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OPTIMIZATION OF YIELD OF A FLAT PLATE SOLAR WATER COLLECTOR BY SIMULATION WITH MATLAB

Yacouba Kanoute[1*], Ivan Zlatanović[1], Nedžad Rudonja[1], Vojislav Simonović[1]

[1]University of Belgrade, Faculty of Mechanical engineering, Belgrade, Serbia

[*]PhD Candidate, E-mail: kanoute1993.yk@gmail.com

Abstract: *This study consists at the modeling and the application of numerical methods in order to optimize the performance of a flat-water solar collector under the meteorological conditions of Mali, particularly in the month of January when the sunshine is low and hot water consumption significant. The results obtained show that when the thickness of the glass pane is increased from 2mm to 5mm, the instantaneous efficiency of the solar collector at the beginning increases from 41.46% to 41.49% with a maximum solar radiation intensity of 462 W/m^2 and an average wind speed of 3.5 m/s. When the thickness of the absorber is increased from 4mm to 5mm, the instantaneous efficiency of the solar collector can reach from 40.64% to 41.65%. When the absorber thickness reaches 6mm, the instantaneous efficiency of the solar collector decreases from 42.35 to 42.14%. Increasing the thickness of the collector's absorber plate can significantly improve the collector's instantaneous efficiency. Increasing the thickness of the lateral side insulation does not contribute to improving the collector's instantaneous efficiency. When the thickness of the lateral side insulation of the collector increases from 2cm to 8cm, the instantaneous efficiency of the collector increases from 53.13% to 53.0%. When the mass flow rate of the fluid increases from 0.0265 Kg/s to 0.04 Kg/s, the efficiency increases from 53.14% to 59.18%. This study also showed that these parameters have very little influence on the temperature of the heat transfer fluid.*

Keywords: *Optimization, flat plate solar collector, efficiency, simulation*

1. INTRODUCTION

The fossil fuels used for the production of energy are becoming more and more expensive and are tending to run out, while energy needs are increasing day by day with industrialization. What's more, the consumption of these non-renewable resources produces significant negative effects, such as the greenhouse gases emission, pollution, deforestation, land degradation, etc. In this context, African countries have no choice but to diversify their energy sources. Renewable energies then appear as an alternative. These energies, which use natural resources such as the sun, wind, water and biomass are clean, inexhaustible and available. This energy such as solar power is available, free, can be used in several areas such as the drying of agricultural produce, generating electricity, solar cooking, heating, the production of hot water.

Indeed, the simplest and most direct use of solar energy is the production of hot water for households and public buildings. In Mali, solar water heating is used very little because of several constraints, including the high cost of installations, the population's unfamiliarity with this type of device and, above all, the aridity of the climate, characterized by a period of cold weather (2 months/year at most), which requires a low need for hot water in homes. Mali's solar deposit is considerable, largely unexploited with very high solar irradiation (on average 6 kWh/m2/d), distributed over the entire territory for a daily sunshine duration of 7 to 10 hours [1]. Exploiting solar energy to heat water requires devices that convert solar radiation incident on the earth's surface, such as photovoltaic panels, flat plate collectors, evacuated tube collectors and concentrator collectors. Several works have been carried out on the optimization of flat-plate solar collectors, with the main aim of improving their instantaneous efficiency, which is the most significant performance [2],[3] and [4]. [5] have shown that numerical simulation methods could be applied to the study of solar collectors and obtain results very close to the experiment.

The objective of this work consists at the modeling and the application of numerical methods in order to optimize the performances of a flat-water solar collector under the meteorological conditions of Mali, particularly in January where the sunshine is very low and high hot water consumption.

The effect of parameters such as glass thickness, absorber thickness and lateral insulation thickness influencing the efficiency and temperature of the flat plate water solar collector will be studied in order to serve as a reference for an appropriate choice or local production.

