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Parabolic Solar Cooker Cooking: Heat Pipes OR Spiral Copper Tubes

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Abstract

The idea of cooking with the sun is not new and most recently solar energy has been identified by many researchers as a solution to the challenges of poverty and hunger in the world. Solar coking is believed to be a contributor to the fight for the elimination of insufficient and or expensive energy supply for homes and industrial cooking. The parabolic types of solar cookers have been identified to cook faster at high temperatures and when they are used indirectly with the cooking section separated from the dish, they often abolish the exposure of the user to the sun and can thus be incorporated to kitchen designs. Despite this breakthrough, indirect parabolic cookers still faces a major problem, which is identifying the right cooking section type as most of the ones in existence often achieve a low utilisation efficiency as compared to their potentials. In order to analyse and predict the best cooking section type for parabolic cookers an experimental cooking was performed at Stellenbosch University, South Africa using two different types of cooker sections, the first being using coiled spiral copper tube and the other using heat pipes of 2 l volume. The cooking section was separated from the dish and was not exposed to the sun, the working fluid was transferred using high temperature flexible hose. Both types of cookers were found to be effective with the heat pipes boiling water in a record time but no heat control; the spiral copper tube also reached boiled water although at a little longer time but the flow of heat to it could be regulated. Both were seen to have their advantages and disadvantages and the selection would be based on the desired use of the cooker by the manufacturer, but base on cost, the use of spiral copper tube is recommended in this report.

Keywords: *Parabolic Solar cookers, Heat pipes, Spiral copper tube*

1. Introduction

Over one-third of the world population has been identified to be using wood as a source of energy either for general heating purpose or specifically for heating (Wentzel & Pouris 2007). This case is worse in Africa where in South Africa (which is one of the least countries with wood usage in Africa) over 84, 000 m^3 of wood is used per year (Christie & Gandar 1994). The continuous reliance on wood has led to deforestation in some communities and frustrations in many others (Diabaté et al. 2004) although over the recent years, many nations has increased their energy generation thereby reducing the over-dependency on wood and many are supporting other renewable energy alternatives. Solar cooking had been described by several authors as having the potential of leading rural industrialisation, elimination hunger and providing employment and can serve as a means of reducing the dependence on gas or electricity for cooking (Craig & Dobson 2015; Yettou et al. 2014; Al-Soud et al. 2010; Cochetel 2012), the need for its optimisation therefore is of utmost importance.

Parabolic types of solar cookers had been identified as the most efficient in terms of heat generation of all the types of solar cookers (Reddy & Ranjan 2003) and they often cook food faster than any other types of solar cooker in existence (Panwar et al. 2012). Some of the problems facing social acceptance of parabolic cookers have been identified as i) exposure to sun by the users ii) the complexity that sets up as a result of need for accurate sun tracking iii) low utilisation efficiencies among others and iv) selecting the right cooking section types.

However, the first problem identified had been overcome by the developing of indirect parabolic cooking systems (Otte 2013; Cuce & Cuce 2013; Muthusivagami et al. 2010; Schwarzer & da Silva 2008). The need for

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accurate tracking had also been overcome by development of simple dual tracking systems (Yao et al. 2014; Arbab et al. 2009; Arturo & Alejandro 2010). Effort to raise the of low utilisation efficiency of parabolic cookers are still continuous (Öztürk 2004; Kaushik & Gupta 2008; Ozturk 2007) and in this research the two popular types of cooking section used for parabolic cookers were tested and the necessary comparison was made.

