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NOVEL CONVECTION PROCESS: EXPERIMENTAL STUDY OF A SOLAR CHIMNEY WITH ITS COLLECTOR MADE OF HEMISPHERICAL CONCENTRATORS.

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ABSTRACT

This paper presents an experimental study of a solar chimney. The prototype is made with a collector of 2.00 x 2.00 m^2, and a chimney of 20 cm of diameter and 2.00 m of height. The collector, in accordance with a novel natural convection process based on the *hot spot* theory, is made of 49 hemispherical concentrators of 28 cm of diameter. The experimental study focused on temperatures measurement along the radius of the collector for a measured insolation of the day, and comparison with a similar solar chimney with usual black-painted absorber. As a result, for three day measurements taken in different cloudy or clear sky conditions and from 8:00 am to 4:00 pm, the shape of the evolution of temperatures along the radius of the collector suggests that the new system could best replace systems with absorbers by guarantying the outlet temperature, allowing more air through its collector and consequently reducing the usual size of solar chimney collectors.

KEYWORDS: Natural convection, Collector, Solar chimney, Spherical reflector, Solar bowl.

1. INTRODUCTION

Solar chimney system is usually made of a collector and a chimney. The collector is usually built with a black plate which is the absorber, covered with a glass sheet to produce a greenhouse effect. The entering air at ambient temperature collects the heat from the absorber as it progresses towards the center of the collector usually due to the smooth slop of the glass sheet and natural convection (Ouedraogo *et al.* [1]). The chimney is usually located in the middle of the collector where the hot air will start ascending through it. The first studies intended to use the solar chimney as power plan-SCPP (Ayadi *et al.* [2]), by placing a turbine in a judicious location, either before the collector outlet, or in the chimney. Many acres are needed to place the collector. At some point, the collector can use an agricultural field as an absorber, and a polystyrene film to produce the greenhouse effect, being of multiple use (Ulian *et al.* [3]). In the case of a power plan, the chimney can rise up to 1 000 meters (Bansod *et al.* [4]). Usual optimal design of the solar chimney is with a circular collector. The covering sheet is smoothly sloped. The collector could be divided by deflectors that guide the air flow to create a vortex, improving the efficiency (L. and E. Michaud [5]). Some had studied an elliptic shape of the cover- chimney (Ousmane *et al*. [6]). Others had proven that a conical or venturi-like chimney gives better efficiency than a cylindrical one (Mahdi and Bellel [7]). Study had also been conducted for solar chimney built with phase change material-PCM (Fadaei *et al.* [8]), floating solar chimney power plant-FSCPP (Nejad and Imanparast, [9]), double chimney power plant (Cao *et al.* [10]), divergent-chimney power plant (Xu and Zhou [11]) and Transpired solar collector without glazing (Eryener *et al.* [12]).

Many other solar chimney systems, in a small scale, had been studied for different use, such as drying agricultural products: okra drying (Ouedraogo *et al.* [13]), tomato drying (Kam *et al.* [14]), banana drying (Maia *et al*. [15]), sea water desalinization (Asayesh *et al.* [16]), hybrid photovoltaic/thermal solar collector-PVT (Boutina *et al.* [17]), etc. Ousmane *et al*, Mahdi and Bellel studied the temperature through the entire system to determine where

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to best place agricultural products according to their drying recommended temperatures and the velocity to best evaluate where to dispose a turbine for best efficiency, etc.
To Give an order of sizing, experimental SCPPs such as Manzanares in Spain has a collector of 46 000 m^2 and a chimney of 194.6 m height, while Borunga in Australia has a collector of 153 938 040 m^2, and its chimney is 1 000 m tall.
The heat gained through the collector is usually calculated using the following equation:

$$\Delta T = T_{Center} - T_{amb} \tag{1}$$

With $\Delta T \approx 20°C$ the medium temperature gained through the collector, T_{Center} the temperature in the center of the collector and T_{amb} the ambient temperature.

The solar radiation absorbed by the collector per unit area $\dot{Q}_{abs}$ (in W) is directly proportional to ΔT as shown by the following equation (Djimli [18]):

$$\dot{Q}_{abs} = \dot{m}\, C_p\, \Delta T \tag{2}$$

With $\dot{m}$ the mass flow rate through the system, C_p the calorific capacity.
This proportionality makes the temperature gain, the most important parameter to increase the thermal efficiency η_{col} of the collector, given by the following equation:

$$\eta_{col} = \frac{\dot{Q}}{A_{col} I} \tag{3}$$

With A_{col} the collector's surface and I the Irradiation.
Amir and Hadi [19] investigated a novel solar chimney made of a canopy at the bottom of the chimney, in which there were a black cone heat by heliostats (Intensifiers) to concentrate the sunlight. They obtained an additional gain of 10°C. But using heliostats with all the complexity of solar tracking is something to avoid. As a matter of fact, if PV systems are widely used, it is because their installations is permanent, which makes them safer with regard to bad weather.

