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RESEARCH ARTICLE

EXPERIMENTAL STUDY OF NATURAL CONVECTION IN A SOLAR CHIMNEY WITH HYPERBOLIC COLLECTOR

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Abstract

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The solar tower consisting of the chimney, the turbine, and the collector, initiated by Jörg Schlaich, is an electrical energy production system. This work aims to understand the phenomenon of natural air convection in the device as a function of solar radiation. A prototype designed at the L.E.T.RE laboratory made it possible to experimentally study the behavior of air in the device. To do this, we carried out readings on the solar tower using measuring devices such as the Midi LOGGER, the pyranometer and the hot wire anemometer. They showed that the air temperature changes depending on the amount of sunlight as well as the speed of the fluid entering the chimney. The temperature of the absorber is maximum between 12:30 p.m. to 1 p.m. with values respectively of 87.1°C; 88.5°C and 91.3°C for the days of October 8, October 9, and November 9, 2022. However, the temperature of the fluid drops from the collector to the chimney. The results show that the collector efficiency reaches 19.32% on average; 34.05% and 33.49% respectively for the days of 08/10/2022, 09/10/2022 and 09/11/2022. The collector is insulated using polystyrene. With improvements the system could meet the needs for ventilation by thermal draft, drying as well as electricity production.

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Introduction:-

Around 31% of the population in sub-Saharan Africa has access to electrical energy [1]. However, energy demand is very high given the demographic boom and development needs. Note that current electrical energy is of fossil origin which comes from non-renewable sources. The current energy production technique constitutes an environmental threat through deforestation which is not restored, its pollution by the release of gases such as NOx and CO2. To overcome environmental threats due to fossil fuels, renewable energies, particularly solar energy, would be an effective solution. Thus, the solar tower consisting of a collector, a chimney and a turbine invented by Jörg Schlaich operated for seven years and served as an information provider [2]. To obtain better yields, numerous studies, both

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theoretical and experimental, were aimed at collectors. Badis et al. [3] developed an experimental prototype consisting of a transparent plastic collector constructed from a polyethylene film. They showed that air speed increases in the same direction as temperature rises. They proved that the speed of the air in the collector increases when one moves in the direction of a decrease in the radius of the collector, a result confirmed by Ousmane et al [4]. Ouédraogo et al in 2021[5] conducted an experimental thermal analysis of a stationary hemispherical concentrator under the climatic conditions of Ouagadougou. They concluded that the receiver and the air inside reached a maximum temperature of 224°C and 97.6°C, respectively. This result proves that the device used is technically favorable to thermal applications requiring intermediate temperatures. In 2022, Ouédraogo et al [6] experimented with a collector equipped with mini hemispherical concentrators in a prototype solar chimney. At the end of their experiment, they found a maximum value of 78.35°C in the collector and 2.87m/s in the chimney. Rezaei et al [7] in 2023 improved the efficiency of the collector by inserting metal tubes into the collector. Thus, they obtained an increase of 33.7% by varying the diameter of the collector while the efficiency improved by 30% by changing the length of the metal tube. Fadaei et al [8] introduced a phase change material. The introduction of the phase change material resulted in an increase in temperature to 72°C and an increase in speed around 2m/s unlike a conventional solar chimney without phase change material. Bashirnezhad et al [9] experimented with the use of water and paraffin as thermal storage materials. They showed that paraffin is the best heat storage material. Chaichan et al [10] studied the impact of pollution and dust deposition on the performance of a solar chimney. They proved that cleaning the solar collector is necessary to restore some of the efficiency loss due to the accumulation of dust and air pollutants.

Materials and Method:-

Description Of the Device

The solar tower that we studied was built at the Renewable Thermal Energy Laboratory (L.E.T.R.E) at the Joseph KI-ZERBO University of Ouagadougou and has a total height of 2 meters. This tower is equipped with a collector whose cover has a hyperbolic profile which is placed on a square absorber measuring 200 cm x 200 cm painted black constituting its base. In the absence of glass, we used a transparent plastic film (polystyrene) to cover the prototype, to create the greenhouse effect and reduce heat exchange with the outside. To identify the hyperbolic profile, we used the hyperbolic coordinates described by Ousmane et al. [2] defined by:

$$\eta = 2xy \qquad (1)$$

Thus, taking 1 m for the radius of the collector and 0.125 m for the radius of the chimney we have the following parameters: x=1 and y=0.125. We establish a hyperbolic function considering these parameters mentioned above.

$$y = f(x) = \frac{1}{8x} \, (2)$$

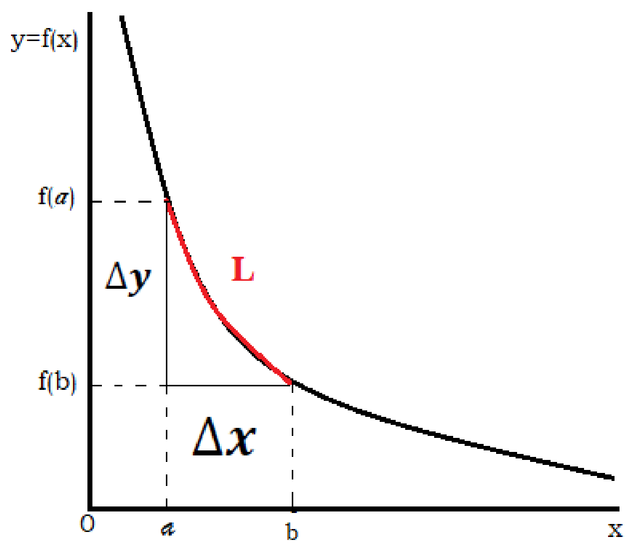
Considering the geometry of the device, to make the use of the device easy, our chimney has rings to be able to reveal the hyperbolic profile. To cover the roof of the collector we cut the plastic film according to the length differences between the rings of the collector. Covering the roof was easy thanks to templates that we used to cut the plastic. Figure .1 illustrates the photo of the solar chimney designed at the L.E.T.R.E laboratory.