2. Experimental Set Up

The experiment was performed in Stellenbosch University with location coordinates of 33˚ 55’ 42.81” S, 18˚ 51’55.08” E, Elevation: 119 m. The heat transfer fluid used was shell oil S2 with maximum fil temperature of 315 °C and maximum bulk temperature of 290 °C. The experiments were carried in winter conditions in June, 2015 in South Africa. The sun path for the location of the tests are shown in figure 1 a and b which were generated from running necessary scripts on University of Oregon Solar Radiation Monitoring Laboratory (2007) online sun path calculator

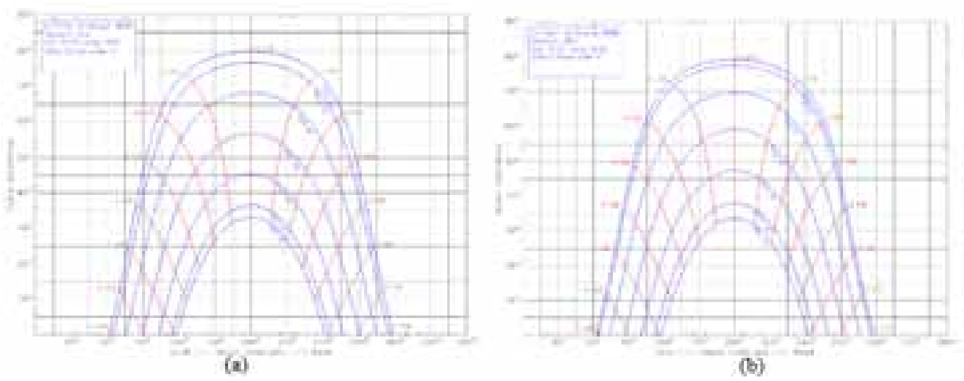

Figure 1: Stellenbosch University sun's path: December to June (a), June to December (a)

The diagram in figure 1 a shows the sun path for December to June while in figure 1 b is displayed the path of the sun for June to December for the location specified above in Stellenbosch, South Africa. The necessary angles of the sun was thus calculated using these data.

Figure 2 below is a CAD drawing of the experimental set up and how the cooking system is separated from the solar energy collection section.

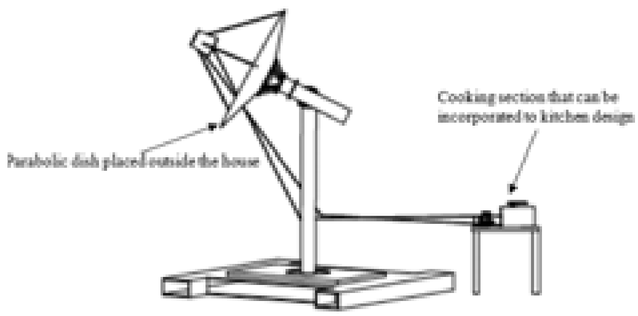

Figure 2: Complete CAD drawing of the experimental setup

A storage tank of 40 l volume was filled with the heat transfer fluid HTF, and a specially modified car pump was used to circulate the HTF throughout the system. The gasket in the automotive car pump was replaced with a high temperature Klingersil C-4430 gasket material to make the modified pump be able to withstand the temperature under which it will be functioning. High temperature hose was used to transfer the oil, the hose was insulated with a black rubber insulation clip. A depression was made inside the storage tank to allow direct cooking on in the storage and to provide a space for the two cooking section to be made. The direct placing of the cooking section in the hot oil was to reduce the heat loss between the storage tank and the cooker. A variable speed drive was connected to a three phase electric motor which was then connected to the pump to power it and also to vary the speed of the motor and ultimately vary the flow rate of the oil in the system.

The parabolic dish used was placed outside on a two axis tracker stand by Prinsloo et al. (2014) and the storage and cooking section was placed under a shade. The parabolic dish on the tracker is shown in figure 3. The two sets of cooking section manufactured is discussed in the following sections

Figure 3: Parabolic dish on tracker stand

2.1. Heat pipe cooking

The first cooking heat type was a heat pipe cooker with methanol and copper material an while the evaporator side was dipped in the storage tank, the condenser part was made to form a pot head and placed on another container beside the tank as shown in figure 4 and the heat transfer analysis is represented in figure 5

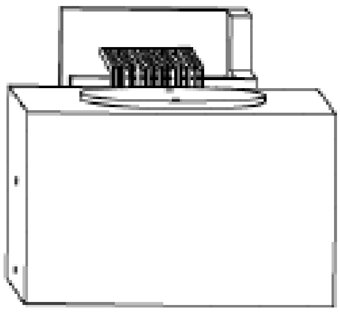

Figure 4: CAD drawing of heat pipe cooking section

The heat energy transfer analysis for the heat pipe experimental set up was performed based on the thermal resistances presented in figure 4 below.

