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Theoretical Optimization of The Storage Tank of A Solar Water Heater using Locally Available Materials

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Abstract: - Hot water production using solar water heaters is one of the most promising applications of solar energy for countries such as Burkina Faso. This study examines the performance of a local solar domestic hot water production system by optimizing the efficiency of the storage tank. The tank is designed using locally available materials such as steel and glass wool. In this study, we determined the temporal evolution of the temperature of the stored water as a function of the thickness of the insulation; the evolution of water temperatures at different levels of the tank during the day and at night; the stored power and the temperatures of the water layers during withdrawal. To calculate the temperature of the water in the storage tank, the stirred model was adopted. This model assumes that the temperature in the tank is uniform. The regime is considered transient, and the total heat loss in the tank is equal to the sum of the radial flows plus the flow through the curved bottoms. The power recovered by the heat transfer fluid is defined as the difference between the incident solar energy and the heat losses. The results show that the theoretical temperature of the stored water varies between 50°C and 65°C for insulation thicknesses ranging from 10 mm to 80 mm; a maximum experimental stored power of approximately 1400 W. The theoretical maximum average daily temperature of the stored water is 70°C and the experimental value is 53°C. These results show that the efficiency of the tank depends both on the daily power stored and the quality of the insulation.

Keywords: Thermal energy; water heater; solar collector; optimization

INTRODUCTION

Solar energy is a fascinating source of green energy. The most common use of solar energy is to convert it into usable heat. Domestic hot water is the second largest source of domestic electricity after lighting[1]. With the growth in energy demand and the aim of reducing greenhouse gas emissions, particularly CO2 in the atmosphere, in addition to a solar resource exceeding 3,000 hours of sunshine per year[2]. BURKINA FASO has decided to implement a strategy to develop various applications for renewable energy. Among the most promising applications are solar water heaters. Solar water heaters are now solar systems used to produce domestic hot water. However, Burkina Faso, like other sub-Saharan countries, remains heavily dependent on imported models. Local designers and technicians in the field are faced with a lack of high-performance local materials available for the production of quality solar water heaters that can compete with imported models. Our work consists of studying a pre-designed device to evaluate its efficiency and propose solutions to optimize its performance. National companies such as the solar energy and appropriate technology workshop "ATESTA" have embarked on manufacturing and marketing. The storage tank is an important link in a solar installation and can be stratified. However, there is disagreement among researchers about its modeling. While Beckman et al.[3] believe the difference is negligible over a long period of time, other researchers believe that a tank consisting of at least three isothermal layers behaves differently from a non-laminated tank.

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The overall objective of this work is to optimize the storage performance of the non-laminated tank in our thermosiphon solar water heater using local materials. Specifically, we studied the evolution of:

- The temporal temperatures of water stored at different heights in the tank
- Heat losses in the tank during the night
- Theoretical optimization of the effect of insulation thickness on tank performance
- Evaluating the effect of temperature mixing in non-stratified levels during withdrawal

In this study, the parameters used for the calculation are generally averaged when determining the performance of a solar water heater, but due to fluctuations in meteorological parameters[11], the results obtained are compared with those of the numerical study.

MATERIALS AND METHODS

The solar prototype studied was designed and built in Burkina Faso by a local workshop called Atelier Nikiema&frère. The water heater is a separate-element type consisting of a solar collector and a storage tank. The system operates by thermosiphon effect, i.e., natural convection. The water is stored in a cylindrical tank placed vertically above the solar collector on a base. Three key criteria were used to select and use the materials: availability, acceptable cost, and thermal properties.

Description of the storage tank

The storage tank is cylindrical in shape. It is made of galvanized steel. It is insulated with glass wool covered by a sheet metal layer. Inside the tank is a heat exchanger immersed in water, occupying two-thirds of the height of the cylindrical tank.

Heat exchanger

The exchanger is shaped like a coil and is placed inside the storage tank at ¾ of its height. It is 3 m long and made of galvanized tubing.

- Thermal insulation

The storage tank is insulated with glass wool. Glass wool is a woolly thermal insulation material obtained by melting sand and recycled glass (cullet).[4]

Tableau 1 : Propriétés physiques et thermiques des matériaux

	Tank (galvanized steel)	Internal insulation (glass wool)	Heat exchanger (copper))	The fluid (drinking water)
Thickness (m)	0.02	0.03	0.0012	-
Conductivity ($W\,m^{-1}\,K^{-1}$)	50	46.7	384	**0.6**
absorptivity	0.95	0.09	0.01	-
Thermal capa city (J/kg/°K)	1465	840	398	4180

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Table 2: Storage tank components

Storage tank	**Acier**
Length of connections	Hydraulic diameter D_H :34mm
Exchanger dimensions	Longer :3 m Diameter D_H : 20 mm External diameter: d_e=27*mm*
Storage tank position	*Vertical*
Storage capacity	Thickness : 2 mm Height :1000 mm
Maximum operating temperature	T_{max}=95°C

Experimental study

Site

The water heater is installed in Burkina Faso at the Institute of Science in the city of Ouagadougou (latitude 12°21'45“ North, longitude 1°29'21.8” West). The water heater is fixed to the ground next to a two-story building that serves as student accommodation.