2. MATERIALS AND METHODS

The flat-plate solar collector that will be modelled in our work is schematized by there figure 1. It comprises:

- A transparent cover (glazing) made of materials that are transparent to visible radiation but opaque to infrared radiation, enabling a greenhouse effect to be achieved; it also protects the inside of the collector from the effects of the environment.
- An absorber that absorbs short wavelengths solar radiation and converts it into heat. It is usually painted black to absorb virtually all radiation in the visible spectrum. It consists of a plate in which are integrated tubes through which the heat transfer fluid circulates..
- A heat transfer fluid responsible for transporting the heat stored by the absorber to the temperature source.
- Thermal insulation used to limit heat loss from the collector on the rear and lateral sides.

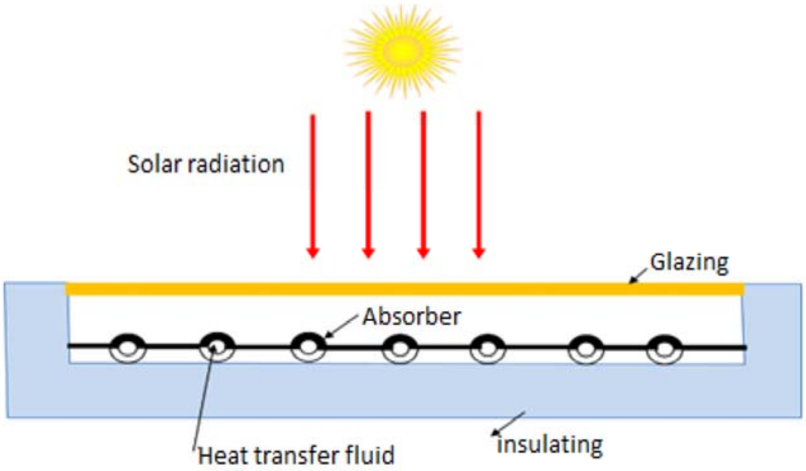

Fig.1 : Flat plate solar collector diagram [6]

2.1. **Assumptions** :

To simplify our study, the following assumptions have been made :

- The sun is assimilated to a black body
- The surface of the collector is uniformly illuminated.
- One-dimensional heat transfer through the layers of the system.
- The mass flow rate is uniform in the collector tubes.
- Heat transfer from the edges of the collector is negligible.
- The external wind speed is assumed to be always parallel to the faces of the collector.
- The heat flux received by the collector is a function of time.
- The physical properties of the materials are not a function of temperature.
- The physical properties of the fluid are not a function of temperature.
- Dust and dirt on the collector are negligible.
- The flow regime is transient.
- The temperature of the absorber plate is assumed to be equal to that of the tubes.
- The ground temperature is assumed to be equal to the ambient temperature.

2.2. **Thermal balance of flat solar collector components**

2.2.1. Energy balance of the transparent cover (glass)

The energy balance of the transparent cover can be written using the following relationship [7],[8] and [6]:

$$m_1 c_1 \frac{dT_1}{dt} = \alpha_1 S_1 I_c + S_2 \left(h_{c12} + h_{r12}\right)\left(T_2 - T_1\right) - h_{c1am} S_1 \left(T_1 - T_{am}\right) - h_{r1ciel} S_1 \left(T_1 - T_{ciel}\right) \tag{1}$$

2.2.2. Energy balance of the absorber plate

The energy balance of the absorber plate is given by [7],[8] and [6]:

$$m_2 c_2 \frac{dT_2}{dt} = \alpha_2 S_2 \tau_1 I_c - (\Psi_1 + \Psi_2)(T_2 - T_{isl}) - S_2 (h_{c12} + h_{r12})(T_2 - T_1) - h_{c23} S_{23} (T_2 - T_3) \tag{2}$$

2.2.3. Heat transfer fluid energy balance

The energy balance for the heat transfer fluid is given by [6], [8]:

$$c_3 \left(m_3 \frac{dT_3}{dt} + \dot{m} \frac{dT_3}{dx} \right) = h_{c23} S_{23} (T_2 - T_3) \tag{3}$$

