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EXPERIMENTAL ANALYSIS OF BANANA DRYING IN AN ELECTRIC HYBRID SOLAR DRYER

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Abstract. *It is estimated that 25% of the world food production since its crop until its consumption is lost, a fact that may be explained by losses in transport, storage, contamination by insects, weather, and the way of production. The drying of products is the oldest method known to the preservation of food, and it is suitable to the reduction of losses for most products. The dryers are divided into solar dryers (the drying airflow is heated by the solar radiation), artificial dryers (the drying airflow is generated by other sources of heating) and hybrid dryers (other sources of heating are used to complement the solar radiation). In this work, it was developed an experimental analysis of the drying of bananas in a hybrid solar dryer, which has an electrical auxiliary heater to complement the solar radiation. It is presented a comparison between the drying performed in the hybrid solar dryer and direct sun drying.*

Keywords: *Hybrid solar dryer, Drying, Experimental analysis, Bananas.*

1. INTRODUCTION

According to the United Nations (2017) there are about 7.6 billion people in the world. By the year 2050, this number is expected to rise to around 9.8 billion. The combination of the increase of the population and the amount of agricultural losses is significantly reducing the food availability in the world.

It is estimated that 25% of the world food production since its crop until its consumption is lost, a fact that may be explained by losses in transport, storage, contamination by insects, weather, and the way of production. In Brazil, about 30% of agricultural production is wasted due to lack of adequate conservation processes (Souza, 2007). These factors imply an emergency measure to reduce the loss of these foods. In this context, drying is considered a good conservation method, due to the fact that the removal of moisture causes an increase in the useful life of the food while preserving its main nutrients (Celestino, 2010).

According to Castro Silva (2014), the last decades have been constantly marked by the increase of the energy demand, being this growth proportional to the world population increase. Therefore, the demand for energy from fossil fuels on a large scale is a source of great concern for the environment. Brazil has 83% of its energy generated by renewable sources, of which 61% is hydroelectric energy and 22% is from other alternative sources (ANEEL, 2016). Geographic location, climatic characteristics, natural resources, and biodiversity make Brazil a privileged country to obtain several other energy sources. A great solar incidence and an extensive coastal territory are excellent factors of wind, oceanic and solar energy exploration.

The solar energy is abundant, permanent, renewable, non-polluting and not harmful to the ecosystem. In numerical data, the annual solar radiation that reaches planet Earth is equivalent to 7500 times the world total primary energy consumption (Thirugnanasambandam, Inyan and Goic, 2010).

Solar radiation can be used directly as a source of thermal energy, based on the absorption of radiant energy by a black surface. Another form of use is from the heating of fluids or environments, as well as the generation of mechanical or electrical power. The energy conversion of solar radiation can also be achieved by means of effects such as thermoelectric and photovoltaic, as well as in chemical energy, with the photo biochemical process (Morais, Marinho Júnior and Barbosa, 2017).

Drying is an important process used in the whole world to conserve food. It plays a key hole in reducing the amount of water contained in the food to a level in which does not occur the deterioration in a longer period (Prasad, 2006). The drying of food can be done naturally, in which food is directly exposed to the sun, or in dryers. There are three types of dryers: solar, artificial and hybrid. Natural drying has as main disadvantages requiring a higher drying time, and a lower quality of products when compared to the drying in artificial dryers (Sontakke et al., 2015). Artificial solar dryers present a higher drying quality since they enable the control of velocity and temperature of the air in the process. However, in general there is a large consumption of energy (fossil or electric) to heat and move the air (Ertekin and Yaldiz, 2004; Doymaz, 2007). Solar dryers present as main advantage the use of renewable and abundant energy in the heating of the drying air, but they have the limitation of dependence on environmental conditions and less control of the drying variables. Hybrid dryers are able to ally the advantages of solar and artificial dryers. They use a renewable energy as a primary source and complement it with an artificial source when necessary.

Figure 1 shows the analyzed dryer in this work. The solar collector is connected to the drying chamber, where the auxiliary resistance stands. A portion of the incident solar radiation passes through the glass cover and reaches the absorber in the solar collector. The ambient temperature air inlets and is heated by natural convection, raising its temperature while it flows towards the drying chamber. The auxiliary resistance is an electrical heater, located on the bottom of the drying chamber, is triggered to maintain the temperature of 60°C, characterizing a hybrid solar dryer. From there a pressure difference will make the drying air passes through the drying trays, removing the moisture from the products. In this way, the drying air leaves the dryer through the chimney, where a fan promotes an artificial movement to increase the mass flow.