Measuring equipment

- A thermocouple: this is a sensor used to measure temperature. Our thermocouple (photo 2) is type K, with a chrome metal positive (+) pole and an aluminum metal negative (-) pole [5], with a measurement error of plus or minus 1.5°C.
- A data logger: the thermocouples are connected to a data recording unit, which is a Keithley data logger with an uncertainty of 1% and powered by SONABEL.
- The solar meter: this is the device used to measure global radiation. It is placed on the surface of our sensor at the same angle. The error made by the device during a given measurement is estimated at 5%. A computer and USB device that enable the recording, retrieval, and processing of measurement data.

Solari meter, Type K thermocouples type keithley Data loger

Figure 1 Experimental measurement equipment

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Experimental protocol

In this work, we focused primarily on global radiation and component temperatures at the sensor level. These data will enable us to study the actual performance of this system. Temperature measurements are taken using type K thermocouples attached to the surface of the system where the temperature is to be measured. The thermocouples are held in place using aluminum adhesive tape. The solar meter, used to measure solar radiation, is placed on the system's glass panel at the same angle as the panel. Finally, all of the thermocouples and the solar meter are connected to a data logger, which automatically records the data on a USB drive for subsequent processing on a computer.

Figure 2 Measuring equipment and storage tank

Determination of power consumption, storage, and losses

The balance at the tank level is:

$$P_{Acc}=Q_{utile}-P_{perte}-P_{cons} \quad \textbf{(1)}$$

In the absence of withdrawal, the heat balance is written as follows:

$$P_{Acc}=Q_{utile}-P_{perte} \quad \textbf{(2)}$$

$$\textit{Ou encore } MC_p\frac{dT_s}{dt}=Q_{utile}-P_{perte} \quad \textbf{(3)}$$

Q_{utile} is the useful power of the sensor, determined from the characteristics of the sensor, and is equal to

$$Q_{utile}=\eta.I_c.S_C=\dot{m}c_p(T_c-T_s) \quad (4)$$

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Where: "the sensor temperature and efficiency η such that:

$$\eta = F_R\left[\eta_0 - U_t\frac{T_s - T_a}{I_C}\right] \quad (5)$$

$$\eta_0 = \frac{I_a}{I_c} \quad (6)$$

P_{loss} Represents losses through the walls of the tank; this value is determined by :

$$P_{loss} = U_t . A_t (T_s - T_a) \quad (7)$$

Avec: T_S *étant respectivement la température du stockage dans le ballon*

et T_a *la température ambiante autour du ballon*

La consommation du puisage de l'eau chaude est :

$$P_{cons} = \dot{m} c_p (T_s - T_e) \quad (8)$$

avec T_e *la température d'entrée de l'eau froide dans l'échangeur*

THEORETICAL STUDY OF THE TANK

Modeling and simulation

Simplifying assumptions

• The storage tank (vertical cylinder) is in laminar flow.

• The physical properties of the fluid in the tank remain constant despite slight expansion of the water.

• The pressure in the tank remains equal to atmospheric pressure.

• The model adopted will be of the unidirectional type.

Incompressible and laminar flow.

• Viscous dissipation in the energy equation is negligible.

• No radiating medium.

• Vertical geometry.

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Physical model and equivalent diagram

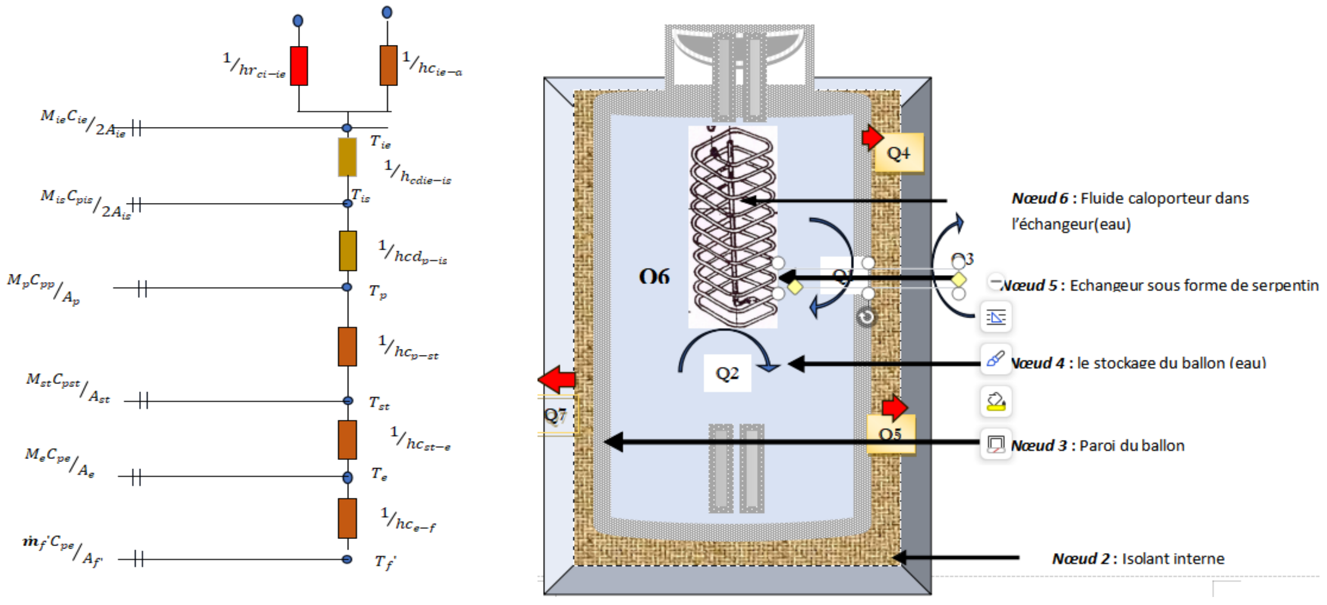

Figure 3 : physical electrical model of the storage tank

Bilan thermique

Heat balance of the external insulation

$$M_{ie}C_{pie}\frac{dT_{ie}}{dt}=hc_aA_{ie}(T_a-T_{is})+hr_{ci}A_{ie}(T_{ci}-T_{ie})+hcd_iA_{ie}(T_{is}-T_{ie}) \quad (9)$$

