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Study and Feasibility of a Flat Collector Cooker using Vegetal Heat Transfer Fluid

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Solar cookers currently produced are solar systems that use parabolic heat transfer to concentrate sun rays on a cooker. The new trend is focus on the cooker that uses a flat collector operating as a thermosiphon where the heat transfer fluid (oil) flows by natural convection. They are developed to address household needs at a lower cost, making them popular both in terms of research and use. Some of vegetable oils were previously investigated and which could be used as heat transfer fluids in such systems. A digital study using vegetable oil called "Kibi oil", an artisanal oil produced in Côte d'Ivoire, as a coolant, was conducted under poor weather conditions to calculate temperatures that could be reached in these cases. In the Sahelian zone, conditions are much better than these, and we can expect fairly excellent results.

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This study focused on temperature variation at different areas (1, 2, 3 and 4 specified in the diagram) of the cooker, on the mass flow of the fluid throughout the study day and to some quantities which enable to follow the performance of the solar collector of the stove. Sunlight measurements used are those of the city of Abidjan made in September, a very cloudy day with poor weather conditions. Temperature T3, very close to that of the hot plate, was around 110 °C between 10:30 am and 12:30 pm, which enables to cook certain dishes during this period. It should be noticed that at the exit of the flat panel collector, over the same period, the temperature is around 120 ° C. At that same time, the collector efficiency varies around 30%.

Keywords: Solar cooker; flat plate; heat transfer fluid; thermosiphon; temperature.

NOMENCLATURE

T : Temperature (°C or K)
Kext : Coefficient of heat exchange at the ambient conditions (kW/K m2)
Dt : diameter of pipe (m)
Q : volume throughput (m3/h)
ρ : density of the coolant (kg/m3)
Cp : heat-storage capacity of the coolant (kcal/kg °C)
L : length of pipe (m)
Rd1 : optical factor of the collector loss (%)
Rd2 : thermal loss ratio of the collector (kW/K m2)
Φs : total solar radiation receipt by the collector (kW/m2)
Hw : convection coefficient due to the wind (kW/K m2)
HRv : coefficient of radiation towards the back of the collector (kW/K m2)
HPCL : overall heat transfer coefficient by natural convection
KCL : linear loss ratio of loads (kg/h m4)
g : intensity of terrestrial gravity (m s-2)
Rcap : output of the sensor (%)
hc : coefficient of the sensor heat exchange (kW/m2)
ΔEsol : solar energy receipt by the coolant (kW/m2)
ΔS : zone of pipes surface of the collector (m2)
λ : conductivity of insulator (kW/K m2)
e : thickness of insulator (m)

1. INTRODUCTION

Currently, several laboratory studies have reached various possible applications of solar energy in thermal and electrical fields. These include, among others, solar water heaters [1], solar cookers [2], [3], [4], solar ovens, electricity produced from solar energy for household needs. In this study, we will test the feasibility of a solar cooker model with natural flow (thermosiphon) of heat transfer fluid, namely vegetable oil which was determined in a previous studied [5]. In general, solar thermal systems with natural circulation of heat transfer fluid, such as solar water heaters, use water as heat transfer fluid [1]. We have chosen vegetable oil because this heat transfer fluid enables to obtain fairly high temperatures and for its high calorific value compared to that of water, offering therefore an interesting productivity.

In this study, we presented temperature variation at different areas of a solar cooking device piping equipped with a flat collector with natural convection of the heat transfer fluid under actual solar radiation available between 6 a.m. to 5 p.m. in September in Abidjan, Republic of Côte d'Ivoire. The typical day of experimentation was characterized by a significant cloud movement at regular intervals. Solar radiation measurements were made in Abidjan in that same month of September. We have also studied the temperature variation of the cooker collector [3], [6] during the same period, as well as the coolant fluid rate in the system. Lastly, we have started to study the thermal loss coefficient of the collector and its optical loss factor.

The advantage of such systems is their fairly low costs compared to systems equipped with parabolas. In most of Sub-Sahelian Africa countries, around 80% to 90% of the populations live in rural areas, with very low purchasing power. The efficiency of such systems and attempts to disseminate them will be very successful because of their affordable costs and the free source.

