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Experimental Study of an Indirect Solar Dryer Using a New Collector System. Application to Mango and Ginger Drying

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Abstract

In this paper, an indirect solar dryer using a new type of collector is studied. The collector is built with hemispherical concentrators with an axially-centered Fresnel lens placed on top of each. That allows the collector's aperture area of 0.32m2 to fully contribute to the hot spot generated in the hemispherical concentrators. The dryer was installed permanently, sun-tracking free, and drying experiments were taken at a cloudy period (From the end of May to the beginning of June) to correspond to the most-needed time of crops conservation in Ouagadougou, Burkina Faso. Mango and ginger were charged in the chamber, weighted separately and without tray permutation to see the weight loss for each of the 5 trays' products. As outcomes, dryer's collector efficiency was evaluated at 42.45%. Mango was

dried with temperatures ranging from 57 to 67°C around the trays with a dryer’s efficiency of 41.2% and in 8 hours.
In conclusion, the novel collector built with hemispherical concentrators, enhanced by Fresnel lenses and mounted on a sun tracking free indirect solar dryer is proven effective for agricultural crops drying.

Keywords: Hemispherical concentrators, Solar bowl, Natural convection, Sun-tracking free indirect solar dryer.

1 Introduction

Indirect solar dryers had been commonly studied to dry crops products. The usual technology of indirect solar dryers’ collector is a black plate (or absorber) to collect heat, covered with a glass for additional greenhouse effect as we see in figure 1.
The air coming from the lower side of the collector collects the heat from the black plate and transfers it to a chamber placed at the upper end of the collector, where the products are disposed on trays. Indirect solar dryers’ chamber is insulated, such that the products are not exposed to sun light, avoiding their degradation by UV rays. These solar dryers are usually steadily installed, sun-tracking free.
Lately, some novel air collectors had been proposed, as we can see in figure 2 (Ky *et al*., 2018a [9]).

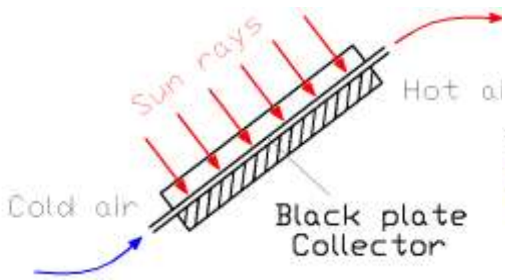

Fig1- Flat black plate collector

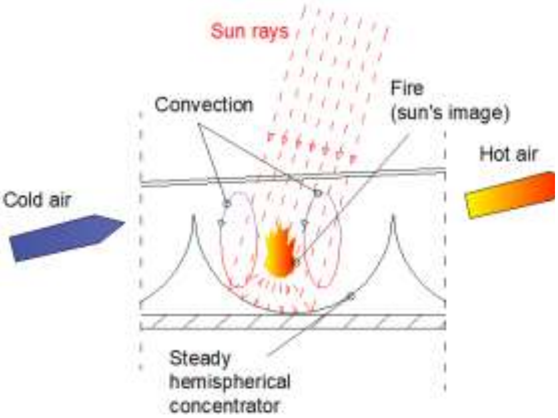

Fig2 - The hot spot principle [9].

They are made with hemispherical concentrators covered by a transparent glazing. The concentrators generate hot spots at their focal points. Then, these hot spots directly exchange heat with the circulating inside air. There is no need to dispose a receiver at the focal point, the sun images (hot spots) being sufficiently hot to provide the heat. The concentrator's geometry makes the resulting collector permanently fixable, sun-tracking free just as usual black plate collectors. This new collector is referred as the "hot spot" collector.
The two main differences between the black plate and the hot spot collectors are the fact that first the hot spot collectors heat the air to $\Delta T \approx 40°C$ (Ky *et al*., 2018b [10]), which is more than the black plate collectors with $\Delta T \approx 25°C$, ΔT being the difference of temperatures between the inlet and the outlet of the collector and

second, due to the fact that the hot spot is the result of a concentration, only the direct sun rays are at work with the hot spot collectors.
Two sub-technologies had been investigated regarding the hot spot collector (Ky *et al.*, 2018c [11]). The first one uses direct sun rays coming on the hemispherical concentrators (Figure 3).
This sub-technology was limited by the fact that only the rays coming with a half angle of 23° are reaching the focal point, as shown in figure 3. That consequently reduced the exposition area's contributing to the hot spot. Temperature difference from the outlet with the inlet ΔT goes up to 40°C, while it is usually around 25°C with a black plate collector. It is then better than the black plate collector for heating air.
The second sub-technology uses pre-concentrated sun rays through lenses (Figure 4) before arriving on the hemispherical concentrators (Ky *et al.*, 2021 [12]).

