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Technical feasibility assessment of a solar chimney for food drying

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Abstract

Solar dryers use free and renewable energy sources, reduce drying losses (as compared to sun drying) and show lower operational costs than the artificial drying, thus presenting an interesting alternative to conventional dryers. This work proposes to study the feasibility of a solar chimney to dry agricultural products. To assess the technical feasibility of this drying device, a prototype solar chimney, in which the air velocity, temperature and humidity parameters were monitored as a function of the solar incident radiation, was built. Drying tests of food, based on theoretical and experimental studies, assure the technical feasibility of solar chimneys used as solar dryers for agricultural products. The constructed chimney generates a hot airflow with a yearly average rise in temperature (compared to the ambient air temperature) of 13 ± 1 °C. In the prototype, the yearly average mass flow was found to be 1.40 ± 0.08 kg/s, which allowed a drying capacity of approximately 440 kg.
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1. Introduction

In the near future, the amount of food produced will be insufficient to feed the world's population (Mühlbauer et al., 1996). This can be explained by the rapid growth of the world's population (particularly in developing countries) as well as by a considerable amount of post-harvest losses in foods. To minimize losses, the food materials need to be dried to reduce moisture and, in turn, increase their shelf life. Natural sun drying requires little investment, but has presented significant losses caused by product humidity reabsorption during the rainy period; by contamination from pathogenic gems, rodents, birds and insects; as well as by enzymatic reactions (caused by heterogeneous and insufficient drying). Though the artificial dryers provide an improved quality of drying (as they control the velocity and the temperature of the airflow), they also consume a significant amount of energy (fossil or electric) to heat and move the airflow.

To ensure a continuous supply of food for an ever-increasing Brazilian population, and to allow farmers to increase their production quality and reduce losses, it is necessary to develop an efficient drying method with low costs. Artificial drying is economically feasible, especially when used on large farms. Nevertheless, the acquisition and operational costs of these dryers significantly increase the costs of the dried product. Therefore, since solar dryers use solar energy (a renewable and low pollutant source of energy) to dry agricultural products, they in turn present an interesting and promising alternative. Many solar food dryers have been developed over the past few years

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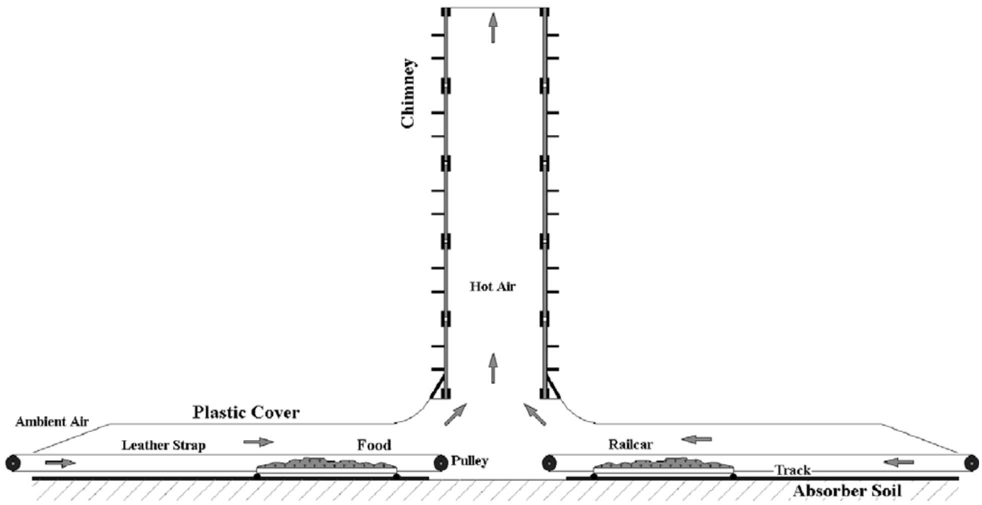

Fig. 1. Schematic representation of the solar chimney prototype as a solar dryer.

