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Research Article

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Numerical Simulation of a Solar Thermal Collector Model for the Production of Hot Water Sanitary (HWS): Comparative Study of Two Nigerien Cities (Niamey and Zinder)

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Abstract Fossil fuel energies and nuclear energy remain the most used energy sources in developing and emerging countries. However, all scientists and policy makers unanimously in agree and are aware that the use of renewable energy sources such as solar energy is indeed one of the main factors for sustainable development and for the protection of the environment of any nation in the world. Niger, with its geographical location (between parallels 11°37 and 23°33 north latitude and meridians 0°10 and 16° west and east longitude) is one of the sunniest areas in the world (more than 2,300 kWh / m^2 / year).

In this work, we present a theoretical study of the outlet temperature of domestic hot water, heated by a single-pane solar collector. The mathematical modeling equations required the use of five (5) experimental parameters which are: global solar radiation, wind speed, insolation duration, minimum temperature and maximum temperature. The yield studies of this sensor were carried out for the cities of Zinder and Niamey, Niger. The simulation of the sensor behavior was performed under the MATLAB MR2015a software environment. The analysis of the results showed fairly high returns (67.5% in Zinder and 62% in Niamey) for the year 2009. For this period, we find that the yield is higher in Zinder than in Niamey. This work could be used to design a single-pane solar collector in a given locality in the Sahel region to produce domestic hot water for maternity services or for domestic use during cold weather.

Keywords solar collector, hot water, simulation, wind speed, solar radiation

1. Introduction

During cold periods, the demand for domestic hot water (HCW) increases more and more in maternity centers, campuses, barracks and hotels. These needs are due mainly to the growth of the population in general [1] and the (increased) number of students and the military in particular. The increase in the number of students is justified by the access to the school of certain social categories which were hostile and an increase of the recruitment of the military because of the multiplication of the centers of tension.

In fact, for the production of this hot sanitary water, the populations most often use fossil fuel energies which are exhaustible and which emit greenhouse gases CO_2,N_2O, CH_4 etc). These are the main causes of climate change [2-3-4]. In the particular case of Third World countries, the abusive use of wood contributes to deforestation. It is necessary to explore other methods of producing hot water. The most reliable and promising method is the production of Hot Water Sanitary by the use of solar thermal collectors [5]. The use of this solar energy is a clean method without greenhouse gases [6-7-8-9-10] and an alternative way for our countries which are part of the sunniest areas in the world [11].

In this study, we model the different thermal exchanges and the use of an experimental global radiation database, wind speed, insolation time, maximum temperature and minimum temperature of a year, we are doing a simulation of mathematical equations. This work, which promotes renewable energies, is a contribution to the fight against deforestation, which is one of the causes of climate change caused by human activities.

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2. Materials and Methods

Methodology and experimental data collection

The global radiation is measured using the KIPP and ZonenPyranometer integrator ELSB-2, with digital displays, which integrates the values of global solar radiation daily. Maximum and minimum temperatures are measured by thermocouples. For the measurement of the wind speed, we used the thermo-anemometer. The experimental measurement data of global radiation, maximum and minimum temperatures, wind speed and duration of insolation for the two Nigerian cities (Niamey, N and Zinder, Z) were obtained at the service of the Nigerien National Meteorology in Niamey and National Center for Solar Energy (CNES). The evolutions of these different parameters are presented in tables 1 to 6. The simulations of the sensor were carried out under the MATLAB MR2015a version 2015 software environment.

2.2. Mathematical modeling [12-13-14-15-16]

The modeling of the heat transfer is an important step that allows to write as rigorously as possible the thermal balance of the solar water collector at the following systems: absorber, glazing, insulation and piping with the heat transfer fluid. We first use a global approach that consists in writing the global energy balance for the different elements of the solar collector on the one hand. Then we use a detailed approach with which the reports are written for the different elements of the sensor components.

We assume that the incident energy received by the blackbody is transmitted to the coolant. Modeling and numerical simulation are important design tools used to predict experimental execution.

