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Mathematical and experimental study of the solar tower for the drying of food products.

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ABSTRACT

This work consists of a 2D numerical study of natural convection air flow in the solar tower followed by validation with experimental results. The simulation made it possible to determine the various hot zones of the chimney where the food products can be dried according to their drying temperature. The temperatures obtained in the chimney or desiccant chamber through the simulation range from 75 °C to 30 °C depending on the height of the chimney with an estimated output velocity of 0.715 m.s^{-1}. Those recorded experimentally are between 61 °C and 52.5 °C with an average maximum velocity estimated at 1.1 m.s^{-1}.

Keywords-

Numerical study; Natural convection; Experimental; Chimney; Output velocity; Air temperature.

I. INTRODUCTION

The solar tower is a solar power station proposed in 1903 by a colonel of artillery named Cabanyes to compensate for the energy crisis in its time [1]. Since then several ideas have been proposed. Thus, in 1926, B. Dubos proposed to exploit the vertical wind blowing in a tube on the side of a mountain as a solar chimney [2]. The first representation of a solar tower was in 1931 by [3]. Then Nazaré proposed a vortex tower whose principle was to artificially generate a large-scale vortex ancestry generated by a natural draft effect [4]. The first prototype with a scale of 50 kW was designed in 1981 in Manzanares in Spain by [5]. The solar tower is a renewable energy power plant whose operating principle is channeled the greenhouse-heated air in the manifold to power turbines to generate electricity. Simulation and experimental work was carried out to improve the system by evaluating the influence of geometry and temperature [6, 7, 8] as well as the influence of the speed or location of turbines in the to increase the electrical power [9, 10, 11]. Due to its function, the greenhouse-heated air can be used for drying food products. This is how OUEDRAOGO G. et al [12] called it "solar tower dryer". Parameters such as temperature, air velocity and humidity are very important and greatly influence the choice of the solar dryer [13].

The objective of this study is to determine numerically the different temperature and air velocity distributions within the small-scale solar tower for drying food products. Then we will carry out an experimental study of the air flow and then compare these results with those of the simulation.

II. EXPERIMENTAL STUDY OF AIR FLOW

The experimental device has the same dimensions as the dryer n°1. It consists of a collector and a chimney which constitutes the chamber to be dried (Fig. 1). The collector is composed of four panes of 1 m² and a absorber painted in matte black between which the air is heated by the greenhouse effect. The drying chamber has a height of 3 m and a diameter of 20 cm and has four racks.

For the experimental study of the air flow, we used:

- a temperature logger (midi logger GL220) coupled to type K thermocouples. The error margin is ± 0.05% of the measured value + 1˚C for temperatures between -100˚C and 1370 ˚C.
- a velocity recorder (anemometer)

coupled to a DO 2003 data logger. It has an accuracy of 0.02 $m.s^{-1}$ for velocities between 0 and 0.99 $m.s^{-1}$ and an accuracy of 0.1 $m.s^{-1}$ for velocity between 1 and 5 $m. s^{-1}$.

Fig. 1. Solar tower dryer

III. MATHEMATICAL MODELING OF AIR FLOW

The objective of this modeling is to observe the evolution of the air flow within the dryer by determining the temperature and velocity profiles. Knowledge of these profiles will make it possible to identify the location of the racks according to the product to be dried.

Description of solar tower dryer

The solar tower dryer consists of two main elements, namely the collector and the drying chamber or the chimney. It is an indirect solar dryer working in natural convection. Like any dryer, it aims to extract the moisture from the product in order to obtain a dried product of good quality. Its operating principle is simple: the air heated by the collector enters the chimney and arrives on racks where are spread out products. At this level, the hot air tears water molecules out of the products and continues its way towards the exit of the chimney (Fig. 2).