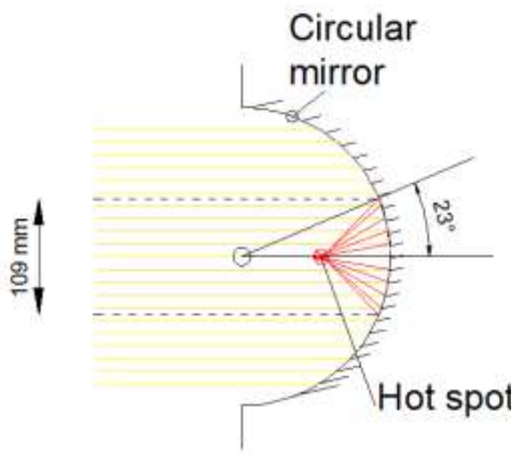

Fig3 - Parallel rays coming on the concentrator [11]

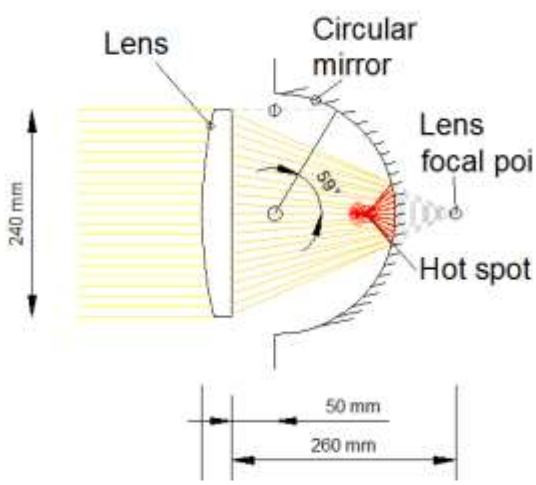

Fig4 - Deviated rays coming on the concentrator through a lens [11]

That second technology compensates that lack of the first one by the use of a lens. We then gain up to 65°C temperature difference ΔT, which is better than the first sub-technology, and even far better than the black plate technology.
Further improvements had also been investigated: these improvements play with the reduction of the air volume to heat up (Ky *et al.*, 2018b [10]) and the multiplication of hot spots for an identical exposition area (Ky *et al.*, 2018c [12]).
The first improvement uses the separation in multiple bands of the hot spot wandering zone by glass sheets (Figure 5).
The second improvement uses the truncating technique to reduce distances between the hot spots while keeping enough concentration surface for the sun rays to produce the hot spot even with the declination angle, as shown in figure 6.

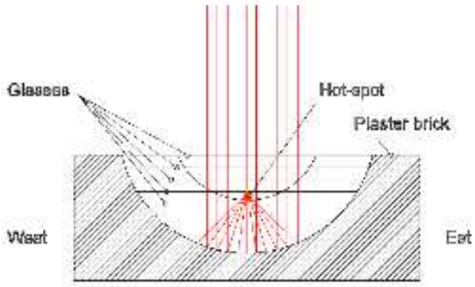

Fig5 - Separation of zones by bands with glasses [12]

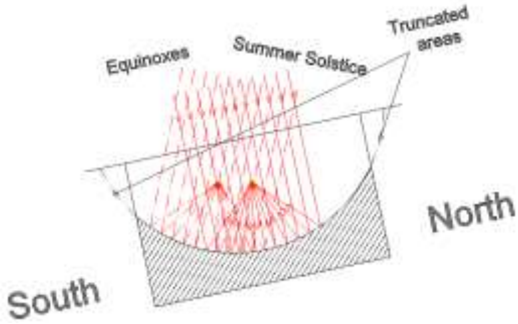

Fig6 - Truncating of the concentrator to fit the declination angle [12]

These improvement technics had been implemented in the first hot spot collector technology using parallel sun rays, with substantial enhancements regarding the rise of temperature difference. Previous solar dryers were built and studied using this improvement [10],[12].