2. DESCRIPTION OF THE PROPOSED SYSTEM

The system we are presenting here is a prototype of solar chimney, having a cylindrical chimney of 2.00 m tall, 0.20 m of diameter and a novel type of collector sizing 2.00 m x 2.00 m. The collector is made of 49 hemispherical concentrators of 0.28 m diameter each, disposed 7 x 7 to form a square. As stated by Ky and Bathiebo [20] in their patent, and later showed through experimental studies on previous natural convection air dryer prototypes (Ky *et al*. [21; 22]), air-flow through a hemispherical concentrator, without any receiver (or absorber) disposed at its focal point, gains more heat than black plate natural convective systems. The use of hemispherical concentrators as steady non-tracking systems, their geometric and geometric mean concentrations had been previously estimated to better understand their optical and thermal performances (Ky *et al*. [23; 24]).
The proposed solar chimney system can be seen on the following figures 1 and 2.

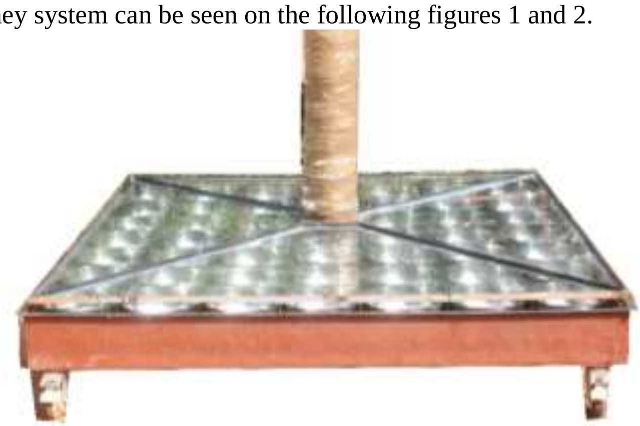

Figure 1: picture of the solar chimney prototype

Figure 2: Picture of the 2 parts disassembled solar chimney with the 49 concentrators clearly aligned.

Our model was built in 2 pieces to allow us to access the solar bowls for maintenance, clean-up etc. The air gets into the collector through a 3 cm gap between the lower part which is the box containing the concentrators and the upper part composed of the glazing and the chimney.

3. FUNCTIONING PRINCIPLE OF THE SYSTEM

The system functions as usual, with the air entering by the collector, and outing by the chimney. This air circulation is done by the fact that concentration brings a hot spot heating the air, which will change density, and therefore, gain speed through natural convection. This system does not need any disposal of receiver at the focal points of the concentrators. The glazing is used to create a greenhouse effect.
The usual use of concentrator known by all is to go from a larger collecting area to a smaller one. The "hot spot theory" is based on the assumption that concentration generates a hot spot, even invisible to eyes, but thermally high enough to heat air with better or quicker heat gain than black plate convection without concentration. This is briefly explained by following figure 3.

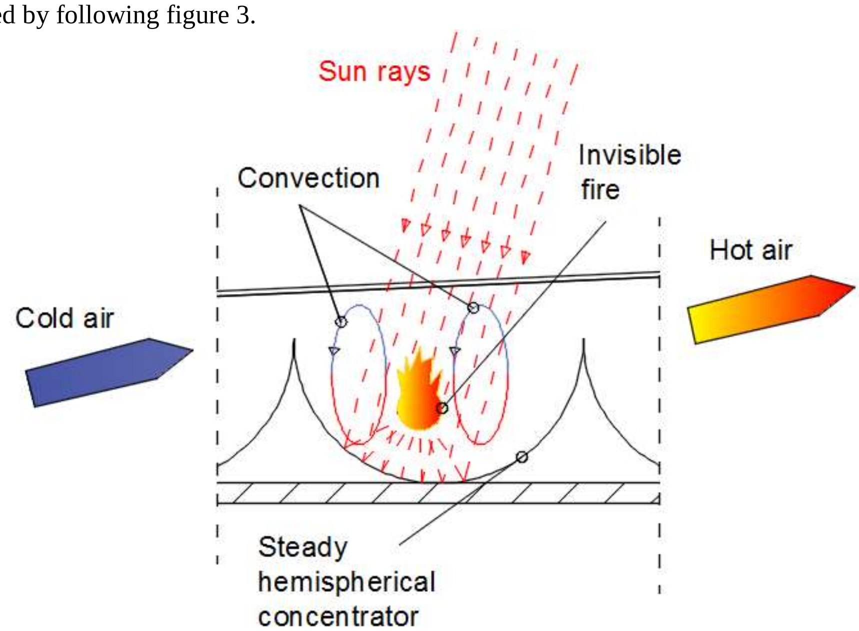

Figure 3: Convection phenomenon through the "hot spot theory"

The novel solar chimney system was somehow built with high similarities with a previous solar chimney power plant prototype studied by Ousmane *et al.*, Kam *et al.* [25] and Ouedraogo *et al.*, and designed with the usual technology of collector with a black plate absorber. This prototype is still studied at the Thermal Renewable

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Energies Laboratory (L.E.T.RE), and the similarities are done for comparison purpose. The only differences are the gap between the lower part and the upper part forming the air inlet, which is of 2 cm on the Ousmane, Kam and Ouedraogo prototype while it is of 3 cm on our system, and also a difference in bottom part volume. These differences make the volume of air passing through the old collector of $0.08m^3$, its inlet section of $0.074\ m^2$ and its outlet section of $0.031\ m^2$, while the new prototype presented here has a volume passing through its collector of $0.68\ m^3$ including the spaces between the concentrators which are not isolated, an inlet section of $0.11\ m^2$ and the same outlet of $0.031\ m^2$ like the first prototype. This supposes that we will have a bigger volume of air to heat up in the collector of the new system.