In practice, the variations in the enthalpy time of solar collector components are very small, that allows us to neglect the termm. $C_p \frac{\mathrm{dT}}{dt}$, from where $\mathrm{m}.C_p \frac{\mathrm{dT}}{dt} \approx 0$[17] in the first place. On the other hand, the expression of the enthalpy of the components as a function of the temperature can be very complicated and, as a result, the numerical models to be implemented become very heavy and expensive according to the research work carried out by [18]. Considering these two research works, the terms $\mathrm{m}.C_p \frac{\mathrm{dT}}{dt}$ do not appear in all the equations of the modeling [12-13-14-15-16].

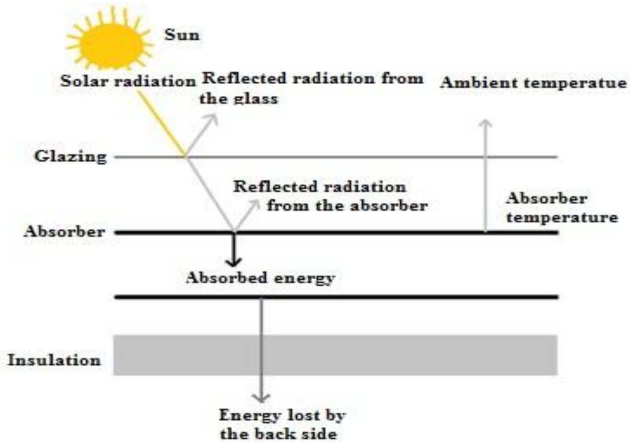

Figure 1: Heat exchange mechanism [16]

The upper surface of the window receives energy from the sun, the one transmitted from the sky by radiation and the one transferred by the convective air (the internal surface of the glazing), we also have the convection exchange from the air layer (air gap) and the glazing (Figure 1). The energy balance is written [12-13-14-15-16]:

$-(T_v - T_{am}).h_{c\_v} - (T_v - T_c).h_{rv\_c} - (T_{La} - T_v).h_{c\_nat} + \alpha_v E = 0$ (1)

With Tc is the temperature of the sky given by the equation (2) in°C and E is the solar energy received in W/m^2:

$T_c = 0{,}0552 T_{am}^{1,5}$ (2)

At the level of the glazing side air blade, heat transfer is carried out by natural convection between the glass and the air gap and between the absorber

$-(T_{La} - T_v).h_{c\_nat} + (T_{ab} - T_{La}).h_{c\_nat} = 0$ (3)

In the previous equation, the temperature of the air space is the arithmetic mean of T_{ab} et T_v in °C :

$T_{La} = \frac{T_{ab} + T_v}{2}$ (4)

Thermal balance of the absorber:

The exchange takes place: by natural convection and conduction between the absorber and the air space, by convection between the absorber and the fluid, by radiation between the absorber and the metal plate, by radiation between the absorber and the window:

$-(T_{ab} - T_{La}).h_{c\_nat} - (T_{ab} - T_f).h_{cab\_f} - (T_{ab} - T_{pl}).h_{rab\_pl} - (T_{ab} - T_v).h_{rab\_v} + \tau_v.\alpha_{ab} E = 0$ (5)

T_{ab} is the temperature of the absorber in°C, T_pl is the temperature of the metal plate in°C, h_ (cab_f) is the convective heat transfer coefficient between the absorber and the coolant in W/m^2K, h_ (rab_pl) is the radiant heat transfer coefficient between l absorber and the metal plate (inner box) in W/m^2K, h_ (rab_v) is the radiation heat transfer coefficient between the absorber and the glazing in W/m^2K and τ_v is the transmission factor of the window.

- Thermal balance at the water level (coolant) and in piping by conduction. The heat transfer is considered to be unidirectional and at the steel-water interface, the heat exchange is only by conduction in water and the losses by Joule effect in the pipe are negligible. The coolant (water) receives as muchenergy as possible.

  $(T_{ab} - T_{La}).h_{cab\_f} - (T_f - T_{pl}).h_{cpl\_f} = 0$ (6)

T_f is the temperature of the coolant in°C and h_ (cpl_f) is the exchange coefficient between convection between the metal plate and the coolant in W/m^2K.

- Thermal balance of the inner box insulating metal plate:

The transfer is by convection between the coolant and the metal plate, between the absorber and the metal plate by radiation and by conduction between the metal plate and the insulation.

