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REVIEW ARTICLE

# AIR HEATING IN A STEADY HEMISPHERICAL CONCENTRATING SYSTEM FOR VARIOUS APPLICATIONS

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ABSTRACT

This publication deals with the heating of air in a fixed hemispherical concentrating system. It differs from other systems that heat first a black plate with fins or not, and then the heat is recovered from the plate with a fluid by convection. The device that we propose uses the sunspot corresponding to the actual image of the sun formed in the focus of a hemispherical concentrator which by effect of concentration, generates a very hot zone. The heat from that zone can be directly transmitted to the circulating air. The recovery zone was gradually reduced to strips (or bands) by 4 mm mirrors to reduce the amount of air to be heated by the spot. There is no receiver to dispose, rather the assumption is made that recuperation of air directly from the sun-spot is more efficient than air-plate convection. The results obtained lead to the following observations: The more bands we have, the higher the temperature of the bands, allowing to suppose that the temperature can still rise with the increase of the number of bands. The bands take the maximum value in turn, indicating the position of the hot spot. The shape of the temperature curves follows the pace of the daily irradiation. By way of example, for a division of the 4-band concentration zone, temperatures in the hottest band are obtained which range from 44°C at 9h 36 min and rise to 102°C at 13 h 35 min, then go down to 60° C at 15h 36min. The maximum irradiation value of the day is 830 W/m2 for the day of March 16, 2016. The main advantage of such a system is that it produces warmer air, without any sun tracking system, and is even better than natural convection systems.



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# INTRODUCTION

It is usually about drying or convection-heating systems that work by heating black plates finned or not and by absorbing the accumulated thermal energy of these plates with a gaseous or liquid coolant (Aoues *et al.*, 2009). Studies show that such systems, with an additional greenhouse effect, elevate temperature in the range of 65°C (Ouédraogo, 2013), Donatien Njomo, 1998). The following device (Figure 1) proposes to heat air by the combined effects of greenhouse and concentrating radiations, without solar tracking system. Concentrator is made with sticking mirrors having a reflectivity of 95% according to the seller on a reinforced concrete hemispherical bowl. As shown by Ky et al. 2016, and 2017, the hemispherical solar concentrator (1), always focuses regardless of the position of the sun. Its global geometric and geometric mean concentration had been defined by equations.

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One more advantage of the hemispherical concentrator with reference to Figures 2 and 3, is that the portion of the axis on which it concentrates is always in the bowl of the hemisphere. The hemispherical portion, corresponding to a hub, is closed by a transparent element of glass 4 mm thick constituting the glazing (3). This simple glazing intents to cause a greenhouse effect trapping the infrared rays (5), while the reflecting surface of the hemisphere causes a concentration (2). Inside the hemispheric transparent bowl circulates a coolant - air (6) that collects the heat created by the combined effects of concentration of the mirror in the hemisphere, and greenhouse glazing. This system as described does not use any receiver. The air is directly absorbing the heat produced by the concentrator. The concentration effect can be considered as a burning spot actually corresponding to the real image of the sun, and this spot may directly heat the surrounding air. In a sense, the assumption here is that it is more effective to heat the air by this sun-spot rather than heating a black plate which will transfer its heat to the air through convection.

This hemispherical concentrator + glazing to be called module can be installed permanently with an optimal positioning by an angle equal to the latitude of the site in the North-South direction (4).