Collectors built with hemispherical concentrators had also been used in previous publications for solar chimney power plant design [9].

2 Description of the system

The system studied here is an indirect solar dryer built with a collector composed of three hemispherical concentrators using Fresnel lenses as shown on following figures 7 and 8.

The Collector used for this system had already been studied for optical and performance analysis in a previous publication [12]. It is composed of three (3) hemispherical concentrators 280mm of diameter, covered by a glass 4mm thick. This collector corresponds to the second technology using Fresnel lenses to pre-concentrate the sun rays before reaching the hemispherical concentrators, so that the larger ratio to the exposition areas can feed the hot spots. Its efficiency had been estimated to ≈56% [12], which is far greater than that of black plates ≈29% (Srivastava *et al.*, 2014 [20]) As presented in the introduction, the collector does not somehow benefit from any improvement such as separation of the hot spot wandering zone or truncating of the concentrators to multiply hot spots, which means that it can be efficiently upgraded in the future. The exposition area of the collector is $0.32m^2$. Its inlet and outlet sections are 320x40mm. It is installed with a slop of 12° corresponding to the latitude of Ouagadougou.

The drying chamber comports five (5) trays on which we intent to dry products. The trays are 100mm distant to one another. The first tray is 344mm distant from the inlet of the chamber. The insulation of the chamber is done by polyester walls 40mm thick. Its dimensions are shown in the figure 7. The chamber section equals 400x400mm with a height of 980mm. The upper end of the chamber is a chimney sized 100x100mm per 300mm of height. There is a likewise 40mm thick polyester insulated side door for products load on the trays. The hot air coming from the collector to the chamber is channeled so that it rises straight from the bottom to the trays.

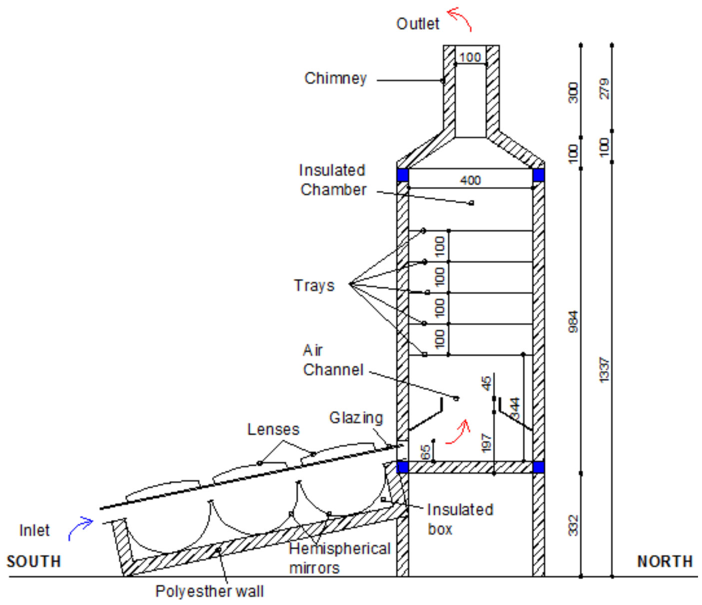

Fig7: Schema of the system

Fig8: Picture of the system

We intent to evaluate the collector efficiency when the chamber is not loaded, the dryer's efficiency when loaded and to dry products like mango and ginger. For each product, the initial moisture content, the maximum allowable temperature and the dried product ratio are mentioned in the following table1 (Simate *et al.*, 2017 [19], Sansaniwal *et al.*, 2015 [18], Kam *et al.*, 2017 [7], Dhurve *et al.*, 2017 [6], Al-Neama *et al.*, 2018 [2]).