$-(T_f - T_{pl}).h_{cpl\_f} + (T_{ab} - T_{pl}).h_{rab\_pl} - (T_{pl} - T_{is}).h_{cd} = 0$ (7)

T_{is} is the temperature of the insulation in°C and h_cd is the coefficient of conduction transfer of the insulation.

- Thermal equilibrium of the external insulating plate at the back of the sensor:

The exchange takes place by conduction between the metal plate and the insulation, by convection between the insulation and the ambient air and by radiation between the insulation and the ground.

$-(T_{pl} - T_{is}).h_{cd} - (T_{is} - T_{am}).h_{c\_v} - (T_{is} - T_s).h_{ris\_s} = 0$ (8)

The soil temperature is given by:

$T_s = T_{am} + 2$ (9)

T_s is the radiation exchange coefficient between the insulation and the ground in°C.

- **Modeling of exchange coefficients:**

The exchange coefficients depend on the thermo-physical characteristics of the solar collector, its design geometry, the nature of the fluid flow and the contact performance between the absorber and the water. These parameters also depend on the heat transfer medium mixing temperature, the absorber temperature and the ambient air temperature [12-13-14-15-16].

Wind transfer: this coefficient is defined as a linear function of the wind speed:

$$h_{c\_v} = a_0 + a_1.V_{vent} \quad (10)$$

In this equation, V_{vent} represents the wind speed and a_0 and a_1 are coefficients represented by the equation (11):

$$h_{c\_v} = 5{,}67 + 3{,}86V_{vent} \quad (11)$$

In most cases, the coefficients are calculated by the equation (12):

$$h = a + b.v^n \quad (12)$$

Sensor performance [17]

Sensor performance is evaluated based on performance. For this, we performed a simulation of the efficiency (efficiency) of the sensor given by the equation (13):

$$E_{eff} = \frac{mC_p(T_{fs} - T_{fe})}{E.\Delta t.S} \quad (13)$$

The study of the model will be based on the following simplifying assumptions

The modeling of a solar collector takes into account the mode of circulation of the fluid vis-à-vis the absorber, the number of glazing, the presence or absence of the metal plate for the protection of the insulation, the materials used for rear and side insulation. This modeling must lead to the determination of the coefficients characterizing the sensor studied, the different equations allowing to evaluate the extracted energy of the sun, the temperatures of the elements and the fluid at the entry and the exit, as well as the returns of the sensors.

Before proceeding to the numerical simulation, we specify certain calculation hypotheses:

- Heat transfer is unidirectional,
- Uniform mass flow in the sensor tubes,
- Heat transfer from the edges of the photo-thermal sensor is negligible,
- The exchange coefficients are considered identical to the transfer between the sensor and the wind,
- The heat flux received by the sensor is in function of time,
- The physical properties of the materials are independent of the temperature,
- The physical properties of the fluid are depend are based on temperature,
- Solar collector component temperatures depend on time,
- Dust and dirt on the collector are negligible,
- At the absorber-water interface, the heat exchange is done only by conduction,

The thermal resistance of the tube is low because the tube is made of material that is a good conductor of heat.

3. Results and Discussion

At the level of the simulation figures of the temperature profiles, the index N and Z respectively represent Niamey and Zinder. r represents the percentage yield. The temperatures of the sensor components and heat transfer fluid are given according to the ambient temperature, the sky and the ground. The different figures (from 2 to 6) give us the profiles of the evolution of the outlet temperatures of the different parts of the solar collector plane to water. Temperatures are based on of ambient temperature, sky temperature, soil and global solar irradiation. Celestial vault temperature and soil believe with ambient temperature. The heat is propagated inside the solar thermal collector with different modes of transfer namely conduction, convection and radiation. The month of April records more solar energy than any month for both regions. It is the month that gives a better percentage of return. The month of August is the least sunny month, so this is the month for which the yield is the lowest. This decrease in performance is explained by the presence of aerosols (clouds, dust ...) that prevent the sun's rays from reaching the surface of the solar collector.