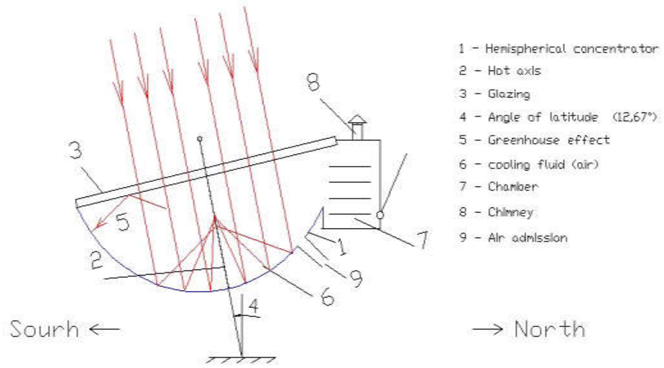



**Figure 1. Schema of the system**

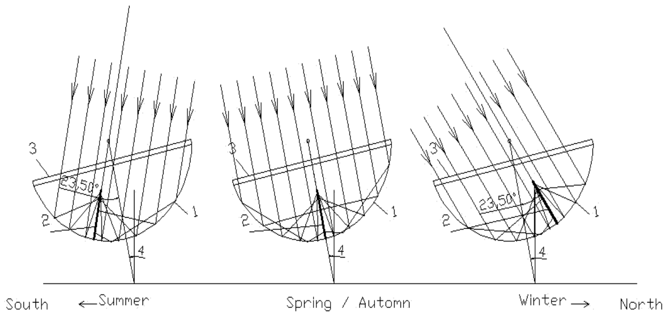



**Figure 2. Evolution of the hot spot position with time**

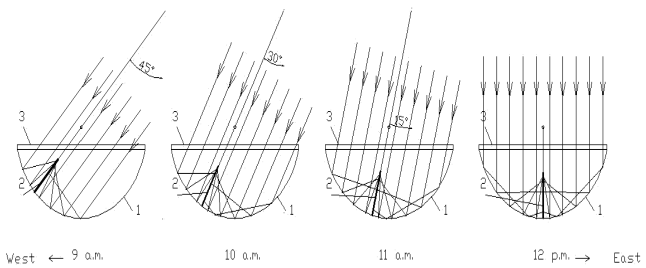



**Figure 3. Evolution of the hot spot with seasons**

## The theory behind the sun-spot image heating method

While studying the hemispherical concentrator and the type of receiver to dispose in the focal axis (Ky *et al*., 2016 and 2017), it appears that for a aperture half angle smaller than 23°, a cavity receiver is recommended while for a greater half angle, a conical receiver is compulsory. As shown in figure 4, the effect of the use of cavity or conical receiver is so noticeable that it is becoming common to see a use of mixt-conical and cavity receiver.

This is explained by the fact that in the first case of using a cavity receiver, for a small angle, the focus is similar to a dot-focus by Gaussian approximation! Figure 5 lets appear the demarcation spot of shift from cavity to conical receiver, on the global geometric and geometric mean concentration curves cross points. By using the equations of global geometric and geometric mean concentrations, it comes to solving the following equation (1) to get the cross points:

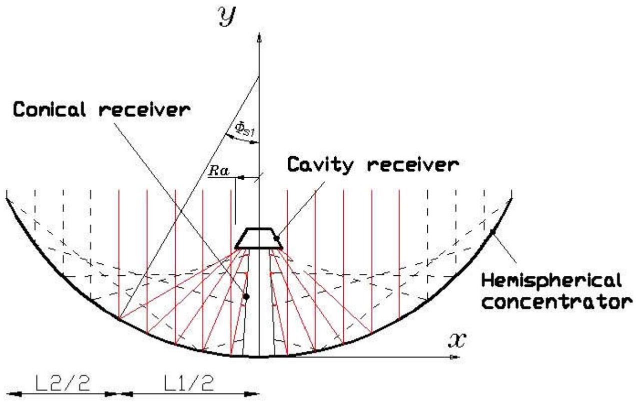



**Figure 4. Hemispherical concentrator with mixt-conical and cavity receiver**

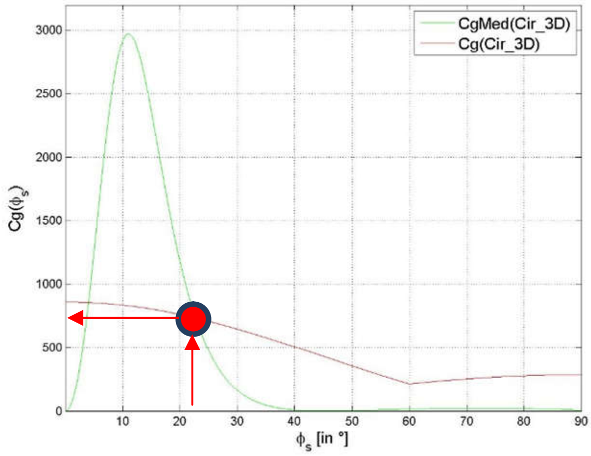



**Figure 5. Comparative curves of global geometric and geometric mean concentration of a hemispherical concentrator. The demarcation spot between the use of cavity and conical receiver can be seen**

$$\left(\frac{\sin(4\phi_s)}{\sin(2\phi_s)\sin^2\left(\frac{\phi_s}{2}\right)+2\sin\theta_s}\right)^2-\frac{4}{\sin\theta_s}\cos^2(\phi_s)=0 \qquad (1)$$

With $\phi_s$ the aperture half angle of the concentrator from the center of the sphere, and $\Theta_s$ the half angle characterizing the apparent radius of the sun. The cross point is therefore determined as shown on the following curve (Figure 6).