Figure.1:- Photo of the solar tower designed at the Laboratory.

The collector of our model is a polystyrene roof (transparent plastic film), serving as a greenhouse covering a square floor of 2m side painted black which is the absorber. To reveal the hyperbolic profile, the collector is supported in its center by 5 round bars of 8 smooth which we called “rings” having respective radii of 50 cm; 31.3cm; 20.8cm; 15.6 cm and 12.5 cm spaced 20 cm from one layer to the next. The collector has openings of 4 cm on each side to allow air entry. Figure.2 below shows the photo of the collector.

Figure.2:- Image of the tower collector.

To cover the roof of the collector, we established equation (7) to be able to cut the plastic film. The method of establishing and solving this equation is described as follows.



According to equation (2) we ask:

$$y = f(x) \quad (3)$$

And

$$\begin{cases} \Delta x = b - a \\ \Delta y = f(a) - f(b) \end{cases} \quad (4)$$

We have:

$$L = \sqrt{(b-a)^2 + \left(f(a) - f(b)\right)^2} \Rightarrow L = \sqrt{(b-a)^2 + \left(\frac{1}{8(a)} - \frac{1}{8(b)}\right)^2} \quad (5)$$

With:

L: Length between ring gaps
a and b: no x depending on the length of the rings
Thus Table.1 gives the different lengths obtained.

Table 1: -

$x \in [a; b]$	$[0.125; 0.250]$	$[0.250; 0.400]$	$[0.400; 0.600]$	$[0.600; 0.800]$	$[0.800; 1.000]$
L (m)	0.517	0.242	0.226	0.206	0.202

The chimney of our solar tower is shown in Figure.3. It is in a cylindrical tubular shape with a radius of 12.5 cm and a height of 1 m and is easily detachable from the tower.

Figure 3:- Image of the tower chimney.

For the experimental study of the device (Figure.1), we used the devices and measurement methods below:

- ✓ A Midi LOGGER GL220 type data logger shown in the figure. 4 measures different temperatures in °C within the prototype. Its accuracy is 1% between 20°C and 50°C then 2% between 50°C and 200°C. We coupled it with 9 type K thermocouples.
- ✓ A pyranometer shown in Figure.5 measures sunshine, was coupled to channel 10 of Midi LOGGER.
- ✓ A TESTO 480 type hot wire anemometer shown in Figure.6, equipped with a probe placed just at the entrance to the chimney to measure the speed of the air rising in the collector as well as the temperature at the entrance of the chimney.

Figure 4:- GL220Midi LOGGER

Figure 5:- SR03 Pyranometer

Figure 6:- Hot wire anemometer.

Experimental Protocol
Our experimental study consisted of measuring the air temperatures at the inlet of the collector, at collector levels, at the inlet and outlet of the chimney as well as the ambient temperature. We also measured the amount of sunlight and the speed of the hot air rising in the collector towards the chimney. Temperature measurements were possible thanks to type K thermocouples all connected to the Data LOGGER. Air speed and sunshine were measured respectively by the anemometer and the pyranometer. It should be remembered that the measurements were recorded every 5 minutes during the day. In fact, the different positions of the thermocouples are as follows:
• Thermocouple 1: measures the temperature at ring 4 located 0.8 m from the ground.
• Thermocouple 2: measures the temperature at ring 3 located 0.6 m from the ground.
• Thermocouple 3: measures the temperature at ring 2 located 0.4 m from the ground.
• Thermocouple 4: measures the temperature at ring 1 located 0.25 m from the ground.
• Thermocouple 5: measures the temperature at the collector inlet.
• Thermocouple 6: measures the temperature at the absorber.
• Thermocouple 7: measures the temperature at the chimney outlet.
• Thermocouple 8: measures the temperature of the center of the collector positioned 5 cm from the ground.
• Thermocouple 9: measures the ambient air temperature.
• Thermocouple 10: coupled to the pyranometer measures sunlight.
• Finally, the anemometer measures the speed of the air entering the chimney and the temperature at the outlet of the collector located 1m from the ground.
The positions of the different thermocouples are shown in the Figure. 7:

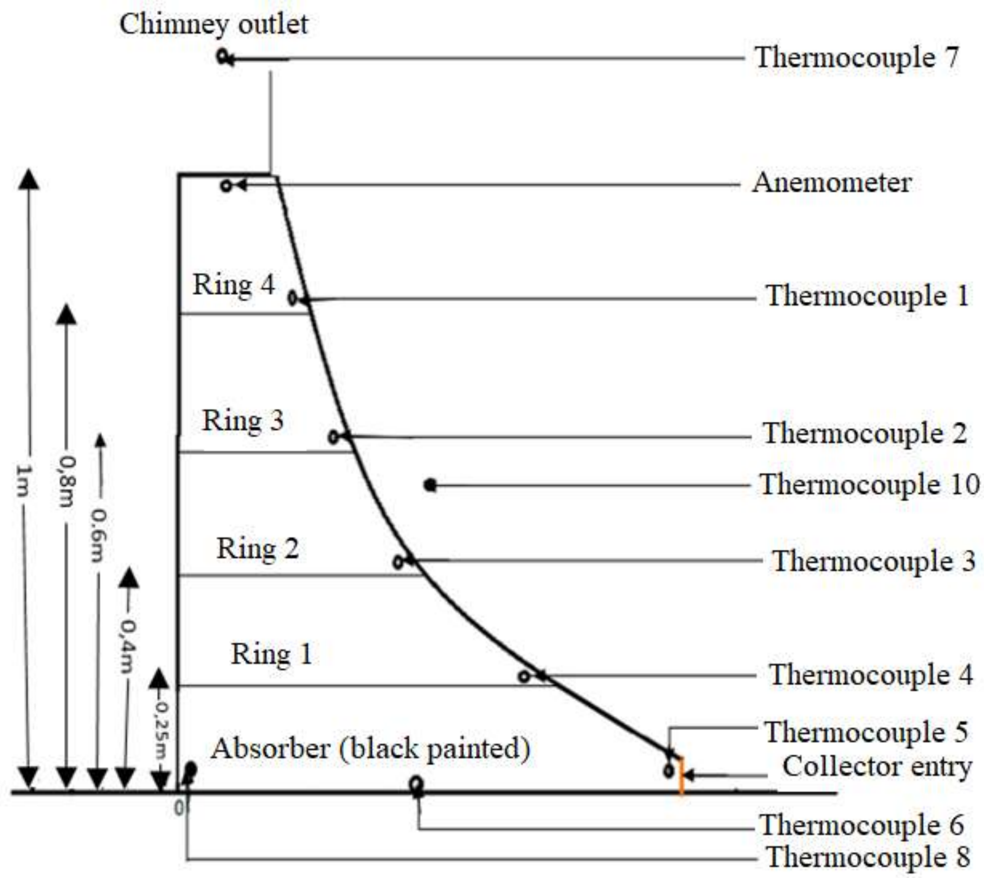


Figure 7:- Position of the thermocouples.

Results and Discussions:-
In this part, we present the temperature measurements, the solar radiation, and speeds.

1. Evolution of temperatures during various days

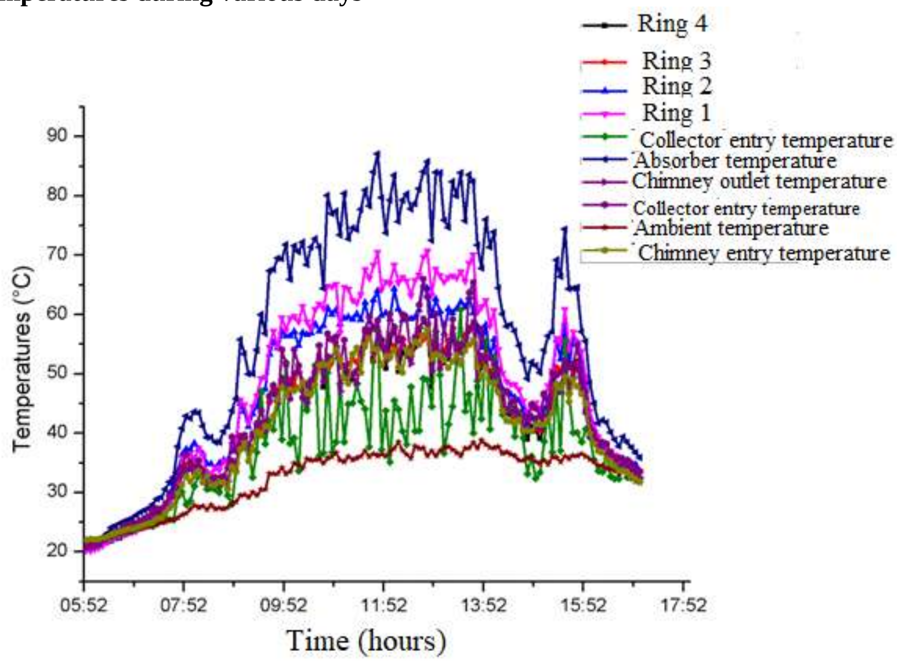


Figure 8:- Temperatures of 08-10-2022.

We observe that all temperatures have the same appearance. However, the curves remain all confused until 8 a.m. because in this hour range there is no sunshine. From 8 a.m., we observe a rapid increase in the absorber temperature and reaches a peak of 87.1°C at 12 p.m. Thereafter it drops slowly until 2 p.m. before decreasing suddenly until 3 p.m. Then follow respectively the temperatures of ring 1 located 0.25m from the ground, of ring 2 located 0.4m from the ground and that in the center of the collector whose peaks are respectively 70°C, 65°C and 61°C between 12 p.m. and 1 p.m. We note a second peak around 4 p.m. Naturally, the ambient temperature and that measured at the collector inlet change very slowly and remain low compared to the other temperatures. We notice that at the exit of the chimney, the temperature is higher than that at the entrance. This is explained by the fact that the chimney is not thermally insulated; therefore, it helps to heat the air, hence the increase in temperature at the outlet. Figure 9 gives us the variations in sunshine during the same day.

