EXPERIMENTAL AND THEORETICAL EVALUATION OF A SOLAR CHIMNEY TEST PLANT. PART II: EXPERIMENTAL RESULTS

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Abstract. *An experimental and theoretical analysis of a solar chimney was developed to evaluate the airflow in a test plant. To this purpose a chimney 12.5 m high and 1.0 m diameter was built, surrounded by a collector 25.0 m in diameter. Temperature, velocity, solar radiation and humidity were measured in the test plant during one year. This paper presents an experimental analysis of the profiles of airflow temperature and velocity, temperature distribution and the optical properties of the ground and collector materials. The temperature and volumetric flow measured indicate that solar chimney can be satisfactorily used to dry agricultural products.*

Keywords*: Solar chimney, Solar chimney tests plant*

1. Introduction

The agriculture plays an important rule in the Brazilian economy. Despite the expressive agricultural production, the drying and storing conditions are deficient (Sousa and Silva, 2000). In order to increase the quality of the products, it is necessary to improve the drying and storing conditions. The small producers do not have technology or financial conditions to acquire industrial dryers and tend to dry the products exposing them directly to the sun. It has the advantage of small or negligible installation and energy costs. However the running costs may be high because solar drying, being a slow process due to climatic variation, is a labor intensive operation. Furthermore, several other factors can decrease the final quality of the products, as product pollution from dust or animal contamination and other types of infestation and microbial and mould contamination in humid environments. Solar dryers capable of reducing the post-harvest losses and of improving the quality of the final products are been studied and built. Ferreira et. al. (2003) present a review of the state-of-the-art of the latest developed solar dryers.

The solar chimney is a device that uses the incident solar radiation to generate a hot airflow. Turbines can be positioned on the base of the tower to convert the thermal energy into electrical power. Since the efficiency of this conversion is not high, large plants must be built to be economically viable. In lower plants, the hot airflow can be used to dry agricultural products (Ferreira, 2004; Maia, 2005).

Experiments were performed in a solar chimney test plant built in Belo Horizonte, Brazil. The temperature, velocity, humidity and solar radiation were measured in the solar chimney during a period of one year. The behavior of the airflow was defined and the optical properties of the materials uses were determined. Drying experiments of several agricultural products were carried out and compared with the sun drying. It was observed that the products in the solar chimney reached the desired moisture content in lower times than the sun dried products. Moreover, the final quality of the products was high. The solar chimney can be satisfactorily used as a solar dryer.

2. The solar chimney prototype

The experimental solar chimney consists of a 12.3 m high and 1.0 m diameter cylindrical vertical tower and of a 25 m diameter solar collector, with a plastic cover located from 0.05 m to 0.5 m above the ground. The tower was built in 5 wooden modules, 2.2 m high each, joined together, forming a 11 m tower. It was supported structurally 1.3 m above the ground by 6 steel tubes. The tower was internally and externally covered with fiberglass, in order to protect it and to improve its strength. The area of the cover is about 500 m^2. The area was divided into small greenhouse plastic film polygons, fixed on boards and supported by steel columns, 0.05 m to 0.5 m above the ground. Experimental tests were undertaken with two plastic films. The ground under the roof was covered with a 5 cm concrete layer, painted black, increasing the solar radiation absorbed. A schematic illustration of the features of this design and a picture of the solar chimney are showed in Fig. 2.