The simulation results of the curves show that the absorber has the highest exit temperature because of its large solar energy absorption coefficient. In addition, the temperature of the air gap is taken as an arithmetic mean. This shows that the pace of its evolution temperature is almost linear. It should be emphasized that the wind speed has a remarkable effect when it is between 0 and 3m / s. It has no influence when it is beyond 3 m / s as illustrated in Figures 2, 3 and 4. This is consistent with the research work of Foued CHABANE [19] encountered in the literature. It should also be noted that even if the wind speed is zero, the transfer exists. The abrupt rise in metal plate temperature for the months of February, May and June for the two cities of Niamey and Zinder is due to the effect of wind speed. Overall, the results obtained after simulation prove that the city of Zinder gives on average more solar energy than Niamey therefore more yield than hot water. The maximum output temperatures are obtained between 13 hours and 14 hours.

Table 1: Experimental climate parameters used for simulation (February)

February 2009				
Climatic parameters	**Global radiation in** W/m^2	**Maximum temperature in°C**	**Minimum temperature in°C**	**Wind speed in** m/s
Niamey	4730,86	38,29	21,83	2,98
Zinder	5936,11	35,28	19,22	2,66

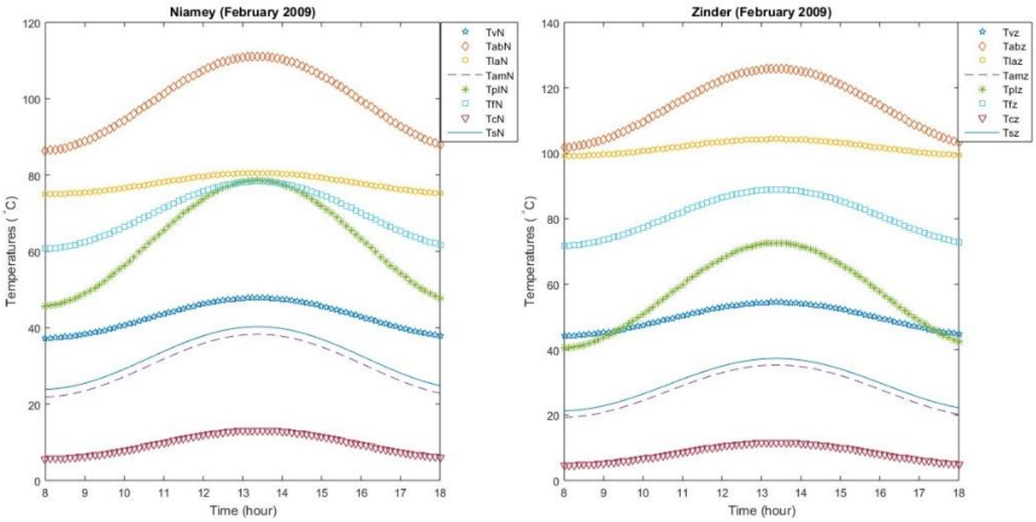

Figure 2: Temperature profile of glazing, absorber, water, metal plate, air space, ambient temperature, sky and soil of February 2009 (Niamey and Zinder).

Table 2: Experimental climate parameters used for simulation (April)

April 2009				
Climatic Parametres	**Global radiatio in** W/m^2	**Maximum temperature in °C**	**Minimum temperature in°C**	**Wind speed in** m/s
Niamey	5695,37	42,10	27,93	3,06
Zinder	6000,00	41,62	25,08	2,61