$\dot{m}$: Heat transfer fluid mass flow rate (Kg/s)

2.2.4. Energy balance for insulation

The energy balance for insulation is [7],[8] and [6] :

$$m_{is} c_{is} \frac{dT_{isl}}{dt} = (\Psi_1 + \Psi_2)(T_2 - T_{isl}) - h_{ris} S_{is} (T_{isl} - T_{sol}) - h_{cis} S_{is} (T_{isl} - T_{am}) \tag{4}$$

The total energy balance which describes the thermal behaviour (heat exchange) of the collector studied is given in the form of equations (1), (2), (3), (4).

2.3. **Determination of Overall heat exchange coefficients with the environment**

Heat losses occur to the front, back and sides of the collector. These losses manifest themselves in all three modes of heat transfer.

The electrical analogy linked to the different thermal resistances during the heat exchanges carried out on the different elements of the collector is illustrated in Figure 2.

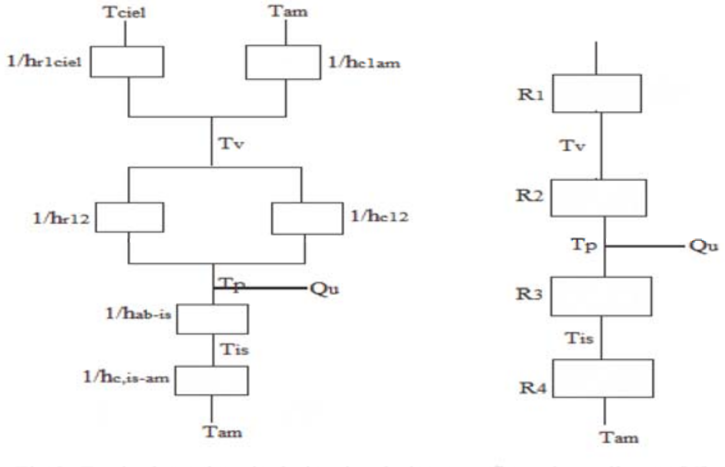

Fig.2: Equivalent electrical circuit relating to a flat solar collector [6]

2.3.1. Loss coefficient thermal to the front

Losses between the glass pane and the outside environment are essentially due to heat transfer by convection and radiation. The overall heat loss coefficient towards the front of the collector is given by the following relationship, as in Figure 2 [9], [7], [3] and [6].

$$U_{av} = \frac{1}{R_1 + R_2} = \frac{1}{\frac{1}{h_{c1am} + h_{r1ciel}} + \frac{1}{h_{c12} + h_{r12}}} \tag{5}$$

2.3.2. loss coefficient thermal to the back

The resistance due to convection is often neglected compared with that due to conduction within the absorber-insulator [9]. The value of this coefficient is less important than that of forward losses, because the collector is very well insulated at the back. Its expression is given by [9], [7], [3] and [6].

$$U_{ar} = \frac{1}{R_3} = \frac{\lambda_{isl}}{e_{isl}} \tag{6}$$

2.3.3. Loss coefficient thermal lateral

This coefficient is lower than that of the rear losses, insofar as the lateral surface of the solar collector is smaller [9], [7], [3] and [6].

$$U_{lat} = \frac{\lambda_{isl}\ \mathrm{S}_{la}}{e_{la}\ \mathrm{A}_c} \tag{7}$$

A_c : Surface of collector exposed to radiation in (m^2).

The overall heat loss exchange coefficient to the environment is the sum of the three coefficients [9], [7], [3] and [6].

$$U_{tot} = U_{av} + U_{ar} + U_{lat} \tag{8}$$

2.4. Solar collector efficiency

The instantaneous efficiency of the flat-plate solar collector is equal to the ratio between the useful flux recovered on the overall incident illumination received by the collector surface [7], [8].

$$\eta_c = \frac{Q_u}{A_c I_c} \tag{9}$$

$$Q_u = \dot{m} c_{pf} \left(T_{fs} - T_{fe} \right) = \rho_f A_f V_f c_{pf} \left(T_{fs} - T_{fe} \right)$$

I_c: incident solar flux received by the collector in (W/m^2)

Q_u: useful flux recovered by the heat transfer fluid (W).