The hemispherical concentrators are in stainless steel, with reflective inner chromed surfaces. To do that, we adapted IKEA's BLANDA BLANK salad mixing bowl 28 cm of diameter and 14cm of height, as we can see on the following picture 4.

Figure 4: 28 cm diameter IKEA's BLANDA BLANK salad mixing bowl used as solar concentrators.

Although these bowls have a small flat bottom of 6 cm diameter, we will consider the prejudice induced by that flat bottom on the geometric concentration negligible. Those bowls are classed in a box which has its bottom mapped with an insulator made of expanded polyester 2 cm thick to maintain heat in it. The chimney is insulated with glass wool, as shown in the following figures 5 and 6.

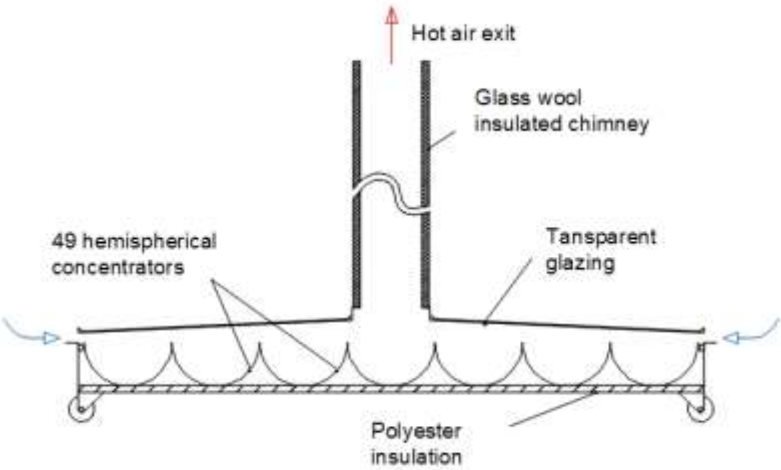

Figure 5: Lateral schema of the solar chimney prototype

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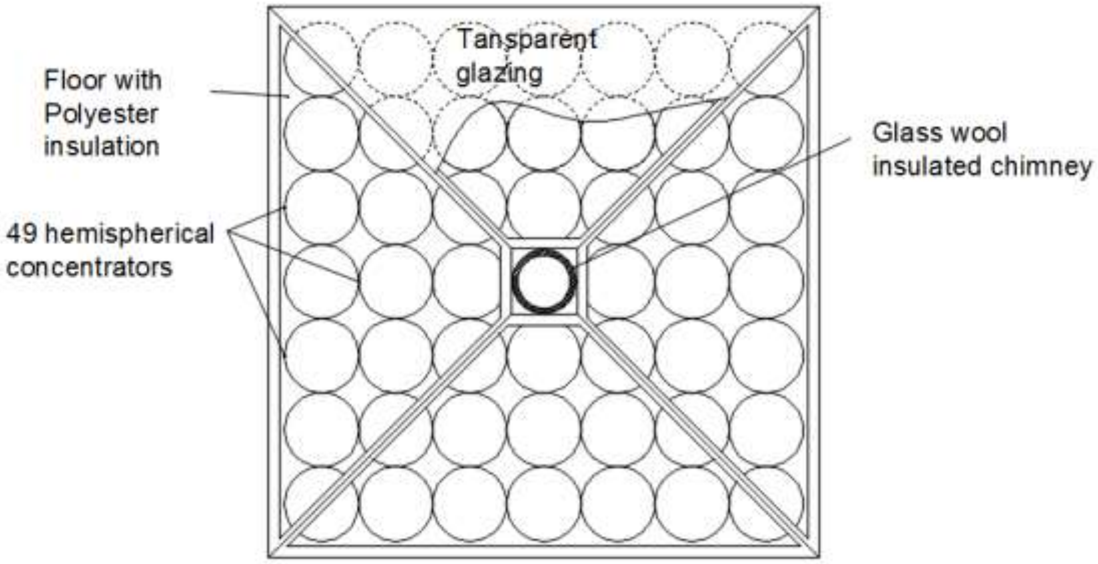

Figure 6: Top view of the solar chimney prototype

4. MATERIALS AND METHODS

To experimentally study the system, we used the equipment listed below and adopted the measurement methods referring to it:
- A data logger Midi LOGGER GL200A of GRAPHTEC brand.
- A probe (Amb) to measure the outdoor (or ambient) temperature.
- Probes (J1 to J3) to measure the temperatures at bowl junctions, as indicated on the following figure 6. These probes do not touch the metallic bowls.
- Probes (H1 to H3) to measure the temperatures below the glass on the almost vertical of the preceding probes. They do not touch the glass.