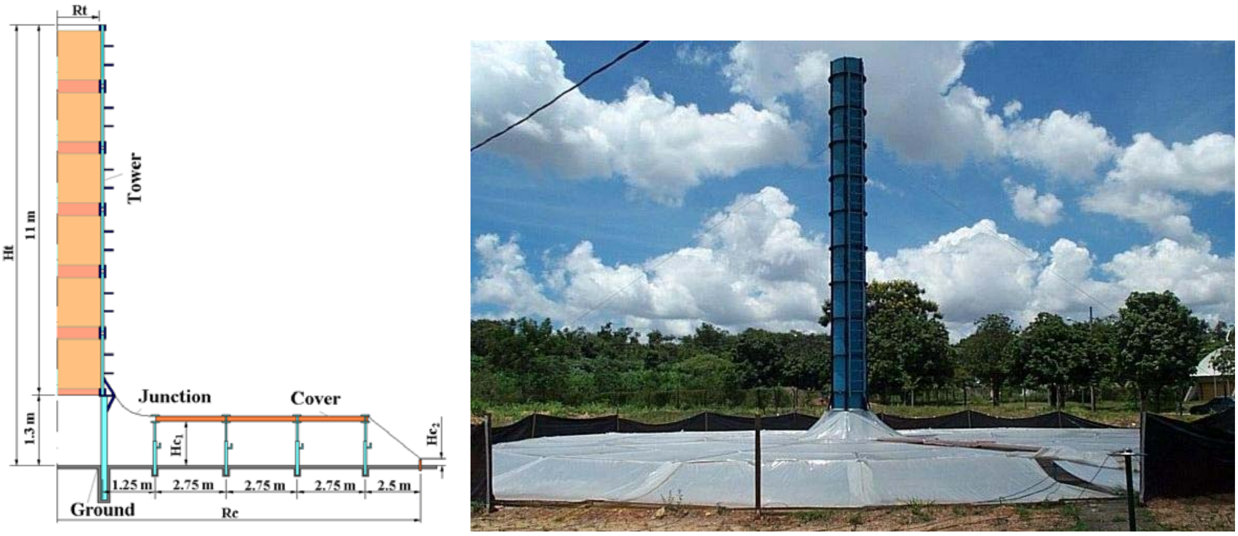

Figure 2 – The solar chimney

3. Experimental Setup and Procedure

Experimental tests were carried out to evaluate the behavior of the airflow in the solar chimney. The airflow velocity, temperature and humidity were measured in the device. The ground temperature was evaluated at the surface and at deeper layers. The incident solar radiation and the solar radiation in the solar chimney were measured.

The airflow temperature was measured under the cover and in the tower. The ground temperature was evaluated at the surface and on deeper layers. 8 k-thermocouples were used to measure the temperatures. The thermocouples were armored against the solar radiation and covered with a rubber hose, minimizing the errors.

To measure the solar radiation in and out of the solar chimney, 7 Eppley Black and White pyranometers were used. These instruments measure the total hemispherical solar radiation. The diffuse radiation was obtained shadowing the pyranometers from the beam radiation by a shade ring. Since the ring shades the pyranometer from part of the diffuse radiation, a correction for this shading was estimates and applied to the observed diffuse radiation (Battles at. al., 1995).

The velocity in the solar chimney was evaluated with 8 propeller anemometers, with a diameter of 0.05 m. The frequency output signal was converted into a voltage signal by using an electronic circuit. It was observed, however, that the sensors were not capable of measure the low velocities encountered under the cover.

In order to evaluate the humidity difference between the airflow inside the solar chimney humidity and the ambient humidity, 2 capacitive psychrometers were used. The sensor output is a current signal.

The sensors were connected to ADAM-4018 modules. The A/D converter is responsible for convert the analogical signal in a digital signal, which is sent to a PC and processes in a software. The uncertainties of the sensors were evaluated in calibration procedures. The thermopiles, pyranometers, anemometers and psychrometers uncertainties were, respectively, 1.4°C, 5.1%, 6.6% and 2.2% (Maia, 2005).

In order to take into account the daily variation of the solar radiation, a complete test was not lower than 24 hours. The time interval between two measurements was 60 s.

The ambient temperature and humidity were evaluated in every test. The sensors were kept in a windy and shadowy shelter, built accordingly to the meteorological standards. The airflow temperature and humidity were also evaluated in every test. In order to measure the ground surface temperature, a thermocouple was maintained in a radius corresponding to 0,15 Rc (where Rc is the cover radius). Aligned with this thermocouple, a second thermocouple and a psychrometer were installed 25 cm above the ground, measuring the airflow temperature and humidity.

The pyranometers were placed as shown in Fig. 3. The sensors indicated by numbers 1 and 5 measure the incident solar radiation on the cover and on the ground, respectively. Number 3 pyranometer measure the solar radiation transmitted through the cover and number 4, the solar radiation reflected by the ground. Finally, the pyranometers indicated by numbers 2 e 6 are evaluate the diffuse solar radiation incident on the cover and on the ground, respectively. This allocation of the pyranometers allowed the determination of the ground and cover optical properties.

