

# Modeling Heat Transfer in a Solar Water Heater for a Typical Guinean Climate

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## ABSTRACT

This study focuses on the numerical modeling of heat transfer in a solar water heater adapted to the typical climate of Guinea. The analyzed system consists of a flat-plate collector, a water storage tank, and connecting pipes. A mathematical model of the heat transfer phenomena was developed and then implemented using the Fortran programming language for numerical computation. The results were processed and visualized using the Origine software. The temperature profiles obtained at the flat-plate collector show that the absorber wall receives a significant amount of solar energy, reaching a maximum temperature of approximately 107 °C. The evolution of the water temperature in the tank indicates a gradual increase over the operating time, with an inflection point located between  $3.5 \times 10^4$  s and  $4 \times 10^4$  s, and a final temperature around 67 °C, demonstrating the system's efficiency for thermal storage. The tank's insulation receives less energy than the side walls, while the collector's glass shows a temperature increase correlated with the evolution of solar radiation throughout the day. Analysis of the tank's internal layers reveals a non-uniform thermal distribution : the first layer absorbs less heat than the upper

layers. Layer 4 reaches a maximum temperature of approximately 37°C, while layers 2, 3, and 4 have maximum temperatures close to 54°C, indicating more intense heat transfer to the upper levels of the tank. These results confirm the internal heating dynamics of the fluid under real-world solar operating conditions in Guinea.

**Keywords:** Solar water heater, thermal modeling, heat transfer, flat-plate collector, storage tank, Fortran, thermal layers, Guinea

## INTRODUCTION

Faced with rising electricity prices and growing environmental concerns, various technologies are being developed to extract energy from all available sources and store surplus energy for later use. Thermal energy storage systems (TESS) are one such solution, allowing excess energy to be stored for future applications. In summer, solar radiation can be stored to provide heating in winter, and cool winter air can be used for air conditioning in summer. Energy storage is particularly important because it allows supply to be decoupled from demand. This characteristic is valuable given the variability of renewable energy sources and grid demand [1]. Seasonal thermal energy storage (STES) promotes the rapid growth of district

solar heating (DSH) and contributes to the decarbonization of the economy by eliminating the imbalance between supply and demand [2, 3]. STES can significantly increase the share of solar energy in the energy grid. Compared to short-term thermal energy storage systems, solar thermal energy storage (STES) can increase the solar share of hydropower systems by 25% to 50%, or even more [4].

Today, most countries are interested in renewable energies as oil reserves begin to dwindle, not to mention the environmental risks and the ever-increasing cost of a barrel of oil. This is why there is a strong incentive to move towards renewable energy sources such as biomass, solar, wind, and hydropower. Solar energy is advantageous from a technical, ecological, and financial standpoint; it sustains human life. It has been harnessed by humans for a very long time in various forms (lighting, cooking, drying, hot water, etc.) [5].

The sizing of domestic hot water production systems (solar water heaters) plays a crucial role, as their operation depends on several parameters: the user's hot water needs in terms of quantity, the desired water temperature, local climatic conditions, and the performance of the flat-plate collector system [6].

The most important basic resource for all renewable energy potentials is solar energy. The Earth receives an average power of 1.4 kW/m<sup>2</sup>, for a surface perpendicular to the Earth-Sun direction. This solar flux is attenuated as it passes through the atmosphere by absorption or scattering, depending on meteorological conditions and the latitude of the location at ground level [7].

The solar water heater is clearly the most widely used solar energy device in the world today. Millions of solar water heaters exist in Japan, Israel, and the USA, tens of thousands in France, and there are few countries where they are completely unknown [8].

A solar water heater is a device that absorbs solar radiation, transforms it into heat, and heats water for storage in a tank or storage

vessel. These collectors can be positioned lower than the storage tank [5].