- Thermal balance of the internal insulation [2]

$$M_{is}C_{pis}\frac{dT_{is}}{dt}=hcd_iA_{is}(T_b-T_{is})+hcd_pA_{is}\left(T_p-T_{is}\right) \quad (10)$$

Thermal balance of the wall

$$\left(M_pC_p\right)_p\frac{dT_p}{dt}=hc_pA_p\left(T_{st}-T_p\right)+hcd_pA_p\left(T_{is}-T_p\right) \quad (11)$$

Heat balance of stored water[6]

$$M_{st}C_{pst}\frac{dT_{st}}{dt}=hc_{st}A_p\left(T_p-T_{st}\right)+hc_{st}A_e(T_e-T_{st}) \quad (12)$$

Heat balance of the internal heat exchanger in the storage tank

$$M_eC_{pe}\frac{dT_e}{dt}=hc_eA_e(T_{st}-T_e)+hc_eA_e(T_{f'}-T_e) \quad (13)$$

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Heat balance of the water in the internal exchanger

$$\rho_f C_{pf}\frac{D_H}{4}\frac{dT_f}{dt}+\rho_f C_{pf}\frac{V_f D_H}{4}\frac{dT_f}{dx}=hc_f A_e(T_e-T_f) \quad \textbf{(14)}$$

Determination of heat transfer coefficients

Nombre de Grashof: $$G_r=\frac{\beta'\cdot g\Delta T\cdot\rho^2\cdot D_H^3}{\mu^2} \quad \textbf{(15)}$$

Nombre de Prandtl: $$Pr=\frac{C_p\cdot\mu}{\lambda} \quad \textbf{(16)}$$

*Nombre de Rayleig*h: $$Ra=G_r\cdot Pr \quad \textbf{(17)}$$

The convection coefficient inside the tank is calculated using the following equation::

$$h_{eau}=\frac{Nu.\lambda_{eau}}{D_H} \quad \textbf{(18)}$$

$$Nu=\left\{0.825+\frac{0.387R_a^{1/6}}{\left[1+(0.492/Pr)^{9/16}\right]^{8/27}}\right\}^2 \quad \textbf{(19)}$$

For natural convection, the Nusselt number is given by the empirical relationship de Morgan V. T

$$Nu_{naturel}=cRa^n \quad \textbf{(20)}$$

$$avec \;\; c=0.5 \;\; et \;\; n=0.25$$

RESULTS AND DISCUSSIONS

Experimental results

Evolution of temperature curves over three and five layers of the tank

Fig. 4 shows the middle and top of the tank. Three main sections can be observed on the curves. These three sections essentially reveal three periods of the day, demonstrating the quality of the storage system. The first phase corresponds to dawn, when there is virtually no sunlight and the ambient temperature is very low, causing a noticeable loss of heat from the tank. The second upward phase shows the impact of sunlight and ambient temperature, which are favorable for heat storage. Finally, the third phase marks the end of the thermosiphon effect at the solar collector, meaning that the tank no longer receives heat. In addition, the trend shows a slight stratification of the tank at the bottom and in the middle, while between the middle and the top, the curves tend towards a mixing of temperatures. These curves agree that, due to the effect of density, the hottest water is at the top, with a maximum of around 53°C. This maximum is acceptable given the very unfavorable climatic conditions for better sunshine in August. These trends were observed by BAGRE SARA.al with maximums varying between 48°C and 60°C depending on the days during the rainy season in Burkina Faso. [7]

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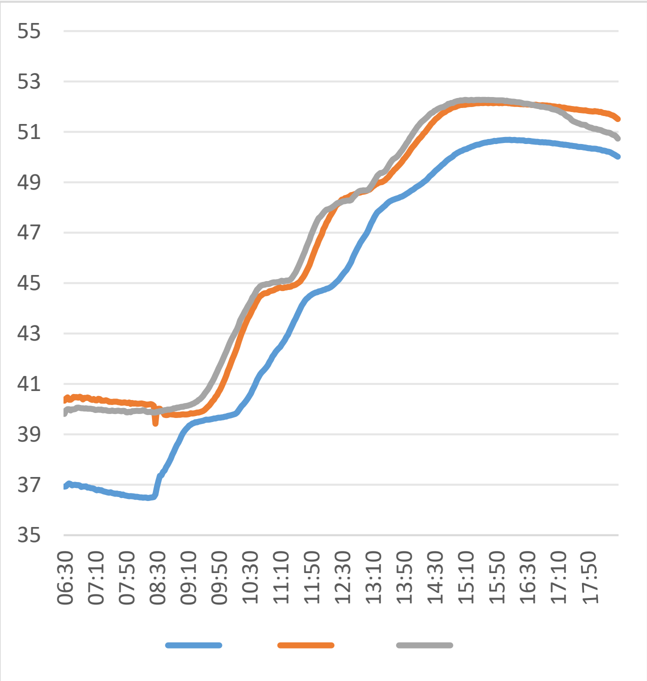
When the number of layers in the tank is increased to five, there is greater mixing between the layers at the end of the day. Therefore, for better performance, the tank must be more stratified to increase its efficiency, as tank stratification is an essential factor in optimizing a solar installation. [8].