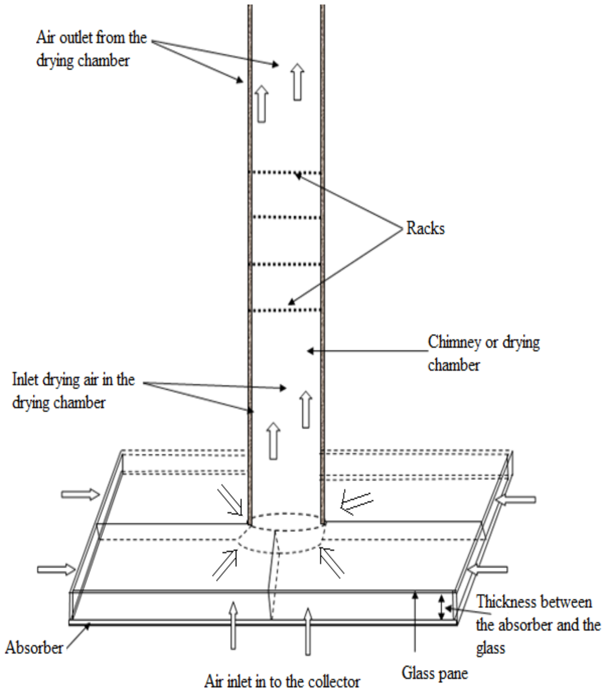

Fig. 2. Schematic of the solar tower dryer [12]

Mathematical modeling

The flow of air in natural convection within the solar tower dryer described in figure 1 is governed by the equations of continuity, momentum and energy. In this paragraph the phenomenon of mass transfer is not studied because we want to have an idea of the behavior of the air in the dryer before the introduction of a food product.

- Simplifying hypotheses of the problem:

The mathematical model developed is defined according to the following assumptions:

- the system is considered two-dimensional and studied in cylindrical coordinates
- the flow considered permanent and laminar
- the system has an axis of symmetry
- no exchange by radiation from the air
- the force of gravity is the only external force Air properties such as dynamic viscosity, thermal conductivity and heat capacity are considered to be constant. Except for the density of the air which obeys the approximation of Boussinesq, translated by equation (1):

$$\rho = \rho_0[1 - \beta(T - T_0)] \qquad (1)$$

Where:

$\beta = \frac{1}{T_0}$: Coefficient of thermal expansion or expansion at constant pressure

T_0: Outside temperature (ambient)

T: Air temperature

ρ_0: Density of air at T_0

- Equations governing the flow of fluid in the system:
  The following equations govern the flow of air in cylindrical coordinates in the system studied taking into account the above assumptions.

➢ Equation of continuity

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho_0 r u) + \frac{\partial}{\partial z}(\rho_0 v) = 0 \qquad (2)$$

Where r: radial coordinate (m), z: vertical coordinate (m), u: radial velocity (m s^{-2}) and v: vertical velocity (m s^{-2})

➢ Equations of momentum along the radial axis

$$\frac{1}{r}\frac{\partial}{\partial r}(ruu) + \frac{\partial}{\partial z}(uv) = -\frac{1}{\rho_0}\frac{\partial P}{\partial r} + \frac{\mu}{\rho_0}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) + \frac{\mu}{\rho_0}\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial z}\right) - 2\frac{\mu}{\rho_0}\frac{u}{r^2} \quad (3)$$

With P, the pressure (Pa) and μ the dynamic viscosity coefficient (Pa·s).

➢ Equations of momentum on the vertical axis

$$\frac{1}{r}\frac{\partial}{\partial r}(ruv) + \frac{\partial}{\partial z}(vv) = -\frac{1}{\rho_0}\frac{\partial P}{\partial z} + \frac{\mu}{\rho_0}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v}{\partial r}\right) + \frac{\mu}{\rho_0}\frac{\partial}{\partial z}\left(\frac{\partial v}{\partial z}\right) - \frac{\rho}{\rho_0}g \quad (4)$$

Where g is the intensity of gravity (m s^{-2}).

➢ The application of the Boussinesq approximation in equation (4) gives

$$\frac{1}{r}\frac{\partial}{\partial r}(ruv) + \frac{\partial}{\partial z}(vv) = -\frac{1}{\rho_0}\frac{\partial P}{\partial z} + \frac{\mu}{\rho_0}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v}{\partial r}\right) + \frac{\mu}{\rho_0}\frac{\partial}{\partial z}\left(\frac{\partial v}{\partial z}\right) - [1 - \beta g(T - T_0)] \quad (5)$$

➢ Equation of energy

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho r u T) + \frac{\partial}{\partial z}(\rho v T) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\lambda}{c_p}\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{\lambda}{c_p}\frac{\partial T}{\partial z}\right) \quad (6)$$

With T, the temperature (K), λ the thermal conductivity (W m^{-1} K^{-1}) and c_p the thermal heat capacity (J kg^{-1} K^{-1}).