In order to solve for the temperature and resistance in the cooking section the conservation of energy law was applied

$$\dot{Q}_{in} = \dot{Q}_{out} + \dot{Q}_{losses} \quad \text{(eq. 1)}$$

Considering the temperature of the oil supplied by the inlet heat transfer hose in relation to the heat supplied to the oil, a balance in the thermal resistances was developed as

$$\frac{T_{in} - T_{h\_oil}}{R_{sto-in}} = \frac{T_{h\_oil} - T_{out}}{R_{sto-out}} + \frac{T_{h\_oil} - T_a}{R_{sto-amb}} + \frac{T_{h_{oil}} - T_a}{R_{sto-ck}} \quad \text{(eq. 2)}$$

Re-arranging eq. 2 above and solving for the T_{h_oil} gives eq. 3

$$T_{h\_oil} = \left(\frac{T_{in}}{R_{sto-in}} + \frac{T_{out}}{R_{sto-out}} + \frac{T_a}{R_{sto-amb}} + \frac{T_a}{R_{sto-ck}}\right) * \left(\frac{1}{R_{sto-in}} + \frac{1}{R_{sto-out}} + \frac{1}{R_{sto-amb}} + \frac{1}{R_{sto-ck}}\right) \quad \text{(eq. 3)}$$

Likewise, the solution for the return temperature (T_{out}) that is fed back to the heat transfer return pipe and from there carried to the receiver cavity was determined as

$$T_{out} = \left(\frac{T_{in} - T_{h\_oil}}{R_{sto-in}} - \frac{T_{h\_oil} - T_a}{R_{sto-amb}} - \frac{T_{h\_oil} - T_a}{R_{sto-ck}} - \frac{T_{h\_oil}}{R_{sto-out}}\right) * R_{sto-out} \quad \text{(eq. 4)}$$