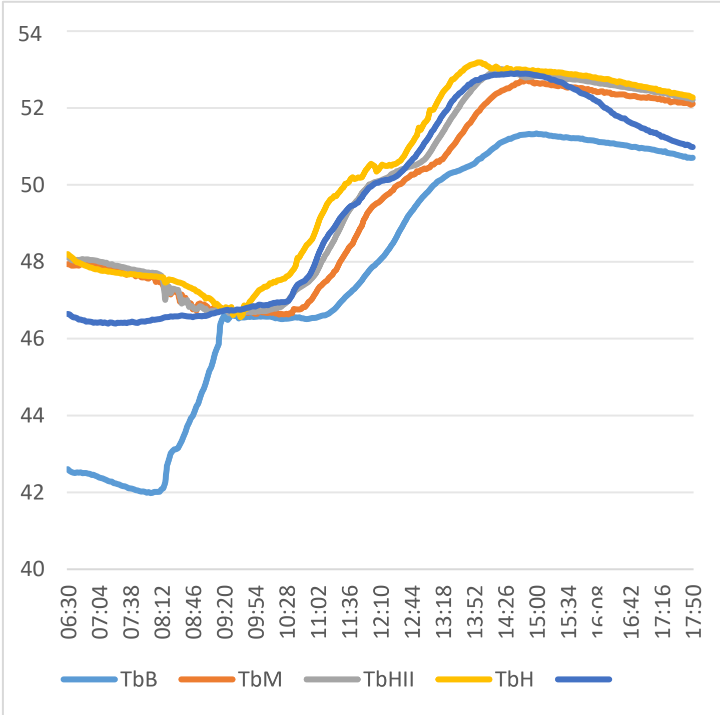


Figure 4: The evolution of the temperature curves on three parts of the balloon, namely the bottom of the balloon

Changes in average water temperature curves in the tank

Fig 5 shows changes in average water temperature in the tank over the course of the day for three days of measurements, namely September 7, October 15, and October 16, 2023. The overall trend in average temperatures for these three days is consistent, with a maximum of around 54°C. The three phases of the day can also be seen in the curve profiles.[9]

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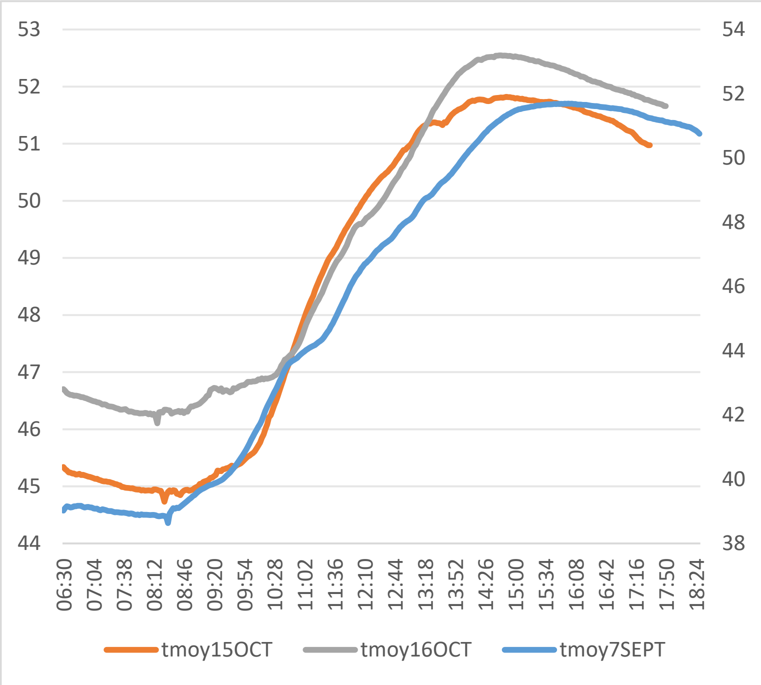

Figure 5: Evolution of average water temperature curves in the tank

Changes in water temperatures in the tank at different layers and during the night.

The curve in **Fig 6** shows a downward trend in water temperatures in the tank during the night. This heat loss is greater at the top layer. This is because the top is not covered by insulation and is therefore not insulated**.**