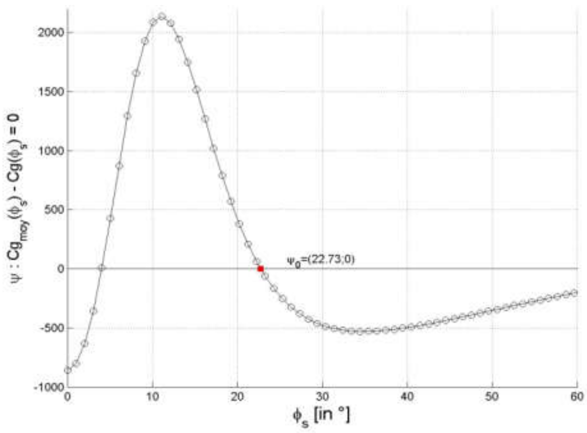



**Figure 6. Cross point of demarcation obtained through equation**

This spot of shift appears for, which gives a global geometric concentration of 720. So the sun-spot heating method rely on the hot spot generated by the area corresponding to the 23° half angle that concentrates 720 times the sun, and forms the real image of the sun as shown by figure 7 which is supposedly an infrared or thermal of that actual image at the focal point generated in a spherical concentrator. The radius $R_{dot}$ of this spot, which is assimilated to a sphere, can be evaluated by using the following equation:

$$R_{dot} = r_s \sqrt{\frac{\sin^2 \phi_s}{C_g}} = 0.015 r_s \text{ for } \phi_s = 23° \qquad (2)$$

With $r_s$ the radius of the reflective sphere and $C_g$ the geometric concentration giving that hot spot.

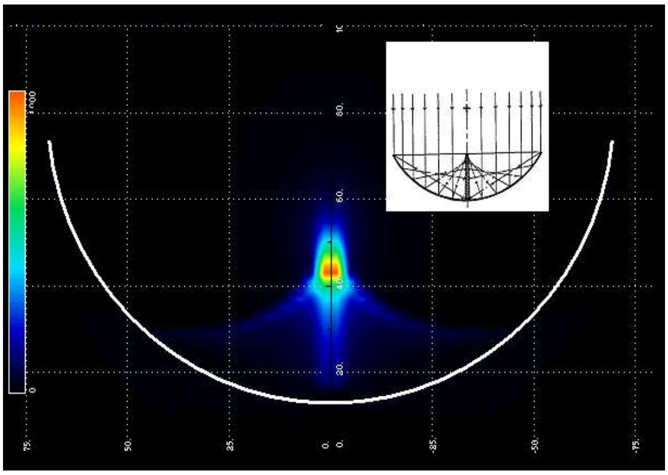


**Figure 7. Energy density along the half-radius in a hemispherical reflector**

To determine what could be the global temperature of the hot spot, we can use the maximal given by the following equation (Fletcher, 200; Steinfeld *et al.*, 2001):

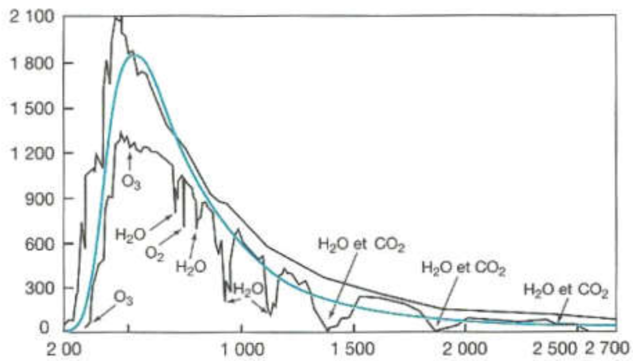
$$T_{Max} = \left( \frac{I C_g}{\sigma} \right)^{\frac{1}{4}} \qquad (3)$$

With $I$ the solar flux in $W.m^{-2}$, $C_g$=720 the geometric concentration, and $\sigma$ = 5.667 $10^{-8}$ $W.m^{-2}.K^{-4}$the Stephan-Boltzmann's constant.