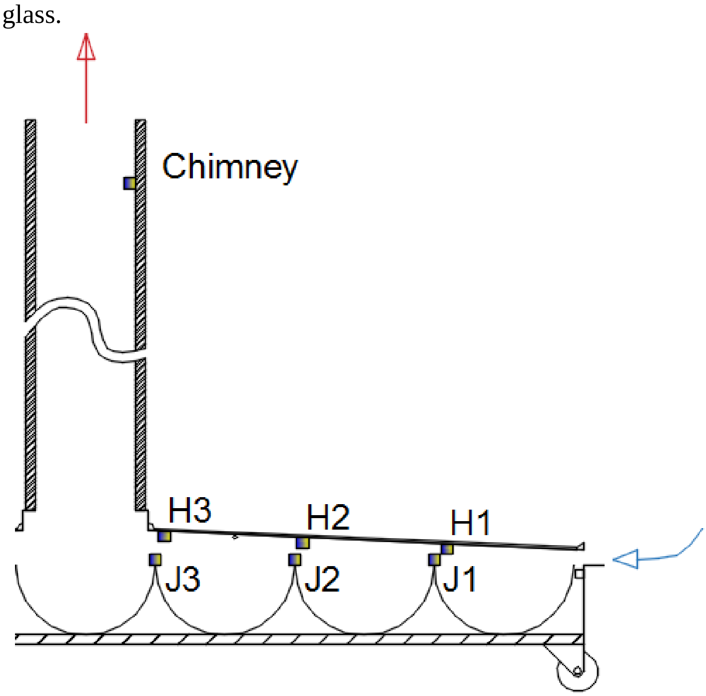

Figure 7: Partial view of solar chimney with probes positions

- A probe (Chim) to measure the temperature at 1.00 m to the inlet of the chimney.
- A pyranometer SR03-05 of Hukseflux brand to measure global insolation.

5. RESULTS AND DISCUSSION

Our measurement will mostly show the effectiveness of the collector by experimentation, without focusing on the chimney. We started the measurement from October 8th to October 14th. These date almost correspond to the autumn equinox with 6.5° south of declination angle. The sun is at 18.5° south with the zenith in Ouagadougou where the measurements are done. However, we are just getting out of the raining season, particularly this year with the rain which hasn't yet stopped. It is important to consider the cloudy condition since we know that concentrators always best work with direct sunlight.

5.1. Measurement of October 8th, 2018.

The insolation curve of the day is presented in the following figure 8.

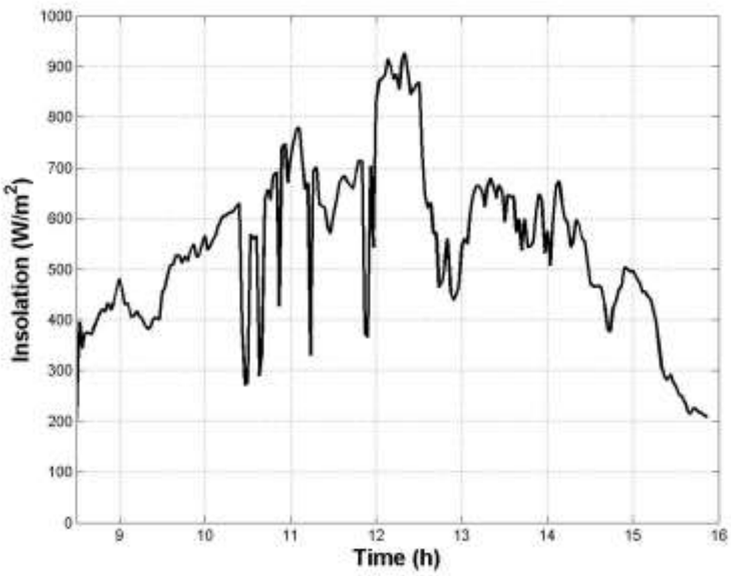

Figure 8: Insolation of October 8th. 2018

That specific day was cloudy, sunshine alternatively giving place to sky coverage. Between 12:00 and 12:45 pm, the insolation reached a pic of 900 W/m^2.

Corresponding temperature curves are presented in the following figure 9.

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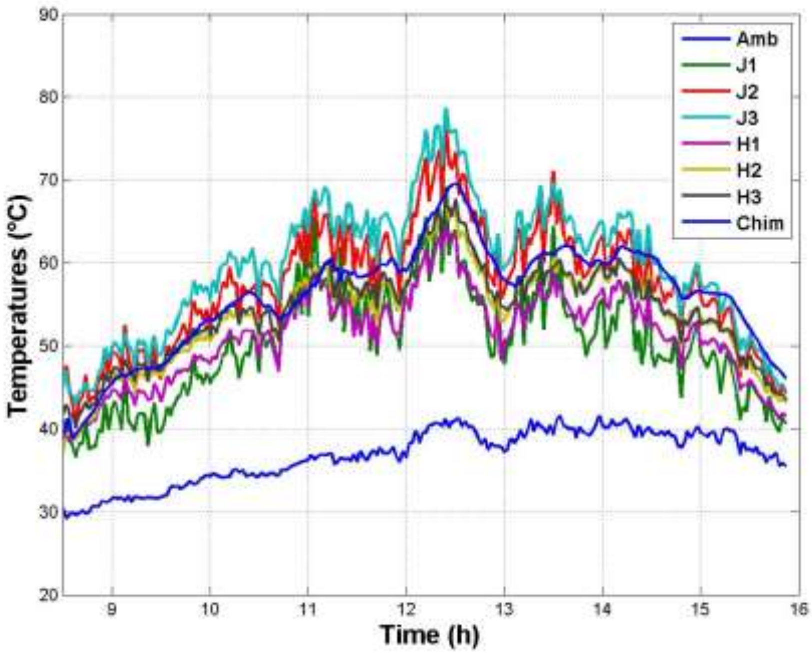

