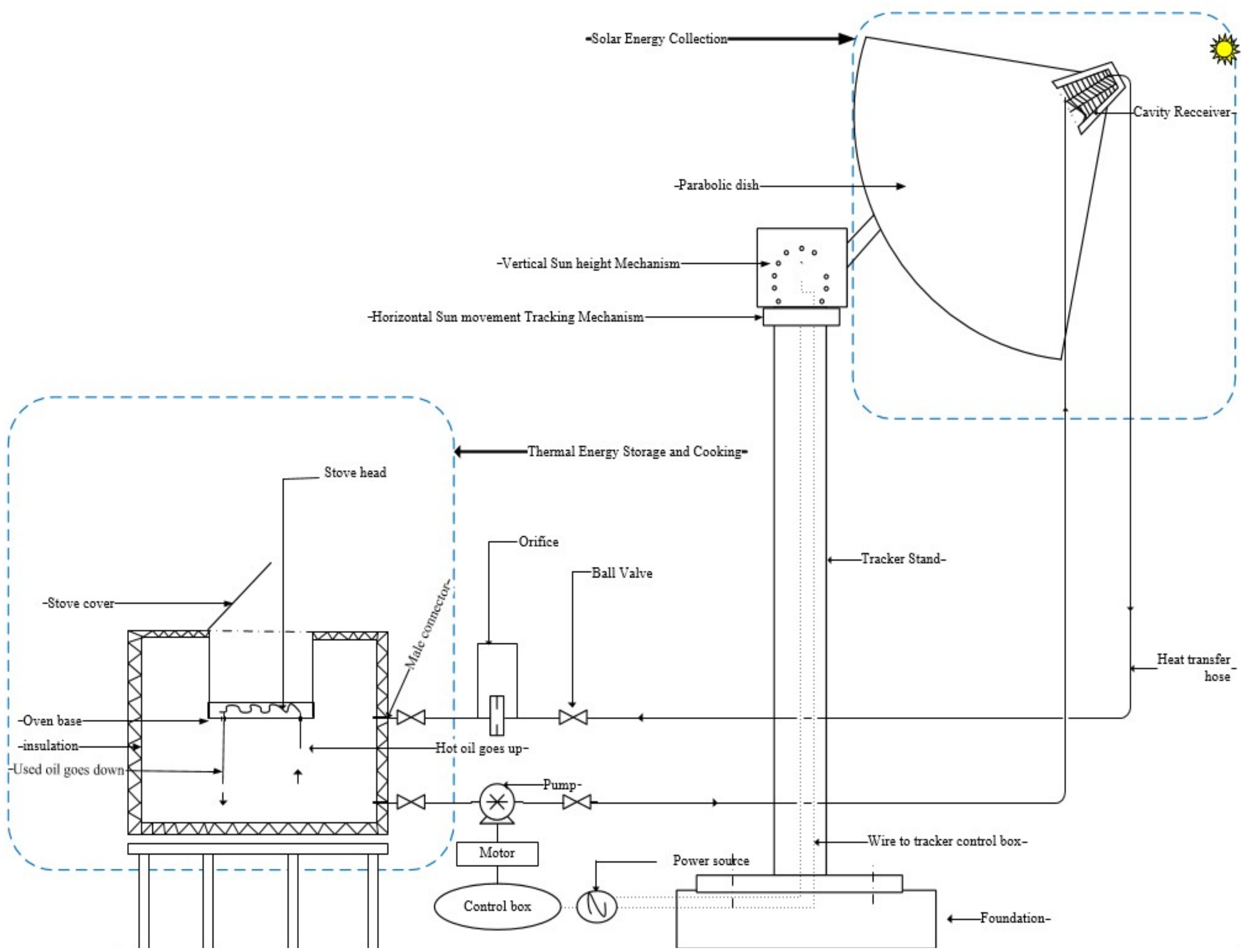

FIGURE 3. Overall experimental set-up

The receiver used is an innovative conical cavity receiver, it consists of copper tube of 0.095 m diameter, which was made to form spiral and frustum shaped tapered helix and the set were silver soldered to form a cavity receiver.

FIGURE 4. Manufactured cavity receiver

The cavity receiver manufactured is shown in figure 4, in which the joined copper tubes was packed inside a stainless steel bucket. Convective and radiative losses were overcome by the use of ceramic wool insulation which was placed around the bucket containing the copper tube, another bucket was used to cover the set up to prevent exposure to rain and other unfavourable conditions. The effect of forced convention on the receiver was reduced by decreasing the entrance aperture area of the cavity, the total length of the spiral and tapered copper tube joined 37 m and this allows for the heat transfer fluid to have enough surface area to achieve the maximum the heating. The system is an active heat transfer process because it uses a pump to push the heat transfer fluid throughout the set-up with the aid of high temperature hose to form a closed system. A sensible heat storage system was incorporated to the system to provide night cooking was used with shell S2 with oil as the heat transfer fluid stored in a mild steel storage container which is insulated with a thick ceramic wool of 0.06m width, the last major section is varied with the first experiment having heat pipes and the other being hot plate copper tube.