Table1: Products' characteristic

	Initial moisture content (%)	Maximum allowable temperature (°C)	Dried product ratio (%)
Mango	75	70	15
Ginger	80	60	11

The collector's efficiency evolution with time $\eta_{col}(t)$ will be drawn using the following equation (Maia *et al.*, 2017 [14], Bakari 2018 [4], Tyagi *et al.*, 2007 [22]):

$$\eta_{col}(t) = \frac{e_{ut}(t)}{e_{tot}(t)} = \frac{q_m(t) C_p \left[T_{ex}(t) - T_{in}(t)\right]}{I_r(t) S_{col} \varpi(t)} \tag{01}$$

The collector's efficiency η_{col} of the day in % is evaluated using the following equation.

$$\eta_{col} = 100 \frac{\sum e_{ut}(t)}{\sum e_{tot}(t)} \tag{02}$$

With:

q_m the air mass flow rate in kg.s^{-1}

C_p the specific heat capacity of the air =1006 J.kg^{-1}.K^{-1}

T_{ex} the temperature of air outing the collector in K

T_{in} the temperature of air entering the collector in K

I_r the solar radiation at the measured time in W.m^{-2}

S_{col} the collector exposed section to the sun in m^2

ϖ The exposition angle cosine of the sun

The following relation will be used to evaluate the air mass flow in relation with time:

$$q_m(t) = \rho(t) v(t) s_{flow} \tag{03}$$

With:

ρ the air density at the flow section in kg.m^{-3}

v the air velocity at the flow section in m.s^{-1}

s_{flow} the flow section size in m^2

The density variation with the temperature will be estimated by the following relation, considering the air being a perfect gas:

$$\rho(t) = 1.292 \frac{T_0}{T_i(t)} \tag{04}$$

With:

T_0 =273.15K and T_i in K.

The exposition cosine of the sun will be evaluated using the following equation.

$$\varpi(t) = \cos\left(15(12-h)\frac{\pi}{180}\right)\cos(\delta) \tag{05}$$

With:

h the time in hour.

δ is the declination angle of the day. It will be neglected for being less than 10°: the system slop switched towards the South azimuth. The declination angle is calculated by the following equation of Cooper:

$$\delta = 23.45 \sin\left(360 \frac{284+n}{365}\right) \tag{06}$$

We previously evaluated the efficiency of the actual collector $\eta_{col} \approx 56\%$ [11].

The efficiency of the dryer η_{dr} (in %) will be evaluated using the following equation (Lingayat *et al*., 2017 [13], Ayyappan *et al.*, 2015 [3], Nayak *et al*., 2011[16], Sahdev *et al.,* 2016 [17], Musembi *et al.*, 2016 [15]).

$$\eta_{dr} = 100\frac{m_w \sum h(t)}{t_f \sum e_{tot}(t)} \quad (07)$$

With:

m_w the removed amount of water in kg

t_f the taken time to dry the product in s.

$h(t)$ water's latent heat of vaporization in $J.kg^{-1}$ that can be considered as a linear function depending on temperature T between 0 and 100°C, so we will use (Torquato *et al.,* 1982 [21]):

$$h(t) = -2.446T(t) + 2501 \quad (08)$$

Products will be dried, weighted every hour and the values will be reported by tray. The moisture content will be evaluated using the following equation ([19], Belessiotis *et al*., 2011 [5], Akoy *et al.*, 2015[1]).

$$Mc_{dry}(t) = \frac{W_{st}(t) - W_{dm}}{W_{dm}} \quad (09)$$

Where:

$Mc_{dry}(t)$ is the moisture content (dry basis) at any time,

$W_{st}(t)$ is the weight of the sample at any time in kg,

W_{dm} is the weight of the dry matter of the sample in kg

3 Material and methods

Products will be dried, weighted every hour and the values will be reported by tray. The moisture content will be evaluated. Table 2 shows the measuring range and accuracy of measurement materials.

Table 2: Measuring range and Accuracy of measurement materials

Instrument	Measuring range	Accuracy
Thermocouples of K type	-100°C – 1370°C	± (0.1% of reading + 0.3°C).
A pyranometer SR03-05 of Hukseflux brand sensibility=9.58 µV ($W.m^{-2}$)	0 – 2000$W.m^{-2}$	± 15$W.m^{-2}$
A hot wire anemometer Model Testo 480	0.6 to 50 m/s -10 to +70 °C	± (0.2 m/s +1 % of m.v.)

- A Midi LOGGER GL220A of GRAPHTEC brand.
- A thermocouple of K type “Ird” for irradiant temperature measurement under sunlight. As a matter of fact, usual drying process in Africa is the exposition of products to direct sun lights.
- K type Probes (Thermocouples) “CB” and “CH” for measurement of temperatures at the outlet of the collector. The lower probe “CB” does not touch the metallic part of the bowl, neither the upper probe “CH” touches the covering glass.
- A medium temperature at the outlet Cm is calculated using the following equation:

$$Cm = \frac{CH + CB}{2} \tag{10}$$

- K type probes “DTr”, “MTr” and “UTr” for measurement of temperatures 80mm above the bottom tray N°1, the middle tray N°3 and the top tray N°5.
- K type probe “Chim” for measurement of temperature at the chimney.