2. MATERIALS AND METHODS

2.1 Diagram of the Cooker Equipped with Flat Collector

The pipes enable the heat transfer fluid to circulate naturally by thermosiphon in the circuit when the flat collector plays its heating role (the hot fluid tends to rise in altitude). Areas 1 and 2 are the entry and exit of the flat panel collector, respectively. Areas 3 and 4 are the entry and exit of the liquid coolant storage tank. With the digital simulation of the system, fluid temperature at the area 3 is very close to that of the heating plate.

2.2 Mathematical Equations

To determine the physical and thermal quantities of the heat transfer oil used ("KIBI oil") [3], [5], the material used is widely described in the paper [5]. We are dealing with mathematical equations that rule on the quantities studied in this work. [3] [7] [8] [9]:

$$TLt = T_0 + (T_a - T_0)\left[1 - EXP\left(-\frac{Kext\,\pi\,Dt\,Lt}{Q\,\rho t\,Cp}\right)\right] \tag{1}$$

By applying this formula to the rising and falling pipes, we successively obtain:

$$T_3 = T_2 + (T_a - T_2)\left[1 - EXP\left(-\frac{Kext\;\pi\;D_T\;L_{23}}{Q\;\rho_{23}\;Cp}\right)\right] \tag{2}$$

$$T_1 = T_4 + (T_a - T_4)\left[1 - EXP\left(-\frac{Kext\;\pi\;D_T\;L_{41}}{Q\;\rho_{23}\;Cp}\right)\right] \tag{3}$$

$$T_4 = T_3 + (T_a - T_3)\left[1 - EXP\left(-\frac{Kext\;\pi\;D_T\;h_C}{Q\;\rho_{34}\;Cp}\right)\right] \tag{4}$$

We have 3 equations with 4 unknowns to solve this system, which is mathematically impossible. Hence the use of computer. Visual Basic 2008 was used to write and run the computer program.

The following equations were set to calculate the other physical quantities of the collector [3] [7] [8] [9].

$$\Delta E_{sol} = R_{d1} * \Phi_S * \Delta S \tag{5}$$

$$R_{d1} = \frac{\alpha\,\tau}{1-[(1-\alpha)\,\rho_d]} \tag{6}$$

For a single glazing, we can write:

$$R_{d2av} = \frac{1}{\frac{1}{Hw+HRv}+\frac{1}{HPCL+HRL}} \tag{7}$$

$$R_{d2ar} = \frac{\lambda_{is}}{e_{is}} \tag{8}$$

$$R_{d2} = R_{d2av} + R_{d2ar} \tag{9}$$

In terms of flow, we have different equations to solve, depending on the value of the Reynolds number in each section of the circuit. For the example below, the speed is laminar (Re <2 300) at any area of the circuit:

$$KCS43\,Q^2 + KCL1\;Q + g\,A = 0 \tag{10}$$

This equation must be solved to find Q in the circuit. But, for a rigorous solving of the equation, we must consider all possible speeds. And for each type of speed, the equation changes slightly.

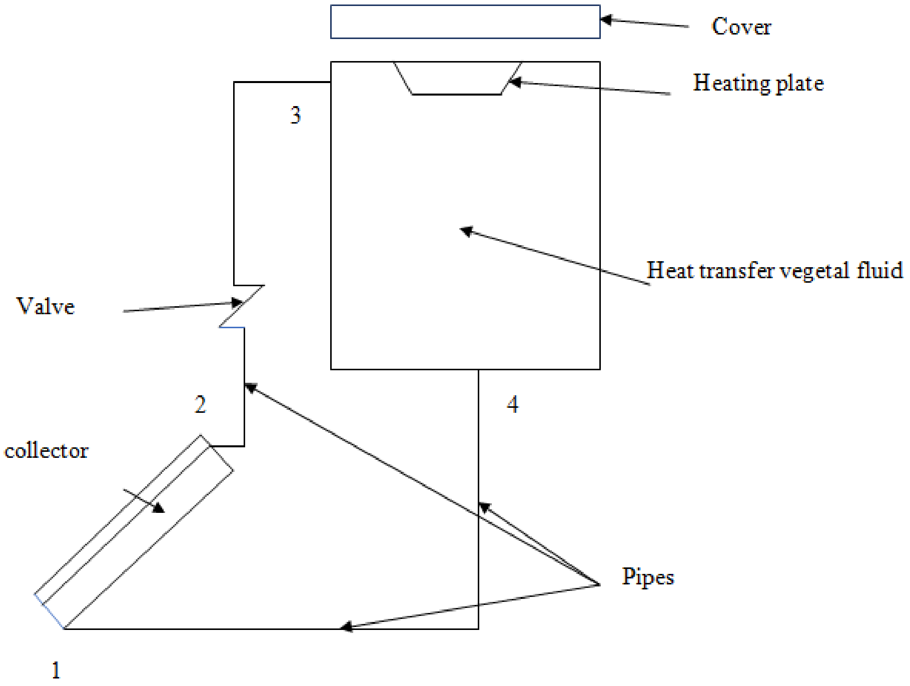

Fig. 1. Diagram of the cooker equipped with flat collector [2], [3]