- Boundary conditions:

To simplify the study of airflow in the system, several authors such as Toufih Chergui et al [14], Amori K.E. et al [15] and Heisler E.M. [16] have adopted boundary conditions similar to the following boundary conditions (Fig. 3):

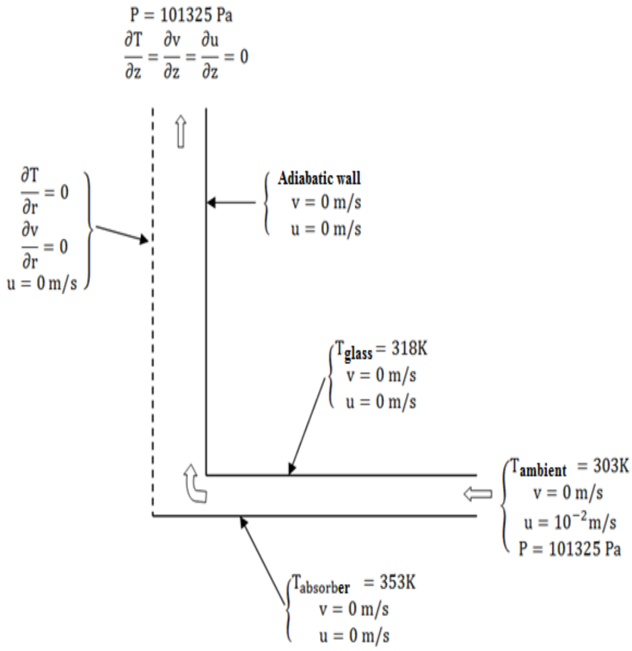

Fig. 3. Diagram illustrating the boundary conditions

IV. RESULTS AND DISCUSSION

Numerical results and discussion

We simulated two solar tower dryers of different chamber diameter to dry. The first dryer (dryer n°1) has a diameter of 20 cm and the second (dryer n°2) has a diameter of 40 cm. Both have a collector diameter of 2 m and a drying chamber height of 3 m. The different results of the simulation were obtained using the COMSOL Multiphysics software.

- Profile of air temperatures in dryers:
  Figs. 4 and 5 show the temperature distributions of air within the dryers.
  In these Figs. 4 and 5, we observe an increase of 45 °C in the temperature of the air from the inlet of the collector to the base of the chimney. This means that the air entering the collector with a temperature of 30 °C has been heated to reach a maximum temperature of 75 °C at the outlet of the collector.