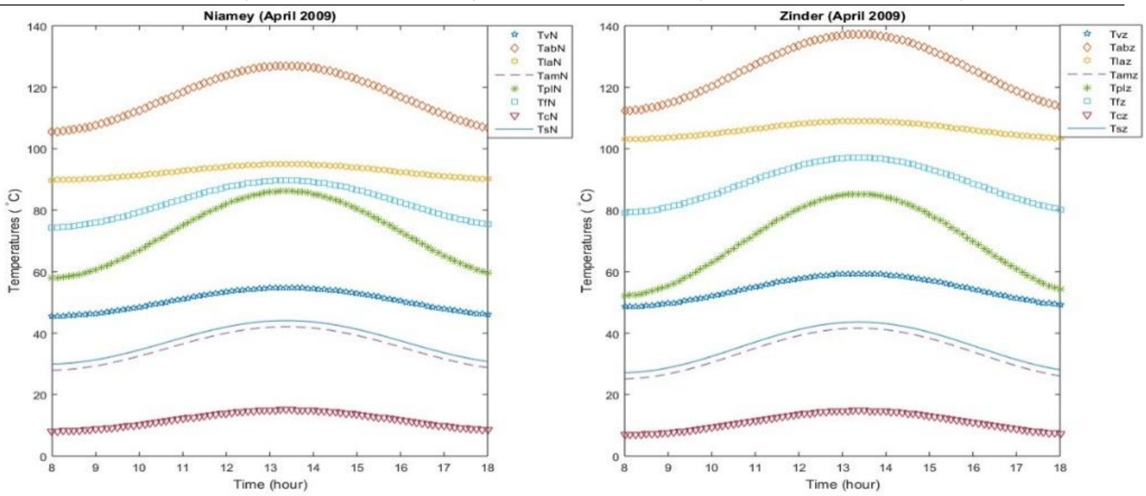

Figure 3: Temperature profile of the glazing, absorber, water, metal plate, air space, ambient temperature, sky and ground of April 2009 (Niamey and Zinder)

Table 3: Experimental climatic parameters used for simulation (May)

May 2009				
Climatic parameters	**Global radiation in W/m^2**	**Maximum temperature in℃**	**Minimum temperature in ℃**	**Wind speed in m/s**
Niamey	5733,52	41,10	28,39	3,62
Zinder	5958,33	39,92	25,57	2,88

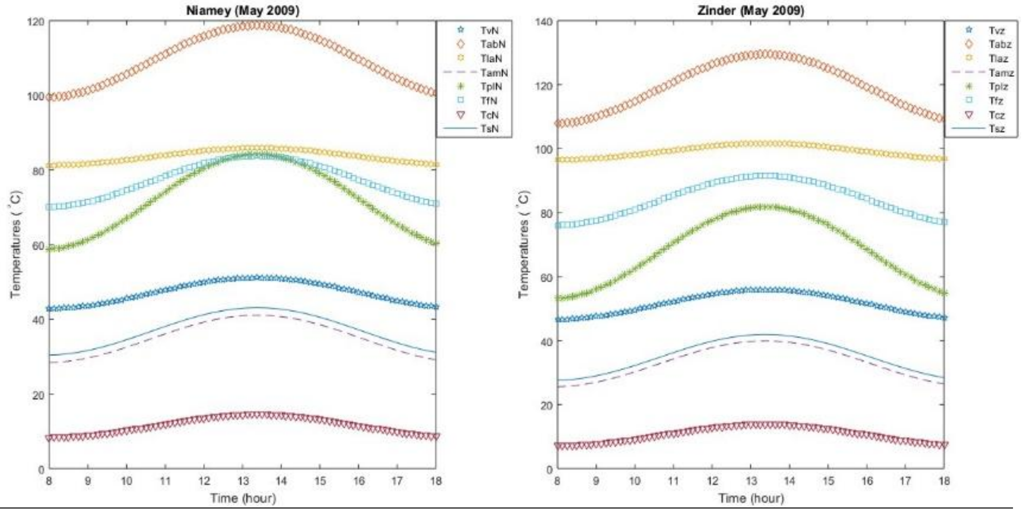

Figure 4: Temperature profile of the glazing, absorber, water, metal plate, air space, ambient temperature, sky and ground of May 2009 (Niamey and Zinder).

Table 4: Experimental climate parameters used for simulation (June)

June 2009				
Climatic parameters	**Global radiation in W/m^2**	**Maximum temperature in ℃**	**minimum temperature in ℃**	**Wind speed in m/s**
Niamey	4960,30	38,45	26,58	4,06
Zinder	5161,11	39,18	25,77	3,77