The dryer is permanently installed with the slope towards the south (due to the sun azimuth switch to north), with no sun-tracking whatsoever.
Measurements were made from the end of May to the beginning of June, which corresponds to the beginning of the raining season in Ouagadougou, and not to the hottest period of the year (End of March to the beginning of April).
Tray products will be weighted each hour and replaced at its original place, without permutation.
Measurements started at 8:00 or 9:00 am and stopped at 3:40 pm, due to the fact that the dryer’s collector was shadowed by a shielding wall.
For the temperature curves outing the collector, we will mainly use and draw the mean temperature Cm of the two, using the equation (10), and all the calculations will be made with the mean temperature. Likewise, for the speed curve, a fitting curve is drawn using a 10th degree polynomic.
Ouagadougou is 12° Latitude North, and at the measurement period, the sun had moved to North. This is a time with lots of cloud inconveniencies, knowing that the solar dryer’s collector works better with direct sun rays. Nevertheless, operating at such a period could predict the efficiency of the system when used to dry agricultural products at the time it is needed the most.

4. Results and discussion

A measurement with an empty chamber had been done in May 21st, 2020. Potato, mango and ginger had been dried the following days of June 3rd and 6th, 2020 respectively.

4.1 Measurements of May 21st, 2020.

Measurements with an empty chamber were taken in May 21st, 2020. The insolation measurement curve is given as follow (Figure 9).

The curve has a regular shape of inversed parabola, with the insolation highest value of 732W.m^{-2} at 11:58 am. The day was a shiny one with no cloud shadow, but the insolation value wasn't that high.

We therefore measured the following temperatures, shown in the following figure (Figure10).

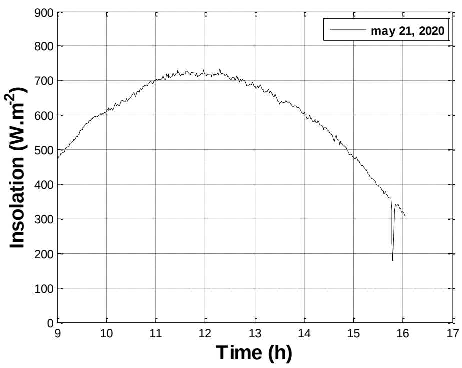

Fig9: Insolation measurement of May 21th, 2020.

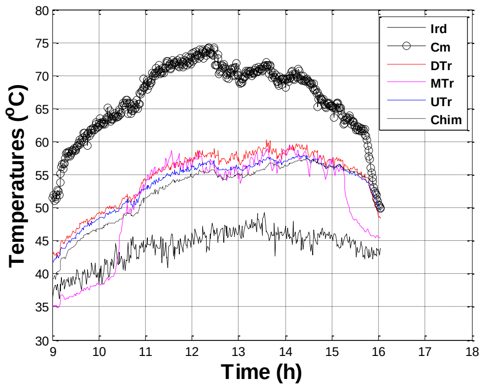

Fig10: Temperature curves of May 21th, 2020.

Temperature curves follow the same shape of the insolation. That of the admission from the collector has its highest pic of 74°C at 12:22 pm. The other curves corresponding to temperature measurements 80 mm above trays 1, 3, 5 and at the chimney are quite identical due to the fact that the chamber is empty. The temperatures evolve from around 42°C from 9:00 am to 60°C at 1:30 pm, then decline to 50°C at 4:00 pm when the collector is reached by shadow. The temperature measured under sun light has its pic of 48°C at 1:30 pm.

A priori, for the seasonal insolation, we can suppose that the drying temperature will not affect the quality of the products to dry for they are under the Maximum allowable ones.

The following figure is about the air speed outing from the chimney (Figure 11).

With the instability of the speed, we evaluated a fitting curve in red to represent the supposed speed. It evolves from 0.3 to 0.4 m.s^{-1}.

Collector's efficiency curve calculation with the equation (01) gives figure 12.