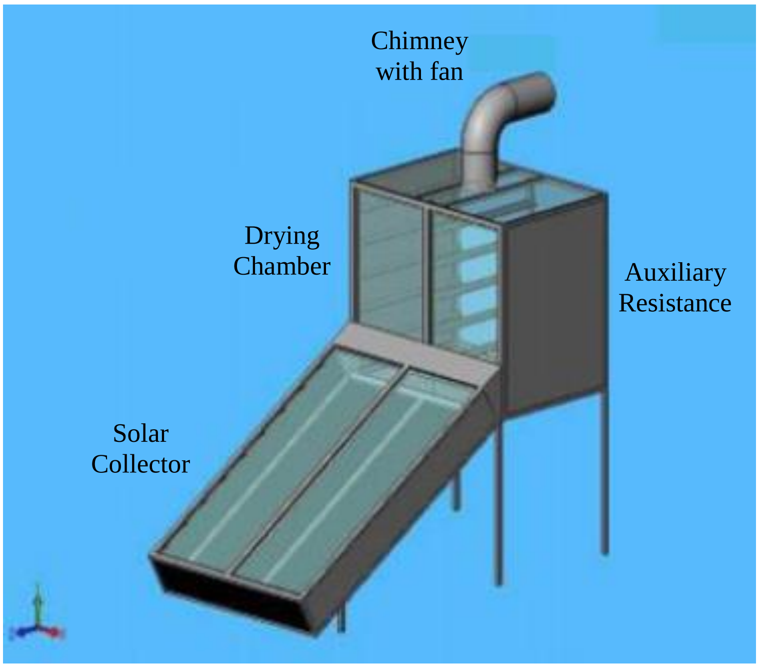

Figure 1. Schematic diagram of the Solar Hybrid Dryer

The main purpose of this paper is to evaluate the performance of the built dryer. The global characteristics of the drying airflow, the thermal homogeneity of the drying chamber and the ambient thermal conditions were evaluated. Three distinct methods of banana drying were executed to determinate the technical feasibility of the device: natural drying, artificial drying by the built dryer with the electrical resistance and artificial drying by the built dryer without the electrical resistance.

2. EXPERIMENTAL METHODOLOGY

The dryer evaluated in this work is a hybrid solar-electric dryer, composed of a solar chamber, where the airflow is heated, and a drying chamber, where the bananas are dried (Fig. 2). The collector chamber is tilted 30° to horizontal, and opened at its edges. It is 1.74m high, 1.30m of width and 0.435m deep. The glass used in the collector, at the front and at the top, are tempered glass with a thickness of 6 mm. The walls of the solar collector were built with galvanized steel plates and painted in matte black to increase the absorbed solar radiation. The drying chamber has 0.73m high, 1.30m of width and 0.89m deep, and it was also painted in matte black. When the air temperature is lower than desired, an auxiliary heating system installed on the bottom of the drying chamber complements the solar heating. This auxiliary heating system is composed of an electrical resistance of 4kW, which has an integrated control system. To allow the drying air to exit, a 0.20m diameter chimney, with a 120 mm fan to help the exhaustion, was installed on the top of the dryer. Four trays (0.75m x 0.50m) were put inside the drying chamber, corresponding to an area of 1.5m². Two doors, located on the back of the drying chamber, are used to introduce and remove the trays. A thermal anemometer was installed at the exit of the chimney to measure the velocity and the temperature of the airflow.

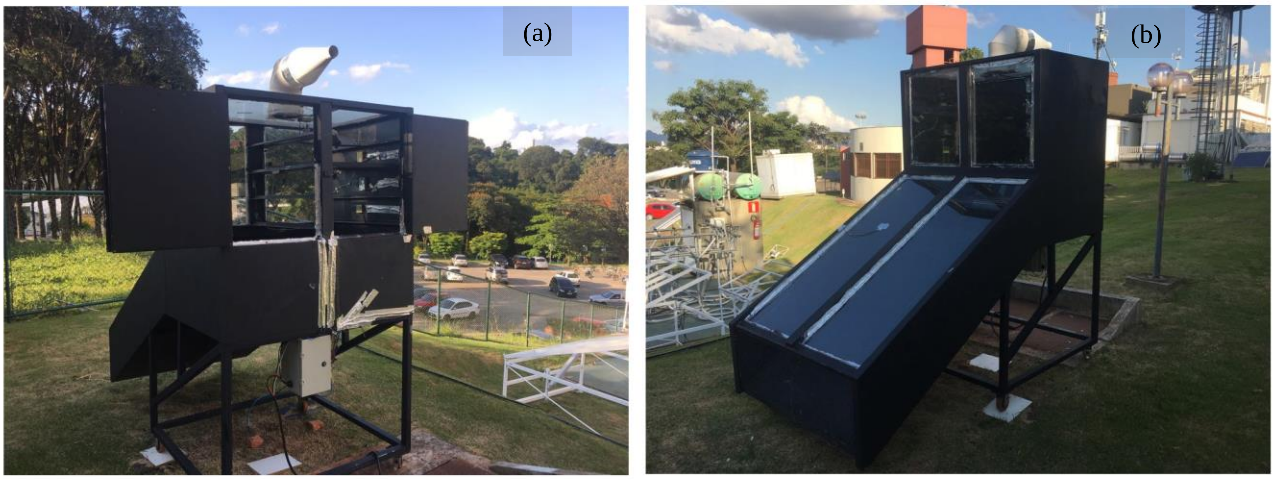

Figure 2. Solar Hybrid Dryer: (a) Rear view with the doors open (b) Side view

The hybrid solar dryer used in this project is located on GREEN (Renewable Energy Studies Group), at PUC Minas. The ambient conditions data were obtained from the meteorological station present at GREEN. In the inlet of the collector chamber there is a DHT11 sensor to monitor the temperature and the humidity of the inlet airflow. This device has a response time lower than 5s, operational temperature from 0°C to 50°C and uncertainty of 2°C, operational humidity from 20% to 90% and uncertainty of 5%. Inside the drying chamber there are four DS18B20 sensors used to measure the temperature in different positions. This type of sensor has the operational temperature from -10°C to 85°C and uncertainty of 0.5°C. The temperature homogeneity of the drying chamber is also observed by a thermographic camera. At the inlet and outlet of the drying chamber, two DHT22 sensors were placed to measure the temperature and humidity of the air flowing inside and outside of the chamber. This type of device has a response time lower than 2s, operational temperature from -40°C to 80°C and uncertainty of 0.5°C, operational humidity from 5% to 100% and uncertainty of 2%. The velocity of the drying air was measured with an Instrutherm TAFR-190 Hot Wire Anemometer placed in the exit of the exhaust pipe, with 0.060m of diameter. This anemometer has 1s sampling time, and it is used to calculate the mass flow of the drying air. A type T thermocouple was installed on the glass surface of the collector to measure its temperature.