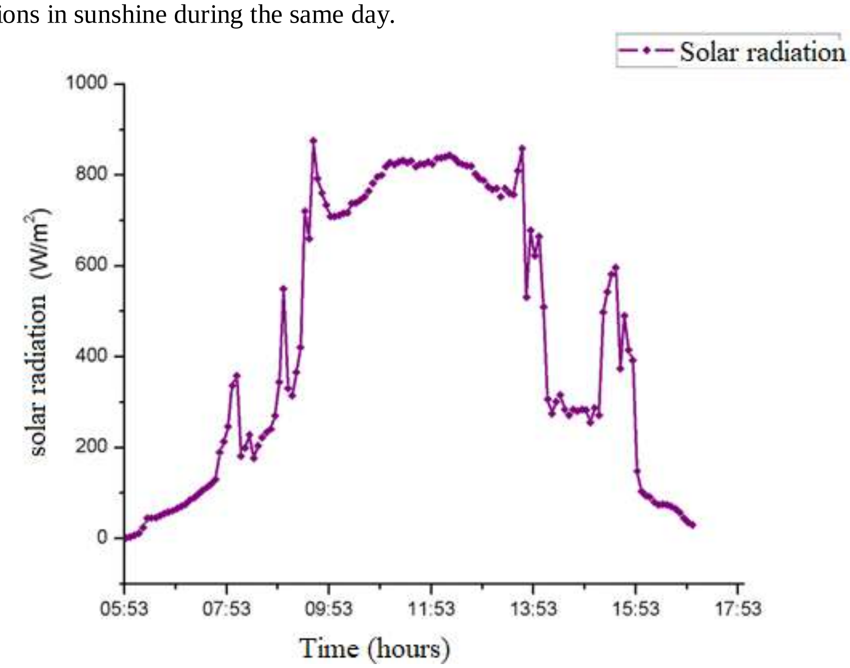


Figure 9:- Sunshine on 08-10-2022.

From this curve we observe an increase in sunshine from 5:50 a.m. until 1:40 p.m. with several peaks where it reaches a maximum value of 858 $W.m^{-2}$. Then, the sunshine gradually decreases until 5 p.m. The curve has a bell shape but there are some irregularities caused by cloudy periods, wind, and dust during the day. We show in figure.10 the variations in air speed during the same day.

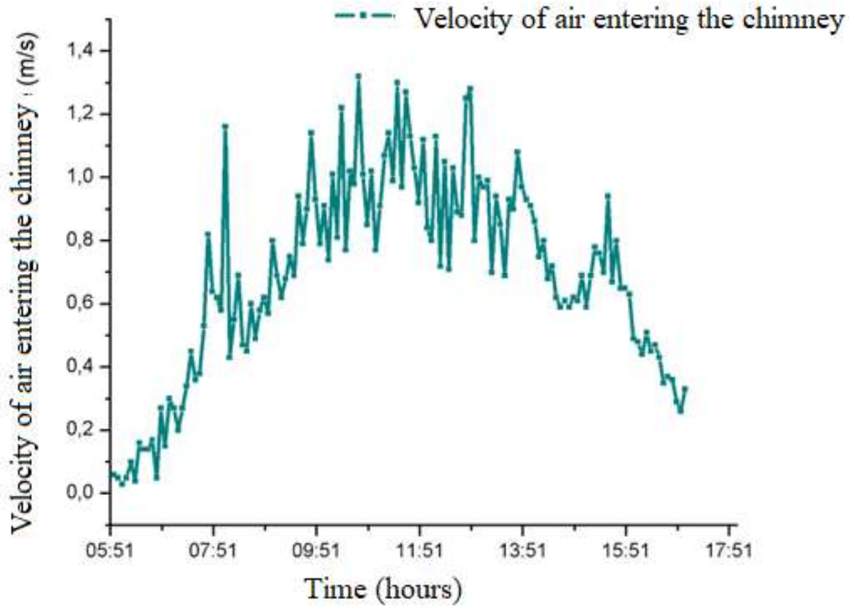


Figure 10:- Air speed in the chimney on 08-10-2022.

From the analysis of this curve, we observe a slight increase in air speed with low values until 12h and reaches a maximum value of 1.2 m. s^{-1}. Then, it gradually decreases until 5 p.m. We also observe irregularities caused by the presence of clouds during the day. As for figure .11, it gives us the temperature variations for the day of 09-10-2022.

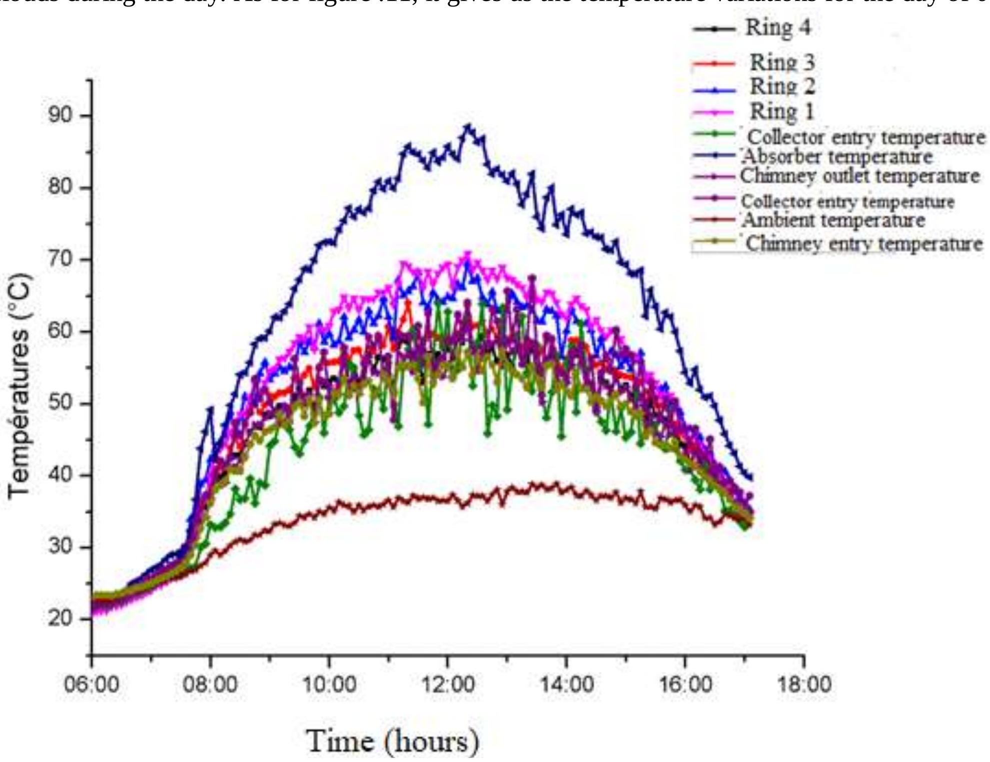


Figure 11:- Temperatures of 09-10-2022.