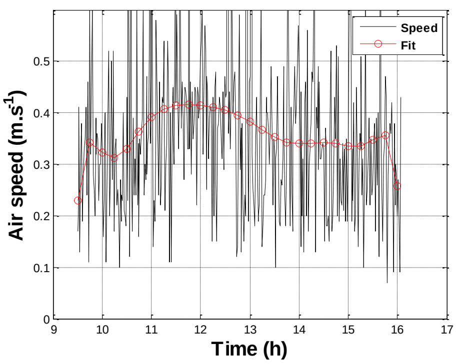

Fig11: Air speed measurement of May 21th, 2020.

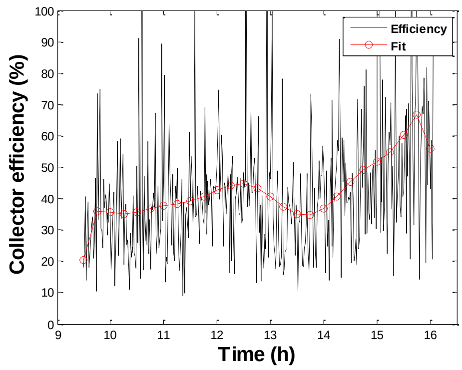

Fig12: Collector efficiency curves evolution of May 21th, 2020.

We could see that the curve evolves between 30 and 68% (looking at the fitting curve). Using equation (02), we found an average daily collector efficiency of 43.9%. This value is consistent with previous value measured in slightly similar conditions (56% [12]). The difference is that the air speed measurement of the day is done at the chimney on top of the chamber instead of at the outlet of the collector. So, we use the assumption that there is no air mass loss while passing through the empty drying chamber.

4.2 Measurements of June 3rd, 2020.

Measurements were also conducted in June 3rd, 2020. The chamber was loaded with 976 g of mango to dry with 200 g disposed on the first 3 trays (starting from bottom), 190 g on the 4th tray and 186 g on the last one. Products were cut 5mm thin. The insolation curve for that day is as follow (Figure 13).

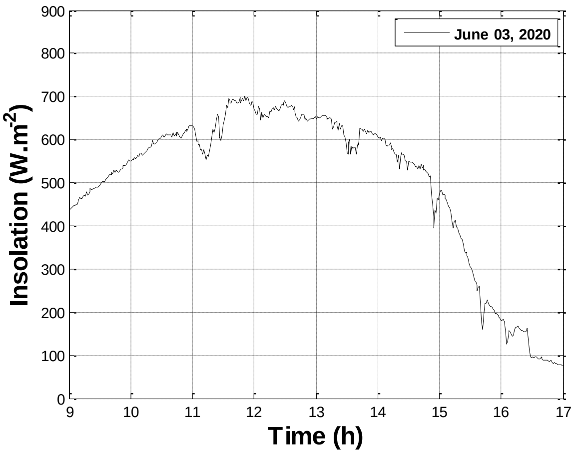

Fig13: Insolation measurement of June 3rd, 2020.

The curve has a regular shape with some cloud passage at 11:10 am, and the insolation highest value is 700W.m^{-2} at 11:51 am.

Temperature measurement curves are shown on figures 14.a and 14.b:

Highest pic of 71.7°C at 11:50 am was found at the inlet of the chamber. Temperature pics of trays are in a gap of 57 to 67°C.

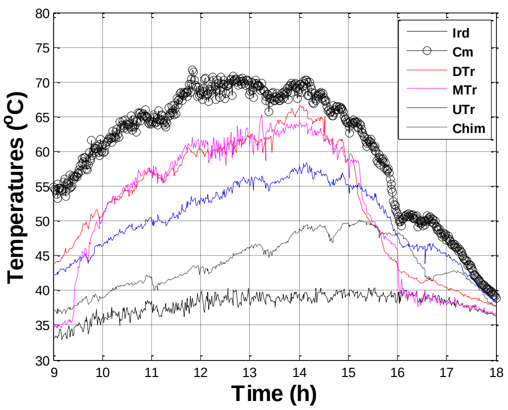

Fig14.a: Temperature measurement of June 3rd, 2020.