According to Maia, Ferreira and Hanriot (2010), during the drying process, the products undergo quality losses such as color, taste and texture. Commercially, most fruits should be treated before dehydration to maintain a good appearance and the vitamin C, prevent browning, and taste loss. Thereby, for this paper, before the drying procedure started, the bananas were sliced and placed in a freezer for 24 hours at a temperature of -24°C. After that, the bananas were divided to be used in three different drying processes. The first one is the hybrid drying process, which happened inside the dryer with the support of the electrical resistance to maintain the temperature of 60°C. The second one is the solar drying process, which happened inside the dryer but without the support of the electrical resistance. And the third one is the natural drying process, that happened outdoors. The experiments were conducted to evaluate the technical feasibility of the dryer and to compare the quality of these three distinct methods of drying during the 2018 winter.

At the back of the drying chamber, two doors allow the insertion and removal of the samples. The hybrid drying process started placing four trays inside the drying chamber, with 1.5kg of bananas on each. At time intervals of 30 minutes, samples of approximately 100g were removed from the chamber and weighed. Then, they were placed in an oven for 24 hours to remove all their humidity. Finally, the samples were weighed again to calculate the amount of moisture lost, and a drying curve was built to analyze the quality of this drying process.

The solar drying process started placing one tray inside the drying chamber, with 1.5kg of bananas. At time intervals of 45 minutes, samples of approximately 40g were removed from the chamber and weighed. Then, they were placed in an oven for 24 hours to remove all their humidity. Finally, the samples were weighed again to calculate the amount of moisture lost, and a drying curve was built.

The natural drying process was performed placing 1.5kg on a tray inclined at 20° from horizontal (Fig. 3). During the test, samples of approximately 50g were removed and weighed, at time intervals of one hour. All the moisture of the samples was removed placing them in an oven for 24 hours. After that, the samples were weighed again and the moisture lost was determined. Finally, the drying curve was built.

Figure 3. Natural drying process. Side view

According to Neto (2008), water activity is one of the most important properties for processing, preserving and storing food. It quantifies the degree pf binding of water contained in the product and consequently its availability to act as a solvent and participate in a chemical, biochemical and microbiological transformations. Yassen and Al-Kayien (2016) state that the total moisture of the product M_i can be evaluated based on the initial mass W_i and the final mass W_d, according to Eq. (1).

$$M_i = \frac{W_i - W_d}{W_i} \quad (1)$$

In the studied hybrid solar dryer, the objective of studying energy efficiency is related to the intention to avoid energy wastage from both the sun and the auxiliary resistance for a better use and quality of banana drying. According to Vasconcelos (2017), the thermal efficiency of a dryer (η_t) is given by the ratio between its useful energy (E_S) and its consumed energy (E_T).

$$\eta_t = \frac{E_S}{E_T} \quad (2)$$

The useful energy for a hybrid dryer is represented by the latent heat, which can be determined by the mass flow ($\dot{m}$), the specific heat of the air (c_p), and the outlet and inlet temperatures of the air (T_s and T_e, respectively). The consumed energy is the sum of the energy consumed by the electrical heater ($W_{consumida}$) and the energy provided by the solar irradiation (I) multiplied by the area of the collector (A). Therefore, the thermal efficiency for an electric dryer is given by Eq. 3:

$$\eta_t = \frac{\dot{m} c_p (T_S - T_e)}{W_{consumida} + IA} \quad (3)$$

Still according to Vasconcelos (2017), the drying efficiency is calculated by the ratio between the latent energy (E_L), and the energy consumed by the dryer (E_T).

$$\eta_s = \frac{E_L}{E_T} \quad (4)$$

The latent energy (E_L) is given by the moisture flow ($\dot{m}_{H2O}$) withdrawn from the product in the dryer and the latent heat of vaporization (h_{lv}). Thus, the drying efficiency for the hybrid dryer is represented by the equation:

$$\eta_{s_{electric}} = \frac{\dot{m}_{H2O} h_{lv}}{W_{consumida} + IA} \quad (5)$$

3. ELECTRONIC CONTROL SYSTEM

The electronic control system developed in this work is based on control panel CP, where is installed an Arduino Mega, a solid-state relay (SSR) and others electronic devices and protection elements. The system controls the temperature in the drying chamber and performs the acquisition and recording of the variables involved in the process in real time. It is placed inside a hermetic box located under the dryer.

The process can be monitored manually and remotely. A supervisory system was developed to allow, remote and wireless, interaction with the dryer. The main actuator of the system is an electrical heater, shown in Figure 4 (b). The supervisory system is associated to ScadaBr Software, which provides the data acquisition system, the control of the electrical resistance power and the chimney fan, access of all the sensors measurements, registers the data obtained and creates reports of specific dates and variables. The electronic system in the CP has a support to a SD card. The card can be disconnected from the panel and opened in a computer. The SD card is used as a backup of the electronic system when the supervisory system loses data.

Temperature and humidity sensors were strategically distributed by the dryer structure as shown in Figure 4 (a). The sensors S1 to S4 represent the temperature sensors DS18B20. S5 is the humidity and temperature sensor DHT11, and S6 and S7 represent the humidity and temperature sensors DHT22. S8 is a type T thermocouple placed on the collector chamber glass. S9 is an Instrutherm TAFR-190 Hot Wire Anemometer, which gives measurements about the outlet airflow speed and temperature.