Depending on the period of use, there are two categories of solar water heaters: seasonal and permanent. Based on size, there are three main types of individual solar water heaters that meet domestic hot water needs for different usage patterns : the self-storing solar water heater, the compact solar water heater, and the split-system solar water heater. Depending on their configuration, solar water heaters can be classified into three categories: monobloc, thermosiphon, and forced circulation [6, 9].

The flat-plate collector, or solar collector, is the heart of the solar water heater system. It is a device used to produce heat from solar energy. It is generally placed on the roof but can also be installed in the eaves or in the garden. The amount of water to be heated is determined by the number of users, which limits its size. It contains the absorber, which absorbs solar radiation and transfers the heat to the heat transfer fluid that flows through it. A flat-plate collector essentially consists of a transparent cover, an absorber, a heat exchanger, a heat transfer fluid, thermal insulation, and a casing, as indicated. There are three main types of collectors: glazed flat-plate collectors, unglazed flat-plate collectors, and evacuated tube collectors [10-14].

Domestic hot water storage tanks are one of the best thermal energy storage technologies due to their low cost and the high specific heat of water. These tanks can be installed in the basement or on the ground floor of a building. A cylindrical shape is preferable as it reduces heat loss. Furthermore, the heat exchange of the water occurs inside the tank, which is usually located in the basement. A control system manages the loading and unloading of thermal energy. Solar energy is used to heat the water, and solar panels are often installed on building roofs to capture solar energy [15]. Many factors influence solar energy storage, such as the temperature inside the tank and the quality of the metal used [16].

The Republic of Guinea has a humid tropical climate with two alternating seasons: a dry season and a rainy season. The average daily temperature varies between 25 and 40°C, the average daily solar radiation is 4.8 kWh/m<sup>2</sup>/day, and the average annual sunshine duration is 2,000 hours, with a maximum of approximately 2,700 hours per year in Upper Guinea (Kankan). Average annual wind speeds in Guinea range from 2 to 4 m/s. Guinea thus benefits from climatic conditions that provide it with considerable renewable energy resources such as hydroelectric, solar, and wind power. Therefore, within the framework of

developing this renewable energy source, we undertook a numerical study on a solar water heater with a storage collector at the Higher Institute of Technology of Mamou in the Republic of Guinea.

## I. Tools and Method

### I.1. Tools

The tools used to create the device to be modeled are: a flat panel collector, piping for connection, a fluid (water) storage tank, and the Fortran programming language for calculations and the Origine software for graphing. Figure 1 illustrates the device to be modeled.

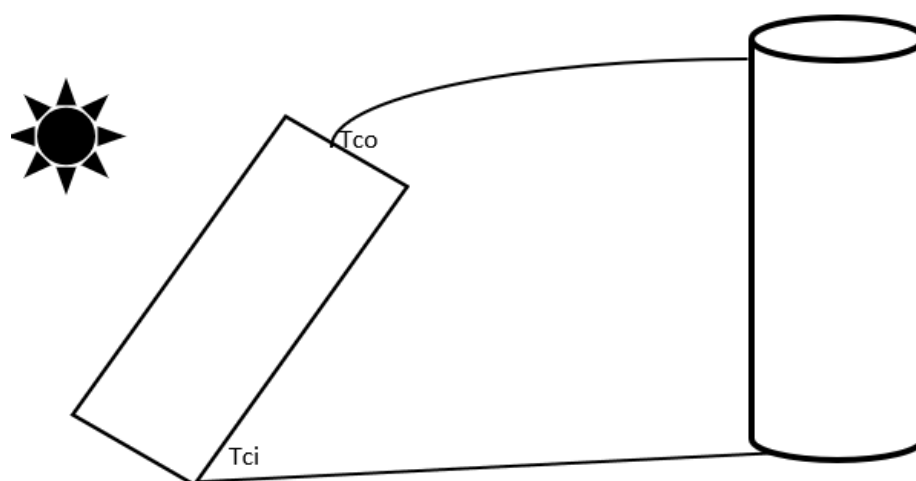


Figure 1 : Physical model of the solar water heater

### I.2. Method

The methodology used in this study is based on several assumptions, namely: the water flow within the sensor is one-dimensional, the thermo-physical properties of the materials used are constant, the sensor is only the site of heat transfer, the absorber is thick enough to absorb almost all of the incident radiation, the water temperature at the sensor outlet is close to that of the absorber, and the temperatures of the different solid media are uniform in a plane perpendicular to the direction of the flow (steady state).