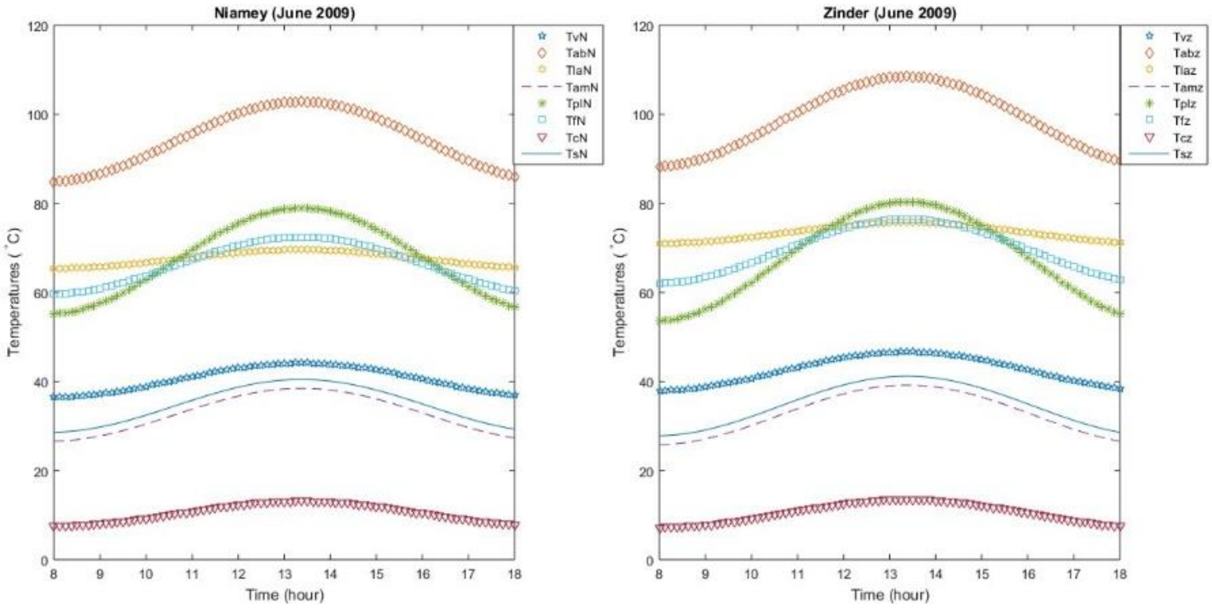

Figure 5: Temperature profile of glazing, absorber, water, metal plate, air space, ambient temperature, air and sky in June 2009 (Niamey and Zinder)

Table 5: Experimental climate parameters used for simulation (August)

August 2009				
Climatic parametres climatic	**Global radiation in w/m^2**	**Maximum temperature in ℃**	**Minimum temperature in ℃**	**Wind speed in m/s**
Niamey	4763,13	33,01	23,62	3,10
Zinder	4972,22	34,65	24,06	2,69