A temperature control system, embedded in the Arduino, was also created to complement the action of solar radiation by controlling the electrical heater power. The controller modulates the dissipated power in an auxiliary electrical resistance HT, by means of a solid-state relay. The fan CLR is installed in the chimney. All the sensors and actuators are connected to the control panel.

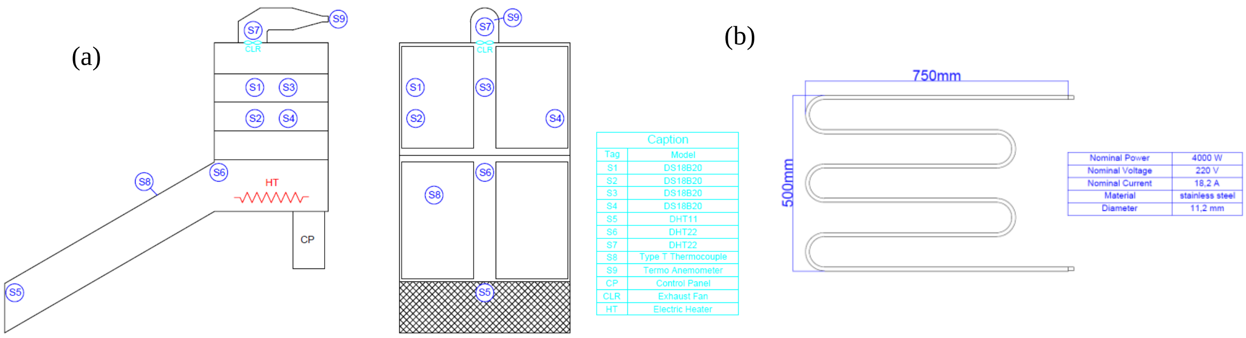

Figure 4. (a) Disposal of the instrumentation components of the dryer. (b) Electric heater built.

4. RESULTS

The drying processes mentioned in this paper were performed in GREEN at Pontifícia Universidade Católica de Minas Gerais (PUC-Minas). During the drying tests, the ambient conditions were monitored by the meteorological station at GREEN. Figures 5 and 6 show the behavior of the solar irradiation and ambient temperature and ambient relative humidity, respectively.