Two separate experiments were performed: i) using heat pipe where the working fluid is ethanol as shown in Figure 5a and ii) Figure 5b using syphon mechanism, where the hot oil is allowed to rise through the copper tube with shorter arm and then circulates through the spiral that looks like electrical cooker head and the colder oil drops down through the longer arm. Several thermocouples were placed on different parts of the set up to measure temperature at different points. Two types of thermocouples were used; T-types were used where the expected temperatures were less than 150 ^{o}C and on the sides where higher temperatures were expected K-type thermocouples were used.

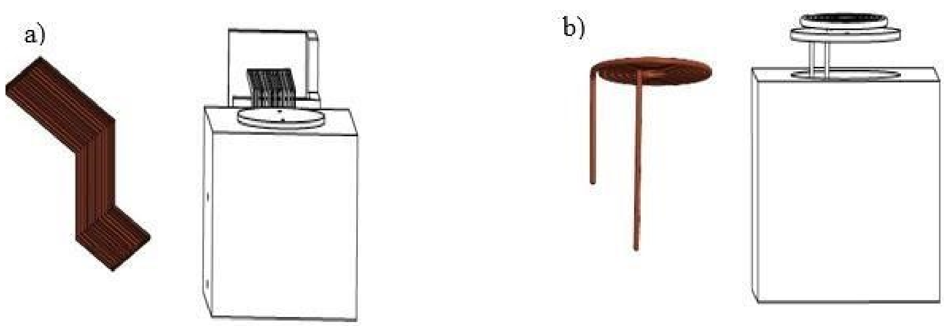

FIGURE 5. Experimental set up for experiment with (a) heat transfer pipe; spiral copper tub, (b)

THEORY

The models offered by [11] and [12] were both combined and modified to suit for the heat pipe theoretical calculations for the heat pipes. Here the heat pipe has two sections the evaporator and the condenser part as shown in figure 6. The heat collected and stored in the storage tank is transferred to the cooking section using the principle of evaporation-condensation cycle of the methanol which is the working fluid in the heat pipe (figure 6).

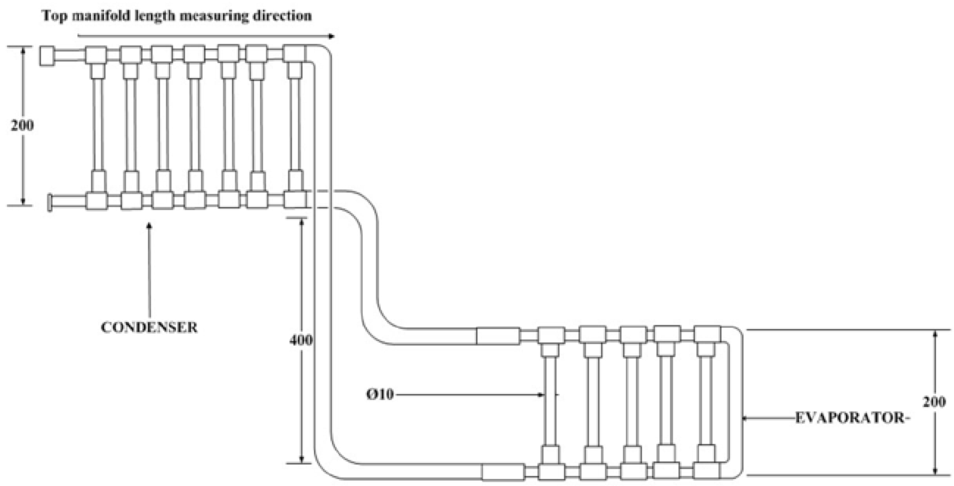

FIGURE 6. Heat pipe with condenser and evaporator dimensions

The heat collected and stored in the storage tank is transferred to the cooking section using the principle of evaporation-condensation cycle of the ethanol which is the working fluid in the heat pipe (figure 6). The evaporation section is dipped into the storage tank and the condenser section is placed under the cook pot. The system was treated as a thermal fluid situation analysis which involves boiling that occurs in the evaporator side followed by its vaporisation and then the second stage that involves how the vapour is then transferred to the condenser and it gets cooler. The interaction that occurs between the different phases was also studied as suggested by [12]. In order to reduce the noticed complexities in the analysis of the boiling heat transfer and the dynamics of vapour flow, the empirical solutions offered by some assumptions made by [13] were used and the calculation assumptions are:

a. Adiabatic situation assume for the tube/pipes linking the evaporator and the condenser
b. There is no vapour flow back and the vapour leaving the evaporator is condensed (flawless heat exchanger)
c. Saturation pressure is read at vapour temperature
d. The fluid doing the whole heat transfer is assumed to be completely saturated [12].