In fact, for the day, the solar flux varies and so the maximum temperature (also called the stagnation temperature) of the hot spot can be evaluated. For a comparison using Equation (3), with a solar flux of $I$=800 $W.m^{-2}$, the hot spot temperature can rise up to $T_{Max}$=1 785 K (Without any lost assumption). This spot is quasi-steady, its moves 15 degree every hour around the center of the hemispherical concentrator from West to Est. We should also notice that the spot is generated by the aperture angle $\phi_s$=23°, so the system mainly uses only the $\sin^2 \phi_S$ = 0.15time the aperture area to heat up the hot spot.The next step will be to reduce the channel of air flow around the sun spot, so that the volume of air flow that will exchange with the sun spot be smaller as possible to give a higher temperature to that volume. For this reason, in our study, we divided the flow zone in bands up to four (4), and analysed the different gains of temperature obtained by the multiplication of bands. We also suppose the glasses thin enough to neglect there refractive effect on the sun rays. The hot spot heating the air had been difficult to admit, because the glass and the air are all transparent and always considered with very low thermal absorbance. It could be easily supposed that the intermediate sheets of glass are the most heated by the hot spot and the air is heated by natural convection in contact with these sheets. But even so, how to explain since these transparent sheets of glass cannot be assimilated to black bodies. The glass transmission factor is given close to zero except for the wavelength of 0.2 < λ < 3.5 mm where it is equal to 0.8. The emission factor is taken equal to 0.3 for λ < 3.5 mm and 0.9 beyond (Jannot, 2012). In the other hand as shown in figure 8, the air may be indeed transparent as well.

But some gases of the air may be absorbing infrared rays such as Ozone (λ ~ 9.5 μm), and mostly non-binary gases also called greenhouse gases such as carbon dioxide and water vapors that absorbs in a wide range of infrared rays (Brahic *et al.*, 1999).

Spectral Irradiance [in $W.m^{-2}.\mu m^{-1}$]




Wavelength in nm

**Figure 8. Gases ray absorbance in the atmosphere**

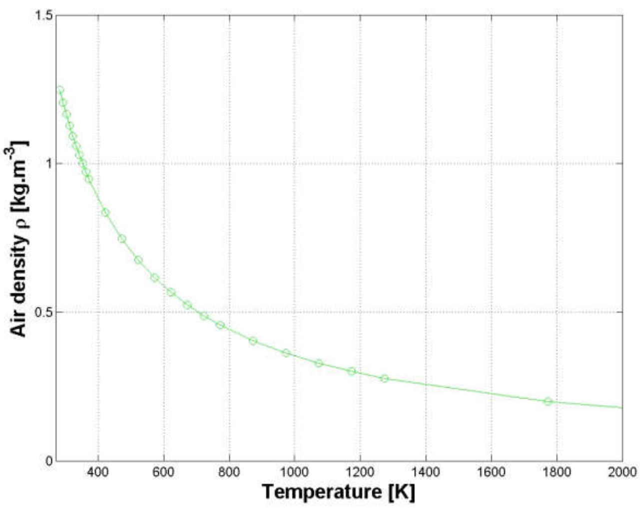



**Figure 9. Evolution of air density in relation to temperature**

In addition, the air density is very sensitive to temperature as we see on the following curve (Figure 9). For instance, at, the density of air is, while at, It is a huge drop in density, and this is most likely to generate air-mixing far more rapidly than other convection system.

### Designing an air heater without sun tracking system

### Experimental values

The studied prototype (Figure 10) is a truncated hemisphere designed in reinforced concrete.

**Fig 10. Picture of the prototype**

The interior is lined with a sticker-type reflector having a reflectivity of 95% according to the seller. The radius of the sphere is 0.59 m and the aperture area is 1.09 $m^2$. The hemisphere is truncated, its height is 0.46 m. The hemisphere is installed inclined by 13° corresponding to Ouagadougou latitude angle, and precisely aligned with the North using a compass. We propose a cutting of the concentration zone by bands of about 5.5 cm wide using 4 mm thick glass, and a measurement of the temperature of the air in these bands as in Figure 11.

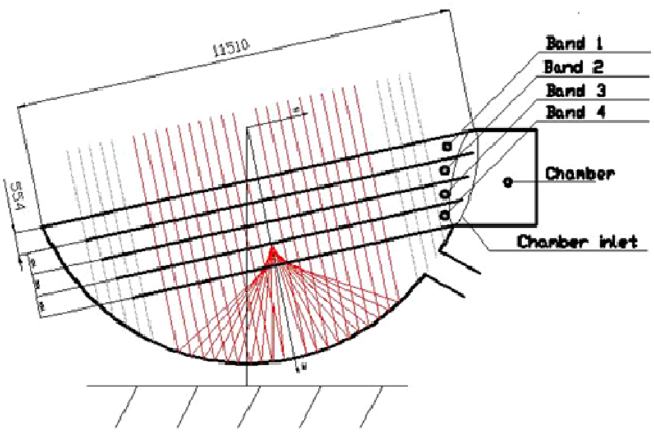



**Figure 11. Schematic layout of the prototype**

In this condition, the hot spot, i.e. the actual solar image, wanders from one band to another following the declination and the day-time, creating hot air-flows at different temperatures in each band that will be measured by thermocouples.