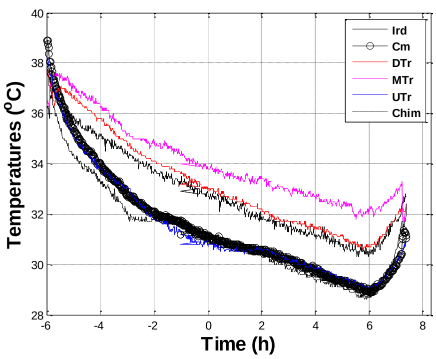

Fig14.b: Temperature measurement overnight between June 3rd and 4th, 2020.

Temperatures inside the dryer continued to drop overnight, allowing the drying process to complete.

Moisture content had been measured by tray, giving the following (figure 15):

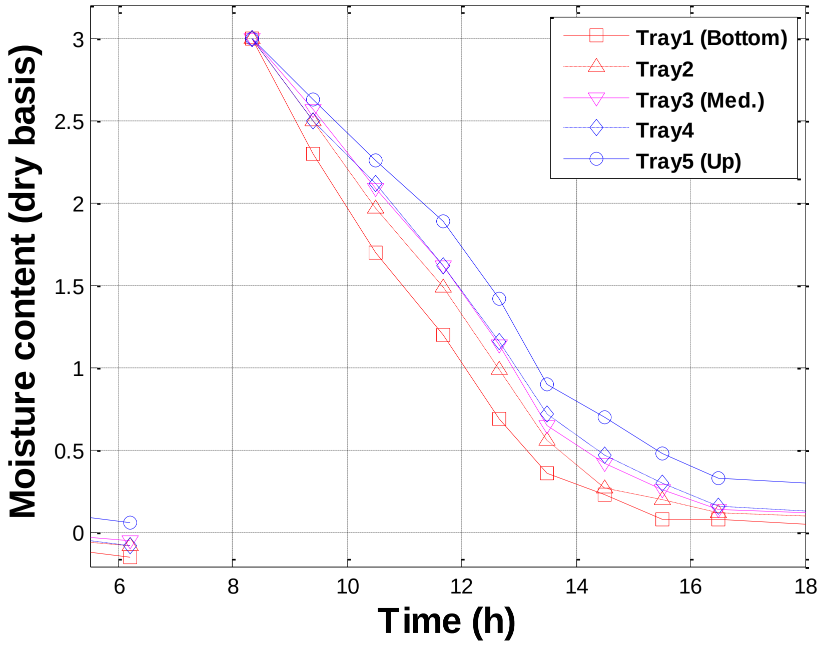

Fig15: Moisture content curves of June 3rd, 2020.

Product of 976 g was reduced to 285 g after 8 hours of drying. Drying process continued overnight till the final mass was brought to 230 g, (224 g as final mass of dry product), but there was not much time left to go through to complete the drying process. Lower trays are losing quickly than upper ones as usual. Dryer's efficiency is evaluated to $\eta_{dr} = 41.2\%$.

Mango aspect is shown on following figure 16.

a. Fresh mango

b. Dried mango

Fig16: Mango shape before and after drying

4.3 Measurements of June 6th, 2020.

Measurements were finally conducted in June 3rd, 2020 with 347 g of ginger to dry, 70 g disposed on the first 4 trays (starting from bottom) and 67 g on the last one. Products were cut 5mm thin.

The insolation curve for that day is show by figure 17 below:

The curve has a regular shape with some cloud passages all day, and the insolation highest value is 731 W.m^{-2} at 11:23 am.

Temperature measurement curves are shown on figure 18:

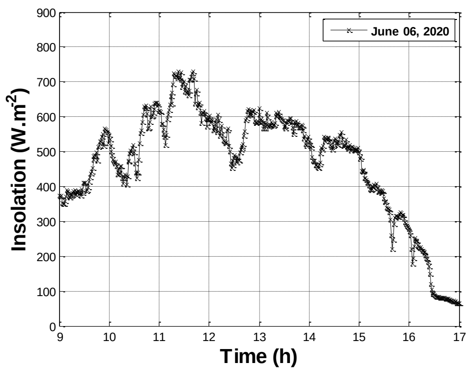

Fig17: Insolation measurement of June 6th, 2020.