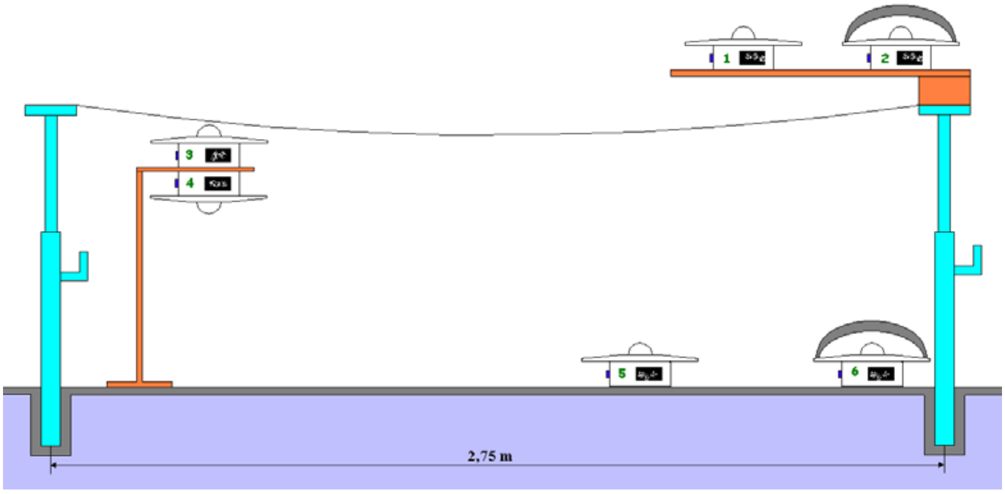

Figure 3 – Pyranometers position

The velocity was only evaluated in the tower, since the sensors were not able to measure the low velocities obtained under the cover. The behavior of the velocity along the tower and the velocity distribution on a cross section of the tower were evaluated. Several tests were performed in order to evaluate the temperature distribution along the cover and the tower. The temperature of the ground was measured in depths of 5 cm, 15 cm, 30 cm and 40 cm, placed in two radial positions.

4. Results and discussions

The tests were carried out in a period of approximately one year. In this period, the daily solar radiation varied between 8,0 ± 0,4 MJ/m^2 and 28 ± 1 MJ/m^2. The radiation evaluated by the pyranometers, positioned as indicated in Fig. 3, allowed the determination of the optical properties of the materials used on the ground and on the cover. The main properties are the ground absorptance and the cover transmittance. The ground absorptance must be close to 1 to increase the solar radiation absorbed by the ground. The solar radiation transmittance of the cover must be high to increase the incident solar radiation on the ground, but the infrared transmittance must be low, to avoid thermal losses to the surroundings. Figure 4 presents the ground absorptance and the cover transmittances on the solar radiation wavelength band, as function of the angle of incidence of the solar radiation. The material used on the ground was concrete painted with an opaque black paint, which provided an average absorptance of (90 ± 7)%. Two materials were tested on the cover. The tests were performed with a diffuser plastic film, with converts part of the beam radiation into diffuse radiation. It was tested another plastic film, suitable for greenhouses. On the one hand, it can be noticed that the transmittance of the diffuser plastic film is lower than the greenhouse film, on the solar radiation wavelength band. On the other hand, by comparing the transmittances on infrared band, it can be seen that the greenhouse film presents greater values. The greenhouse film is thinner, lighter and cheaper than the diffuser film, becoming more suitable for the solar chimney.