[12] proved that the equation offered by [13], [14] can be used to determine the useful heat energy transferred to the cooking section, we therefore adopted the equation , firstly the heat transfer coefficient of the evaporator was determined using Shiraishi's model [14].

$$h_{ev} = 0.32\,\frac{{\rho_l}^{0.65}{k_l}^{0.3}{C_{pl}}^{0.7}g^{0.2}}{{\rho_v}^{0.25}{h_{fg}}^{0.4}{\mu_l}^{0.1}}\left(\frac{P_{sat}}{P_a}\right)^{0.23} q_{ev}^{0.4} \quad (1)$$

When the heat in the storage tank is constant, we can assume that the whole heat supplied to the heat pipe is used to evaporate the ethanol in the heat pipes and we can adapt the quasi useful heat for heat pipe equation derived by [12] as

$$Q_u = \pi d_i q_{ev} \quad (2)$$

The useful heat from cooking with the spiral copper tube was easier to determine. It was measured when the heat transfer oil and the spiral copper tube's temperature was at parity in terms of the specific heat capacity of the oil, the mass flow rate of the oil and the difference between the hot spiral copper and the temperature of the pot

$$Q = mc_{oil}\Delta T \quad (3)$$

RESULTS AND DISCUSSION

The heating of the oil was done and the various temperature distributions for the two experiments are presented in the figures 7 and below.

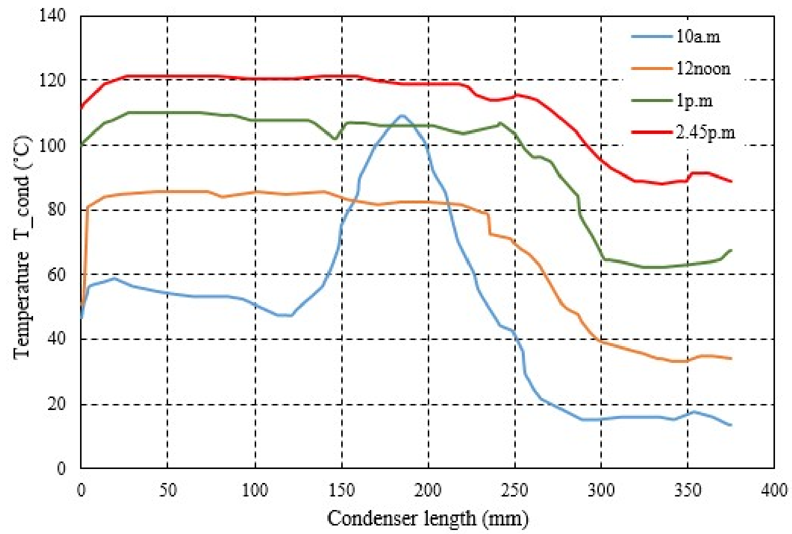

FIGURE 7. Wall temperature as a function length of inlet manifold of the condenser of the heat pipe

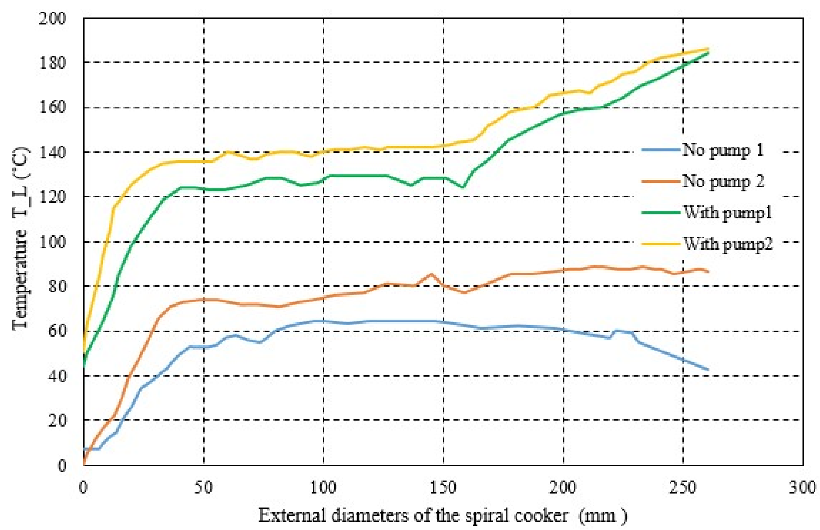

FIGURE 8. Average day temperature measured at various diameter of the spiral cooker

Figure 7 shows the temperature distribution on heat pipe measured at different parts and at different times. Figure 8 has two in one experiment with and without pump to prime the cooker tube shows the overall hourly temperature in the spiral cooker coil, as measured from the inner to the outer diameter. When a leg pump was added to the second experiment, an appreciable rise in the output temperature was noticed.