We notice that these temperature curves all have a Gaussian shape. So, from 6 a.m. to 8 a.m., we observe that all temperatures are combined because there is not enough sunshine in this interval. From 8 a.m. to 12 p.m., temperatures increase and reach their maximum values, then beyond 12 p.m., they decrease until 5 p.m. Within the collector, the temperature of the absorber increases more quickly and reaches a maximum of 88.5°C; then follow respectively the temperatures of rings 1, 2, 3, that in the center of the collector, ring 4, then that at the outlet of the chimney, and finally that at the entrance of the chimney with differences of a few degrees Celsius close. However, the temperature at the collector inlet experiences a slight increase above the ambient temperature from 6 a.m. to 7 a.m. Figure .12 below shows the variations in sunshine on the same day.

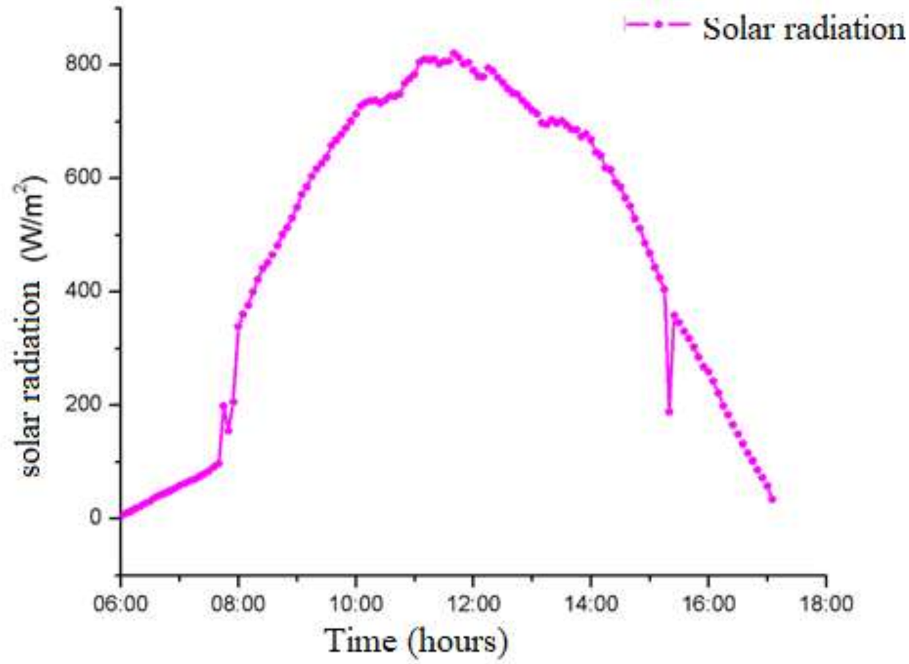


Figure 12:- Sunshine on 09-10-2022.

We observe a slight growth from 6 a.m. to 8 a.m. then a sudden increase in the curve until 12 p.m. with a maximum value of 821 $W.m^{-2}$. From 12 p.m. to 5 p.m., it gradually decreases while maintaining its Gaussian shape. However, we observe a jump from 8 a.m. and a drop around 3 p.m. Figure 13 illustrates the variations in air speed during the same day.

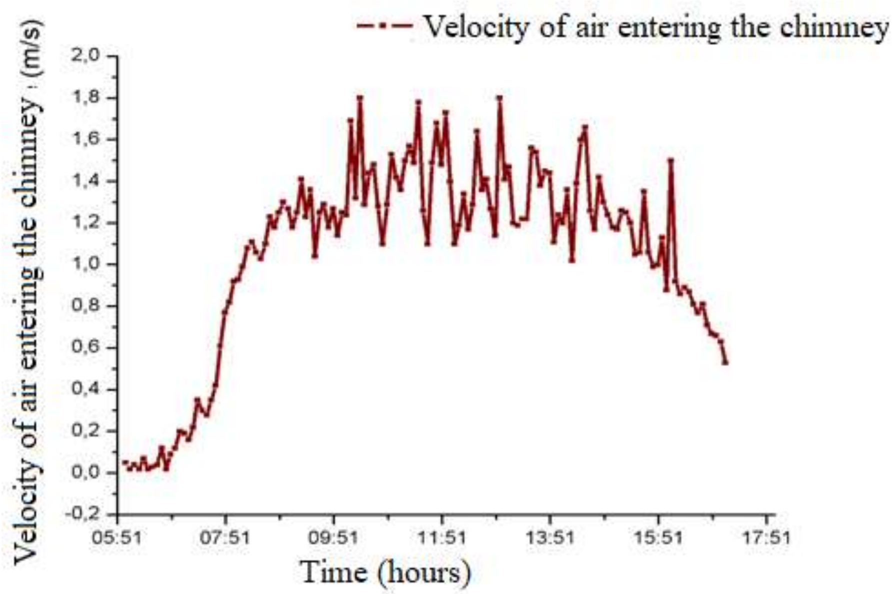


Figure 13:- Air speed in the chimney on 09-10-2022.

The speed increases very quickly and reaches a maximum peak of 1.6 m. s^{-1} at 1 p.m., then it decreases until 5 p.m. However, the various irregularities observed relate to cloudy periods. Figure .14 shows the temperature variations on November 9, 2022.