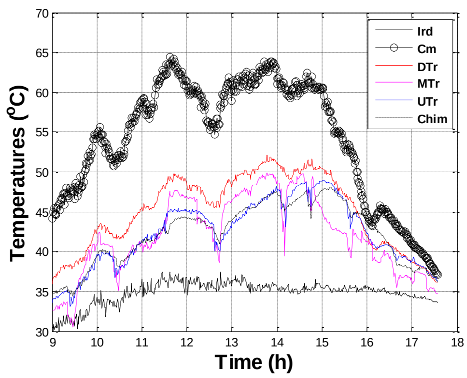

Fig18: Temperature measurement of June 6th, 2020.

The inlet of the chamber has the highest pic of 64.4°C at 11:38 am. Temperature pics of trays are in a gap of 47 to 52°C.

Moisture content had been measured by tray, giving the following figure 19:

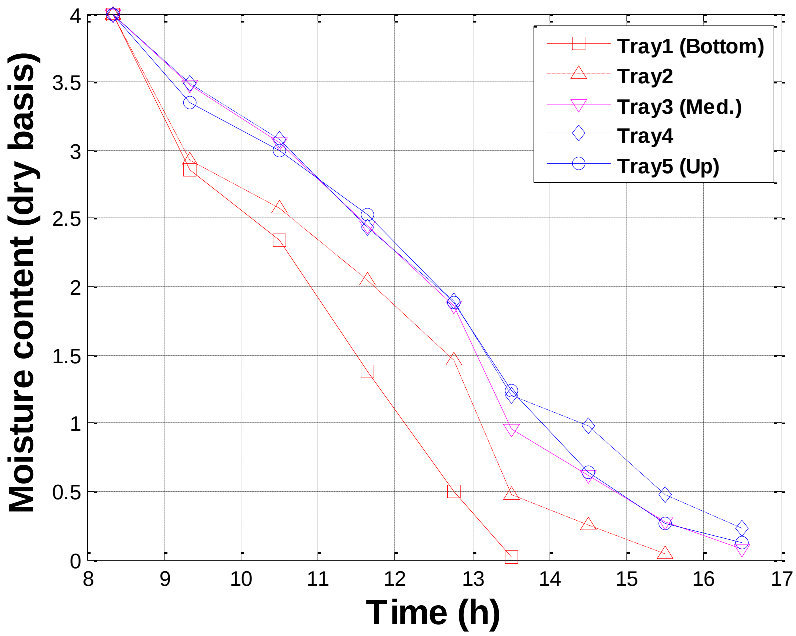

Fig19: Moisture content curves of June 6th, 2020.

Ginger product of 347 g was reduced to 72 g after 8 hours of drying. Drying process can be considered as completed (69 g as final mass of dry product), since some trays' product were removed before that time. Dryer efficiency is evaluated to $\eta_{dr} = 22.2\%$. The loading was not sufficient.

The fresh and dried ginger aspects are shown below on figure 20:

a. Fresh ginger

b. Dried ginger

Fig20: ginger shape before and after drying

4.4 Discussions.

From the measurement results, we got 74°C, 71.7°C and 64.4°C at the outlet of the novel collector at May 21st, June 3rd and 6th respectively. These temperatures differences with ambient temperature's pic (36°C) are quite above the 25°C of usual black plate collectors.

That gives a collector efficiency $\eta_{col} = 42.45\%$ measured on May 21^{st} while the chamber is empty.

Temperatures around the trays were 57 to 67°C for drying 0.976kg of mango and 47 to 52°C for 0.347kg of ginger, with the novel type of collector of 0.32m2 of aperture area. These temperatures differences with ambient temperature's pic (36°C) are quite above temperatures obtained around the trays with systems without Fresnel lenses and usual black plate collectors.

The system efficiency, for June 3^{rd} for drying process of mango was $\eta_{dr} = 41.2\%$. Product got dried in one day.

5. Conclusion

From this work, we can draw following conclusions:

1- Air speed outing the chimney with an empty chamber allowed to calculate a collector efficiency of 42.45%. This efficiency is aligned with the efficiency previously established for the collector (56% [4]), and above the usual black plate collector's efficiency (29% [11]).

2- Temperatures around the trays are quite convenient for products to dry: 0.976 kg of mango dried in 8 hours with a temperature range of 57 to 67°C.

3- The dryer's efficiency of that day was 41.2%. Mango and ginger got dried in a day.

In conclusion, the indirect solar dryer using a novel collector built with hemispherical concentrators, enhanced by Fresnel lenses and installed sun tracking free is definitely proven effective for agricultural crop drying.

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