(El-Sebaii et al., 2002; Pangavhane et al., 2002; Bena and Fuller, 2002; Condorí and Saravia, 2003; Ivanova et al., 2003; Simate, 2003; Chen et al., 2005; Forson et al., 2007; Hossain and Bala, 2007; Madhlopa and Ngwalo, 2007). Fig. 1 shows a sketch of the solar chimney as a dryer device, which shows some advantages when compared to conventional solar dryers.

The solar chimney is composed of a central tubular tower fixed to a translucent circular cover, opened at the edges (Fig. 1). During the solar radiation incidence period, a fraction of the incident solar radiation on the cover is absorbed by the ground and the drying product, which is then converted into thermal energy. The heat is transferred by convection through the air and in turn to the product. The hot airflow enters the tower and creates an updraught from buoyant forces. The ambient air flows from the periphery to the center of the circular collector. In the process, it is heated by the ground absorber and removes humidity from the drying products. At night, part of the thermal energy stored by the ground during the solar radiation incidence period is transferred to the airflow, allowing the continuous operation of the dryer.

As it is a new application for this device, the use of the solar chimney to dry agricultural products requires a technical feasibility study. This article aims to investigate the technical feasibility of the solar chimney in solar food drying. Drying tests of coffee grains, bananas, and tomatoes were performed inside the dryer, and the results were compared with natural sun drying, under the same climatic conditions.

2. Experimental analysis

2.1. Prototype

A prototype solar chimney was built specifically for this study (Fig. 2). A tower of 12.3 m in height was constructed with sheets of wood and covered by fiberglass at a diameter of 1.0 m. The cover was made of a plastic thermodiffusor film. The cover, with a diameter of 25 m, was set 0.5 m above the ground level, using a metallic structure. The absorber ground was built in concrete and painted in black opaque.

The height of the air entrance was reduced to 0.05 m to minimize the effects of the external wind speed under the coverage and the consequent cooling of the absorber ground. For the same purpose, a plastic film was installed around the dryer (at a distance of 2.5 m from the device boundaries) to avoid the cooling of the absorber ground. Railcars were used to aid the placement and removal of the drying products inside the solar chimney, as shown in Fig. 1.

2.2. Measurement sensors

In order to study the characteristics of the solar chimney as a solar dryer for agricultural products, the ambient conditions (temperature, humidity, wind velocity and solar radiation components) were measured and the thermal profile (velocity, humidity and temperature) of the air flow inside the prototype unit was recorded.

Six pyranometers (Eppley Black and White Model 8-48) were used to measure the diffuse and global components of the incident solar radiation, inside and outside the device. The uncertainty of the pyranometers was determined to be 5%, with a probability of 95%.

Two capacitive psychrometers were used to measure the ambient relative humidity and the relative humidity of the airflow. The relative uncertainty of each psychrometer was determined to be 6%, with a probability of 95%.

The measurement of the ambient temperature, ground temperature, and flow temperature was made using eight (8) *k*-thermocouples, with mineral insulation. The thermocouples were calibrated and an analysis resulted in an

Fig. 2. Solar chimney prototype.

uncertainty of measurement of the thermocouples of 1 °C, with a probability of 95%.

For the measurement of the airflow velocity, eight (8) blade Homis anemometers, with a propeller of 50 mm in diameter, were used. The uncertainty of measurement of the anemometers took into account the calibration and the uncertainty of the air density correction (due to the temperature and relative humidity). The global uncertainty of the anemometers was determined to be 6% with a probability of 95%.

The analogical voltage or current signals from the humidity, temperature, velocity and solar radiation measurement sensors were converted into digital signals through ADAMS 4018 Modules in a data acquisition system. These modules have eight input analogical channels (defining the maximum number of each kind of sensor), with an acquisition frequency of one sample per second.

An analogical scale was used to assess product mass in the performed drying tests. The absolute uncertainty of the plate scale was defined as the maximum calibration error: 0.3 g.