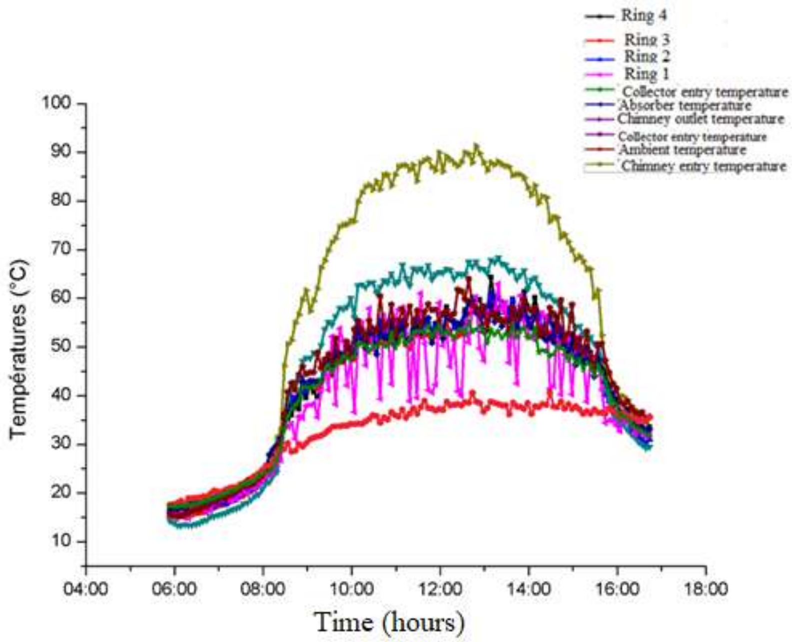


Figure 14:- Temperatures of 09-11-2022.

The appearance of these curves is like that of figure. 8. We note that from 8 a.m., the temperature of the absorber evolves more quickly and reaches its maximum around 12 p.m. with a value of 92°C. Subsequently, respectively come the temperature curves of rings 1, the center of the collector, rings 2, 3 and 4, as well as the temperatures at the outlet of the chimney and at the outlet of the collector. They reach their maximums around 12 p.m. and 1 p.m. In fact, just like on other days, the air heated in the collector becomes light and rises through the chimney effect into the chimney. As it rises, the hot air cools as it exits the chimney. But we observe that at the outlet of the chimney, the temperature is higher than that measured at the outlet of the collector. This is explained by the fact that the chimney helps to heat the air which rises in temperature, because it is not thermally insulated. Figure 15 gives us the sunshine curve for the same day.

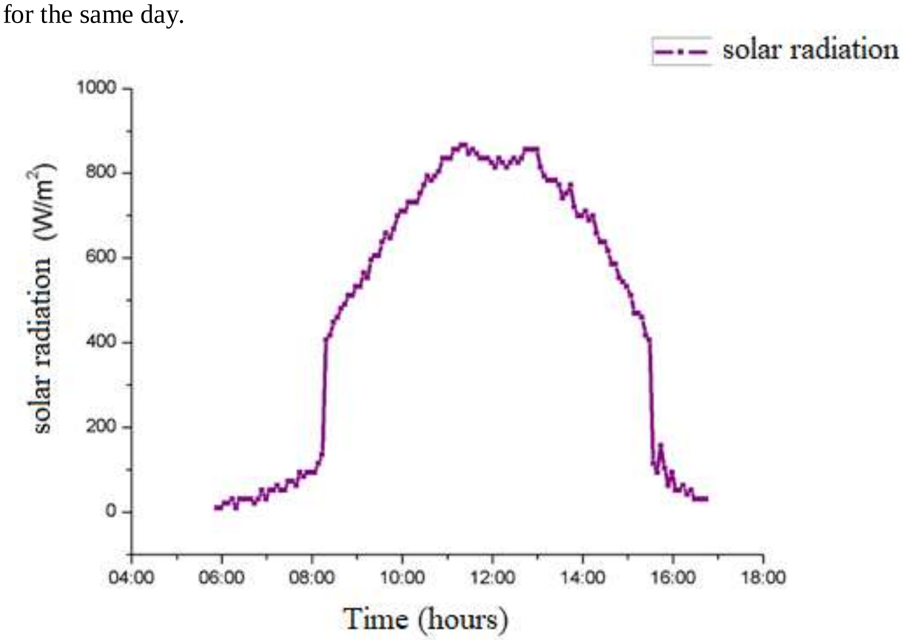
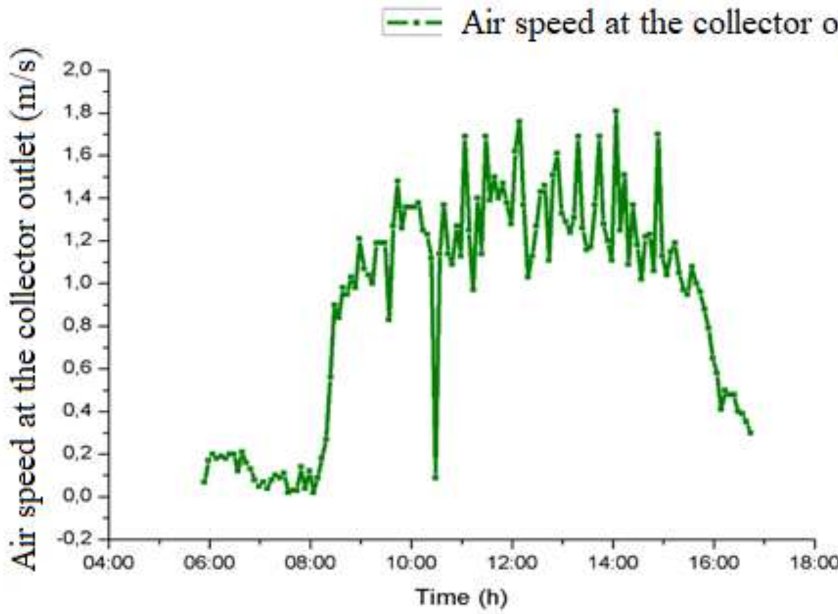


Figure 15: - Sunshine on 09-11-2022.