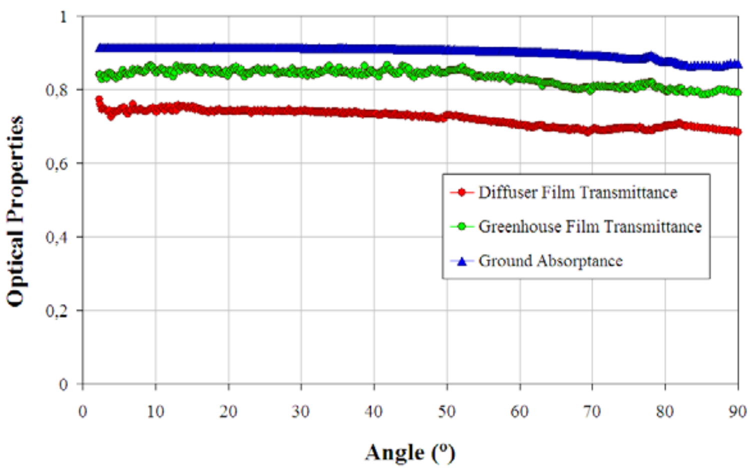

Figure 4 – Optical properties of the ground and the cover

Figure 5 presents the minimum, average and maximum values of the ambient temperature measured in the shelter, along with the average values of Belo Horizonte, given by Meteorology National Institute – INMET (Ferreira, 2004). The minimum ambient temperature measured was (9 ± 1) °C and the maximum, (41 ± 1°C).

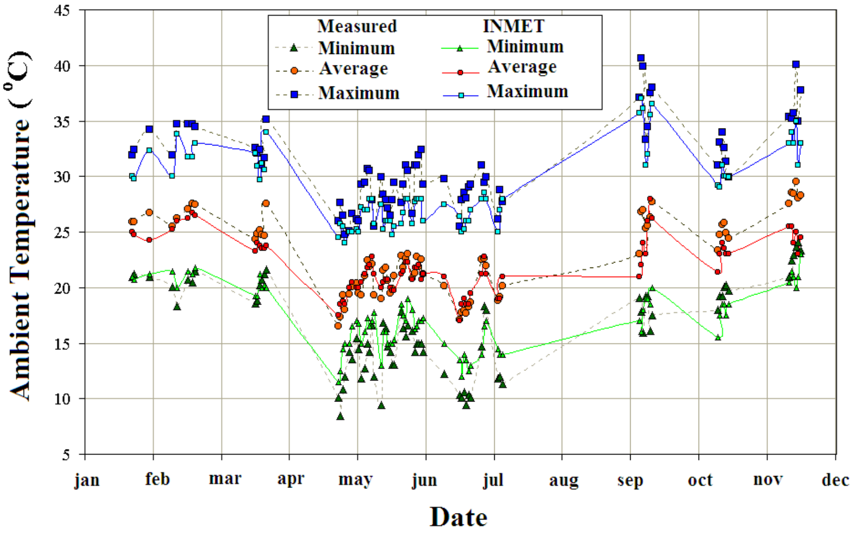

Figure 5 – Ambient temperature measured along one year
Source: Ferreira, 2004

During the day, the solar radiation reaches the ground, increasing its temperature. Since the temperature is bigger on the ground surface than on the deeper layers, heat is transferred on this direction during the day, and the thermal energy is stored in the ground. At night, the superficial temperature decreases, becoming lower than the deeper temperatures. The behavior is inverted: the deeper layers transfer heat to the surface. As the depth increases, the temperature deviations from the average value become lower. This behavior is illustrated in Fig. 6, which presents the ground temperatures at the surface and at depths of 15 cm, 30 cm and 40 cm, along with the ambient temperature. It can be observed that the temperature variations become smoother with the depth. The differences of the temperature along the time are insignificant for depths superior to 40 cm.