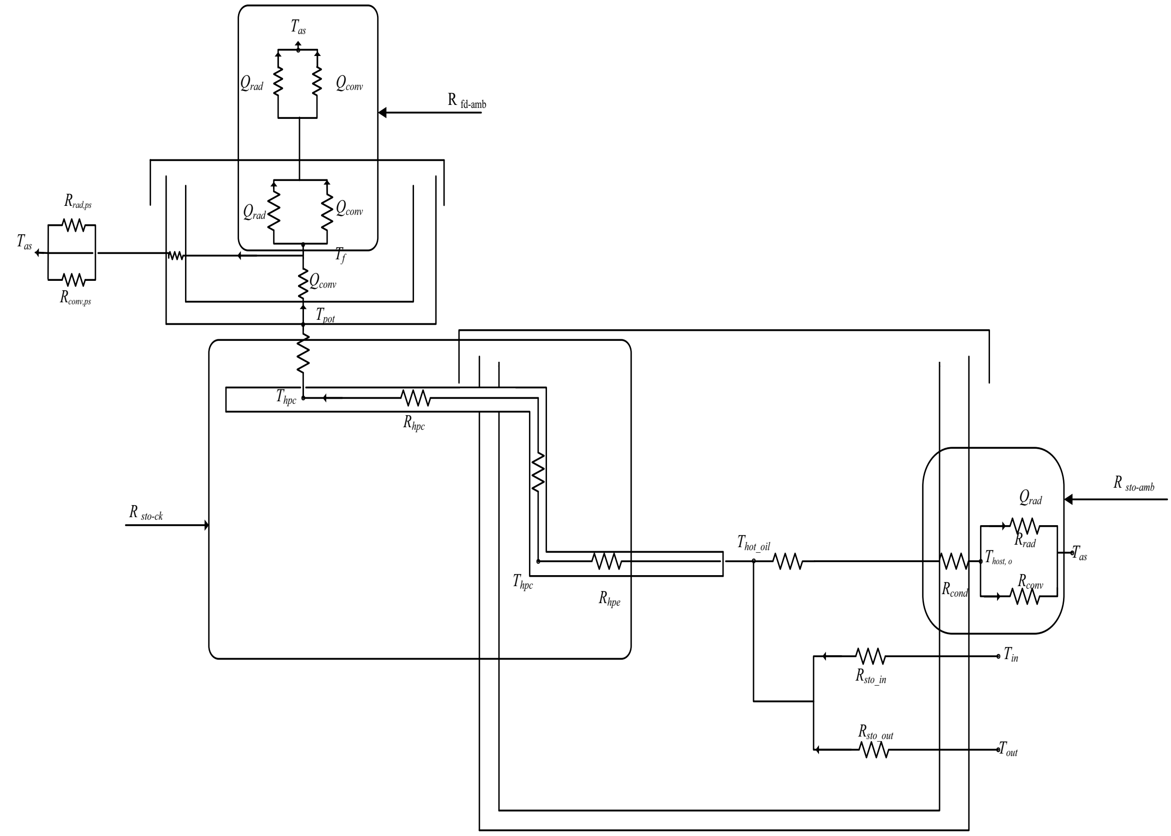

Figure 5: Thermal resistance diagram for heat pipe cooker

In order to solve for the temperature of the food item that was heated in the coking section of the solar cooker an equation for the temperature T_{fd} is developed.

The energy balance for the food can be expressed as

$$\dot{Q}_{fd} = \dot{Q}_{hp} - \left(\dot{Q}_{pot,s} + \dot{Q}_{pot,b} + \dot{Q}_{pot,cov}\right) \qquad \text{(eq. 5)}$$

When eq. 5 was expressed in terms of the temperatures and the resistances, eq. 6 was developed

$$\frac{T_{fd} - T_{hot\_oil}}{R_{ho-conv} + R_{hp} + R_{pot} + R_{sto-amb}} = \frac{T_{hp} - T_{hot\_oil}}{R_{hp} + R_{sto-amb}} - \frac{T_{fd} - T_a}{R_{pot,s}} - \frac{T_{fd} - T_a}{R_{pot,cov}} \qquad \text{(eq. 6)}$$

Rearranging the above equation, collecting the like terms and solving for T_{fd} gives

$$T_{fd} = \left[\left(R_{sto-a} + R_{ho-conv} + R_{hp} + R_{pot}\right)\left(R_{pot,s} * R_{pot,cov}\right)\left(\frac{T_{hp} - T_{hot\_oil}}{R_{hp} + R_{sto-amb}}\right)\right]$$
$$+ \ \left[T_a * \left(R_{ho-conv} + R_{hp} + R_{pot} + R_{sto-amb}\right)\left(R_{pot,s} * R_{pot,cov}\right)\right] \qquad \text{(eq. 7)}$$

The temperature of the food when cooked using the condenser part of heat pipe as a cooker head was thus determined using equation 7 presented above.

2.2. Spiral Copper tube

The second type of cooking section made was the spiral copper tub the diameter of the tube used is 3/8 inch and this was rolled into a flat spiral form as shown in figure 6b and this was then placed in the depression made in the cooking section as shown in figure 6a. One arm of the spiral tube enters the side wall of the depression and at a higher level than the second arm which enters the tank at a lower level, this allows hot oil to flow in freely and the cold oil flows back to the tank and the cycles repeated.

