Study and feasibility of a solar cooker with plane sensor using a vegetable fluid coolant

Abstract :
Concentration solar cookers developed until our days are solar systems using the parabolic collector to concentrate the solar rays on a focus. The new trend is the cooker using a flat collector operating in thermosyphon where the heat transfer fluid (oil) circulates by natural convection. They are intended for the domestic needs at lower cost, which gives them a popularity on the level of research and use. In this work, we were interested in the variation of the temperature at different points of the cooker, in the mass flow rate of the fluid throughout the day and in certain parameters which allow you to monitor the performance of the stove's solar collector. The solar radiation measurements used are those of the city of Abidjan in September, where the days are very cloudy with adverse weather conditions.

Key words: Solar cooker, plane collector, coolant, thermosyphon, temperature

NOMENCLATURE

T : temperature (°C or K)
Kext : coefficient of heat exchange at the ambient conditions (kW/K m^2)
Dt : diameter of pipe (m)
Q : volume throughput (m^3/h)
ρ: density of the coolant (kg/m^3)
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 m^2)
Φs : total solar radiation receipt by the collector (kW/m^2)
Hw : convection coefficient due to the wind (kW/K m^2)
HRv : coefficient of radiation towards the back of the collector (kW/K m^2)
HPCL : overall heat transfer coefficient by natural convection
KCL : linear loss ratio of loads (kg/h m^4)
g : intensity of terrestrial gravity (m s^{-2})
Rcap : output of the sensor (%)
hc : coefficient of the sensor heat exchange (kW/m^2)
ΔEsol : solar energy receipt by the coolant (kW/m^2)
ΔS : zone of pipes surface of the collector (m^2)
λ : conductivity of insulator (kW/K m^2)
e : thickness of insulator (m)

1. Introduction

To date, many laboratory studies have led to different types of applications of solar energy in the thermal and electricity fields. There are already solar water heaters [1], solar cookers [2], [3], solar ovens, electricity generated from solar energy, for domestic needs. In this study, we will carry out a theoretical study of a solar cooker with natural circulation (thermosiphon) of the circulating heat transfer fluid [4] which is in this work a vegetable oil. We have evaluated the physical an thermal properties of this vegetable oil in precedent study [3].

In general, solar thermal systems with natural heat transfer fluid such as solar water heaters use water as the heat transfer fluid [1]. We choose to use vegetable oil because this heat transfer fluid makes it possible to obtain fairly high temperatures and its high calorific value compared to that of water, makes it possible to achieve interesting energy efficiency.

In this work, we present the variation of the temperature at different points of the piping of a solar cooking device with flat collector with natural convection of the heat transfer fluid under conditions of radiation available between 6 a.m. to 5 p.m. during the month of September in Abidjan, Republic of Ivory Coast.

The typical day of experimentation was characterized by the passage of a lot of clouds. Solar irradiance measurements were taken in Abidjan in September. We also study the variation of the temperature of the collector ([4], [5]) of the cooker during the same period, as well as the flow rate of the heat transfer fluid in the system. Finally we initiated a study of the thermal loss coefficient of the sensor and its optical loss factor.

2. Materials and method

a. Diagram of the cooker :