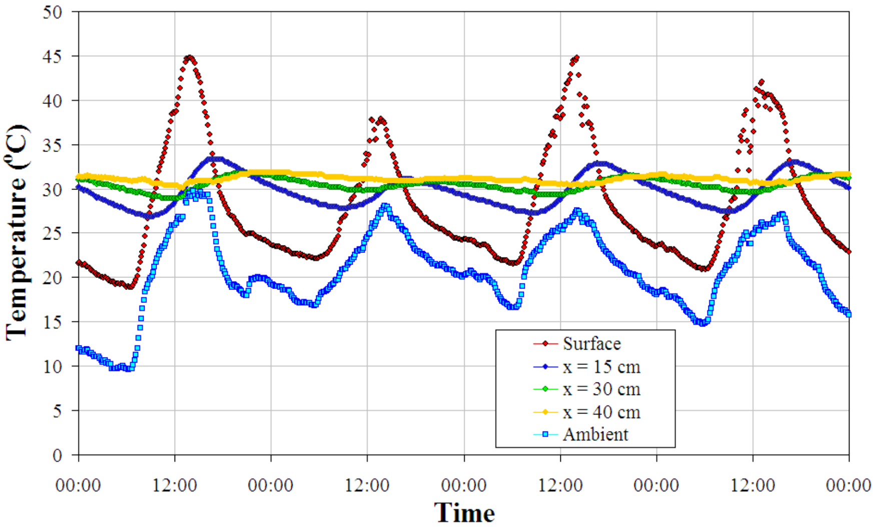

Figure 6 – Ground temperatures as function of the time

Figure 7 shows the temperature distribution along the cover height, on a radius corresponding to 0,15 *Rc*. The air temperature decreases from the ground to the cover surface, and heat is transferred in this direction. It is important to notice that the airflow temperature is always greater than the ambient temperature, even at night. Part of the energy stored in the ground during the day is transferred to the airflow at night, guaranteeing the generation of a continuous hot airflow.

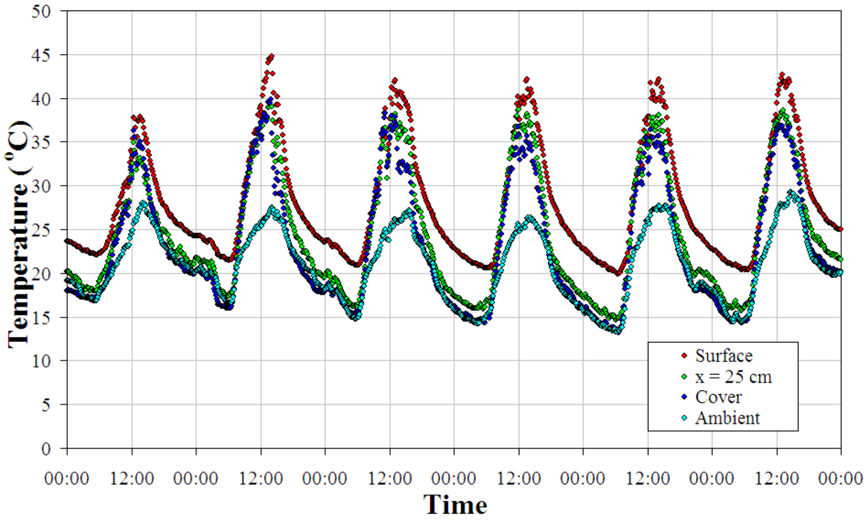

Figure 7 – Air temperature under the cover, as function of time

The air temperature under the cover was evaluated, positioning the thermocouples in several radiuses. The results are shown in Fig. 8, as function of the time, for a 24 hour period. The position r/Rc = 0 corresponds to the center of the system and r/Rc = 1, to the entrance of the cover. It can be seen that the air inlets at ambient temperature and increases its temperature towards the center of the solar chimney. In order to evaluate the angular variations of temperature under the cover, four thermocouples were installed at a height of 0.25 m and at a radius of 2 m, close to the junction between the cover and the tower. The differences of the temperatures were lower than the thermocouples uncertainties, meaning that the air temperature did not show significant deviations. On the other hand, when the sensors were positioned close to the cover inlet (in a radius of 10.5 m), significant deviations occurred. The peripheral modules of the cover are tilted, causing an angular variation of the solar radiation angle of incidence. Lower angles of incidence increase the incident solar radiation on the ground (Duffie and Beckman, 1991).