This curve shows an increase in sunshine from 6 a.m. to 1 p.m. where it reaches a peak of 850 W.m-2 then it slowly decreases until 5 p.m. As for the air speed, its variations are given in figure 16 below.



Speed of hot air leaving the collector from 09-11-2022

With an improvement in the junction between the collector and the chimney, we obtained better results. Thus, we recorded a maximum value of 1.8 m. s^{-1} during this day. From 8 a.m., the speed increases quickly and reaches its maximum at 1 p.m. Then, it gradually decreases until 5 p.m. Figure 17 tells us about the evolution of the maximum temperatures of the rings as a function of the distance of the rings.

Different maximum temperature rings evolution

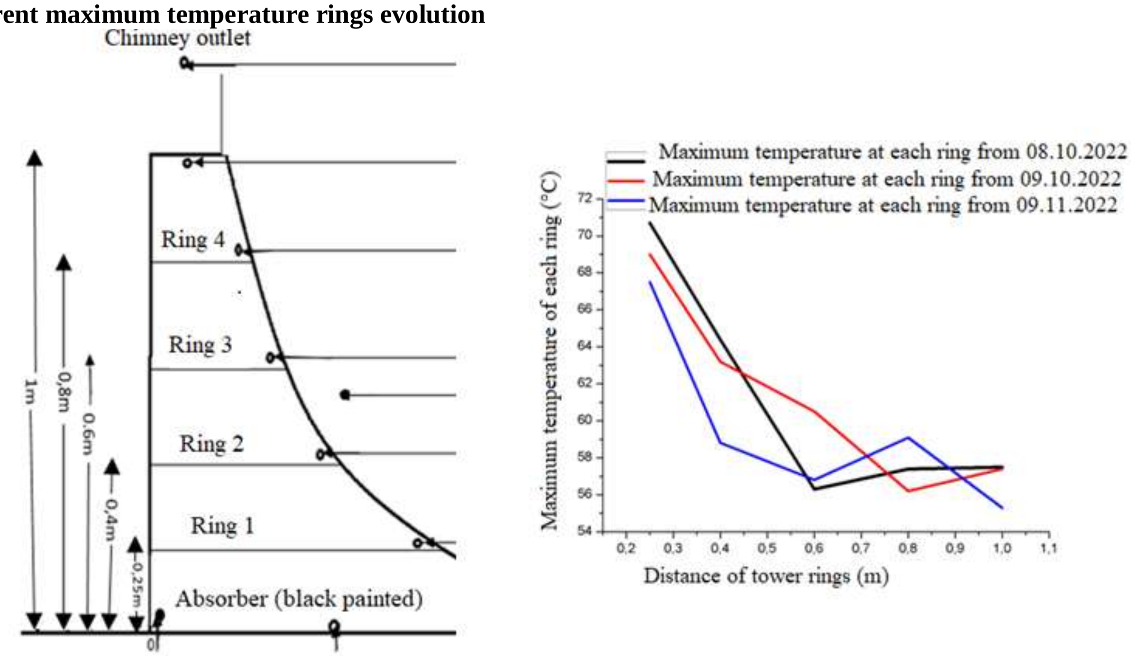


Figure 17: - Maximum temperature of the solar tower rings.

We note that the evolution of maximum temperatures at different levels of the solar chimney obtained on October 8, 2022, October 9, 2022, and November 9, 2022, shows that the different rates present a hyperbolic profile. This is consistent with the geometry of the collector. However, the disturbances observed are due to cloudy periods.

Study of air speeds

To assess the flow of air in natural convection we also studied the theoretical speeds and the efficiency of the solar chimney. Thus, Figures 18 to 20 provide information on the theoretical speed curves for the days of 08-10-2022, 09-10-2022 and 09-11-2022. These theoretical speeds are obtained using the formula of Unger, 1988 [11] given by equation (6).