3. RESULTS AND DISCUSSION

We used Origin Pro 8 to draw the various curves.

Temperatures T1, T2, T3 and T4 are presented in the diagram below.

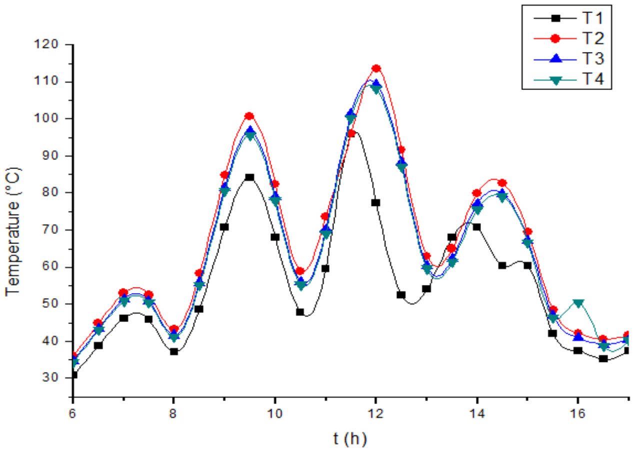

Fig. 2. Diagram of temperatures T1, T2, T3 et T4

As previously specified, the calculations are made for a very cloudy day in Abidjan with an ambient temperature not exceeding 30°C. The high fluctuation of solar radiation captured on ground [10] strongly influences the temperatures in the circuit. There are 2 significant peaks between 8 am and 10:30 am and between 10:30 am and 12:30 pm. Temperature T3, which is very close to the temperature of the hot plate, is nearly 110°C. These intervals correspond to the usual food cooking times. It should be noted that solar radiation intensity is higher in Burkina Faso, notably in the Central Plateau and the Northern Regions of the country with less clouds. In future studies for this region of West Africa, it will be shown that the temperature of the hot plate can reach 160 ° C and even higher than this in periods of significant peaks of solar radiation received on ground [10]. In these regions, the ambient temperature fluctuates between 45°C and 50°C.

The mass flow rate of the heat transfer fluid is represented here according to time:

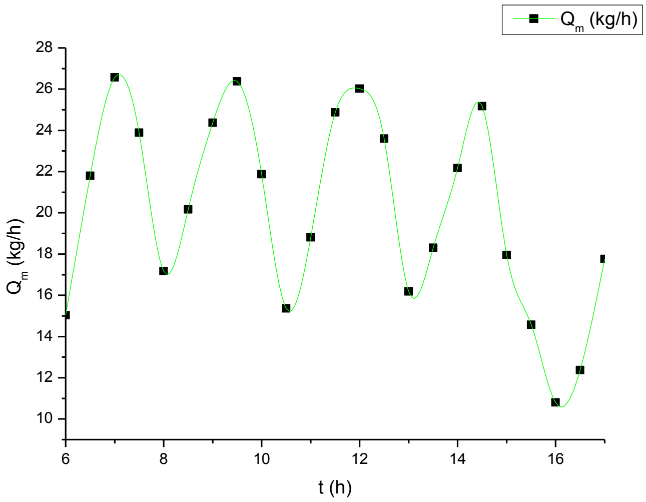

Fig. 3. Variation of the mass flow in pipes [11]

The strong circulation of clouds on the day when the solar radiation measurements were made caused a large fluctuation of results. Flow peaks around 27 kg / h are recorded. However, at around 4 p.m., we have the lowest flow rate at around 10 kg / h. The flow rate is used to calculate the Reynolds number, when the diameter of the pipe is given. This number shows whether the flow rate at that precise moment is either laminar or turbulent. Fluctuations in the mass flow rate of the heat transfer fluid show that we go regularly from one flow rate to another (from laminar to transient (located between laminar and turbulent) and sometimes to turbulent). The quadratic flow rate equation given is only valid for the laminar rate.