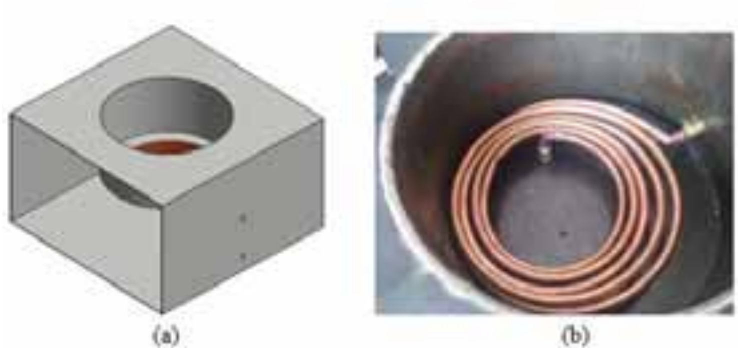

Figure 6: Thermal energy storage and cooker: cut-away 3D CAD drawing (a), spiral cook top (b)

The cooking pot was placed on the spiral head and the section was covered appropriately. The temperature of the food in the cooking pot was determined by analysing the heat transfer between the from the hot oil in the storage tank to the spiral cooker head as shown in figure 7

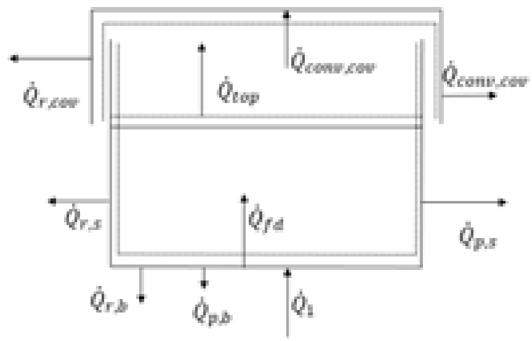

Figure 7: Heat transfer in spiral cooking section

The energy supplied the food $\dot{Q}_{fd}$ was assumed to be performing dual function, first is to overcome the internal energy of the food and the second is to balance the convection losses that occurs through the upper part of the pot and this shown in equation 8

$$\dot{Q}_{fd} = \dot{Q}_{top} + U_{fd,i} \qquad \text{(eq. 8)}$$

If the mass of fluid to be cooked is taken to be m_{fd} and the temperature is considered instantaneous, then eq. 8 can be expressed explicitly as

$$\dot{Q}_{fd} = \dot{Q}_{top} + m_{fd} c_{fd} \frac{dT_{fd}}{dt} = h_{fd} A_{fd} \left(T_{pot} - T_{fd}\right) \qquad \text{(eq. 9)}$$

The total heat supplied to the pot from the spiral copper tube can be taken as $\dot{Q}_1$ and it is used overcome the resistance of the pot, $\dot{Q}_{fd}$ and the convection losses through the side $\dot{Q}_{c,s}$ and the bottom of the pot $\dot{Q}_{c,b}$ as well as the radiation losses through the side $\dot{Q}_{r,s}$ and bottom $\dot{Q}_{r,b}$ respectively s shown in eq. 10

$$\dot{Q}_1 = m_{pot}\, c_{pot} \frac{dT_{pot}}{dt} + \dot{Q}_{fd} + \dot{Q}_{c,s} + \dot{Q}_{r,s} + \dot{Q}_{c,b} + \dot{Q}_{r,b} \qquad \text{(eq. 10)}$$

The various terms in eq. 10 above can be expressed shown in equation 11 to 15

$$\dot{Q}_{c,s} = h_g\, A_{side} \left(T_{pot} - T_a\right) \qquad \text{(eq. 11)}$$

$$\dot{Q}_{c,b} = h_a\, A_{top} \left(T_{top} - T_a\right) \qquad \text{(eq. 12)}$$

$$\dot{Q}_{r,b} = \sigma\, \varepsilon_{pot}\, A_{top} \left({T_{pot}}^4 - {T_a}^4\right) \qquad \text{(eq. 13)}$$

$$\dot{Q}_{r,s} = \sigma\, A_{side} \left({T_{pot}}^4 - {T_a}^4\right)\left(1/\varepsilon_{pot} - 1/\varepsilon_{cover} - 1\right) \qquad \text{(eq. 14)}$$

$$\dot{Q}_{p,s} + \dot{Q}_{top} + \dot{Q}_{p,s2} = m_a c_a \frac{dT_g}{dt} \qquad \text{(eq. 15)}$$