2.3. Drying tests

Drying tests of coffee grains, whole bananas and tomatoes (cut into two parts) were performed. Before beginning the drying tests, each product received a pretreatment (according to Aguirre and Gasparino Filho, 1999). The products were put into three immersion baths. The bananas were hand peeled, the tomatoes were cut into two parts and the seeds removed, and the pulp of the coffee grains was removed. After these procedures, the products were divided into three samples. The first sample was used to assess the initial moisture content (in a stove with forced circulation), the second was submitted to natural sun drying and the third sample was dried inside the solar chimney. Each sample was subdivided into nine samples, to allow the suitable statistic treatment of the results. Repetition tests were not performed due the random behavior of the solar energy and of the ambient conditions.

3. Results and discussion

The experimental tests were performed from February to November of 2003. The daily values of the extraterrestrial solar radiation and of the global solar radiation measured (incident over the cover of the solar chimney) are presented on Fig. 3. During the tests, the higher daily solar radiation measured on the cover was 28 ± 1 MJ/m^2, occurring in October (spring), while the lowest solar radiation measured was 8.0 ± 0.4 MJ/m^2, which occurred in the same month.

Fig. 4 shows the values (daily maximum, minimum and average) of the ambient air temperature, for each day, compared with the National Institute of Meteorology values for the ambient air temperature measured at Belo Horizonte's meteorological station (INMET, 2004). The difference between the measured values of ambient air temperature (compared to the values of the National Institute of Meteorology) can be explained by the distance between the measurement locations and by the uncertainty of the instruments used. The yearly average ambient air temperature was 23 ± 1 °C. During the tests, the minimum ambient air temperature (9 ± 1 °C) was observed in May (fall), while the maximum ambient air temperature (41 ± 1 °C) occurred in September (spring).

The airflow temperature was measured under the solar chimney cover, at a radial position corresponding to $r/\mathrm{Rc} = 0.15$ (where Rc represents the cover radius) and at an axial position corresponding to $x/\mathrm{Hc} = 0.50$ (where Hc represents the cover height). The daily minimum, average and maximum airflow temperatures are shown in Fig. 5. The maximum airflow temperature (56 ± 1 °C) occurred in February (summer), presenting a yearly

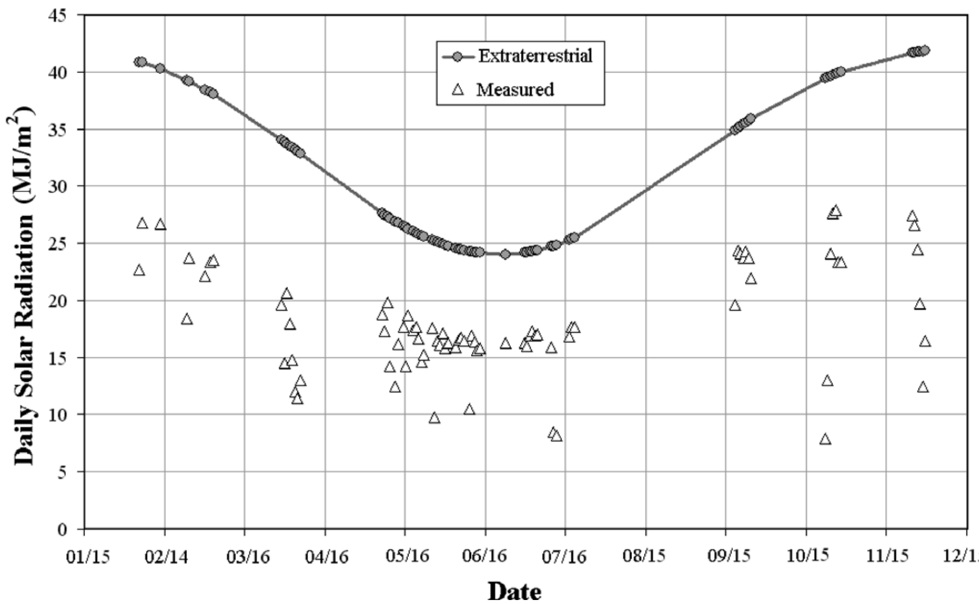

Fig. 3. Distribution of the daily solar radiation.