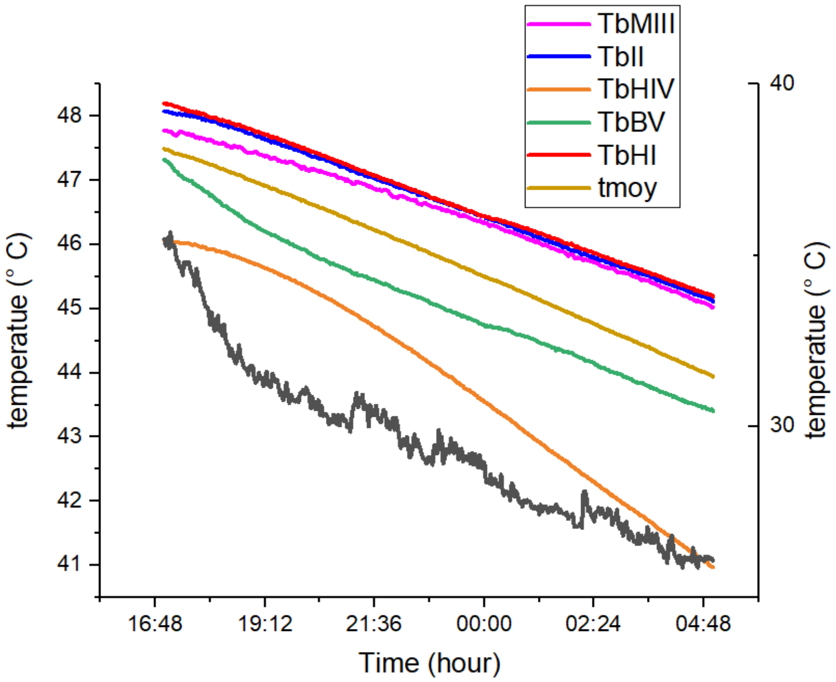

Figure 6: Changes in water temperatures in the tank at different layers and during the night

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Temperature changes in the layers of the tank and in the water entering the exchanger

The curve in **Fig 7** shows the temperature changes in the layers of the tank and in the water entering the exchanger from the drinking water supply network during a 1L/min withdrawal at the end of the day for a period of approximately 30 minutes. These curves show the temperature drop trends according to the layers. Among the curves, a rapid decrease is observed in the middle layer of the storage tank, which can be explained by the presence of the exchanger, which occupies most of the middle of the tank. Therefore, in order to obtain a good temperature during withdrawal, it is recommended to allow a pause to enable the temperatures within the tank to homogenize..[10]

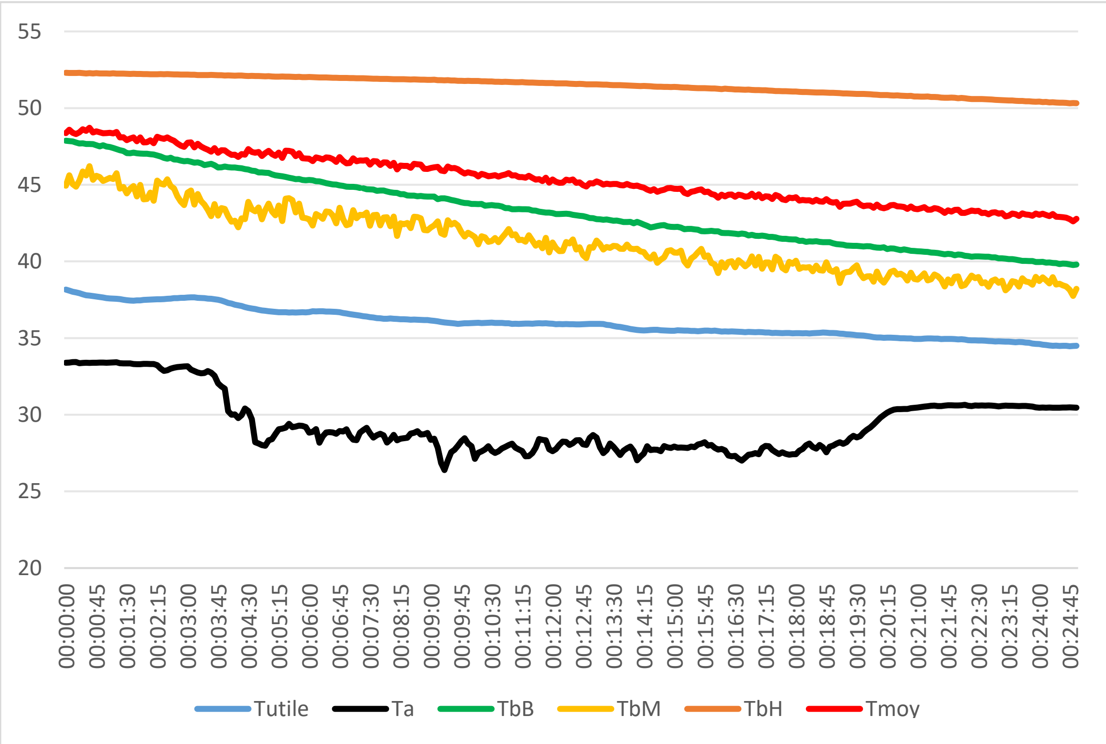

Figure 7: Temperature changes in the layers of the tank and in the water entering and leaving the exchanger

Change in thermal power stored in the tank during the day

Overall, the curve in **Fig 8** shows that the power stored in hot water is related to radiation. In addition, the curves indicate that from around 4 p.m. onwards, the stored power is virtually zero. This increases the storage life of the hot water until the next storage cycle begins. This necessarily implies that the tank must be very well insulated to minimize losses.