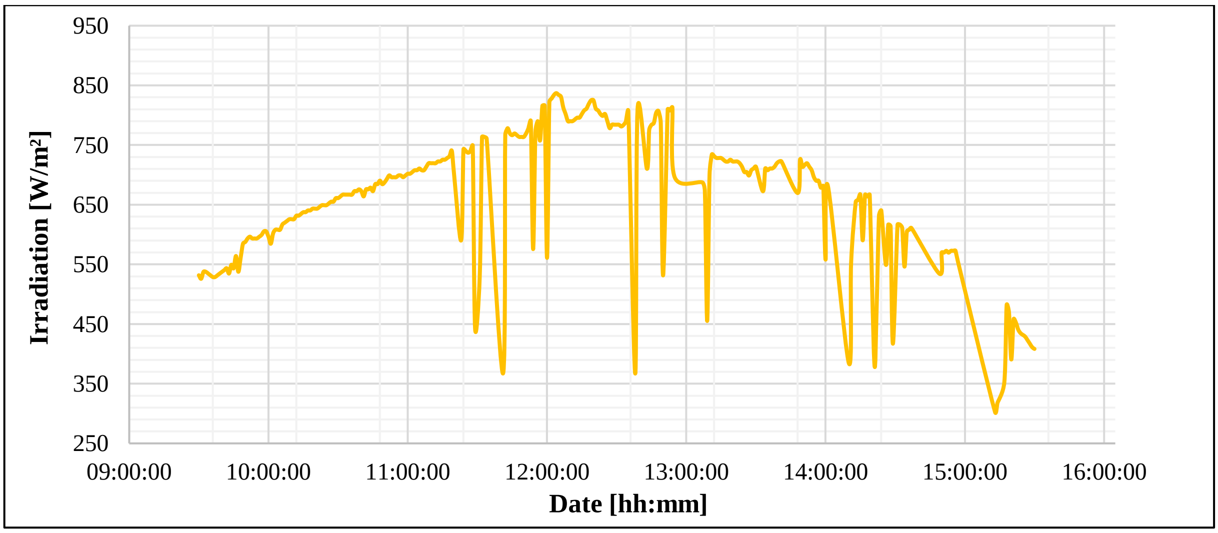

Figure 5. Solar irradiation – Belo Horizonte – MG – 27/07/2018

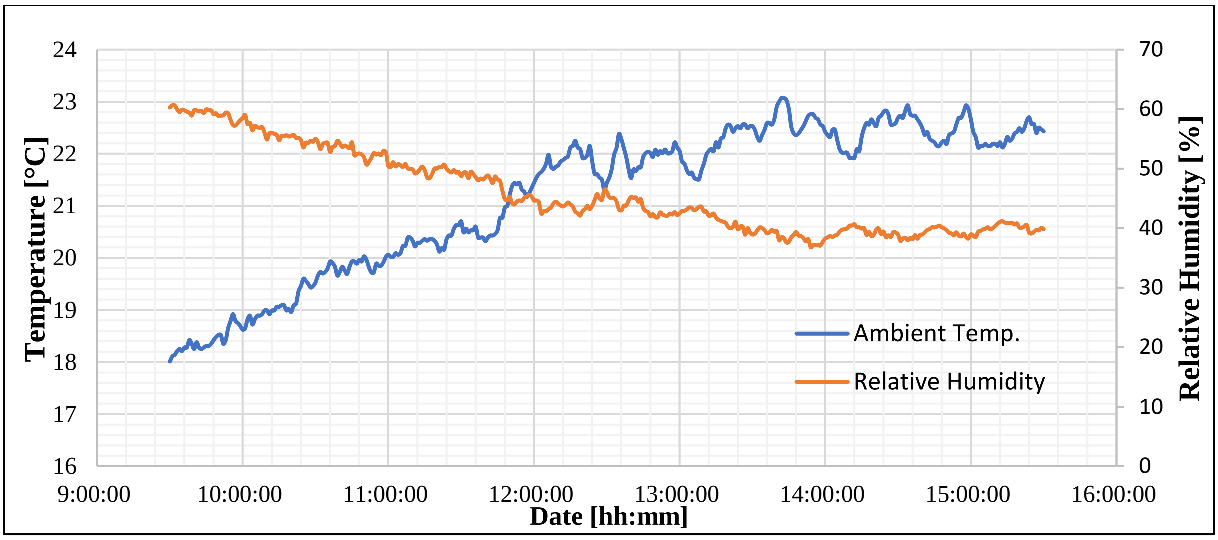

Figure 6. Ambient temperature and relative humidity – Belo Horizonte – MG – 27/07/2018

The Figure 5 shows that the day 27/08/2018 was a sunny day, with just sparse clouds. The relative humidity, as expected, decay with the increment of the ambient temperature at the middle of the day (Fig. 6). Despite of the external ambient conditions, the dryer was supposed to maintain a temperature of approximately 60°C in the drying chamber. This ability was evaluated during the experiment performed in the dryer using the electrical resistance. There were four trays placed in different positions inside the drying chamber, and to ensure an equal drying in all trays it was necessary to have a homogeneous temperature throughout the drying chamber. A way of presenting the homogeneous temperature of approximately 60°C is through the sensors S1, S2, S3 and S4. The Figure 7 shows the working temperature range of the dryer at different points in the drying chamber. The sensors S1 and S2 are close to the right dryer wall. In the beginning of the day, this wall receives the direct solar irradiation, hence the temperature of the right side of the chamber is higher. And the end of the day, the sensor S4 present this behavior, showing a higher temperature at the left wall.

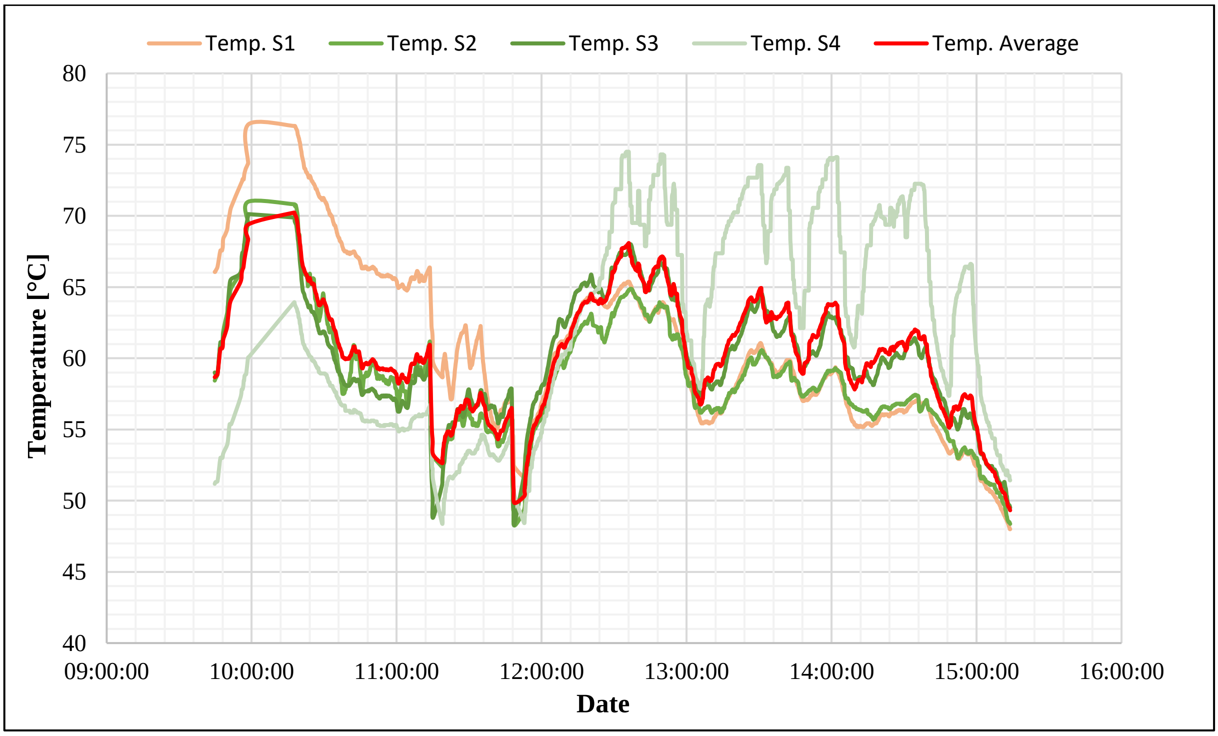

Figure 7. Working temperature range (DS18B20 measurements) – Belo Horizonte – MG – 27/07/2018

Another way of evaluating the temperature distribution inside the drying chamber is using a thermographic camera. The photo shown in Fig. 8 was taken by NEC Thermo Tracer TH7102MX and shows the temperature of five different points in the drying chamber at 12:30.