2.5. Numerical resolution

The equations describing the different heat exchanges involved inside a collector in transient state (1) (2) (3) (4) were discretized using the finite difference method. This system of equations and the heat transfer coefficients were then solved numerically with MATLAB software using the iterative Gauss-Seidel method.

The component temperatures were taken to be equal to the ambient temperature (initialization), with the exception of the absorber temperature, which is slightly higher. Ambient temperature and global solar radiation data were collected on 01/01/2019 at the meteorological station of the Faculty of Science and Technology of Bamako.

Table 1: Input parameters for the simulation of the flat collector studied

Setting	Value	Reference
Latitude Bamako	12.65°	
Longitude Bamako	-8°	
Altitude Bamako	$338\ m$	
Dimension solar collector (m)	1.950×1.205×0.105	
β : The angle of inclination	12.65°	
n: number of slices	10	[10], [11] and [12]
D_{in} : Inner diameter of the tube	0.015m	
D_{in} : Outside diameter of the tube	0.017m	
L_{tu} : pipe length	1.8m	
S_{ab} Absorber area	2.07 m^2	
e_1 : Glass thickness _	0.00 4m	
e_2 : Thickness of the absorber	0.005m	
e_{ish} : Insulation thickness _ back	0.05m	
e_{la} : Insulation thickness _ lateral	0.02m	
τ_1 : Pane transmission coefficient	0.9	
ε_1 : Glazing emissivity	0.94	
ε_2 : Emissivity of the absorber	0.09	
ε_{isl} : Emissivity of the insulation	0.05	
α_1 : Glass absorption coefficient	0.06	
α_2 : Absorption coefficient of the absorber	0.63	
ρ_c : Glass density	2700 Kg/ m^3	
ρ_{ab} : Density of the absorber	2700 Kg/ m^3	
ρ_{isl} : Density of the insulation	40 Kg/ m^3	
c_{pc} : Specific heat of glass	840 J/ Kg.K	
c_{pab} : Specific heat of the absorber	879 J/ Kg.K	
c_{pisl} : Specific heat of the insulation	840 J/ Kg.K	

λ_c : Thermal conductivity of glass	0.93 W m $^{-1}$ K $^{-1}$	
λ_{ab} : Thermal conductivity of the absorber	204 W m $^{-1}$ K $^{-1}$	
λ_{isl} Thermal conductivity of insulation	0.041 W m $^{-1}$ K $^{-1}$	
σ : Constant of Stéphane Boltzman	$5.67\times\ 10^{-8}$ W/ (m ^{2} K ^{4})	

2.6. Validation of the numerical code

Figure 3 shows the evolution of the different temperatures of the collector as a function of time with a maximum solar radiation of the day 462 w/m^2. The absorber temperature is the highest. Indeed, the absorber absorbs most of the solar radiation thanks to its high absorption coefficient to heat the fluid. The temperature of the heat transfer fluid is fairly high compared to the other components of the collector. The difference between the temperature of the absorber and that the heat transfer fluid is mainly due to the convection coefficient of the latter, which has significant values. The temperature of the insulation is quite low compared with that of the fluid because it resists thermal loss towards the sides of the absorber as well as those due to the action of the wind. The temperature of the glass pane is low compared to the other components of the collector because of heat loss to the outside and its low absorption coefficient. Fluctuations due to solar radiation appear during the first few hours, in agreement with the result of [13], [14].