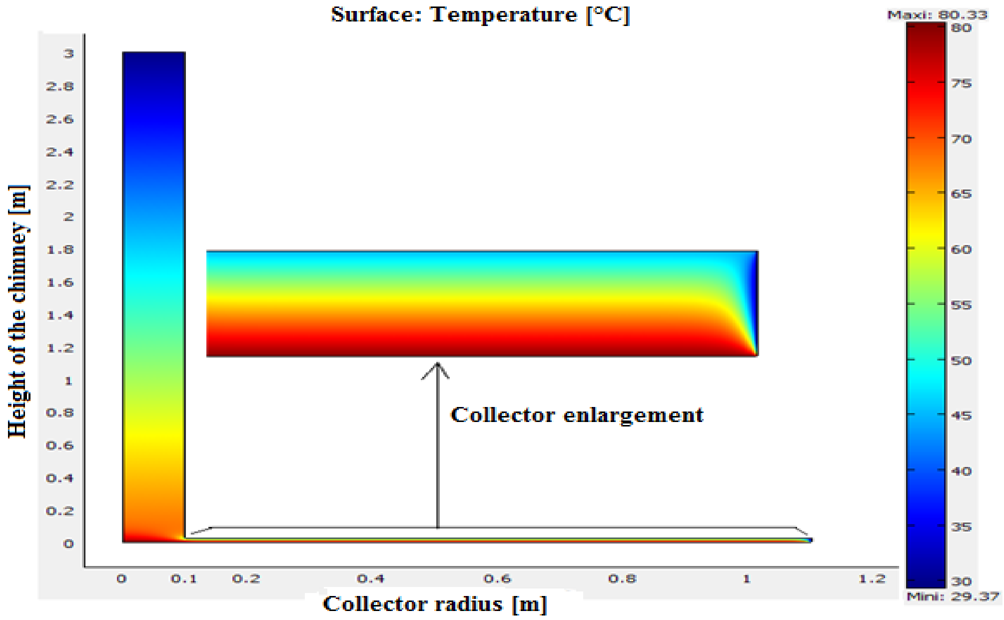

Fig. 4. Distribution of air temperature in dryer n°1

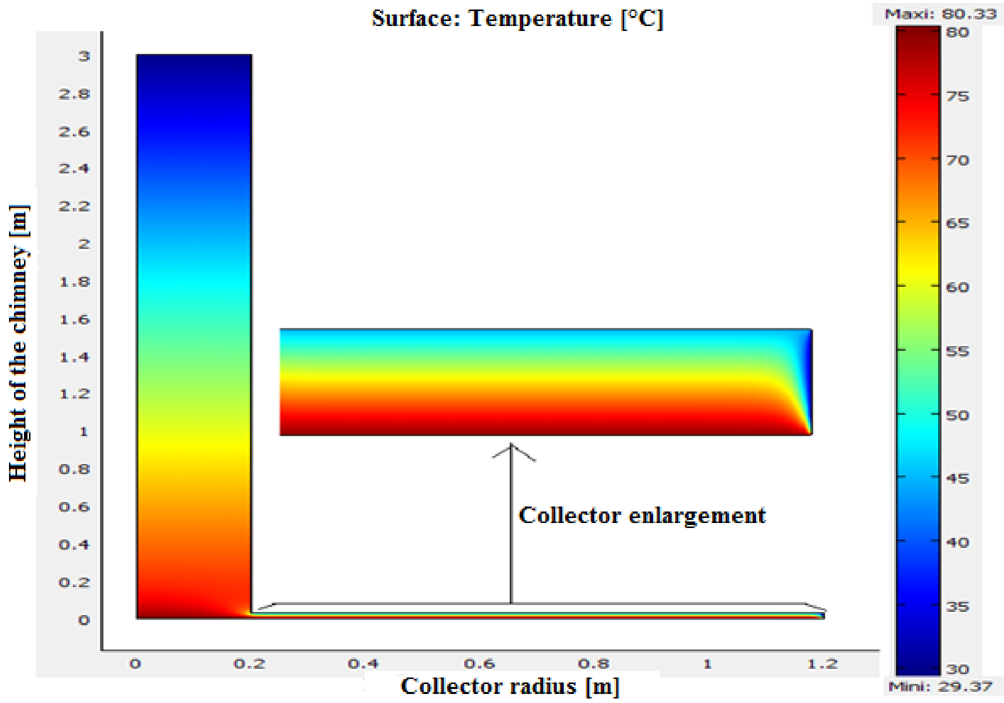

Fig.5. Distribution of air temperature in dryer n°2

The distribution of temperatures in the collector naturally shows that the air is warmer in the vicinity of the absorber than that of the window. Because the absorber being a metal painted in matt black absorbs the heat more than a window.
On the other hand, throughout the chamber to be dried, we observe a decrease in the temperature of the air as a function of the elevation of the chimney [17]. This decreases from 75˚C to 30˚C for dryer n °1 and from 77˚C to 30˚C for dryer n °2 whose details are as follows:

- Between 0.05 m and 1 m height of the chamber the air temperature varies from 75 °C to 57 °C in dryer n °1, while it varies from 77 °C to 60 °C in the dryer n °2. In this zone, racks can be installed for drying products with high water content such as tomato, banana, grapes, green beans, sweet potatoes and okra [13].