Figure 9: Curves of temperatures throughout the collector of October 8th, 2018

The curves of temperatures are following the same shape of that of the insolation, with a specific rise between 12:00 and 1.00 pm. Temperatures are quite grouped and differences between le highest and the lowest have a closed gap of 10 to 15°C.

5.2. Measurement of October 9th, 2018.

The insolation curve is presented by the following figure 10.

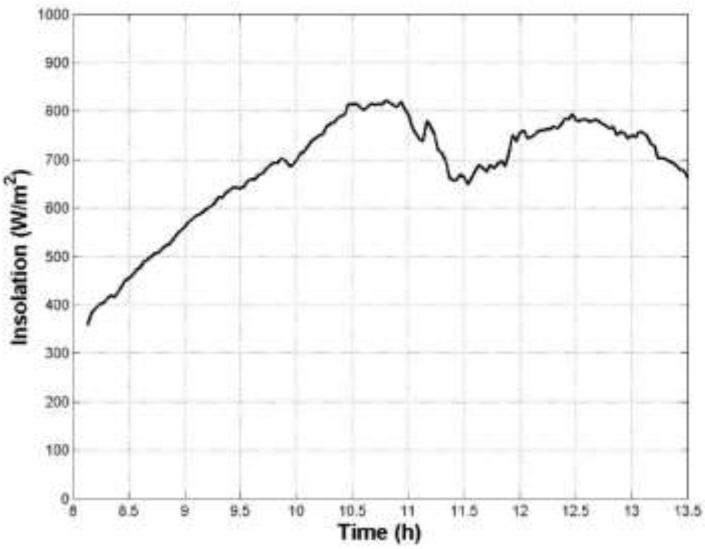

Figure 10: Insolation of October 9th 2018

It shows a consistent evolution from 8.00 am till 10:45 am, then a gathering of clouds suddenly covered the sky, then at 12:30 pm, the sky started to get better. There were somehow a power shortage from 1:30 to 3:50 pm, so we cannot tell the temperatures profile after 1:30 pm. The highest insolation is around 800 W.m^{-2}.

The curves of temperature are shown in the following figure 11.

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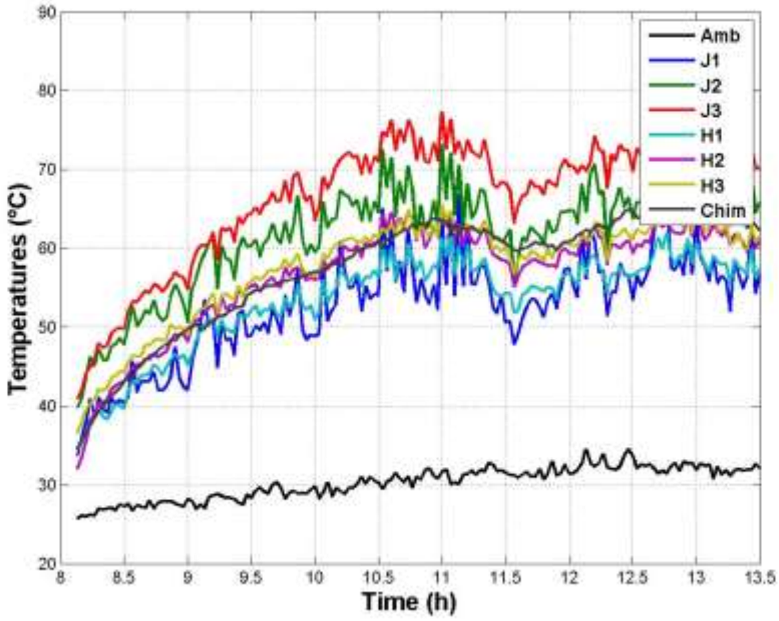

Figure 11: Temperature curves of October 9th, 2018

Like the preceding day curves, the curves follow the same shape like that of the insolation, going clocklike with an inflection between 11:00 am and 12:30 pm. The measurements are stopped at 1:30 pm due to the power shortage. The highest and lowest temperature are in a gap of 20°C at the maximum insolation period.

5.3. Measurement of October 14th, 2018

Insolation curve is given by the figure 12 bellow.