Re-arranging the above Equations to form a first order differential Equation that can be solved numerically gives the following sets of Equation:

$$\frac{dT_{fd}}{dt} = F_{fd} \left(T_{fd}, T_{pot}, t\right) \qquad \text{(eq. 16)}$$

$$\frac{dT_{pot}}{dt} = F_{pot} \left(T_{fd}, T_{pot}, T_g, t\right) \qquad \text{(eq. 17)}$$

$$\frac{dT_g}{dt} = F_g\,(T_{fd}, T_{pot}, T_g, t) \qquad \text{(eq. 18)}$$

The generated equations was then be solved numerically using Runge-Kutta fourth-order algorithm.

3. Experimental Result and Discussion

An initial experiments without any load was performed on the two types of cooking sections made. The evaporator arm of the cooker was deepen into the oil and all leaked were blocked. The electric motor was turned on using the variable speed drive and the HTF is transferred to a cavity receiver placed at the focus of the parabolic dish and the cycle continued. No cooking was performed because the aim of the experiment was to determine the variation of the heat pipe temperature with the temperature inside the tank.
The result is diagrammatically presented in figure 8 below, where the maximum difference between

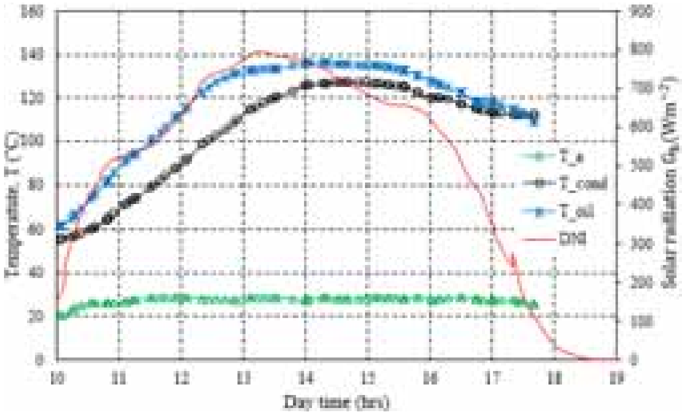

Figure 8: Condenser, oil and ambient temperature as a function of day time

the temperature of the condenser and the average oil temperature was 25 ˚C during charging of the storage system and the temperature difference reduced with time. An interesting discovery was that the temperature difference was less than 5 ˚C during discharging which predicts that the heat pipe will work well if the cooking is done in close doors or during night cooking.
Cooking experiment was done on this system by boiling 2.5 kg of water on the following day. Two sets of water was boiled by placing an aluminium pot container on the condenser part of the heat pipe and the results are displayed in figure 9. The first boiling took 2 hours 30 minutes before boiling while in the second experiment, the water boiled in 1 hour and 10 minutes, the difference can be said to be because the first experiment began when the system is still charging while the second was done when the system is fully charged.

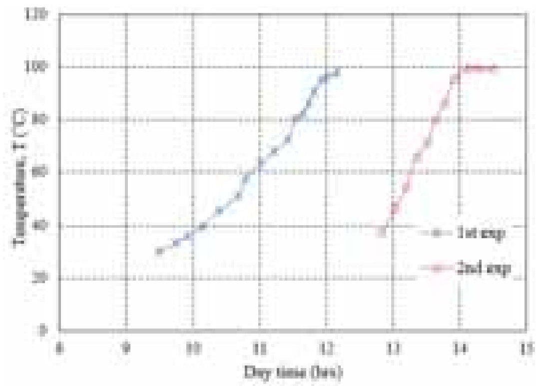

Figure 9: Water boiling Experiments on the heat pipe

The no load experiment was also performed on the spiral copper head cooking type and the result is shown in figure 10 below