- Between 1 m and 2 m height of the chamber, the variation of the air temperature is between 57 °C and 44 °C in the dryer n ° 1 and varies from 60 °C to 45 °C in the dryer n°2. This part of the room is suitable for drying cassava, apricot and green peas [8].
- Between 2 m and 3 m high, the air drying temperature varies from 44 °C to 30 °C in the first dryer and from 45 °C to 30 °C in the second dryer. This temperature range is adapted to the drying of certain medicinal or flavored leaves, as well as to products with low water content such as tea, leather, and coffee [13].

- Air velocities in dryers:

In natural convection, the air velocity varies incessantly depending on the climatic zone, so it is difficult to predict the velocity of the air at the inlet of the system. This is how we applied an air velocity of the order of 10^{-2} m.s^{-1} to the inlet of the manifold. This value allows the simulation of the air flow in our system to be started, but it is then recalculated by iteration to adapt to the actual conditions.

Figs. 6 and 7 show the air velocity distributions within the dryers. The air velocity increases as air flows from the inlet of the manifold to the outlet of the manifold to achieve maximum speeds of 0.89 m.s^{-1} and 0.54 m.s^{-1} respectively in dryer n°1 and dryer n°2. This increase in the air velocity in the collector is due to the rise in air temperature which increases its kinetic energy [16-18].

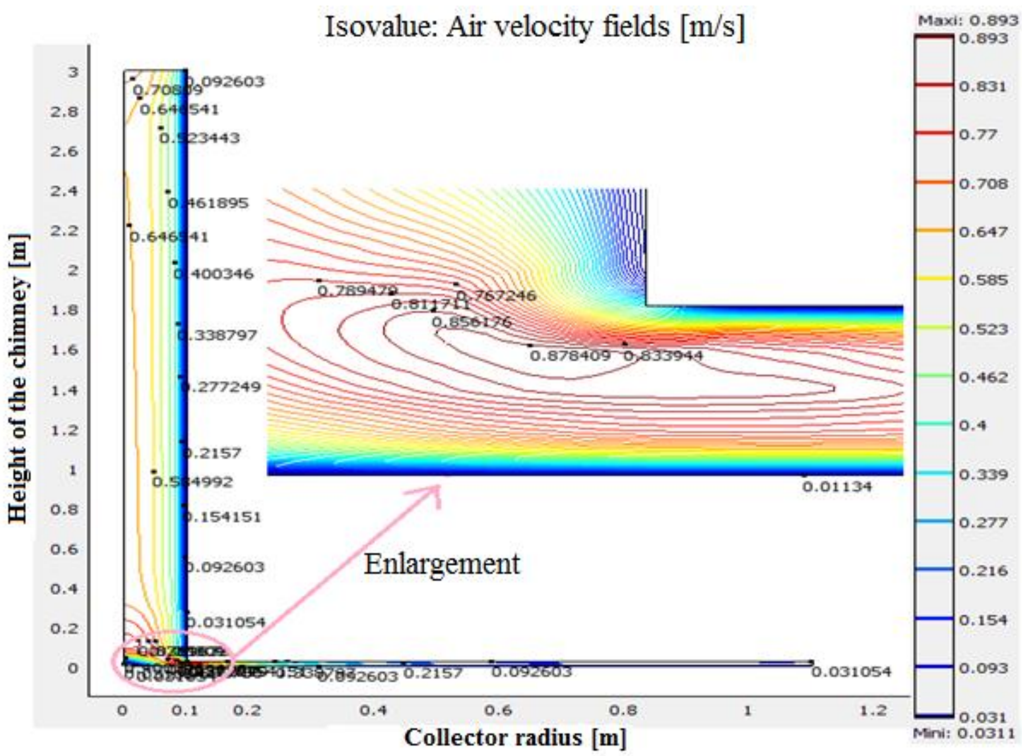

Fig. 6. Distribution of the air velocity in the dryer n °1

At the entrance to the chamber to be dried, we observe a decrease in the velocity of the air during its ascent. The singular charge losses can explain this decrease in air velocity. It is observed that after the air enters the chamber to be dried, its speed increases when it is upward and is maximum on the axis of symmetry. The depression of the air between the base and the outlet of the chamber to be dried allows the air velocity to increase to 0.715 m.s^{-1} at the outlet of dryer n°1 and
0.228 m.s^{-1} to the outlet of the second dryer.