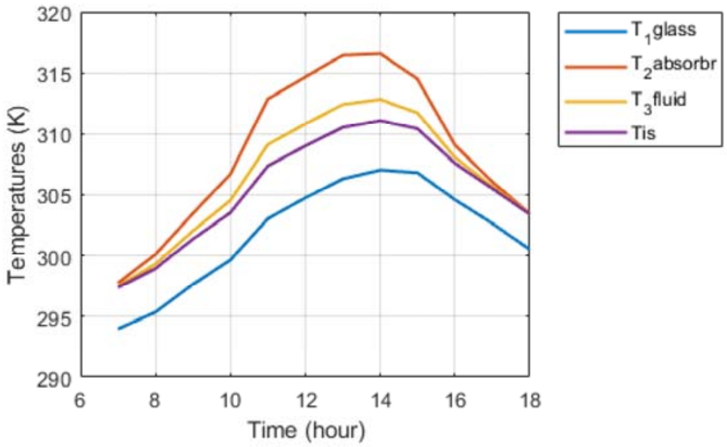

Fig.3: Evolution of the Temperatures of different components of the sensor as a function of time [6].

3. RESULTS AND DISCUSION

In Figures 4-9, we present the numerical results obtained from the flat-water collector with the main characteristics given in Table 1. The temperatures of the fluid, glass and insulator at the collector inlet are taken to be equal to the ambient temperature at initialization, except for the temperature of the absorber, which is slightly higher by one, in order to study the effect of several operating and design parameters on the transient performance of the collector.

3.1. Temporal variation in global solar radiation and ambient temperature

The intensity of solar radiation and ambient temperature as a function of time recorded on 01/01/2019 by the radiometric station located on the site of the Faculty of Science and Technology is shown in Figure 4. At 7 a.m., the intensity solar is 30.90 W/m^2, and increases as time goes by, until reaching the peak with a value of 462.079 W/m^2 around 1 p.m., then decreases about 5.8 W/m^2 at the end of the experiment.

It can be seen that the ambient temperature varied throughout the day. As shown in Figure 4, at the start of the test, the ambient temperature is low, with a value of 297.211 K, and it begins to increase as time passes until it reaches a maximum value of 308.064 K around 3 p.m., then it decreases.

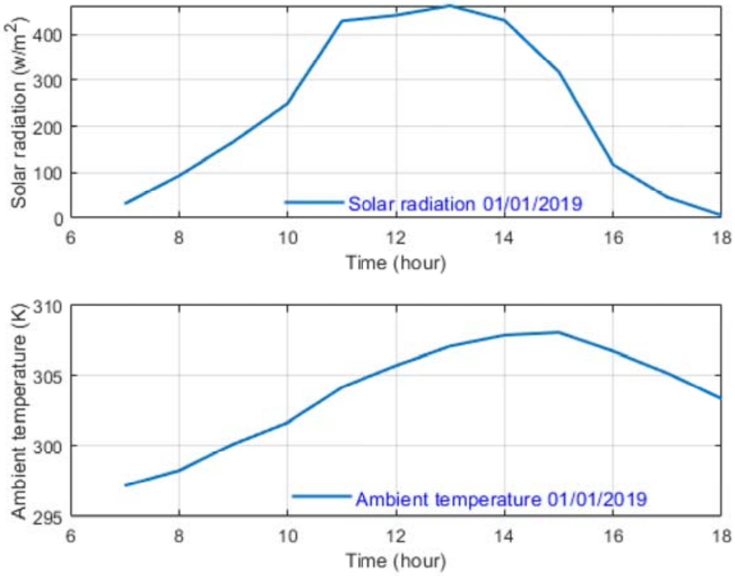

Fig.4: Variation in solar intensity and ambient temperature as a function of time.

3.2. Effect of glass thickness on collector efficiency

According to figure 5, we note that the instantaneous efficiency of the collector increases little at the beginning with the increase in the thickness of the glass pane for a solar radiation lower than 462 w/m^2 and an average wind speed of 3.5 m /s. Indeed, the greater the thickness of the glass, the greater its heat capacity and the better its thermal inertia, consequently a lower transmission coefficient, hence the reduction in collector temperature which results in a lower efficiency.