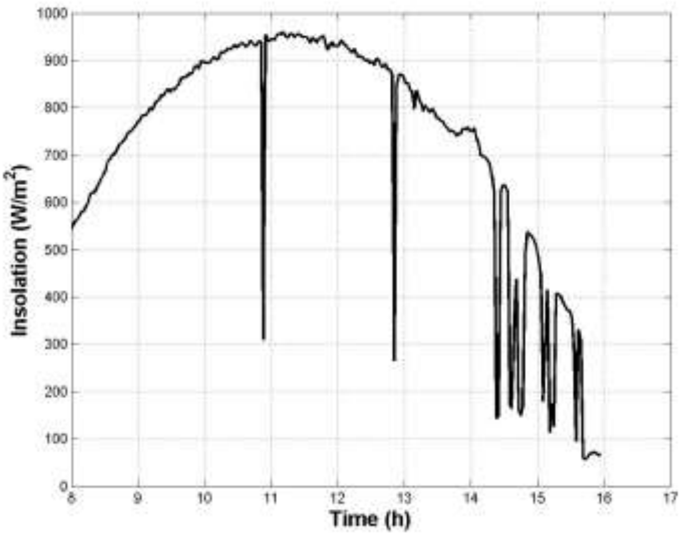

Figure 12: Insolation curve of October 14th, 2018

That curve is a perfect clock with some sharp drop due to cloud passages, especially in the end of the day from 2:20 pm. The maximum reaches 950W.m^{-2}.
The corresponding temperature curves are seen in the following figure 13.

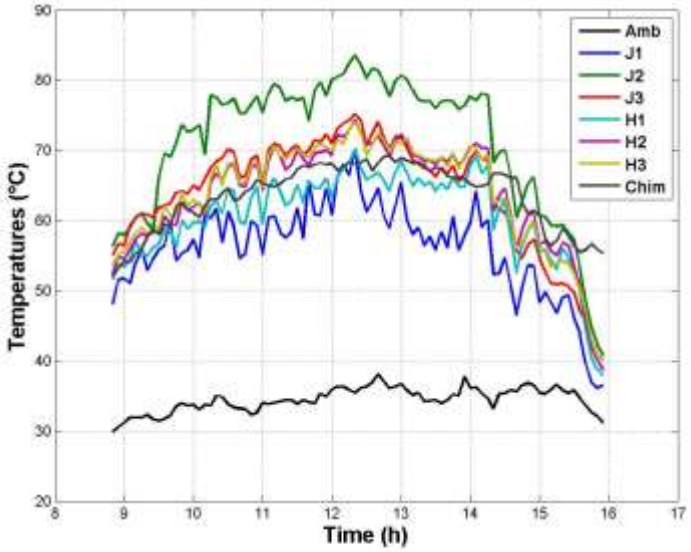

Figure 13: Temperature curves of October 14th, 2018

The curve is shaped like that of the insolation, and the difference between the highest and the lowest is around 10 to 15°C except for the J2 which as a sharp increase between 9:30 am and 2:10 pm. That could be due to a specific flow stream of high temperature getting out of the related concentrator.

5.4. Discussion of the results

To discuss the curves, we will mainly use the following values corresponding to medium temperatures from the inlet to the outlet of the collector, by summing the upper and lower temperatures and dividing by 2:

$$P_1 = \frac{H_1 + J_1}{2} \tag{4}$$

$$P_2 = \frac{H_2 + J_2}{2} \tag{5}$$

$$P_3 = \frac{H_3 + J_3}{2} \tag{6}$$

These dots P1, P2 and P3 are positions along the path of the air stream from the inlet to the outlet of the collector. They correspond to 0 for the ambient temperature (Amb), 30 cm for P1, 58 cm for P2 and 86 cm for P3. Chim is the position at 100 cm height from the bottom corresponding to the inlet of the chimney.

The curves showing the temperatures at P1, P2, P3 and Chim for October 8th, 2018 is presented by the figure 14.

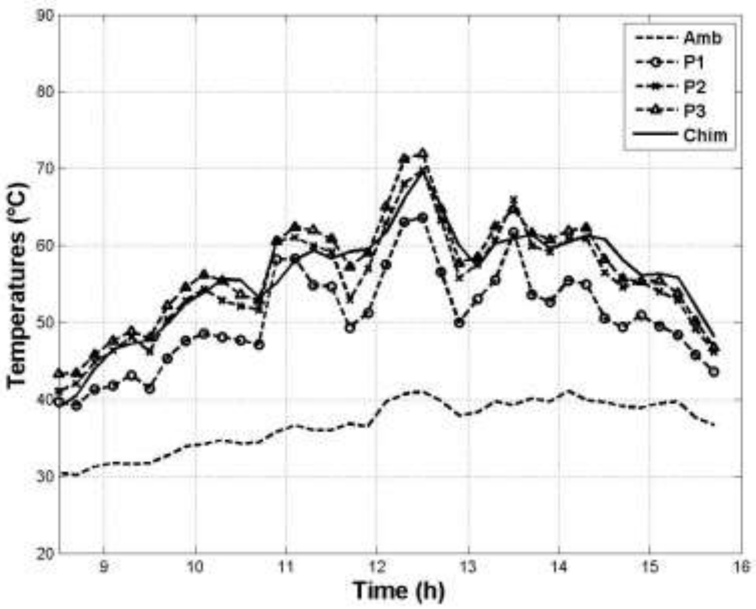

Figure 14: Temperatures at P1, P2, P3 and Chim positions for October 8th, 2018

The system gains in temperature from the position P1 to the position P3. There are some losses before it reaches the Chim position. However, the highest temperature is at the position P3 and equal to 73°C.
The following figure 15 shows the evolution of temperature from the inlet to the outlet of the collector.