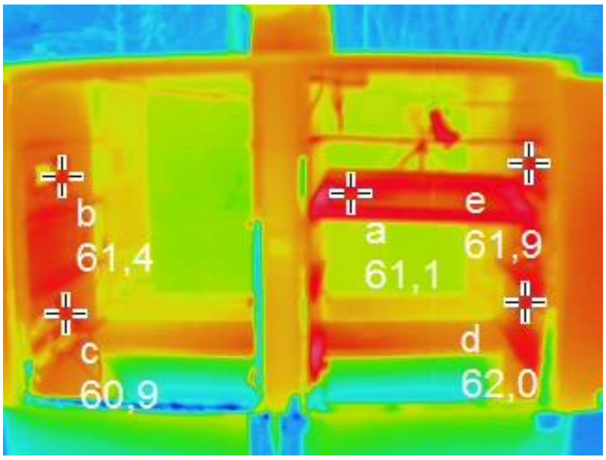

Figure 8. Thermographic photo of the drying chamber

Factors as appearance, color, texture and smell have a high importance when working with food. To qualitatively analyze the three different methods of drying, photos of the samples were taken at the beginning and at the end of the experiment. Figures 9, 10 and 11 show some samples before and after the drying process: hybrid, solar and natural, respectively.

(a)

(b)

Figure 9. Photos of the samples, (a) before and (b) after, the hybrid drying process

(a)

(b)

Figure 10. Photos of the samples, (a) before and (b) after, the solar drying process

(a) (b)

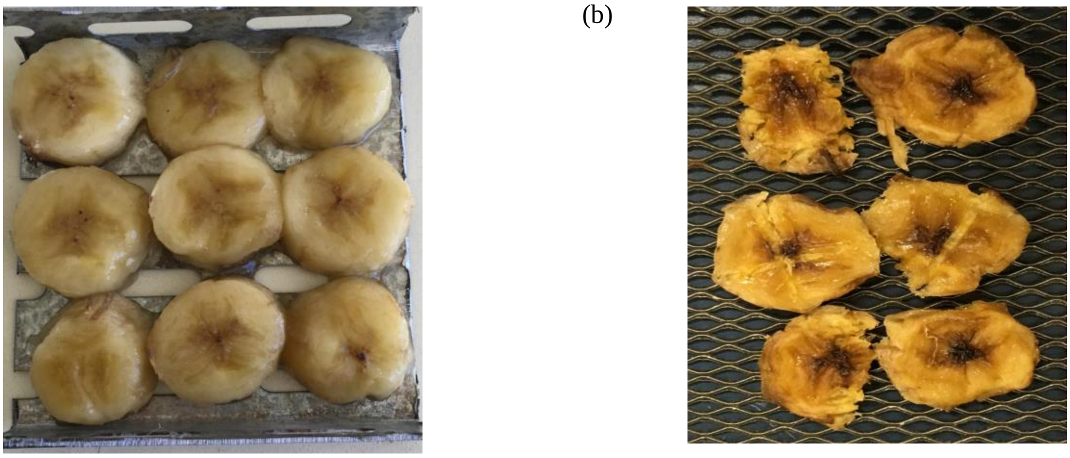

Figure 11. Photos of the samples, (a) before and (b) after, the natural drying process

To assess the technical feasibility of the dryer and to analyze the quality if the drying process, drying curves for each method discussed in this work were created (Fig. 12).

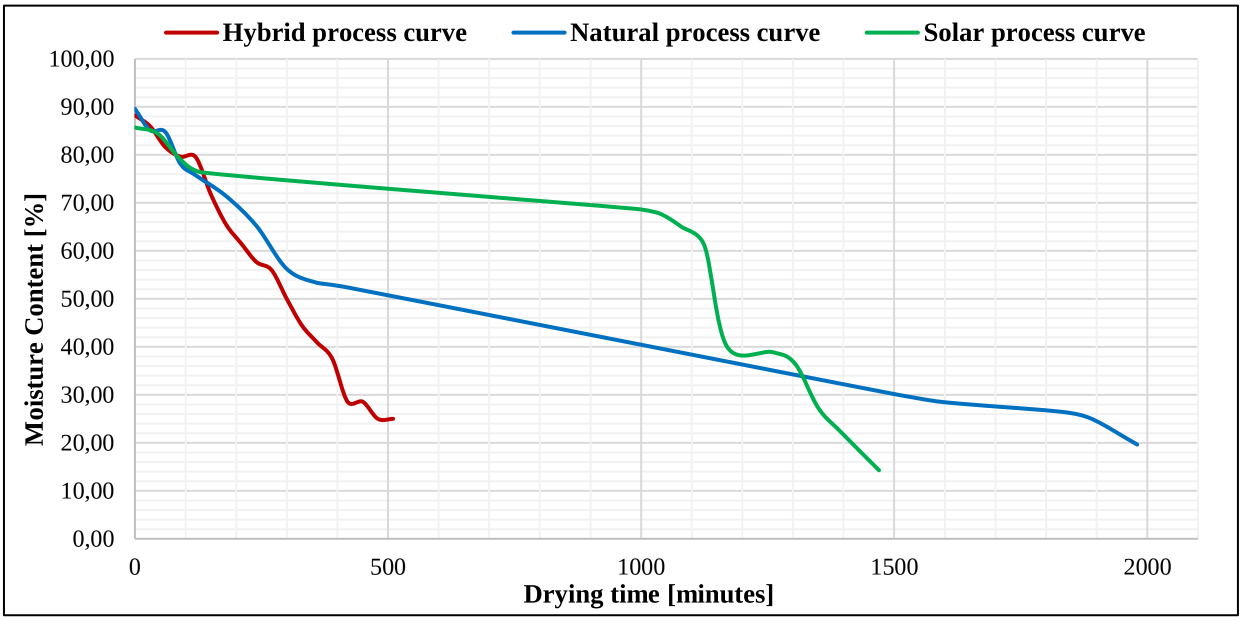

Figure 12. Drying curve of the three drying processes

According to Fig. 12, initially, all the samples of bananas had approximately 85% of moisture content. In the end of the processes, the moisture content dropped to about 25% to the hybrid process, 15% to the natural process, and 20% to the solar process. As expected, the hybrid process is the fastest method of drying, what proves that the auxiliary heater has an important role in stabilizing the temperature and keeping it constant even when there is no solar radiation, such as at night or in cloudy days.