For other rates, the equation changes slightly and is sometimes of third degree.

Rd1 and Rd2 variation curves are as follow:

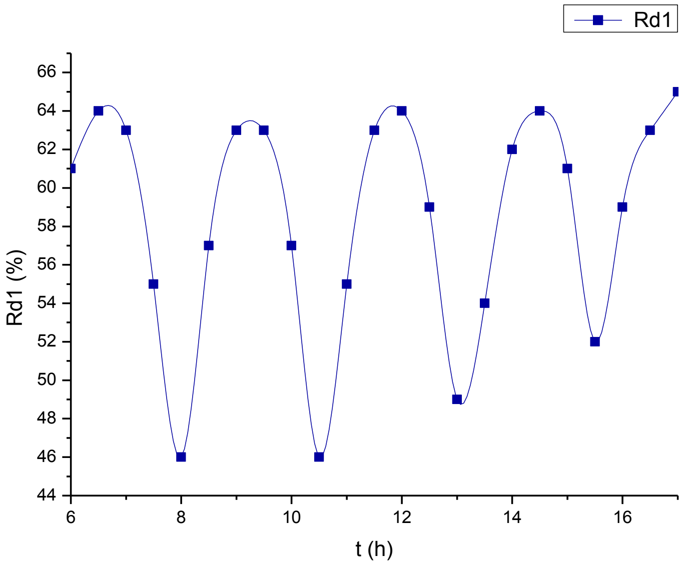

Fig. 4. Variation of the optical loss factor of the collector [10]

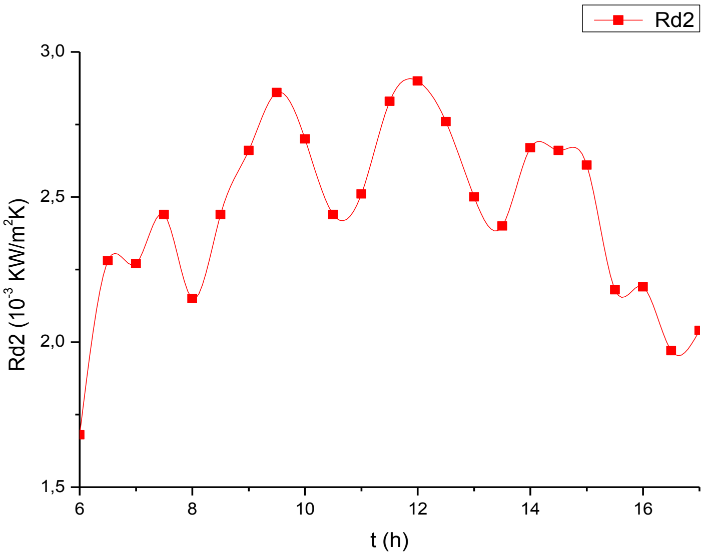

Fig. 5. Variation of the thermal losses of the collector [12]

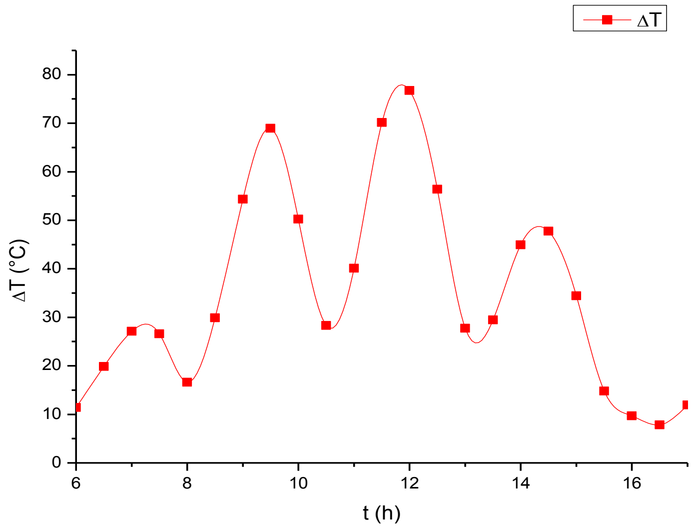

Fig. 6. Variation of temperature gap between the collector and the surrounding environment