#### I.1.1. Sensor Modeling

#### I.1.2. Simplifying Assumptions

The methodology used for this study is based on several assumptions, including:

- The water flow within the sensor is one-dimensional;
- The thermophysical properties of the materials used are constant ;
- The sensor only facilitates heat transfer ;
- The absorber is thick enough to absorb almost all of the incident radiation ;
- The water temperature at the sensor outlet is close to that of the absorber ;
- The temperatures of the different solid media are uniform in a plane perpendicular to the flow direction.

#### I.1.3. Equation formulation

The energy balance at the sensor level is given by the following equation:

$$m_{eau} C_{peau} \times \frac{dT_c}{dt} = A_c F_R S - (A_c F_R U_L - \dot{m} C_p) T_{ci} + A_c F_R U_L T_a - \dot{m} C_p T_{co} + UA_{kx} DTLM \quad (1)$$

The conductance factor  $F_R$  is expressed as a function of the absorber efficiency, the flow rate and the overall heat loss coefficient given by :

$$F_R = \frac{\dot{m}_{eau} \times C_{peau}}{A_c \times U_L} \times \left[ \left( 1 - \exp\left(-\frac{A_c F' U_L}{\dot{m}_{eau} \times C_{peau}}\right) \right) \right] \quad (2)$$

$F'$  : Absorber efficiency ;

$U_L$  : The overall heat loss coefficient depends on the thermal resistance of the fluid to the environment through the wall thickness; in other words, this coefficient combines heat losses by conduction, radiation, and convection between the various components of the solar collector and the environment through exchanges analogous to electrical heat transfer.

$A_c$  : Sensor surface ( $m^2$ ) ;

$UA_{kx}DTLM$  : the total heat flux transferred in the coil (W) ;

$U$  : heat exchange coefficient between water and walls ( $W.m^{-2}.K^{-1}$ ) ;

$DTLM$  : the logarithmic mean (DTLM) of the difference  $\Delta T$  between the inlet and outlet of the coil.

Where this average is expressed by the relation :

$$DTLM = \frac{\Delta T_{ci} - \Delta T_{co}}{\ln\left(\frac{\Delta T_{ci}}{\Delta T_{co}}\right)} \quad (3)$$

The sensor's efficiency depends on the inlet and outlet temperatures, and on climatic conditions (solar irradiance  $G$  and ambient temperature). It is determined by :

$$\eta = 0.798 - 2.275 \left(\frac{T_{moy} - T_a}{G}\right) - 0.022 \left(\frac{(T_{moy} - T_a)^2}{G}\right) \quad (4)$$

$$\text{Avec } T_{moy} = \left(\frac{T_{ci} + T_{co}}{2}\right)$$

Where :

$T_{ci}$ ,  $T_{co}$  et  $T_a$  are respectively the inlet temperature, the outlet temperature of the sensor, and the ambient temperature.

The outlet temperature of the heat exchanger (coil) and the inlet temperature of the coil (temperature of the water flowing inside the pipe connecting the storage tank to the collector after losing some of its heat to the ambient air before entering the collector) are defined, respectively, by :

$$T_{HXO} = T_p - \exp\left[\frac{-PLU}{(m\dot{C}_p)_{HX}}\right] (T_p - T_{HXi}) \quad (5)$$

$$T_{ci} = T_p - \exp\left[\frac{-PLU}{(m\dot{C}_p)_{HX}}\right] (T_p - T_{HXo}) \quad (6)$$

With :

$T_p$  : heat exchanger pipe wall temperature (K) ;

$P$  : wet perimeter (m) ;

$L$  : the length of the pipe (m) ;

$U$  : heat transfer coefficient of the heat exchanger pipe ( $W.m^{-2}.K^{-1}$ ) ;

The flow rate of water in the pipe is determined by the following equation :

$$V^2 = \frac{2}{J} H \Delta T$$

$J$  : overall pressure loss coefficient in the circulation pipe (J/kg) ;

$H$  : distance between the two horizontal median planes of the storage tank and the sensor (m) ;

$\Delta T$  : temperature difference between hot and cold water (K).