The natural process took the longest time to dry the samples to a low moisture content. In fact, the drying process in the hybrid dryer takes a quarter of the natural drying process to bring the samples to the same final moisture content. The natural drying process is effective only in some parts of the day. Figure 5 and 6 show that between 11am and 2pm the ambient temperature and the solar radiation have their highest points, increasing the drying activity of the natural process.

The drying process performed inside the dryer without the use of the electrical heater revealed to be in a middle term between the natural and the hybrid process. During cold or cloudy days, the efficiency of this method decreases, but when temperature rises the dryer is able to keep this heat during the day, stimulating the drying activity. Therefore, this process is highly dependent on the weather, and the variables present in the drying process cannot be controlled.

Figure 13 represents the instantaneous thermal efficiency of the drying along July 26th and 27th, when the hybrid drying of the samples was performed. The thermal efficiency of the drying performed in the hybrid dryer had an enormous variation throughout the process, reaching values from less than 10% up to higher than 70%. The highest values occurred at 1:36 p.m. on July 26 and at 2:46 p.m. on July 27. On both occasions, it reached 75%. The lowest result happened at 4:07 am on July 27, when the thermal efficiency was approximately 5%. During the two days in which the drying was performed, the thermal efficiency remained most of the time between 20% and 30%. The medium value of the thermal efficiency was 25.32%. Figure 14 shows the values of the drying efficiency. Along the process, they varied from about 20% to 85%. The medium value of the thermal efficiency is 40.05%.