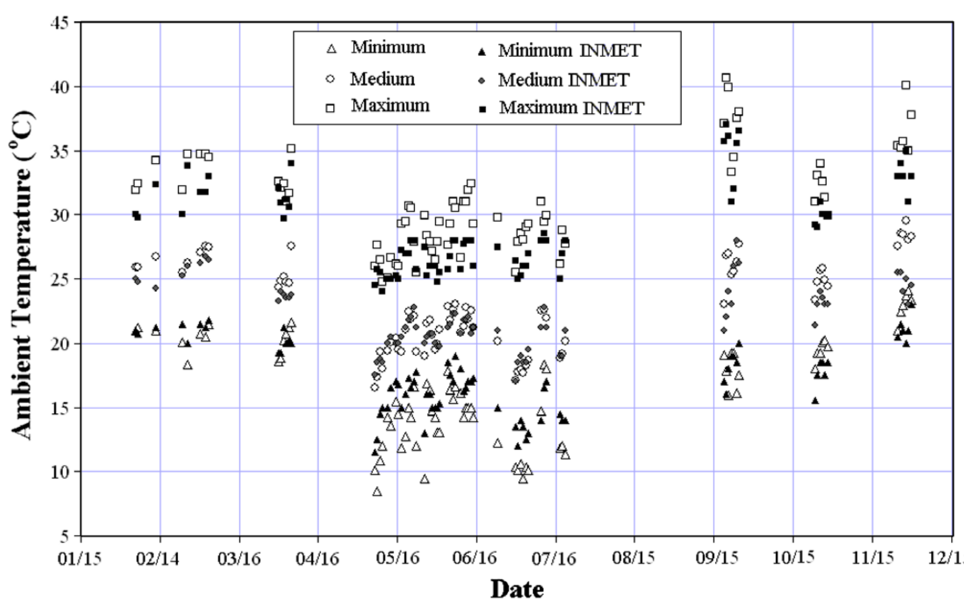

Fig. 4. Daily minimum, average and maximum ambient air temperature for the performed tests.

maximum flow temperature average of 42 ± 1 °C. It is important to note that the maximum average temperatures were obtained when the average incident solar radiation had reached its maximum values. During the year, it was observed a maximum increase of the airflow temperature over the ambient air temperature of 27 ± 1 °C, reached in February.

Fig. 6 shows the maximum, minimum and average values of mass flow, during the testing periods. The maximum mass flow (2.8 ± 0.2 kg/s) was observed in November (spring), while the minimum mass flow (0.70 ± 0.04 kg/s) was observed in July (winter). The yearly average of the mass flow was 1.40 ± 0.08 kg/s. The mass flow of the hot airflow allowed the estimation of the drying capacity of the physic model. According to Leon et al. (2002), the ideal drying capacity of a solar dryer is 4 kg per 0.0125 m^3/s of airflow. Considering the yearly average mass flow of 1.40 ± 0.08 kg/s, the drying capacity of the built physic model is approximately 440 kg.

A yearly average ambient air relative humidity of 63 ± 4% was obtained. The minimum ambient air relative humidity (21 ± 1%) occurred in March, whereas the maximum ambient air relative humidity (91 ± 5%) occurred in September. The yearly average airflow relative humidity measured was 54 ± 3%. The minimum airflow relative humidity was 8.0 ± 0.5% (in March), while the maximum