#### 1.1.4. Expressions for transfer coefficients

Heat exchange occurs via three known modes : convective, radiative, and conductive. The architecture and fluid flow pattern within the sensor must be considered to compile a complete inventory of the heat transfers that take place.

➤ *Convective heat transfer coefficient between the glass and the outside air (ambient environment).*

According to the report of HOTTEL and WOERTZ :

$$h_{cv,amb} = 5,7 + 3,8 \times V \quad (7)$$

➤ The convective heat transfer coefficient between the water and the pipe wall is estimated using empirical formulas via the Nusselt number.

$$N_u = 1 + 1.44 \left[ 1 - \frac{1708(\sin 1.8\beta)^{1.6}}{R_a \cos \beta} \right] \left[ 1 - \frac{1708}{R_a \cos \beta} \right]^+ + \left[ \left( \frac{R_a \cos \beta}{5830} \right)^{1/3} - 1 \right]^+ \quad (8)$$

The convective heat transfer coefficient is then given by :

$$U = \frac{\lambda_{eau} \times N_u}{d}$$

With :  $\lambda_{eau}$  : thermal conductivity of water (W.m<sup>-1</sup>.K<sup>-1</sup>)  
d : diameter (m)

### 1.1.5. Calculation of solar radiation

The average monthly daily radiation on the sensor is calculated using the following equation :

$$\overline{H_T} = \overline{H_b} \overline{R_b} + \overline{H_d} \left( \frac{1 + \cos \beta}{2} \right) + \overline{H_{\rho_g}} \left( \frac{1 - \cos \beta}{2} \right) \quad (9)$$

With  $\overline{H}$  , the average monthly daily radiation on a horizontal surface,  $\overline{R}$  is the monthly average of the radiation on a plane inclined to that on a horizontal surface,  $\rho$  is the reflectance, and  $\beta$  is the slope of the collector. The indices « b », « d » ; and "g" respectively designate the beam, the diffuse and the ground.

Solar radiation per unit area is determined by :

$$\overline{S} = \overline{H_b} \overline{R_b} (\overline{\tau\alpha})_b + \overline{H_d} (\overline{\tau\alpha})_d \left( \frac{1 + \cos \beta}{2} \right) + \overline{H_{\rho_g}} (\overline{\tau\alpha})_g \left( \frac{1 - \cos \beta}{2} \right) \quad (10)$$

With  $(\overline{\tau\alpha})_b$  ,  $(\overline{\tau\alpha})_d$  ,  $(\overline{\tau\alpha})_g$  are the terms beams, diffuse and reflected by the ground.

## 1.2. Storage tank modeling

### 1.2.1. Simplifying assumptions

For the study of the storage tank, we adopt the following simplifying assumptions:

- Heat fluxes are unidirectional;
- There is no interaction between losses through the cylinder and losses through the circular flat ends;

- Linear and singular pressure losses are neglected;
- The thermophysical properties of the water are constant.

The modeling of the solar water heater with a flat-plate collector allowed us to establish certain prerequisites, namely :

- Time= 12h
- Glass transmission coefficient : 0,7
- Absorber absorption coefficient : 0,7
- Water mass in the sensor : 10 litres
- Mass of water in the balloon : 235 litres
- Maximum flow = 1000 W/m<sup>2</sup>
- Ambient temperature 25 °C.

The stratified hot water tank is represented by figure 2.