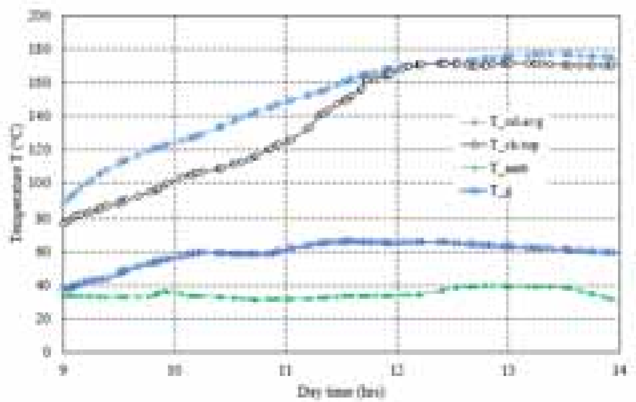

Figure 10: Cook top, oil and ambient temperature as a function of day time (08 June 2015)

The average solar radiation during the testing was 601Wm^{-2}, the storage tank became fully charged after four hours although the oil temperature was above 80 ˚C when the reading began. The initial temperature difference was less than 10 ˚C because the spiral tube was left inserted in the oil from the previous day experiment, however during the oil charging the temperature difference increased to above 20 ˚C and this temperature difference however diminished towards the time the system was almost going to be fully charged. This predict that the spiral cooker can only be effective when the system is fully charged and when the storage oil temperature fluctuation is reduced.

Cooking oil of 3 kg was used as food to be cooked on the spiral copper tube and the result is shown in figure 11 but a great temperature difference was recorded between the oil and the spiral copper tube.

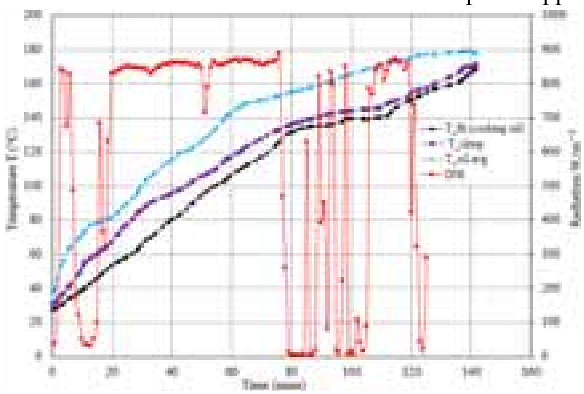

Figure 11: Cooking oil, storage oil, cook top, solar radiation as a function of experiment time

The cooking oil reached 100 ˚C after 60 minutes; the cooking oil temperature and the temperature of the spiral cooker head displayed a reduction in their temperature difference as the cooking continued and at 160 ˚C, the two temperature were almost at parity.

4. Conclusions and Recommendations

In the experiments presented in this paper, the two most popular cooking section types for indirect solar parabolic cookers had been tested under similar conditions at the same location. It can be concluded that the two types are actually a viable technology for the future. The heat pipe was noticed to transfer heat from the storage tank to the cooking section faster than the spiral cooker head and was seen to be able to work more effectively during discharging. However the spiral copper tube also performed well when the cooking was be done for a longer period, the spiral cooker head is cheap and the longer cooking time could be traced to the small surface area (single arm sucking the hot oil) of the tube inserted in the oil, as compared to the heat pipes in which several pipes were inserted into the oil. The spiral cooker is expected to perform better if an array of the tubes are combine to allow more hot oil flow to the head. Although the heat pipe cooked faster, the spiral head was preferred in this experiment because of the simplicity of its manufacturing and less complexity in its theoretical analysis. More experiments are still ongoing to use other criteria for this comparison to make necessary recommendations.

Nomenclature

Quantity	Symbol	Unit
Specific heat	c	J kg^{-1} K^{-1}
Solar radiation	G_b	W m^{-2}
Extinction coefficient$^+$	K	m^{-1}
Mass	m	kg
Emittance	ε	
Thermal resistance	R	
Density	ρ	kg m^{-3}

Subscripts

Quantity	symbol
ambient	a
food	fd
cook	ck
convection	conv
Heat pipe	hp
Hot oil	h_oil
Pot bottom part	pot,b
The side of the pot	pot,s
Storage to ambient	sto-a

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