### Experimental values: materials and methods

To study the system, we used the equipment listed below and measurement methods referring to it:

- A data logger Midi LOGGER GL200A of GRAPHTEC brand.
- A probe (Outdoor) measures outdoor (or ambient) temperature.
- Probes (B1 to B4) measure the temperatures of each band, from the highest to the lowest one.
- A probe (Chamber) measures enclosed temperature in the chamber.
- A solar meter St-1307 and brand STANDARD for measuring solar radiation.

## RESULTS AND DISCUSSION

The system due to its location is gained by the sun around 9.30 a.m. and the shadow at the end of the day at 3.30 p.m., explaining the values of measurement ranges.

### Measurements of March 18, 2016

The bands B1 to B4 were fused to become B(1-4), the separation from the bottom of the hemisphere had been maintained.

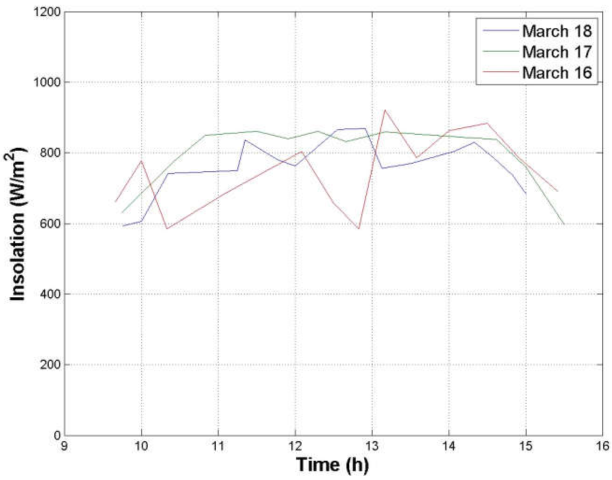



**Figure 12. Insolation measured at March 16, 17 and 18**

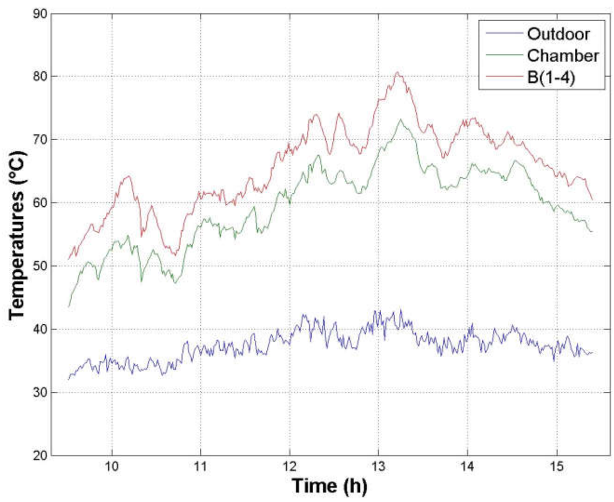



**Fig 13. Temperatures measured at March 18**

We are seeing an increase in temperature of the band B(1-4) from 50 °C in the morning at 9.36 a.m. to temperature up to 81

°C at 1.13 p.m. (Figure 13). This temperature decreases thereafter down to 60 °C at 3.30 p.m. The chamber temperature follows the band with a difference of about 7 °C throughout the day. The temperature curves are in accordance with the irradiation of the day which is between 585 and 922 W/m$^2$ (Figure 12).

### Measurements of March 17, 2016

The bands B1 to B2 were merged in B(1+2), and B3 and B4 bands merged in B(3+4), separation from the bottom of the hemisphere had been maintained (Figure 14).We see an increase of the temperature of the band B(3+4) from 50 °C in the morning at 9.36 a.m. to temperature up to 93 °C at 12.00 p.m. Cloudy passages from 12.00 to 1.12 p.m. and an electrical load shedding from 1.12 p.m. to 2.15 p.m. failed to pronounce on these time slots. The temperature of the B(3+4) band then decreases from 2.15 p.m. to 3.36 p.m. That of the band B(1+2) is less than 5 ° to 7 °C than B(1+2) in the portion preceding the cloudiness and load shedding, and that of the chamber is even lower than 5 °C with respect to B(3+4). Irradiation of the day is from 630 to 861 W/m$^2$ (Figure 12).