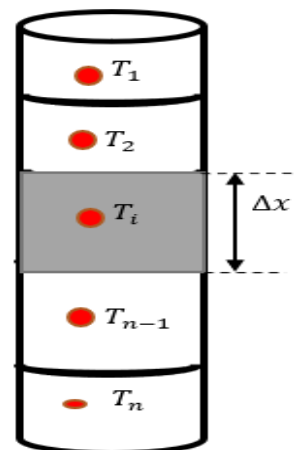


Figure 2 : Stratified hot water tank

### 1.2.2. Setting up an equation

The heat balance around the storage tank is given by equation (11) using variable volume and multilayer models. The tank is divided into N constant volume sections or nodes; each section is assumed to be mixed and at a uniform temperature.

$$M_i C_p \frac{dT_i}{dt} = UA_s (T_{env} - T_i) + \frac{\lambda A_c}{\Delta x} (T_{i-1} - T_i) + \frac{\lambda A_c}{\Delta x} (T_{i+1} - T_i) + \dot{m}_{lin} C_p (T_{lin} - T_i) + \dot{m}_{up} C_p (T_{i+1} - T_i) + \dot{m}_{down} C_p (T_{i-1} - T_i) \quad (11)$$

With :

- $i$  : node of the layer under consideration ;
- $M_i$  : mass of the volume  $i$  (kg) ;
- $C_p$  : specific heat of the fluid J. Kg<sup>-1</sup>K<sup>-1</sup> ;
- $dT_i/dt$  : temperature variation over time (K/s) ;
- $\lambda$  : thermal conductivity of the fluid (W.m<sup>-1</sup>.K<sup>-1</sup>) ;
- $\Delta\lambda$  : Destratification conductivity, which allows for the consideration of potential thermal bridges (W.m<sup>-1</sup>.K<sup>-1</sup>) ;
- $\Delta x_i$  : distance between nodes (m) ;
- $U$  : heat exchange coefficient (W.m<sup>-2</sup>. K<sup>-1</sup>) ;
- $\dot{m}_{up}$  et  $\dot{m}_{down}$  are respectively the mass flow rates of the fluid (water) upwards and downwards in the reservoir.

## II. RESULTS AND DISCUSSION

Figure 3 illustrates the temperature profiles of the flat-plate collector. In this figure, we observe that the absorber wall receives significantly more heat than the other elements, with a maximum temperature approaching 107°C. In contrast, the temperature profile of the water in the tank evolves gradually over operating time, reaching an inflection point between 3.5 and 4 x 10<sup>4</sup> s. This water temperature evolution demonstrates that the objective is achieved by maintaining heat in the tank for a final temperature of approximately 67°C. The insulation receives less heat compared to the two side walls of the tank, while the glass plate acting as the collector shows a temperature evolution in relation to the sun's position until the device's operating time is exhausted.