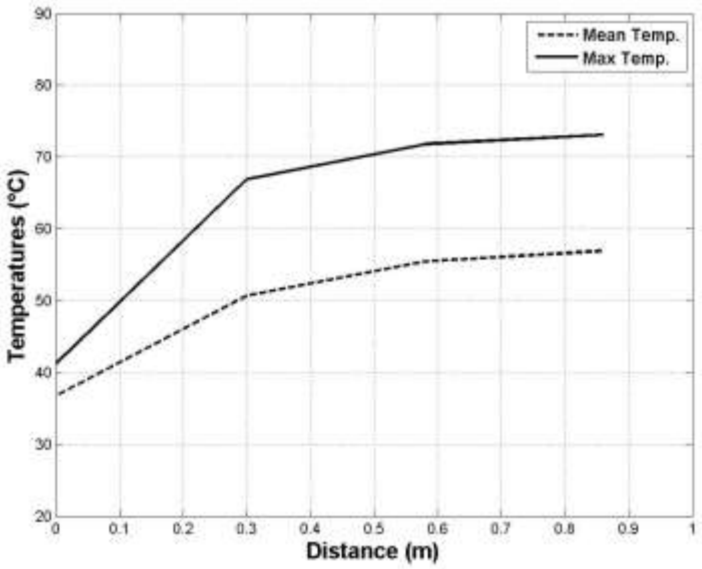

Figure 15: Evolution of temperatures along the radial axes of the collector, from ambient to P3 position for October 8th, 2018.

The first curve *Mean Temp* is built by using the mean of Amb, P1, P2 and P3 temperatures of the day, to see the shape of the curve at any time, while the second curve *Max Temp* corresponds to the maximum values of Amb, P1, P2 and P3 of the day. We notice a similar evolution, which suggests that the temperature rises from the ambient to P1 after passing the 1st concentrator, to P2 after passing the 2nd and so on. The overall shape is presenting a curve that evolves to an asymptote, suggesting that putting more distance or more concentrators will not make us gain more in temperature.
The curves showing the temperatures at P1, P2, P3 and Chim for October 9th, 2018 is presented by the figure 16.

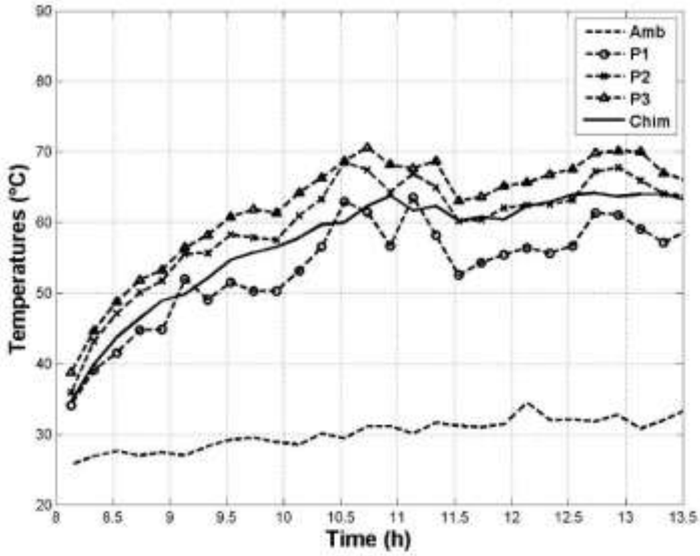

Figure 16: Temperatures at P1, P2, P3 and Chim positions for October 9th, 2018

Just like the former day, temperatures evolve from Amb to P3, showing the drop at Chim. The highest value of the day is 72°C.
The following figure 17 is showing the evolution of the temperature along the collector.

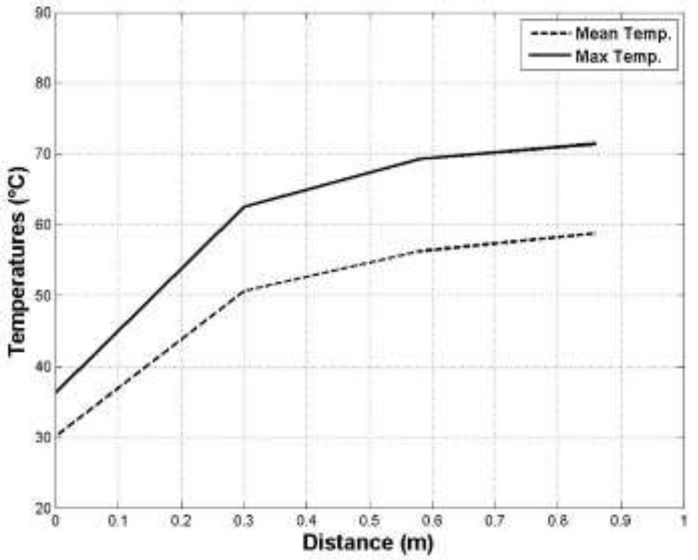

Figure 17: Evolution of temperatures along the radial axes of the collector, from ambient to P3 position for October 9th, 2018.