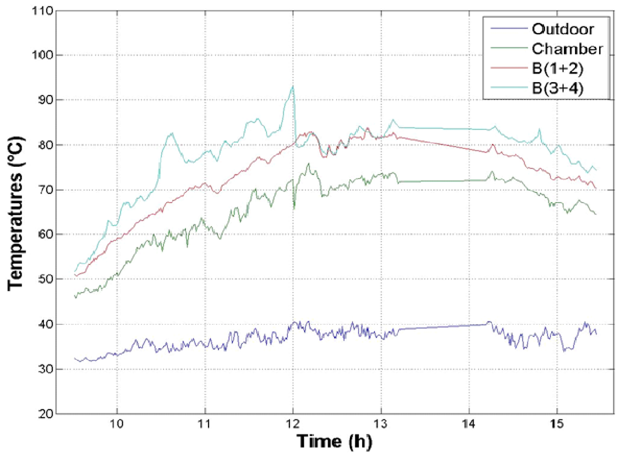



**Fig 14. Temperatures measured at March 17**

### Measurements of March 16, 2016

The 4 bands B1 to B4 are maintained, the separation from the bottom of the hemisphere is also maintained.

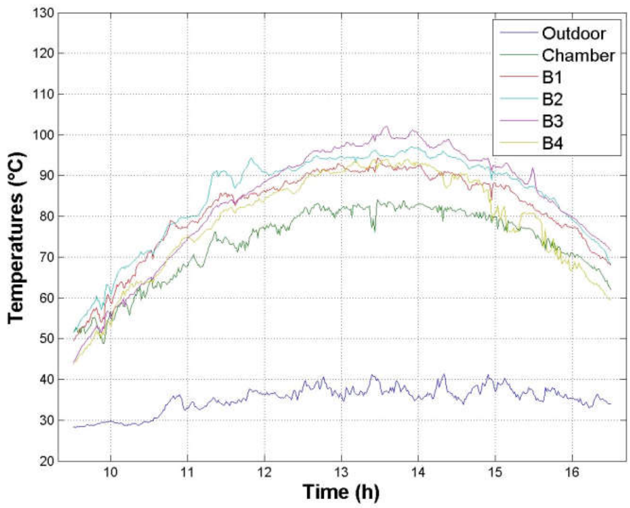



**Fig 15. Temperatures measured at March 16**

We see an increase in the temperature of the bands B1 to B4 from 44 °C in the morning at 9.36 a.m. to temperature up to 102 °C at 1.35 p.m., followed by a decrease to 60 °C at 3.36 p.m. The temperatures of the 4 bands are very similar and the most important differences are around 8 °C. We can also notice the predominance temperatures of some bands (B2 and B3). The temperature in the chamber is less than 20 °C in comparison with the temperature of the highest band. Irradiation of the day is from 593 to 869 W/m$^2$ (Figures 12 and 15).

### Conclusion of the study and perspectives in the use of the system

The temperature readings allow us to make the following observations:

The temperature in the chamber is low because of the non-adiabatic isolation from the outside, it is actually in black sheet of steel 1.5 mm thick without insulation. The more bands we have, more the temperature rises. Multiplying the sheets of glass further increases the temperatures. In the four bands case, the fact that the bands B2 and B3 are the hottest logically indicates that the hot spot moves primarily in these bands. For the hot spot to get in the band B1 would require the measurements to be done rather earlier in the morning before 9 a.m., and for it to get in the band B4 would require measurements at the equinoxes. The temperatures achieved by this system are from 90 °C to 102 °C for 4 bands, and that with an irradiation of 869 W/m$^2$. The possible use of such a device would be a laundry or some specific vegetables dryer for instance, or a low temperature cooker (100-120 °C) by increasing the bands, or a solar chimney (Ky and Bathiebo, 2015). One perspective from the model proposed here and in view of the expression of the constant ratio of the spot radius on the hemisphere radius, is that temperatures obtained are independent to the diameter of the hemisphere. Joining several hemispheres might help achieve greater powers according to the necessary time of temperature rise, and this without complicating the system because of the fixed and permanent installation of these hemispherical concentrators. Furthermore, this study allows to state that air can be heat directly by hot-spots generated through hemispheric concentrators without receivers, and the result is even better than black plates' natural convection systems.

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