$$V_{ch} = \sqrt{2.g.h.\frac{\Delta T}{T_{am}}} \quad (6)$$

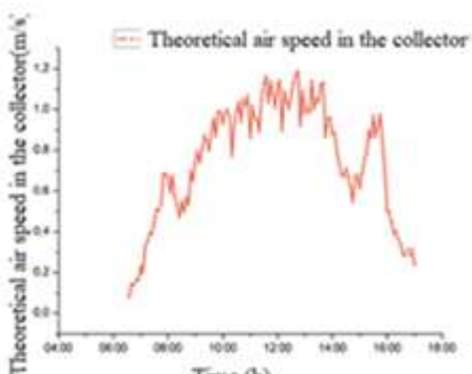


Figure.18: : Air speed from 08.102022

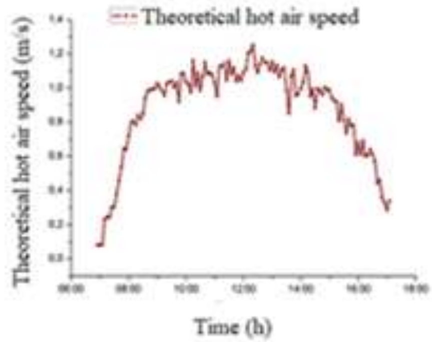


Figure.19: Air speed from 09.10.2022

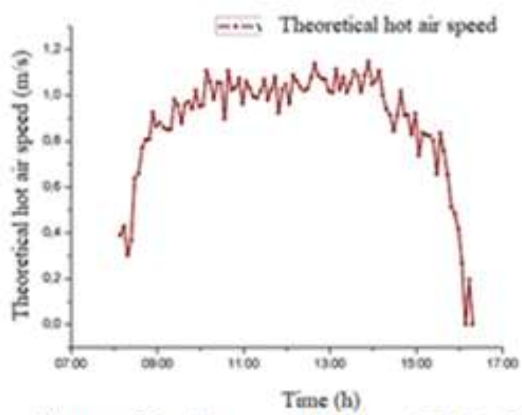


Figure.20: Air speed from 09.11.2022

Observation of these three curves shows that the shape of these theoretical curves is found at the level of the experimental curves. Theoretical speeds remain low compared to those obtained through experimental data. These results disagree with those of Ouédraogo et al. [12]. This is explained by the fact that the speed being a function of the height of the chimney [11], while our device is for a chimney having a height of one meter, this is very negligible and influences the theoretical speed of the chimney. air.

The chimney efficiency

The chimney efficiency is given by equation (7) below.

$$\eta_{ch} = \frac{g.h_{ch}}{C_p.T_{amb}} \quad (7)$$

Figures 21 to 23:- Correspond to the chimney yields for the days of 08-10-2022, 09-10-2022 and 09-11-2022.

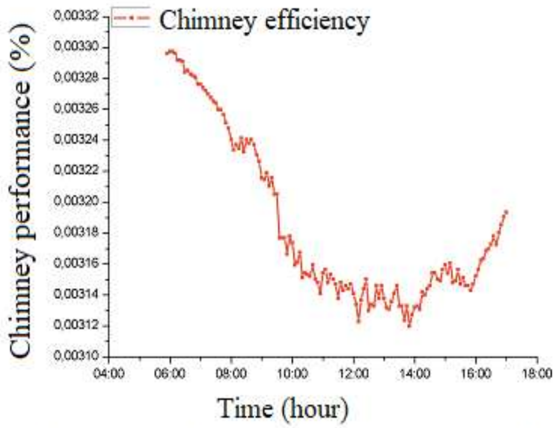


Figure.21: Chimney efficiency as of 8.10.2022

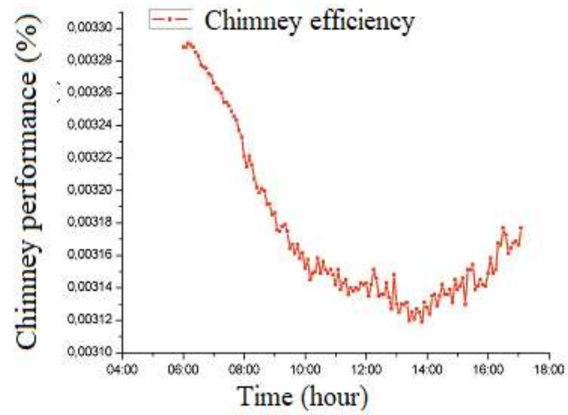


Figure.22: Chimney performance as of 09-10-2023

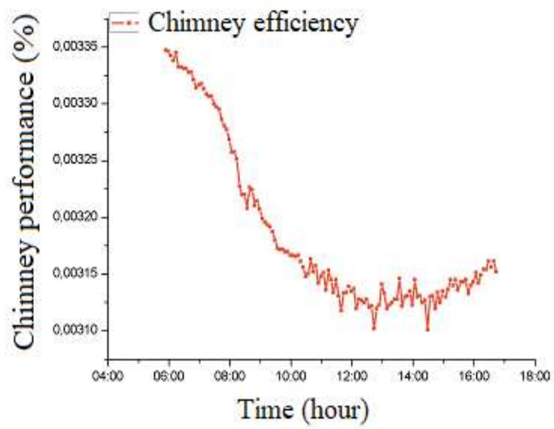


Figure.23: Chimney performance as of 09-11-2023

We observe low values of the efficiency of these chimneys, which values are entirely compatible with the overall efficiency of the solar tower in general low. The advantage of these solar chimneys lies in the mastery of technology and the availability of construction materials. The low height may be an explanation, it should also be noted that the collector is made of plastic which cools quickly and does not retain too much heat; therefore, it exchanges heat with the environment.

Conclusion:-

In this article, an experimental study of the airflow in natural convection was carried out in a solar tower with a hyperbolic collector.

The different series of experiments carried out on the solar chimney allowed us to analyze the performance of the experimental device. This is shown by the theoretical yields calculated through the mathematical model. We showed that the collector efficiency reached on average respectively 19.32%; 34.05% and 33.49% for the days of October 8, October 9, and November 9, 2022, while that of the chimney presents very low values. This is explained by the low height of the chimney of the device and the plastic film used to cover the roof of the collector loses significant energy by exchanging radiation from the collector with the outside. This allowed us to observe maximum temperatures of 87.1°C; 88.5°C and 91.3°C at the collector respectively for the days of October 8, 2022, October 9, 2022, and November 9, 2022. For these same days the speeds of the air leaving the collector measured experimentally are respectively 1.3 m. s^{-1}; 1.8 m. s^{-1} and 1.8 m. s^{-1}. From these results, we have an improvement in the level of speed and the temperature of the fluid compared to the results of Ousmane et al. [13], who carried out studies on solar towers with a flat glass roof collector. However, by using the plastic film as the roof of our device, it exchanges heat with the outside, therefore a drop in the temperature level is observed when it evolves towards the outlet of the collector.

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