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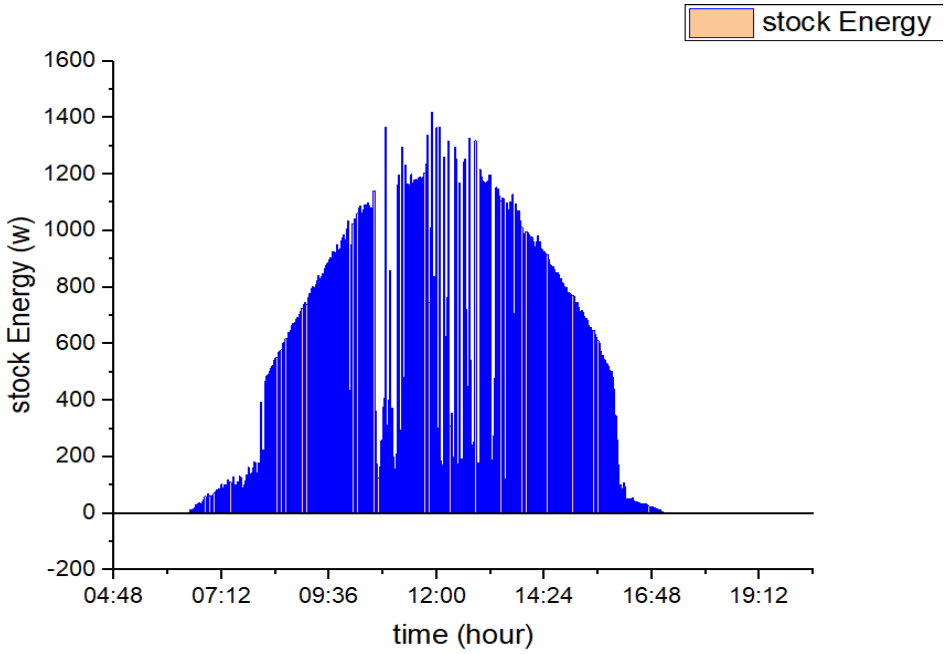

Figure 8: Thermal energy stored in the tank during the day

THEORETICAL RESULTS

Changes in theoretical temperatures in the four layers of the balloon

Fig 9 illustrates the temperature trends in the three layers of the balloon. They look good because temperatures increase according to the position of the layer in the tank, i.e., from the bottom of the tank to the top, with a maximum of around 70°C. We can see that at the end of the day, temperatures become more uniform. This indicates mixing of the temperatures in the layers and, consequently, poor stratification in the storage tank**.**.[11]

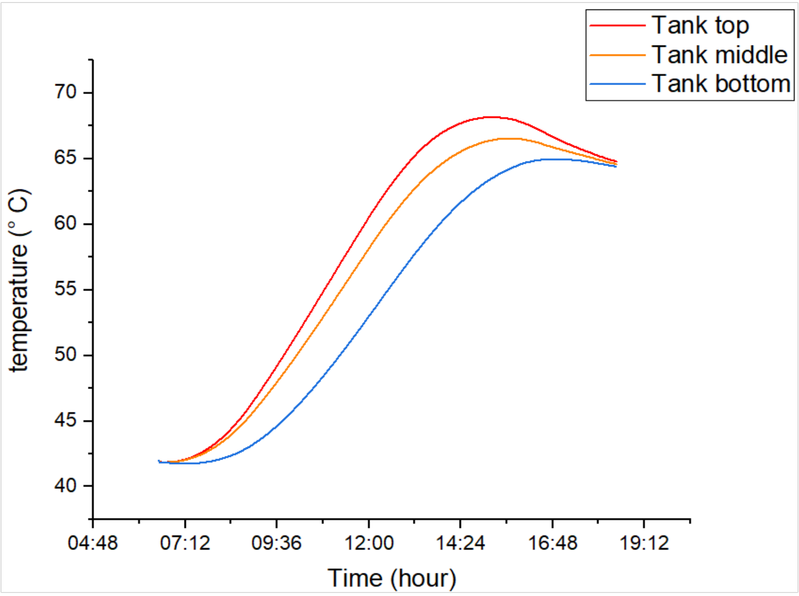

Figure 9: Evolution of theoretical temperatures in the four layers of the ball

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Change in the theoretical average temperature of the water in the storage tank.

Fig 10 shows the change in the theoretical average water temperature in the storage tank. The temperature profile has three phases corresponding to the three phases of the day, namely sunrise, midday, and sunset, with a maximum temperature between 65°C and 70°C at the end of the day.