The air velocities in dryer n°1 are acceptable for natural convection drying. On the other hand, the air velocities in the dryer n°2 are very low, which will require forced convection to accelerate the drying process.

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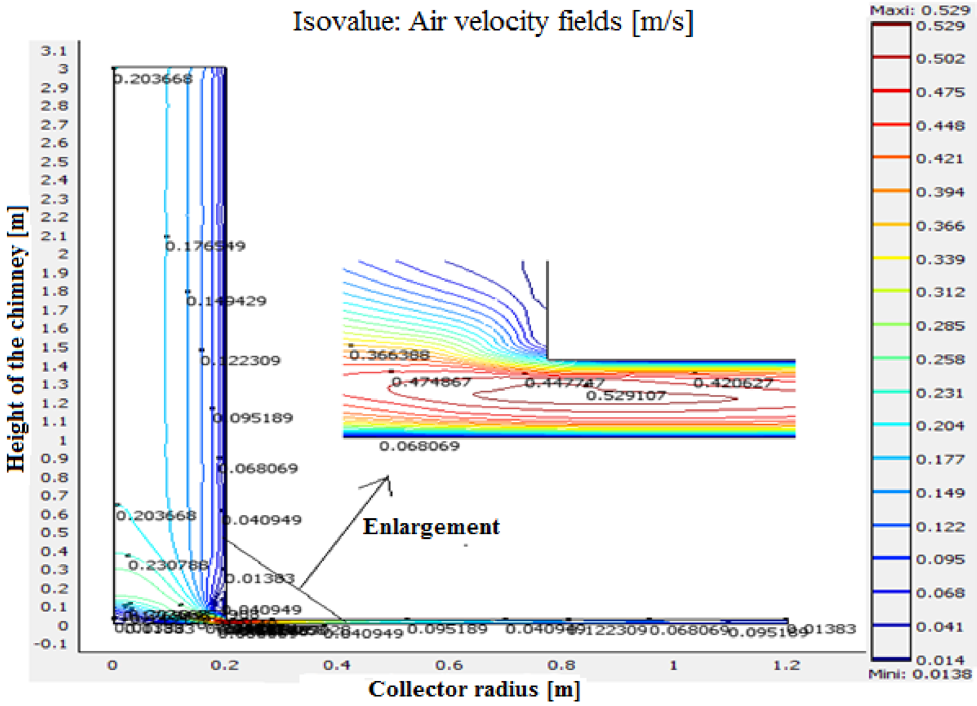

Fig.7. Distribution of the air velocity in the dryer n °2

Experimental results and validation of numerical results

- Drying air temperature profiles:

Fig. 8 shows the variation of the temperature of the air in the drying chamber of the dryer.

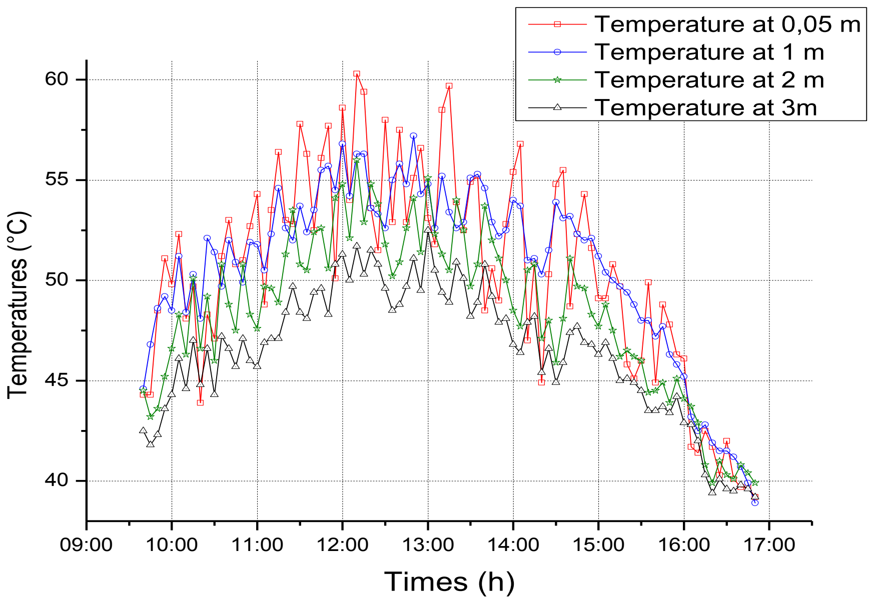

Fig. 8. Variation of the air temperature according to the height of the chamber to be dried