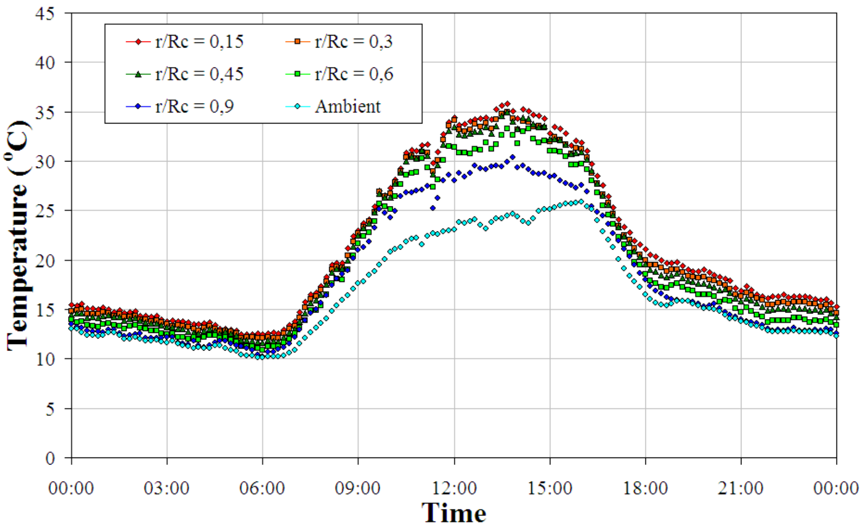

Figure 8 – Air temperature under the cover, as function of the time

The airflow in the tower is approximately isothermal. Figure 9 shows the air temperatures on heights of 2.3 m and 10.3 m, at the center of the tower (r = 0) and in radius of 0.20 m and 0.40 m. It can be seen that the temperatures at the center (r = 0) are only slightly superior to the temperatures close to the wall (r = 0.40 m), when comparing temperatures at the same height. To the same radial position, in different heights, the temperatures presented only insignificant variations, lower than the uncertainty of the thermocouples.

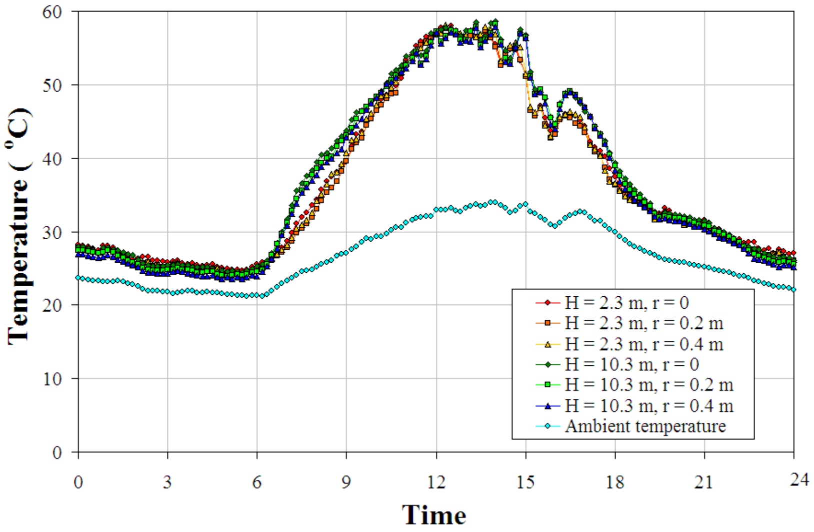

Figure 9 – Air temperature in the tower

Since the anemometers were not capable of measuring the velocities under the cover, the velocity was only evaluated in the tower. The anemometers were placed along one cross section of the tower, in a height of 5.5 m. Figure 10 presents the dimensionless profiles of velocities, as function of the dimensionless radius of the tower, to 00:00h, 12:00h and 18:00h. The dimensionless velocity was defined as the ratio between the local velocity and the velocity at the center of the tower, in the same height and the dimensionless radius of the tower was defined as the ratio between the local radius and the tower radius. The obtained profiles are characteristic of turbulent flows. The Reynolds number was evaluated along the day, varying between $5.6x10^4$ and $1,3x10^5$. Since at Reynolds numbers of 4000, flows are fully turbulent, the flow in the solar chimney is really turbulent. It can be also noticed that the obtained velocity profiles are very similar.