We see the same shape with former day, and the tendency to an asymptote of both Mean and Max temperatures.
The curves showing the temperatures at P1, P2, P3 and Chim for October 14th, 2018 are presented on the figure 18.

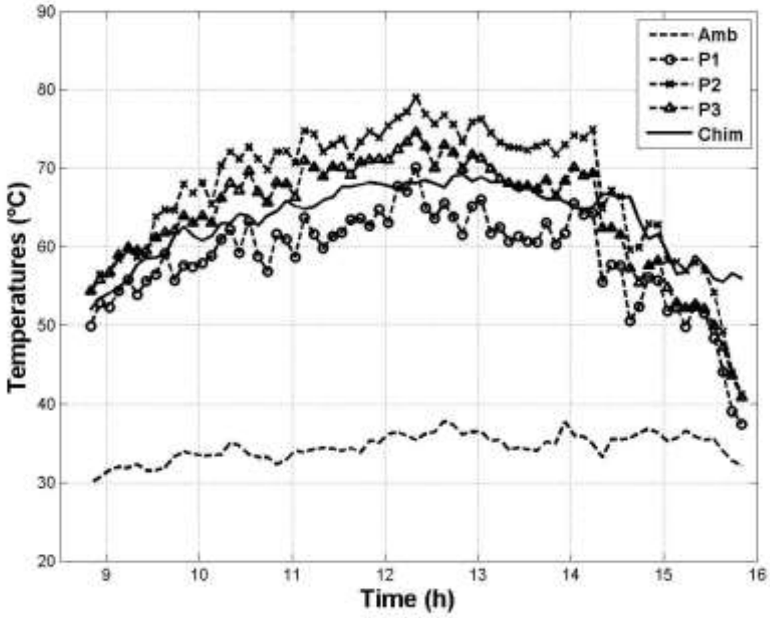

Figure 18: Temperatures at P1, P2, P3 and Chim positions for October 14th,, 2018

This figure corresponds to a consistent insolation with less clouds in the sky. The temperatures grow from ambient to P2 where they reached the highest values, then drop at P3.
The curve of evolution is shown it the following figure 19.

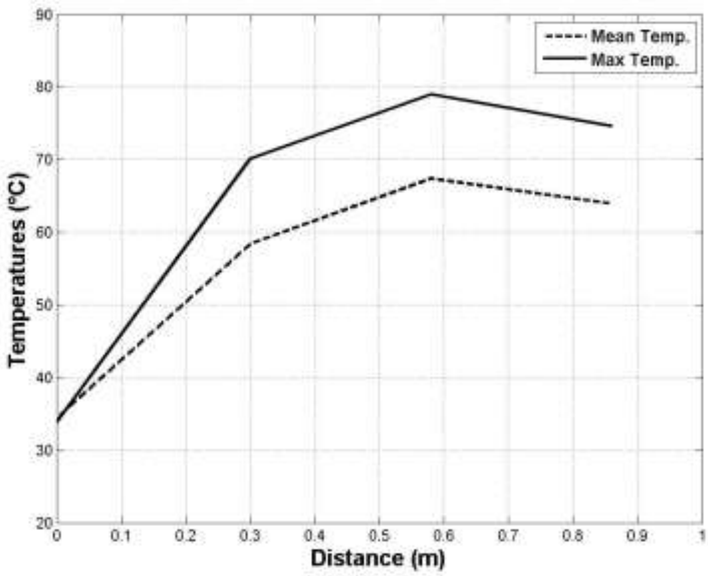

Figure 19: Evolution of temperatures along the radial axes of the collector, from ambient to P3 position for October 14th, 2018.

We see a shape that starts like previous till P2. Then there is an inflexion to P3. The value of P2 is higher than that of P3. That could be due to the fact that the thermocouple J2 could be in the stream outing the related concentrator. Somehow, the final temperature at P3 is 76°C, not so high in comparison with other days.
Ousmane *et al*. [6] had presented similar curves along the radius of a usual black-painted absorber. Temperatures tended to evolve less sharply, and show in inflection when arriving to the outlet of the collector just like the last curves. This suggests that the gain in temperature with black-painted absorber is less sharp, explaining also why

the gap between the absorber and the glazing is tiny and the volume of air moving in the collector is consequently reduced than in our system.

6. CONCLUSION

Following conclusion can be taken after experimental evaluation of a collector made with hemispherical concentrators:

- Because of the space needed to inbox the concentrators, the system admitted 8.5 times more volume of air than the usual system studied by Ouedraogo, Kam and Ousmane.
- Although the system had to heat more volume than the usual black-painted absorber collector, the temperature tends to be sharply increasing, suggesting that our system heats quicker than the usual collectors.
- With insulations ranging from 800 to 950 $W.m^{-2}$, cloudy or clear sky, from 9:00 am to 4:00 pm, the present system guaranteed above 70°c of highest temperature and 56°C of medium temperature at the outlet of the collector, which is not so evident with usual systems, and knowing that concentrators work only with direct sunlight.

All these positive points strongly suggest that the new system could best replace systems with absorbers by guarantying the outlet temperature, allowing more air through its collector and consequently reducing the usual size of solar chimney collectors.

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