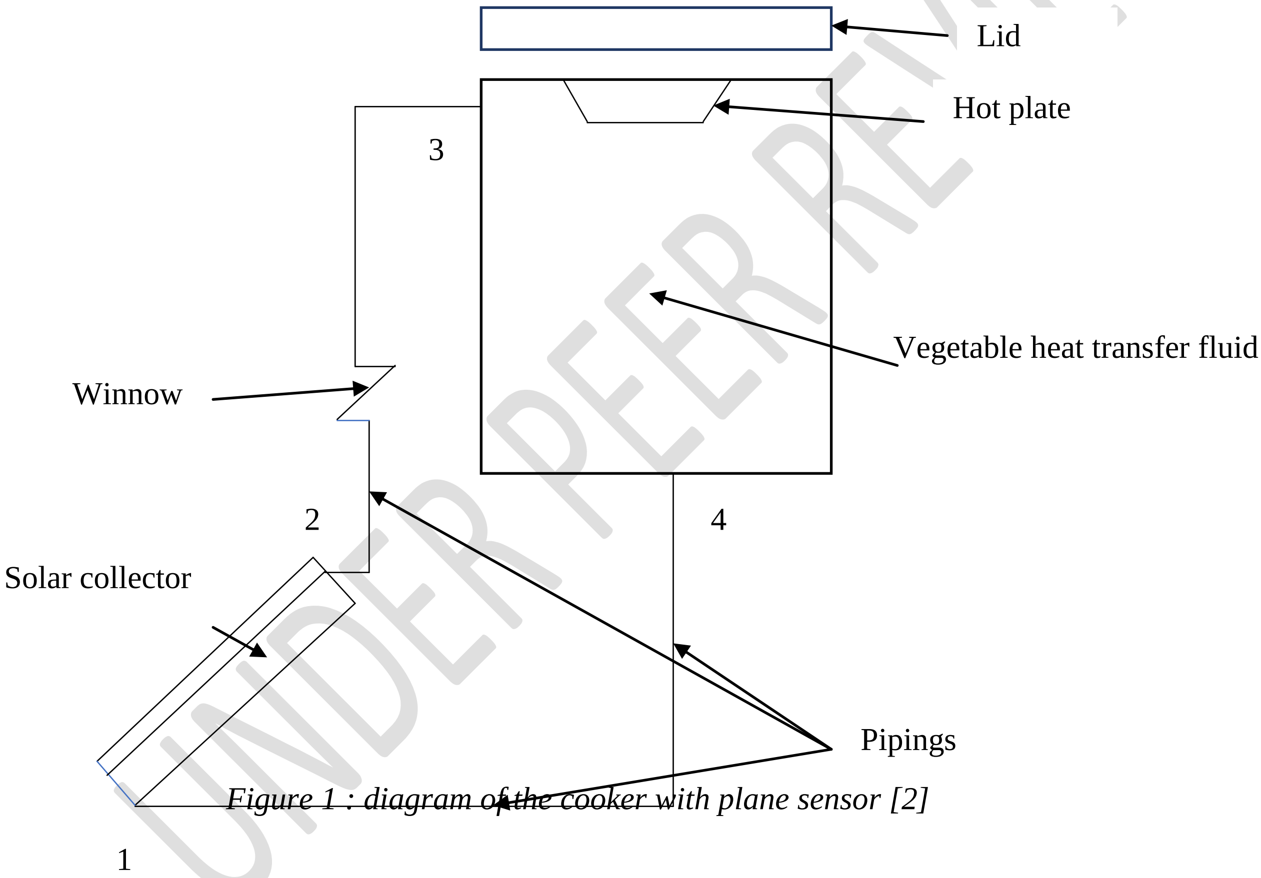

Figure 1 : diagram of the cooker with plane sensor [2]

b. Mathematical equations :

For the determination of the physical and thermal sizes of oil coolant used ("oil of KIBI") [2], [3], the material used is largely described elsewhere [3]. We will focus on the mathematical equations which govern the quantities studied in this work [2] [6] [7] [8] :

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

By applying this formula to pipings rising and downward, we obtain successively:

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

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

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

We have 3 equations with 4 unknown variables to solve which is mathematically impossible. It is thus essential to use computer tool. We used for the writing and the execution a program using the software Visual BASIC 2008. The following equations were used for the determination of the other physical sizes of the sensor ([2] [6] [7] [8]).

$$\Delta E_{sol} = R_{d1} * \Phi_S * \Delta S \qquad (5)$$

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

For only one glazing, we can write :

$$R_{d2av} = \frac{1}{\frac{1}{Hw+HRv}+\frac{1}{HPCL+HRL}} \qquad (7)$$

$$R_{d2ar} = \frac{\lambda_{is}}{e_{is}} \qquad (8)$$

$$R_{d2} = R_{d2av} + R_{d2ar} \qquad (9)$$

Depending on the value of the Reynolds number in each section of the circuit, we obtain various equations to be solved for the flow. We will present here, the case where the mode is laminar ($Re < 2\,300$) at any point of the circuitry :

$$KCS43\,Q^2 + KCL1\ Q + g\,A = 0 \qquad (10)$$

This equation is to be solved to derive Q in the circuit. But, in a rigorous resolution, it is necessary to consider all the possible modes. And for each type of mode, the equation changes slightly.