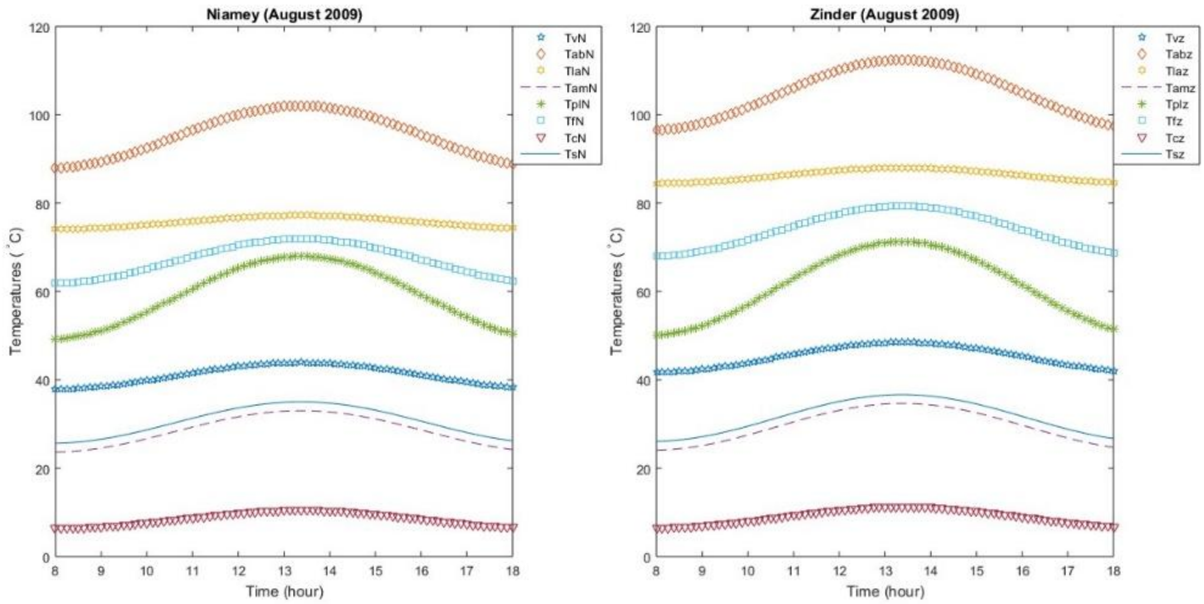

Figure 6: Temperature profile of glazing, absorber, water, metal plate, air space, room temperature, sky and soil of August 2009 (Niamey and Zinder)

For the sunniest months (the month of April) and the least sunny (the month of August) of both cities. The results of Figure 7 show that the city of Zinder has a better performance compared to the city of Niamey. This is justified by the fact that Zinder is sunnier than Niamey. The yield of the month of April is of the order of 67.5% in Zinder and 62% in Niamey. That of August is 63% in Zinder and 57% in Niamey. The differences in yield are respectively 5.5% and 6% between the two cities. These differences could be due to the fact that the region of Zinder receives a quantity of solar energy higher than that of Niamey.

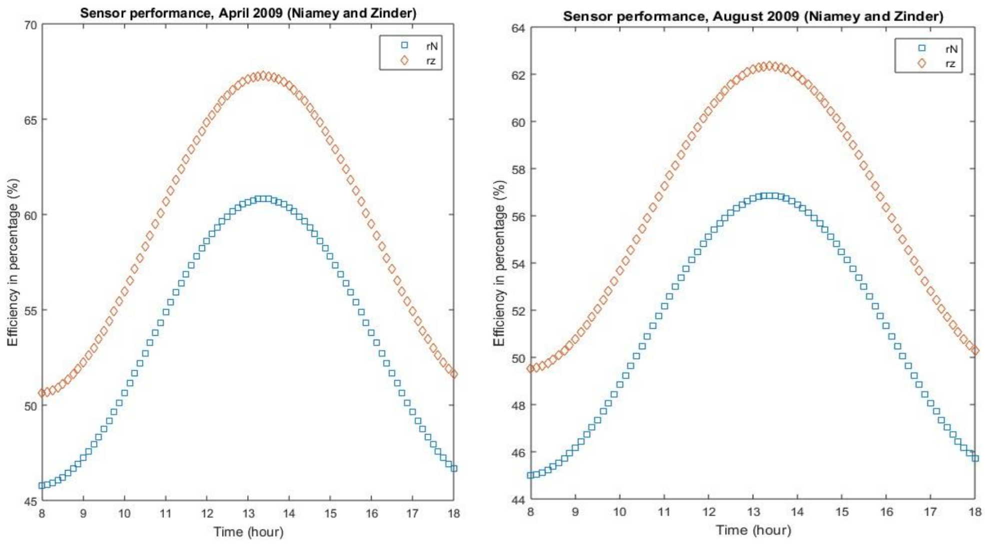

Figure 7: Sensor performance for the city of Niamey and Zinder, April and August, 2009