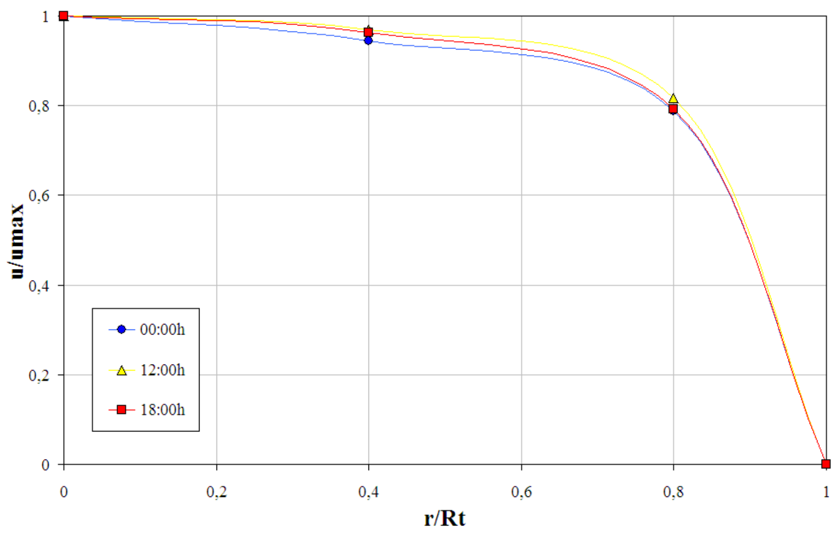

Figure 10 – Dimensionless velocity profile in the tower

The velocity at the center of the tower, plotted to several heights on the tower, as function of the time, is shown in Fig. 11. Only insignificant differences among the velocities are encountered. The greater air velocities are obtained during the day, because of the solar radiation. Nevertheless, it can be noticed that there is an airflow even at night, meaning that the solar chimney operates during all day. This continuous operation of the solar chimney is due to the heat fluxes transferred from the deeper layer to the surface of the ground and to the airflow. The mass flow is an important parameter on the evaluation of the airflow. During the whole period of tests on the solar chimney prototype, it was observed an average mass flow of (1.4 ± 0.1) kg/s in the device. The mass flow varied between (0.7 ± 0.1) kg/s and (2.8 ± 0.2) kg/s.

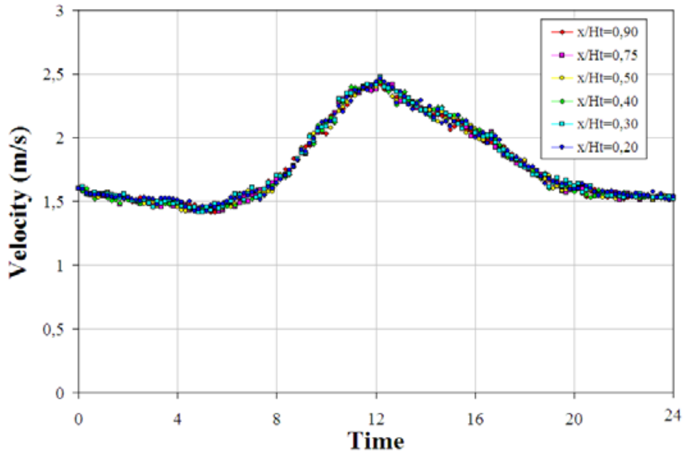

Figure 11 – Air velocity at the center of the tower

The relative humidity and the humidity ratio of the airflow are important on the characterization of the solar chimney as a dryer. Fig. 12 presents the airflow and the ambient relative humidity, along with the airflow and ambient temperatures, as function of the time. Fig. 13 presents the airflow and the ambient humidity ratios, along with the airflow and ambient temperatures, against the time. The airflow temperature is always superior to the ambient temperature; therefore, the airflow relative humidity is always lower than the ambient relative humidity. The relative humidities are bigger at night, when the temperatures are lower. The humidity ratio behavior is oppost; the lower values are found when the temperatures are lower. The airflow and the ambient humidity ratios are very similar.