3. Results and discussions

For the plotting of the different curves, we used the software Origin Pro 8.

- The temperatures T1, T2, T3 and T4 are presented in the following graph.

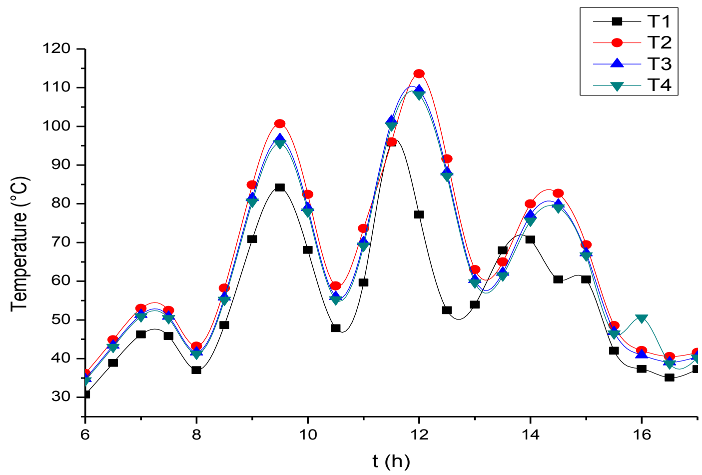

Figure 2 : chart of the temperatures T1, T2, T3 and T4

As mentionned above, the calculations are made for a very cloudy day in Abidjan. The strong fluctuation of the solar radiation collected on the ground [9] strongly influences the temperatures in the circuit. We notice two significant peaks between 8 am and 10 :30 am and between 10 :30 mn am and 12 : 30 mn pm. The temperature T3 which is very close to the temperature of the hotplate, is around 120 °C. These intervals correspond to usual periods of cooking of food. Let us notice that the intensity of the solar radiation is more significant in Burkina Faso, especially in the central plate and the North of the country with less clouds in the sky. In a forthcoming publication for this area of West Africa, we will show that we can reach 160 °C and even exceed it during the period of significant peaks of the solar radiation.

- The mass throughput of the thermal fluid is represented below versus time :