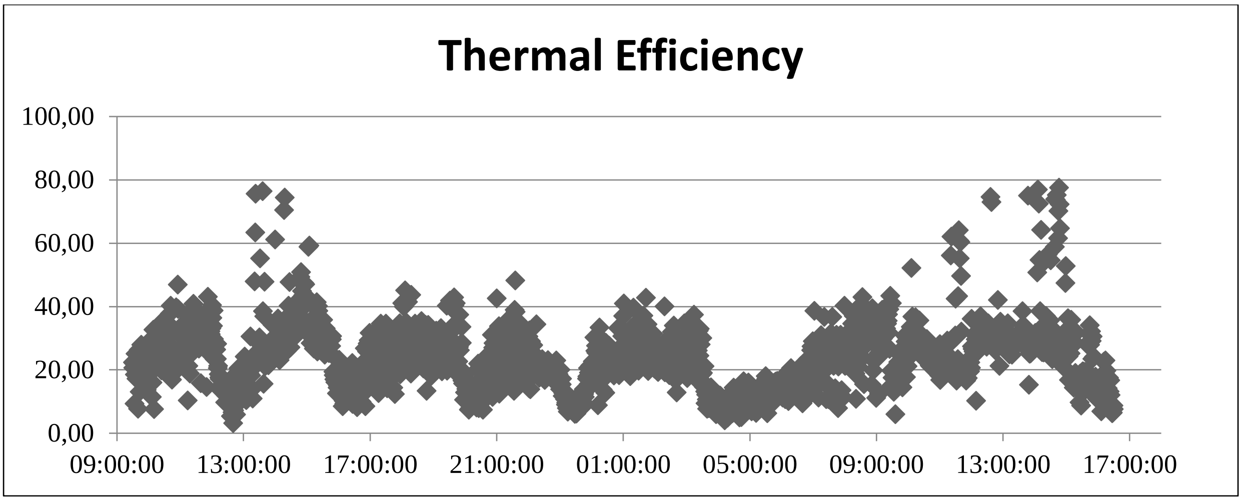

Figure 13. Thermal efficiency of the hybrid dryer

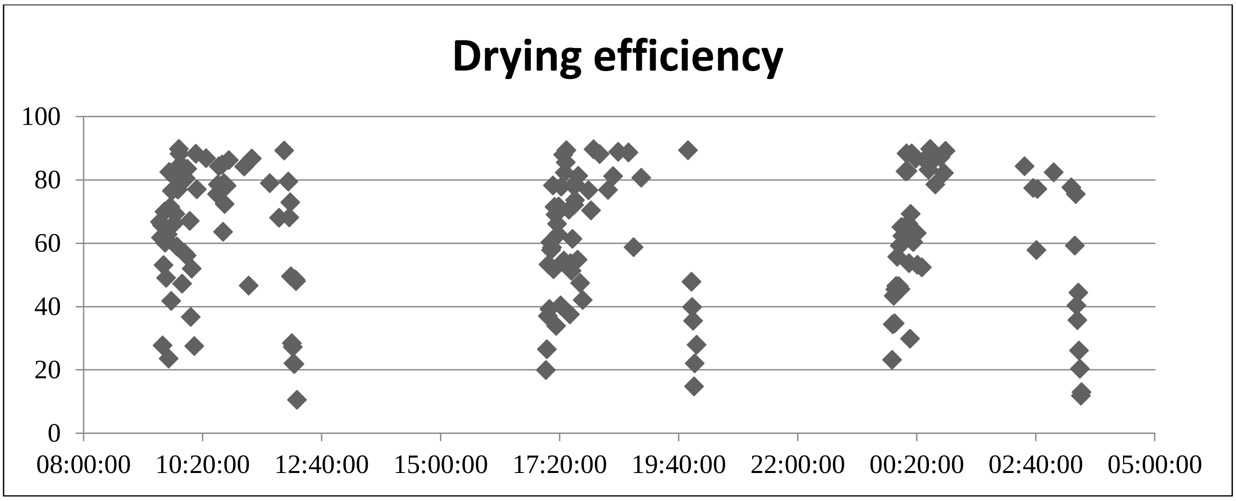

Figure 14. Drying efficiency of the hybrid dryer

5. CONCLUSIONS

The results of experimental tests performed in a electric hybrid solar dryer showed that the dryer used in this work is capable to dry up to 8kg of bananas. Three different methods of drying were studied: the hybrid process, the solar process, and the natural sun process. Before each of these processes the bananas were spliced and frozen to preserve the quality of the fruit after the drying procedure.

During the tests, samples were removed from the drying process and the moisture content was calculated to obtain the drying curve. A comparison between the three curves showed that the time required by the samples of the hybrid process to reach the desired final moisture content was lower than the other processes. The electrical heater was able to maintain a high temperature and a high drying rate for a long period of time. The curves of the other two drying procedures showed that the samples required a long period of time to reach the desired final moisture content. Therefore, it is possible to conclude that electric hybrid solar dryers are able to ally the advantages of solar and artificial dryers.

The hybrid solar dryer performed the drying of the bananas with a good performance and homogeneity of fruit processing. Comparing the results in the solar dryer with those obtained in direct drying in the sun, the samples inside the solar dryer were much more attractive than the ones dried by the exclusive action of the sun. They were able to keep the texture, prevent browning and maintain a good taste.

In this way, it is true to ensure that an electric hybrid solar dryer represents a suitable alternative to dry agricultural products. They use a renewable energy as a primary source and complement it with an artificial source when necessary.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

ANDRADE, L. F. O.; NEVES, D. A. F.; FERREIRA, A. G.; MAIA, C. B., 2008. “Constructive Analysis of a Hybrid Solar Electrical Dryer”. In: *Brazilian Congress of Thermal Engineering and Sciences – ENCIT 2008*. Belo Horizonte, Brazil.

ANEEL. “Matriz de Energia Elétrica”. 17 Jul. 2018 < http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/OperacaoCapacidadeBrasil.cfm>.

CELESTINO, Sonia Maria Costa, 2010. “Princípios da Secagem de Alimentos”. EMBRAPA Cerrados. Jun. 2018 <http://www.escoladecha.com.br/biblioteca/Principios-de-Secagem-de-Alimentos.pdf>.

DOYMAZ, I., 2007. “Air-drying characteristics of tomatoes”. *Journal of Food Engineering*, Vol. 78, p. 1291–1297.

ERTEKIN, C.; YALDIZ, O., 2004. “Drying of eggplant and selection of a suitable thin layer drying model”. *Journal of Food Engineering*, Vol. 63, p 349–359.

MAIA, C. B.; FERREIRA, A. G.; HANRIOT, S. de M., 2010. “Projeto, Construção e Operação de um Secador Híbrido Solar-Elétrico”. *Relatório do Projeto de pesquisa FAPEMIG TEC 84379601/07*. Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte.

MORAIS, B. L. F.; MARINHO JÚNIOR, P. F.; BARBOSA, R. R. C., 2017. *Análise Experimental da Secagem de Bananas em um Secador Solar Híbrido*. Graduation thesis, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte.

NETO, H. J. L., 2008. *Obtenção de tomate seco através do uso de um sistema solar alternativo de baixo custo.* Masters thesis, Universidade Federal do Rio Grande do Norte, Natal.

PRASAD, J., VIJAY, V.K., TIWARI, G.N and SORAYAN, V.P.S., 2006. “Study on Performance Evaluation of Hybrid Dryer for Turmeric (Curcuma longa L.) Drying at Village Scale”. *Journal of Food Engineering*, Vol. 75, p. 497-502.

SILVA, J. O. C., 2014. *Modelagem do Escoamento de Ar e Otimização de uma Chaminé Solar.* Masters thesis, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte.

SONTAKKE, M.S.; SALVE, S.P., 2015. “Solar drying technologies: a review”. *International Refereed Journal of Engineering and Science,* Vol. 4, p. 29-35.

SOUZA, L.G.M.; MENDES, J.U.L.; LIMA NETO, H.J.; SANTOS, N.R.G.; MELO,A.V.; SANTOS, R.D, 2007. “Obtenção de tomate seco utilizando um sistema de secagem solar construído com materiais alternativos. 8º Congresso Iberoamericano de Engenharia Mecânica”. In *Proceedings of the 8th Ibero-American Congress of Mechanical Engineering.* Cusco, Peru.

THIRUGNANASAMBANDAM, M.; INIYAN, S.; GOIC, R, 2010. “A review of solar thermal Technologies”. *Renewable and Sustainable Energy Reviews,* Vol. 14, p. 312 – 322.

UNITED NATIONS. *World Population Prospects The 2017 Revision: Key Findings and Advance Tables.* New York, 2017.

VASCONCELOS, A. C.B. B., 2017. *Análise da Eficiência Energética e Exergética em Secadores Solar e Elétrico na Secagem de Café.* Masters thesis. Universidade Federal de São João Del Rey, São João Del Rey.

YASSEN, T. A.; AL-KAYIEM, H., 2016. “ Experimental investigation and evaluation of hybrid solar/thermal dryer combined with supplementary recovery dryer”. *Solar Energy,* Vol. 134, p. 284 – 293.

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