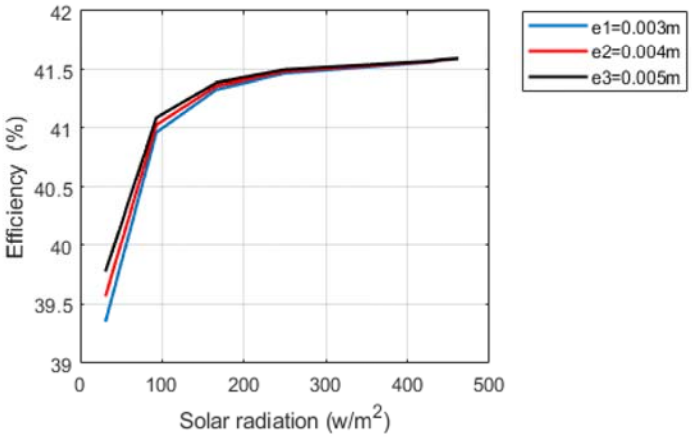

Fig.5: Evolution of efficiency as a function of solar radiation for different values of glass thickness.

3.3. Effect of absorber thickness on collector efficiency

Figure 6 clearly shows that the instantaneous efficiency of the solar collector increases with the first two values of the absorber thickness, then decreases with the last value of the thickness. Indeed, increasing the thickness of the absorber plate increases the contact surface between the absorber plate and the collector tubes, and then reduces the resistance to thermal conduction, so that the heat from the absorber plate is more easily transferred to the working fluid inside the collector tubes, and the instantaneous efficiency of the collector is improved.

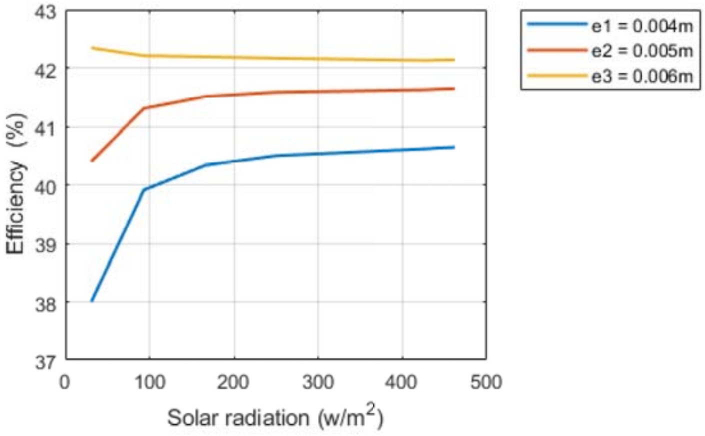

Fig.6: Evolution of efficiency as a function of solar radiation for different values of absorber thickness

3.4. Effect of lateral side insulation thickness on the collector's instantaneous efficiency

Figure 7 shows that there is almost no difference in the variation of the collector's instantaneous efficiency with different thicknesses of the lateral side insulation used in this study. The efficiency increases slightly with decreasing thickness of side insulation. This is because it is less exposed to the thermal fluctuations produced by the direct absorption of solar heat.

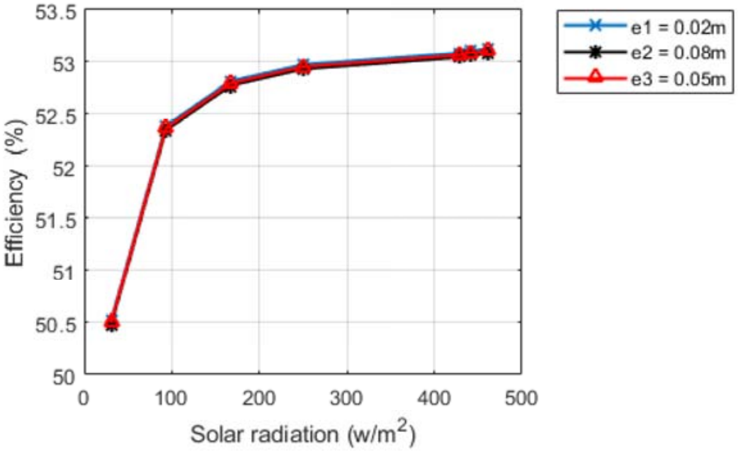

Fig.7: Evolution of efficiency as a function of solar radiation for different values of lateral insulation thickness.