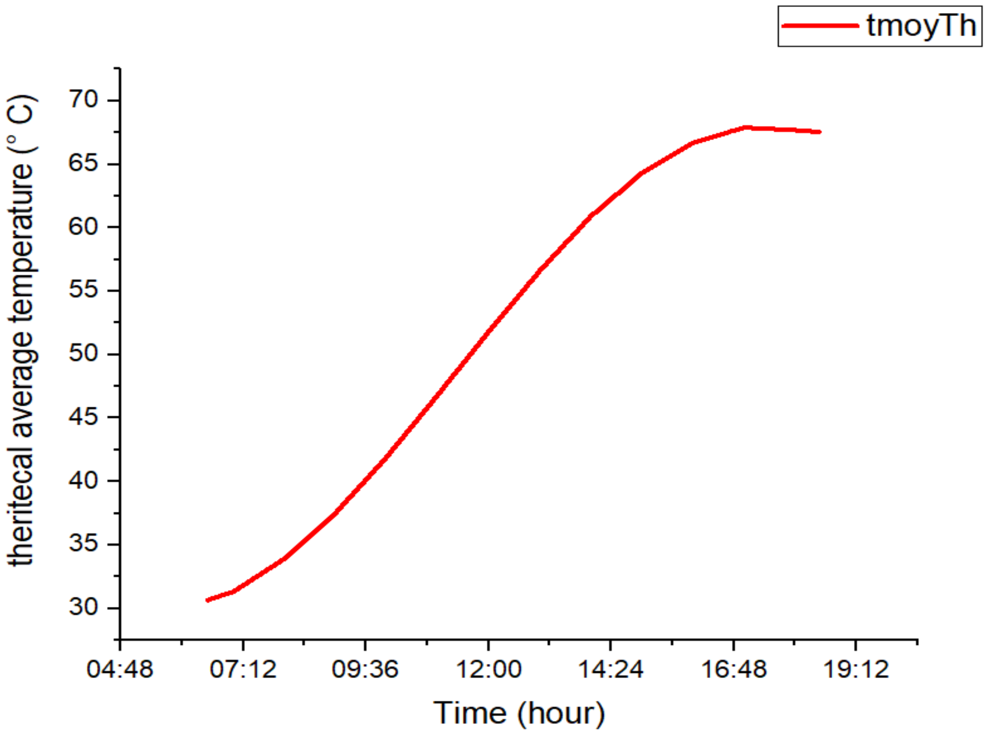

Figure 10: Change in the theoretical average water temperature in the storage tank.

Changes in water temperatures in the tank according to the thickness of the insulation

Fig 11 illustrates the changes in water temperatures in the tank according to the thickness of the insulation, which is glass wool. It can be seen that although the quality of the tank insulation increases with the thickness of the insulation, it is clear that above 50 mm, the impact of insulation thickness on the quality of the tank insulation becomes negligible. Therefore, good tank insulation requires approximately 50 mm of glass wool.[12]

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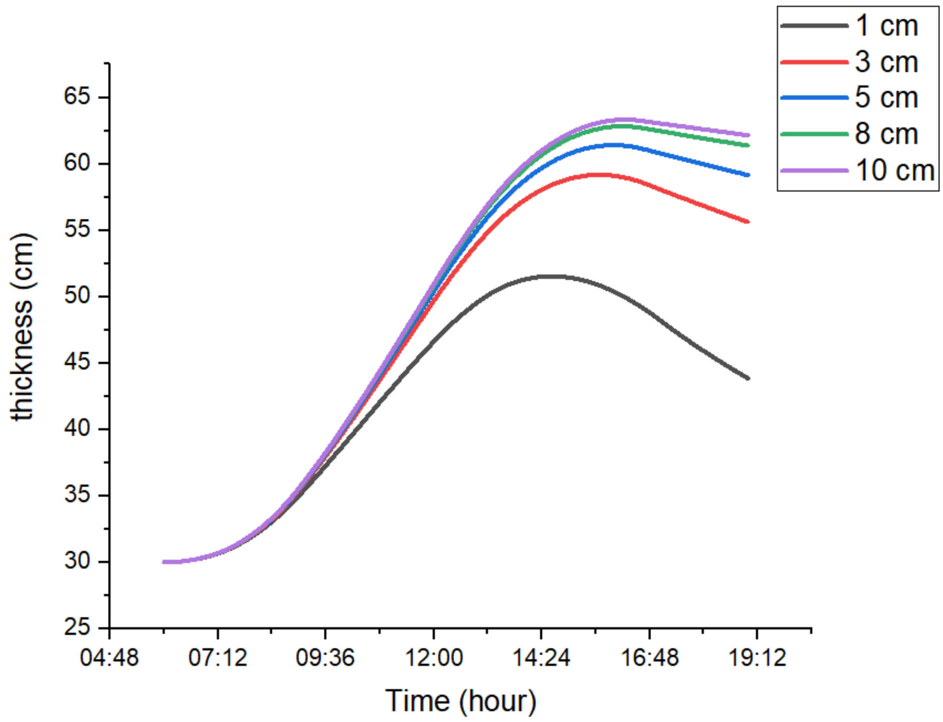
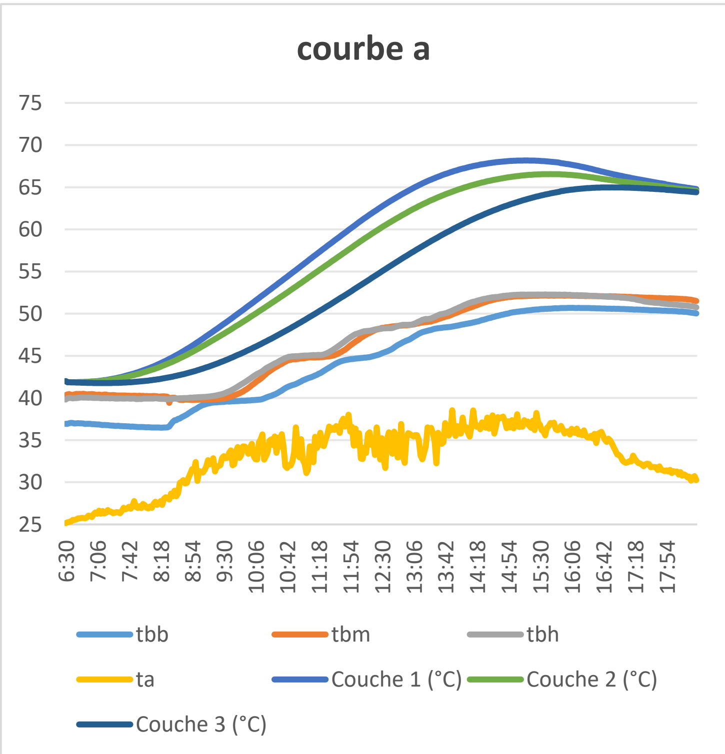