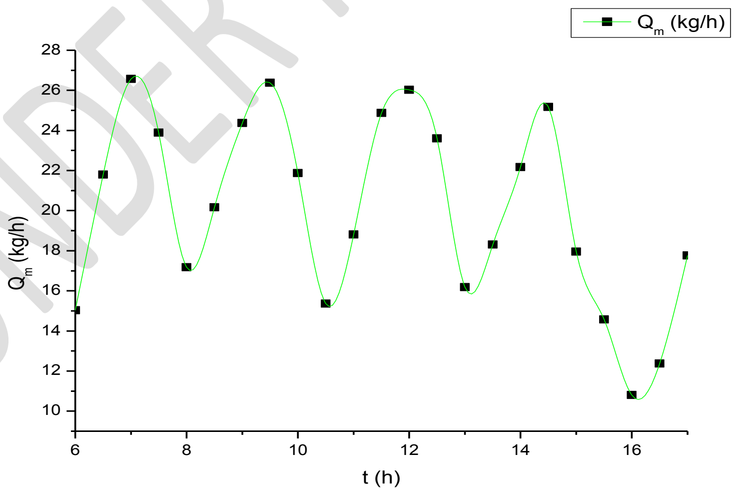

Figure 3 : variation of the mass throughput of the fluid in pipings

The strong circulation of clouds the day of measurements of the solar radiation brought a strong fluctuation of the results. We note peaks of flow close to 27 kg/h. On the other hand towards 4 pm, we low have the flow which is in the neighbourhoods of 10 kg/h. The flow makes it possible to calculate the Reynolds number knowing the diameter of piping. This number makes it possible to know if the mode of flow at this moment is either laminar, or turbulent. The fluctuations of the mass throughput of the coolant show that we passe regularly from a mode of flow to another (of laminar with the transient (located between the laminar one and the turbulent one) and sometimes with turbulent). The quadratic equation of the flow that we gave is valid only for the laminar flow. For the other mode, the equation changes slightly and is sometimes with the third degree.

- The curves of Rd1 and Rd2 variations are presented as follows :

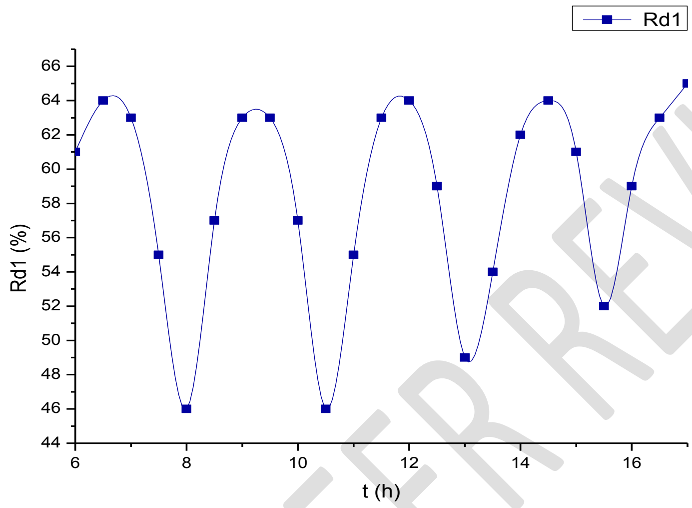

Figure 4 : variation of the loss of optical factor of the collector

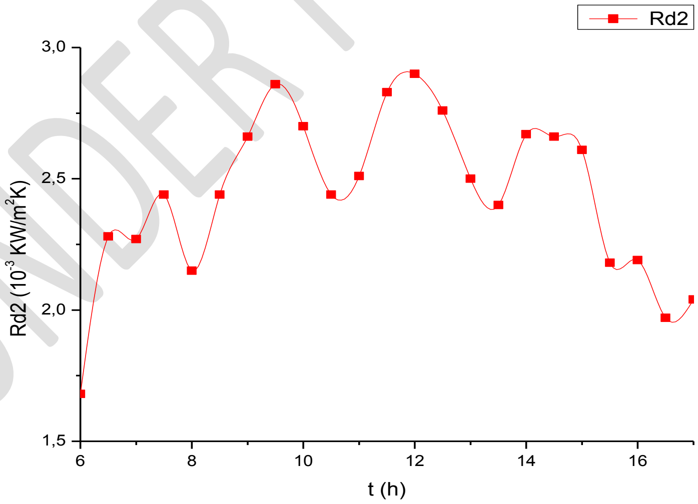

Figure 5 : variation of the sensor thermal losses

The factor of optical loss of the glazing also fluctuates very much taking into account the conditions under which solar measurements of radiations were carried out.

We note peaks of 64% by places, which clearly shows (formula below) that the efficiency of the collector of the cooker cannot go beyond. The minimum turns around 40% at specific times. The rhythm and the manner of these fluctuations, indicate that the periods of cookings of food suit well with the shape of these curves. Rd1 and Rd2, once known, make it possible to calculate the cooker collector output by the following formula :

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

This formula has the advantage to be flow independent. Looking at it more closely, we note that to have a good performance, the glazing must be very good (very high Rd1) and have good insulation at the level of the collector, which minimizes thermal losses (very small Rd2). Thus, part of the member between hooks (that of in top) is represented in figure 6 according to time.