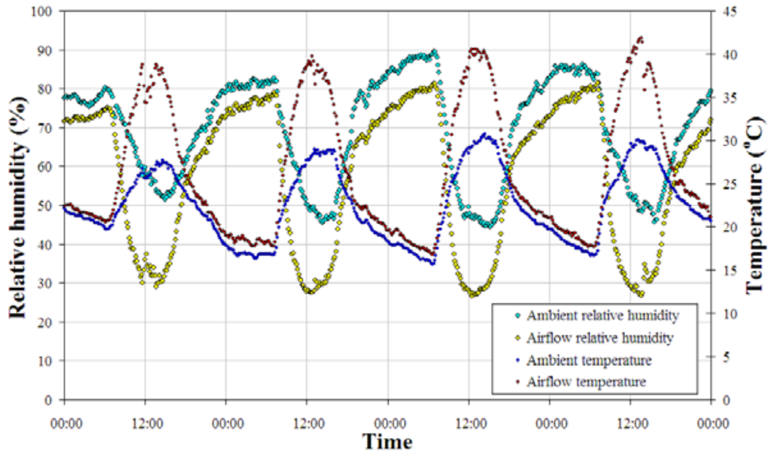

Figure 12 – Ambient and airflow relative humidities

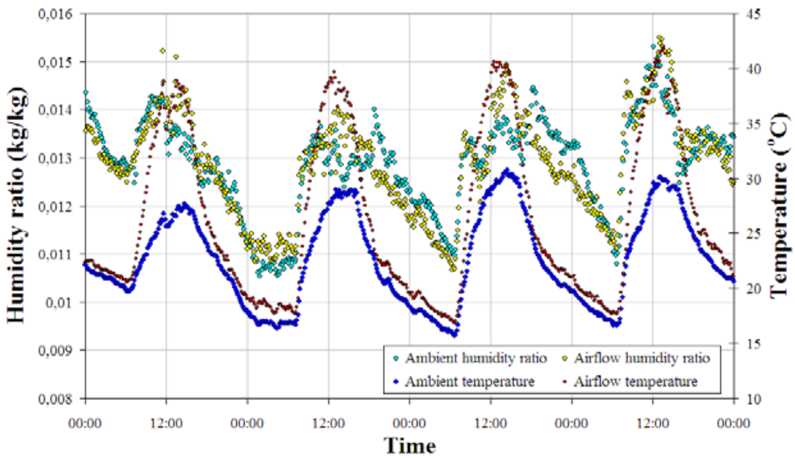

Figure 13 – Ambient and airflow humidity ratios

The viability of the solar chimney as a solar dryer was evaluated through the drying of bananas, tomatoes, pineapple, apple, pears, grapes and coffee cherries. The products were exposed to the pre-treatment suggested on the literature. The initial moisture content was determined in a stove with controlled temperature. The drying in the solar chimney was compared with solar drying. It was observed that the products maintained in the solar chimney reached the final moisture content in lower times. The products dried in the solar chimney were protected from rain, insects and dust and the dried products presented high quality (Ferreira, 2004; Maia, 2005). According to Leon et. al. (2002), there is an ideal relationship between the drying area and the rate flow in the order of 0,0125 $m^3/s/m^2$. Considering the average rate flow obtained in the solar chimney, the area used to dry agricultural products should be 110 m^2. According to Leon et. al. (2002), in an area of 1 m^2, approximately 4 kg of agricultural products can be satisfactorily dried. As a result, the solar chimney can dry up to 440 kg of products.

5. Conclusions

A prototype of a solar chimney was built in Belo Horizonte, Brasil. During one year, several experimental tests were performed in order to describe the airflow in the device and to validate a numerical model of the airflow developed. The temperature, velocity, humidity and solar radiation were evaluated. With the measured values, the optical properties of the ground and the cover were determined and the behavior of the airflow was described. The concrete layer painted black used on the ground showed a good absorptance, being capable of absorbing about 90% of the incident radiation. Two plastic films were tested on the cover. The diffuser film presented lower transmittances on the solar radiation and on the infrared wavelength bands. Since its weight and costs were high, the greenhouse film is more suitable to be used on the cover.

The average airflow temperature obtained was (27 ± 1)°C and the average ambient temperature was (23 ± 1)°C. The airflow temperature was always greater than the ambient temperature. It was observed an average increase of the airflow of (5 ± 2)°C, related to the ambient temperature. An increase of (27 ± 1)°C was obtained on the summer. It was also observed a reduction of the airflow humidity, compared to the ambient humidity. The average airflow humidity was (63 ± 4)%, while the average ambient humidity was (54 ± 3)%. The increase of the temperature and the reduction of the humidity, associated with the average mass flow of (1.4 ± 0,1) kg/s, indicate that the solar chimney can be used as a solar dryer for agricultural products. Drying experiments carried out in the solar chimney reduced the time required to dry some agricultural products, compared to the time spent on a solar drying. Moreover, the final products presented high quality. The solar chimney uses a renewable source of energy to generate the airflow, can generate a 24 hour airflow and can operate with diffuse radiation.

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7. Responsibility notice

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8. Thanks

This job was realized with the support of the Fundação de Amparo à Pesquisa do Estado de Minas Gerais - FAPEMIG and Conselho Nacional de Desenvolvimento Cientifico e Tecnológico CNPq – Brazil.