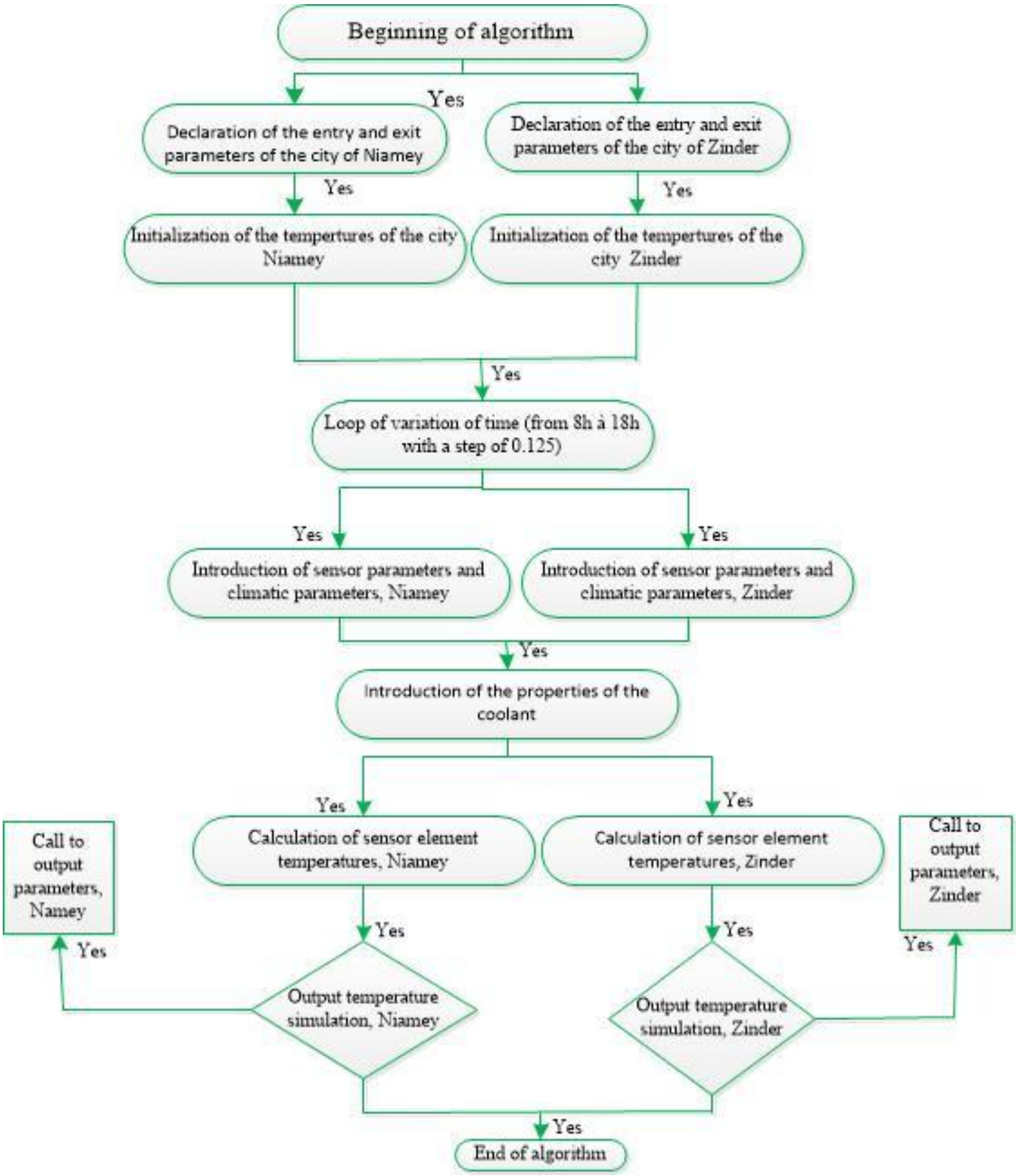

Figure 8: Simulation Algorithm

Conclusion

The influence of climatic parameters on the efficiency of a solar thermal collector for the production of hot water in two main cities of Niger is simulated numerically and evaluated on Matlab. Five (5) solar experimental data are used: the global solar irradiation, the wind speed, the duration of sunshine and the two extreme temperatures. Simulation results are given for each month of the year.

They show that the temperature of the hot water at the sensor outlet increases with global radiation and wind speed.

The main results obtained for the cities of Zinder and Niamey are the following:

- sensor efficiency increases as solar parameters increase; Yields of 67.5% are obtained in Zinder and 62% in Niamey. (You have to give an interval from this period to another one)
- the efficiency of the sensor decreases with the increase of aerosols: 63% for Zinder and 57% for Niamey.

The results obtained show that the city of Zinder offers a better performance for two identical sensors installed one in Zinder and the other in Niamey. We can say that the solar field that Niger has, when it is used optimally, can significantly reduce greenhouse gases. This solar field will help reduce the use of conventional energy and energy needs.

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