We observe a strong fluctuation during the day due to the frequent passages of the clouds. Using the data from the previous figures allows us to calculate the flow data which allows us to plot Figure 7. The thermal losses on the level of the collector are more significant between 9 a.m. and 2 p.m. although there are fluctuations. The peak reached is approximately 3 kW/m^2. On the other hand, at the beginning of day or at the end of the day, these thermal losses are quite low and are around 2 kW/m^2.

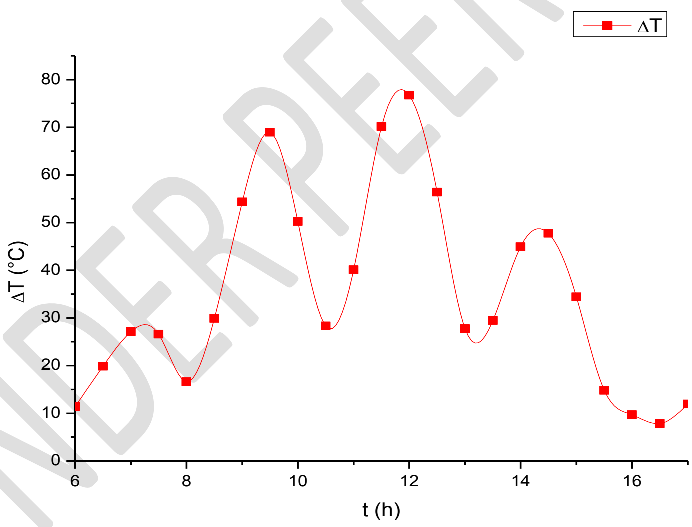

Figure 6 : Variation of the temperature difference between the collector and the ambiant conditions

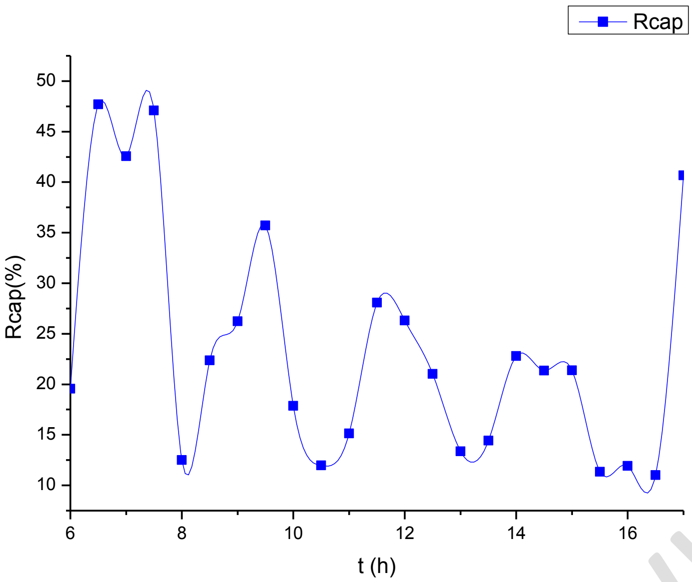

Figure 7 : variation of the collector output according to time

We note that the collector presents a good output the morning between 6 a.m. and 8 a.m. This output reach almost 50% at certain time. 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%. On the other hand, 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 at around at 1 p.m. and at around 4 p.m., which corresponds to a period of freshness in Ouagadougou.

4. Conclusion

Our study enabled us to state some mathematical equations necessary to tdetermine the temperatures at specific locations of a solar cooker with natural circulation of the heat transfer fluid and at equal time intervals. We were also able to analyze the optical loss factor of the collector, its thermal loss ratio and its efficiency during these same time intervals. In these figures, we observe many significant fluctuations due to the weather conditions of the day [9] in Abidjan. Studies carried out by Mathias Rommel in Germany ([5]) show that it could reach to 150 °C with an oil as heat transfer fluid (we do not know the nature of this oil). We, in our case, reached 120 °C under unfavourable weather conditions in Abidjan. In Ouagadougou, where the solar radiation is definitely more significant, we should reach 160 °C during the time of high heat (the ambient temperature often exceeds 47 °C).

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