3.5. Effect of mass flow rate on collector efficiency and heat transfer fluid temperature

It appears in figure 8, the evolution of the instantaneous efficiency according to the mass flow of the fluid. Indeed, increasing the mass flow rate of the fluid increases the speed of the fluid flow, promoting heat transfer by convection between the absorber plate and the heat transfer fluid, and therefore increasing the efficiency of the collector. On the other hand, the higher the flow velocity, the shorter the time taken to heat the fluid, resulting in a reduction in the temperature of the heat transfer fluid (Figure 9).

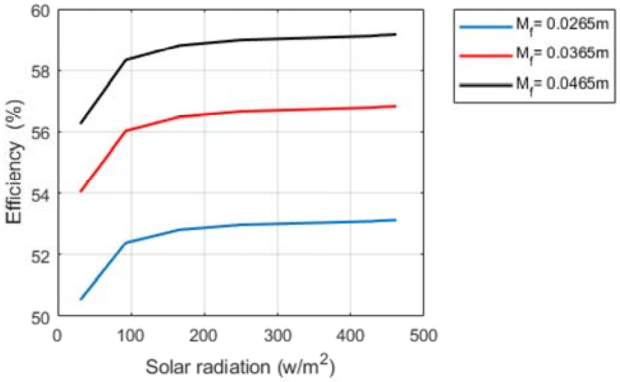

Fig.8: Evolution of efficiency as a function of solar radiation for different mass flow rate values.

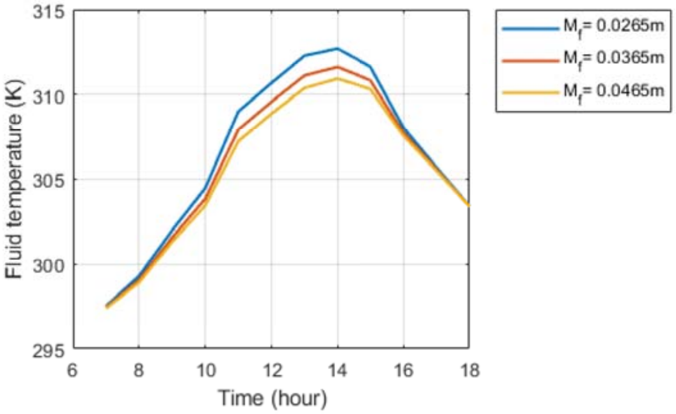

Fig.9: Evolution of heat transfer fluid temperature as a function of time for different mass flow rate values.

4. CONCLUSION

This study made it possible to elaborate a numerical model, to simulate some external (ambient temperature, solar radiation) and internal (thickness of the various components of the collector and the mass flow rate of the heat transfer fluid) parameters influencing the efficiency and the temperature of the heat transfer fluid of the flat-plate water solar collector in January under the weather conditions in Mali. The results showed that for a maximum solar radiation of 462 W/m2 and a wind speed of 3.5 m/s:

- Efficiency increases little at the beginning of the day, when the thickness of the glass increases from 0.003 to 0.005 m ;

- When the thickness of the absorber increases from 0.004 to 0.005 m, the efficiency increases and for 0.006 m, the efficiency decreases;
- LeThe efficiency decreases when the thickness of the lateral insulation increases from 0.02m, 0.05m and 0.08m;
- L'augThe increase in fluid mass flow leads to an increase in efficiency, reaching a maximum value of 59.18%

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