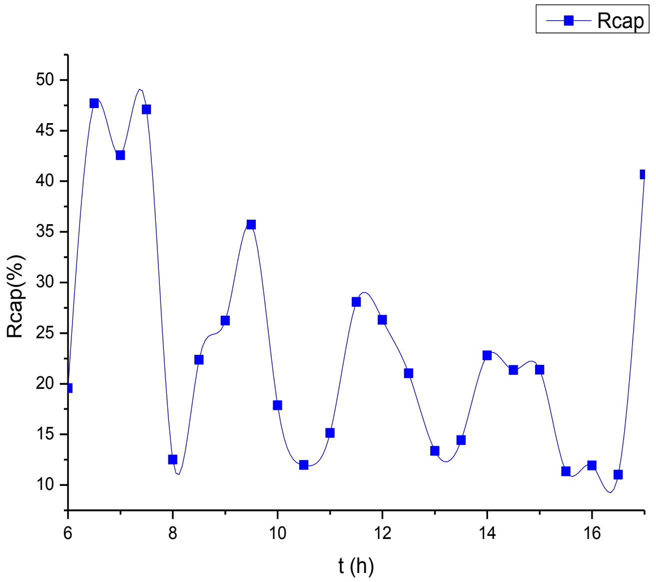

Fig. 7. Variation of the efficiency of the collector according to the time [12]

The optical loss factor of the glazing also fluctuates a lot given the conditions under which the solar radiation measurements are made. Peaks of 64% are encountered in some areas, which clearly shows (formula below) that the efficiency of the cooker collector cannot go beyond. The minimum is around 40% at specific times [13]. The pace and the way these fluctuations occur show that food cooking periods clearly match the trend of these curves. Rd1 and Rd2, once known, enable to calculate the cooker collector efficiency using the following formula:

$$R_{cap} = Rd1 - Rd2\left[\frac{\left(\frac{\theta s+\theta e}{2}\right)-\theta ext}{\phi s/\Delta t}\right] \quad (11)$$

This formula has the advantage of not depending on the rate. When considering more closely, it can be noticed that in order to have a good performance, the glazing must be very good (very high Rd1) and have good insulation in the collector [13], which minimizes thermal losses (very small Rd2). Thus, one part of the term of the equation in square brackets (the one at the top) is shown in Fig. 6 according to time. We can notice a strong fluctuation during the day due to the regular clouds movements. Using the data from the previous figures enable us to calculate flow data which allow us to draw the Fig. 7. The thermal losses in the collector are significant between 9 a.m. and 2 p.m. despite fluctuations. The peak reached is nearly 3 kW / m^2. However, at the beginning of the day or at the end of the day, these heat losses are quite low and are around 2 kW / m^2.

We can notice that the collector performs well in the morning between 6 a.m. and 8 a.m. This rate reaches almost 50% at times. But very quickly, it decreases to around 35% and even 25%. Towards the end of the day, it is not good at all because it is around 10%. However, after 4:30 p.m., it rises very quickly to reach 40%. It should be noted that in Abidjan, on that day, the ambient temperature reached a maximum of 30 ° C around 1p.m. and around 4p.m., which corresponds to a period of cool weather in Ouagadougou. Studies conducted by Mathias Rommel [1] in the Federal Republic of Germany (FRG) show that one could reach up to 150 ° C with oil used as a heat transfer fluid (we do not know the nature of this oil)

4. CONCLUSION

This study has enabled to state some mathematical equations necessary to calculate temperatures at specific areas of a solar cooker with natural circulation of the heat transfer fluid and at equal time intervals. It was also possible to analyze the optical loss factor of the collector, its thermal loss coefficient and its efficiency during these same time intervals. In these figures, we notice a lot of significant fluctuations due to weather conditions of the day in Abidjan. Studies conducted by Mathias Rommel in the FRG show that we could reach up to 150 ° C with oil used as heat transfer fluid (we do not know the nature of this oil). In the current study, the temperature is around 120 ° C in adverse weather conditions as for Abidjan. Concerning Ouagadougou, where solar radiation is much higher, it should reach 160 ° C in periods of high temperatures (the ambient temperature often exceeds 47°C). The scientific interest of this study is to encourage the use of this type of cookers by households, notably by rural families in the Sub-Sahelian countries where the rural population is very high, and where the fight against the excessive wood cutting is very tough. Above all, it should be noticed that this is one of the parts in the world where solar radiation received annually is very huge. Solar energy remains ultimately the free and clean one.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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