An improvement was achieved in the spiral cooking head, by changing the orientation of the shorter arm and rotating it by 90^o so that the shorter arm is open straight to the hot oil to eliminate the use of pump as shown in figure 9. An appreciable overall increase in efficiency was noticed as the hot oil flows straight into the spiral and the cold used oil flows back to the tank through the other arm.

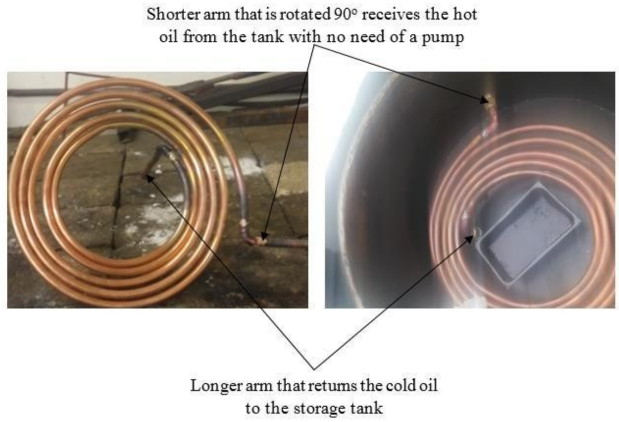

FIGURE 9: Optimised spiral cooker

Another experiment was performed, which is the boiling of 2 kg water on the two cooking section. That is the optimised spiral with rotated arm and the heat pipe. The results are shown in the table 1. There are several criteria found in literature to compare the efficiency of cookers [8], [15]–[17] but for the purpose of this study we choose the characteristic boiling time t_c which is calculated in terms of the temperature difference between the initial and final temperature of the cooking ΔT and the utilisation efficiency η_{ut}. The characteristic boiling time has been given a standard irradiation of 900 W/m^2 for an aperture area of 1 m^2 to allow easy comparison for several locations.

$$t_c = \frac{c\ \Delta T}{5 * 10^4}\ \eta_{ut} \quad (4)$$

Where

$$\eta_{ut} = \frac{m\ c\Delta T}{A_{ap} I_s t} \quad (5)$$

The utilisation efficiency is the overall efficiency of the system, comparing the incident radiation and the area of aperture to the rate at which cooking is done. The η_{ut} and the t_c of this system can be compared to other ones manufactured by interested authors.

TABLE 1: Cookers efficiency comparison with the other cookers

Author	**location**	**Cooker type**	**Sensible heating efficiency**	**Utilisation efficiency, η_{ut}**	**Characteristic boiling time t_c, min/kg**
Schwarzer & Kings, 1996	India	parabolic	0.3-0.34	0.17	23
Silva et al. 2002	Brazil	parabolic	0.38	0.12	42
Current set-up	South Africa	spiral	0.41	0.29	28
Current set-up	South Africa	Heat pipe	0.38	0.27	30

CONCLUSIONS

It is seen from the above experiment that the heat pipe eradicates the safety concern of whether water or any liquid will find its way back into the hot storage which can lead to explosion over long usage as compared to the direct cooker. Both systems are highly recommendable, but with respect to price, the spiral system would be preferred over the heat pipes because of production cost. The initial spiral system's requirement of a pump for higher temperature made it ambiguous but can also be seen as a blessing in disguise as this can be used to vary the flow rate of oil through the tubes and thus control the rate of heat flow to the cooking pot. The optimised spiral was highly effective as compared to the other cooking methods as shown in table 1 and it eliminates the complexity that set in with the use of pump. This will be confirmed in future studies. The heat pipe on the other hand is a technology to look into as it can be useful during freezing and boiling conditions and it overcomes the ambiguity of the solar cookers. This experiment is ongoing and several other optimisations are expected to be made, one of which is regulating the heat flow into the cooking head of the spiral cooker. It seems that any of these technologies can improve the cooking efficiency of parabolic solar cookers and thus give parabolic solar cookers a competitive edge over other conventional cookers.

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