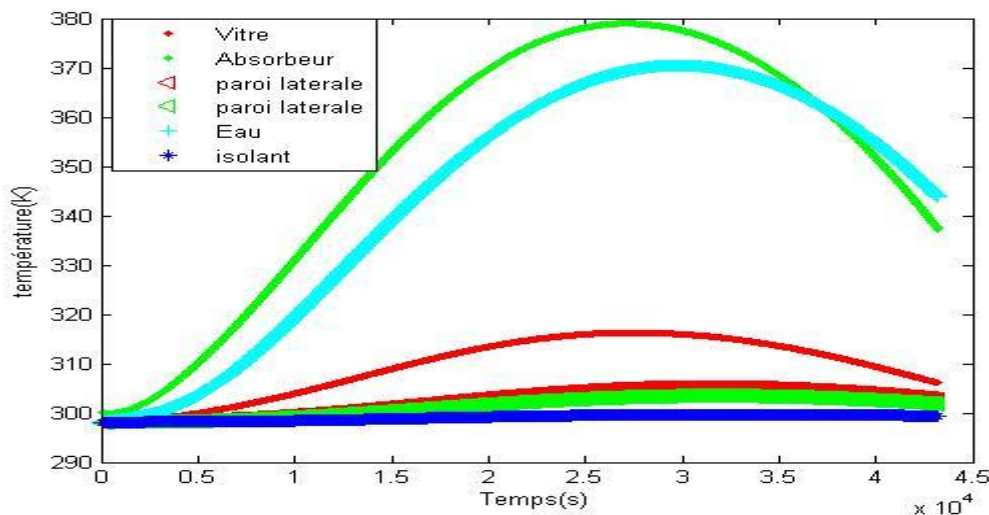


Figure 3 : Temperature profiles at the flat panel sensor

Figure 4 illustrates the temperature evolution at the four-level strata. The first layer receives less heat compared to the other three, which have roughly the same temperature changes. The maximum temperature observed at layer 4 is approximately 37°C, while the other three

layers share a common maximum temperature of 54°C. This analysis demonstrates that layers 2, 3, and 4 are more exposed to heat than layer 1. This is entirely logical, because inside the balloon, layer 1 receives the heat first, and as the heat

propagates to the other layers, there is an exponential temperature increase.

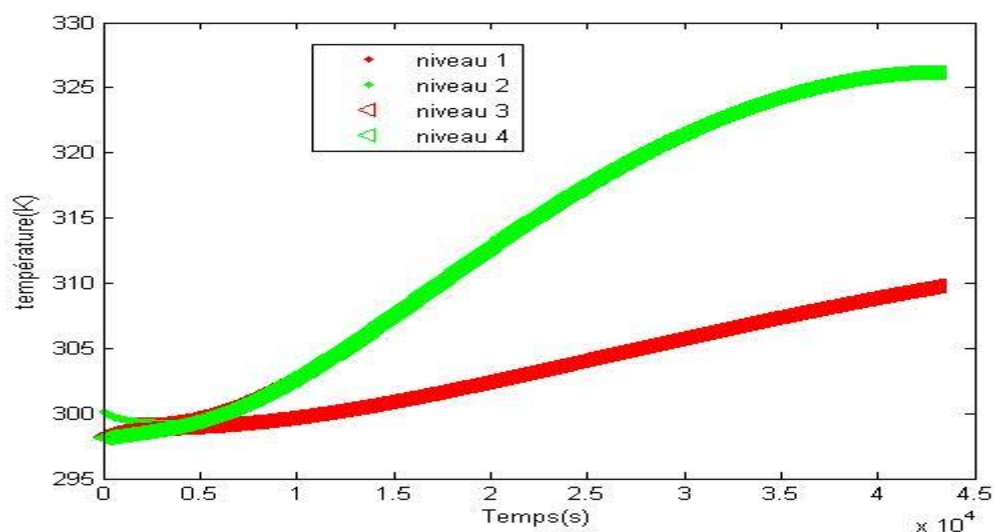


Figure 4 : Temperature profiles in the balloon, divided into four layers

## CONCLUSION

This study has enabled the development of a reliable model of heat transfer in a solar water heater adapted to Guinean climatic conditions. Numerical simulations showed that the flat-plate collector provides sufficient thermal energy to raise the temperature of the stored water to levels compatible with domestic needs, while revealing a gradual heat distribution within the tank.

The analysis highlighted that the absorber wall of the collector is the structural element that captures the most energy, while the temperature evolution within the tank confirms a gradual propagation of heat through the internal layers of the fluid. The results obtained suggest that the tank's insulation and the design of the layers significantly influence the system's thermal performance.

In conclusion, the modeling not only allows us to understand the thermal mechanisms of the solar water heater but also to optimize its design for improved energy efficiency in areas with high levels of sunshine, such as Guinea. This work paves the way for future improvements focusing on optimizing geometric parameters, materials, and operating conditions. As a follow-up to this

study, we plan to develop an experimental model of this storage system.

### Declaration by Authors

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