Figure 11: évolution des températures de l'eau dans le ballon selon l'épaisseur de l'isolant qui est la laine de

VALIDATION OF RESULTATS

Curves a and b in **Fig 13** show a good correlation between the trends in experimental and theoretical water temperatures in the tank throughout the day. The correlation coefficient is approximately 0.95. The profile of these curves is similar to those obtained in the model studied by David. B[8]



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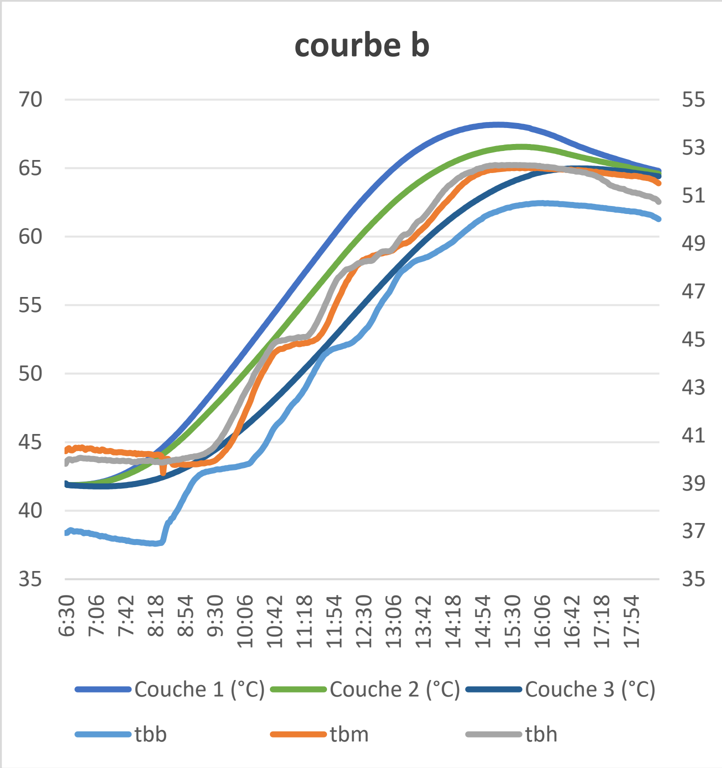

Figure 13: Experimental and theoretical water temperatures in the balloon during the day

La fig14 allows us to observe the three phases of the curves with good consistency. This similarity in the trend of the numerical and experimental mean temperature curves implies a good correlation between the theoretical and experimental results, with a correlation coefficient of 0.94. The results were obtained by[13]

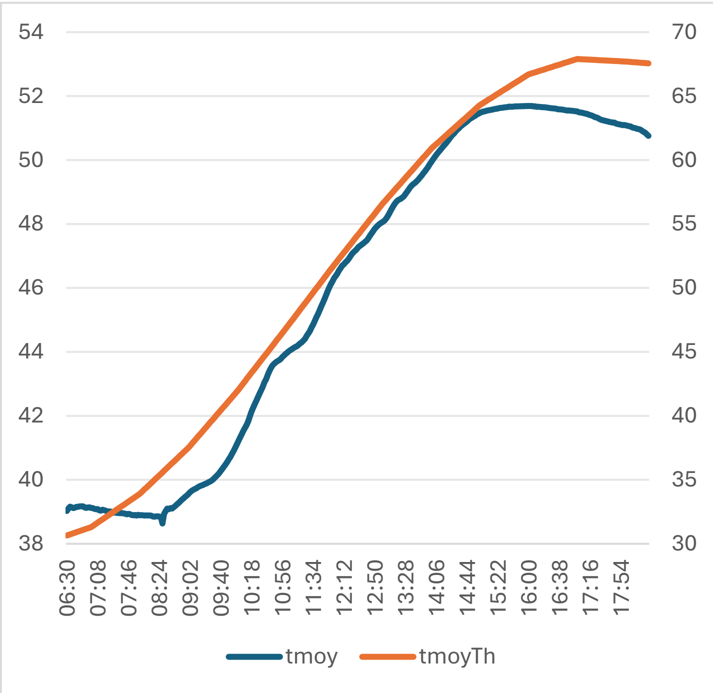

Figure 13: Numerical and experimental average temperature curves

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NOMENCLATURE:

Q_{utile} useful Is the useful power of the solar collector,
P_{perte} the losses through the walls of the tank
T_a ambient temperature
Ra : $Rayleigh\ nomber$

λ_i :thermal conductivity

D_H : hydrolic diameter

Pr : $Prandtl\ Nomber$

heau : water convection coefficient
T_{bal} : tank intlet temperature

h_a : air convection coefficient

G_r : $Grashof\ n\ omber$

C_p : specific heat capacity
μ : dynamic viscosity
$\boldsymbol{T_{is}}$ **:** insulation temperature
$\boldsymbol{T_{st}}$ **:** Temperature of the water stored in the tank
$\boldsymbol{T_p}$ **:** Temperature of the wall
A : surface

T_{ci} : sky temperature

CONCLUSION

In this study, we investigated the performance of the storage tank in our solar water heater. Based on the results obtained, we observed that the tank temperature remained around 52 °C, which is sufficient for hot water production for the user. The temperature within the tank also varied, even with 8 m thick insulation. Therefore, we can conclude that performance can be optimized through proper tank stratification; improved thermal insulation to reduce nighttime heat loss; and longer draw-off intervals to increase the outlet water temperature.

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