We observe that the mean maximum air temperatures are recorded between 12h and 13h. The air temperature decreases according to the height of the chamber to be dried.

- Between 0.05m and 1m height of the chamber, the maximum average temperatures recorded are 61 °C and 57.5 °C respectively.
- Between 1m and 2m height of the chamber, the maximum temperatures are between 57.5 °C and 56 °C.

- Between 2m and 3m height of the chamber, the maximum temperatures are 56 °C and 52.5 °C respectively.

  Compared to simulation results, experimental temperatures are lower at the base of the chamber and decrease from 61 °C to 52.5 °C as a function of height. On the other hand, the simulation decreases from 75 °C to 30°C. This difference can be due to the variations of the day's solar irradiation and also to certain simplifying hypotheses.

- Drying air velocity profiles:

  The air velocities at the inlet of the device are lower than the velocities at its outlet (Fig. 9). The maximum speed at the outlet of the chamber is 1.1 $m.s^{-1}$ and has been recorded at 11h30min while that at the collector inlet is 0.6 $m.s^{-2}$. The air entering the collector at low speeds becomes heated and increases its speed at the outlet of the chamber thanks to the vacuum between the base and the outlet of the chamber. These velocities are more or less superior to those of theory.

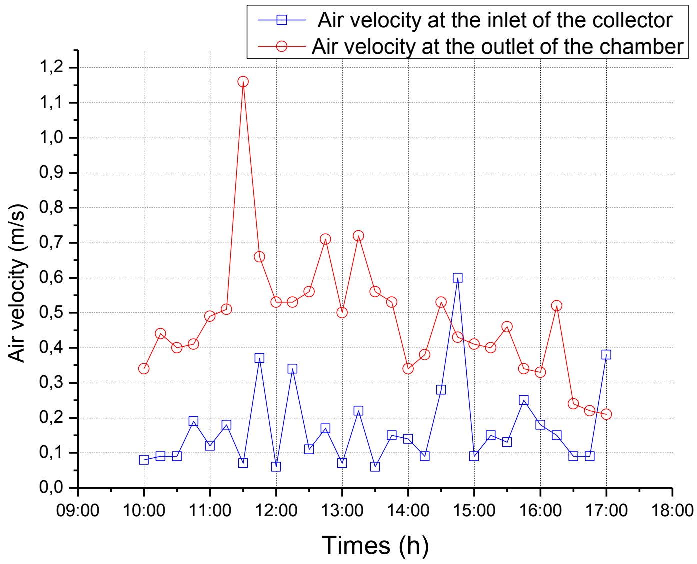

Fig. 9. Variation of the air velocity in the solar dryer

All these results make it possible to affirm that the small solar tower can be used as a solar dryer and that it can dry several types of food products according to their drying temperatures.

CONCLUSION

Simulation and experimentation allowed having an idea on the profiles of temperatures and speeds when the air flows in a solar tower of reduced size. Thanks to these results, we can say that this device can be used as a solar dryer. The maximum experimental temperatures in the drying chamber vary from 61 °C to 52.5 °C depending on the height of the chamber. The minimum temperature is 37 °C and varies according to the sunshine to reach the maximum temperatures. This temperature range is suitable for drying several food products such as banana, tomato, green bean. The speed of the order of 0.715 $m.s^{-1}$ permits the renewal of the air in the device, which promotes the drying of the products. On the other hand, for a solar tower dryer whose chamber diameter is greater than or equal to 40 cm, it is necessary to introduce fans at the inlet of the collector or an extractor at the outlet of the chamber to speed up the drying process.

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