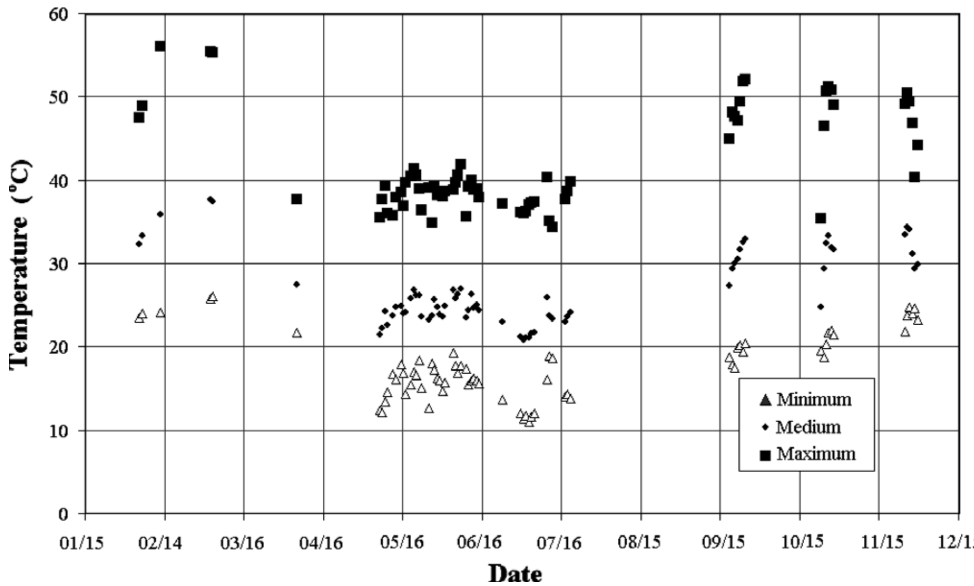

Fig. 5. Daily minimum, average and maximum flow temperature for the performed tests.

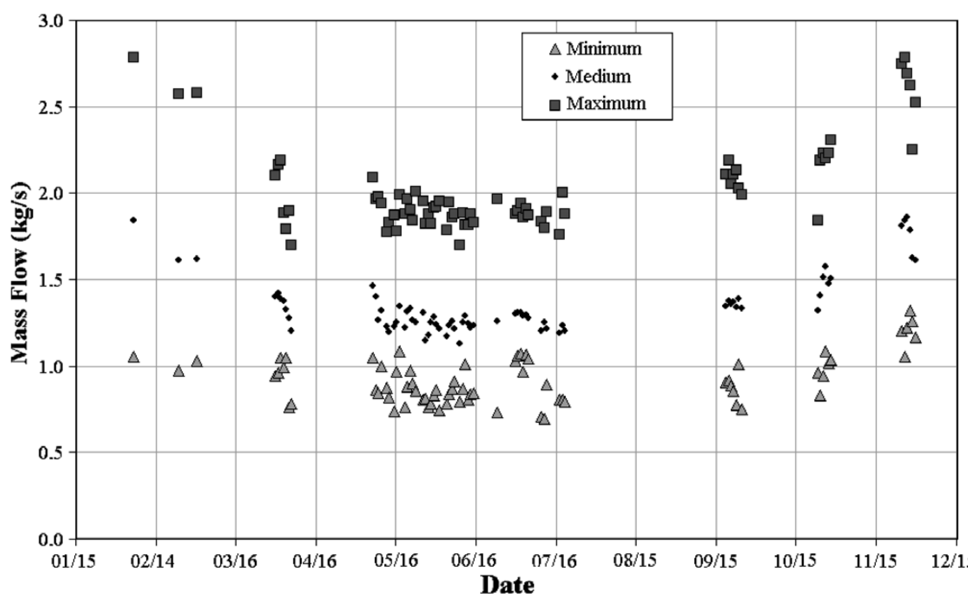

Fig. 6. Minimum, average and maximum daily mass flow for the performed tests.

value was 87 ± 5% (in October). When the yearly average for the airflow's relative humidity in the prototype (54 ± 3%) is compared to the yearly average for the ambient air's relative humidity (63 ± 4%), the advantage of the drying on the solar chimney becomes clear. This occurs due to the increase in temperature and the reduction of the flow's relative humidity, thus reducing the equilibrium moisture content and increasing the free humidity and the drying velocity (Aguirre and Gasparino Filho, 1999).

The temperature profile measured under the cover indicates that the higher temperature occurred at the center, near the tower and the ground surface. As the flow area was decreased in the radial direction towards the center of the device, higher airflow velocities were also found near the tower. These higher values of velocity and temperature in the central area improved the drying the process, indicating that the central area is the most suitable place to position the products to be dried.

Drying tests of coffee grains, bananas, and tomatoes were performed. In all the tests, the time required for drying inside the solar chimney was lower than that required for natural sun drying. It is important to note that the desired final moisture content was reached for the products dried in the solar chimney.

The drying curve of the coffee grains is shown in Fig. 7. The coffee grains needed 152 h to be dried when directly

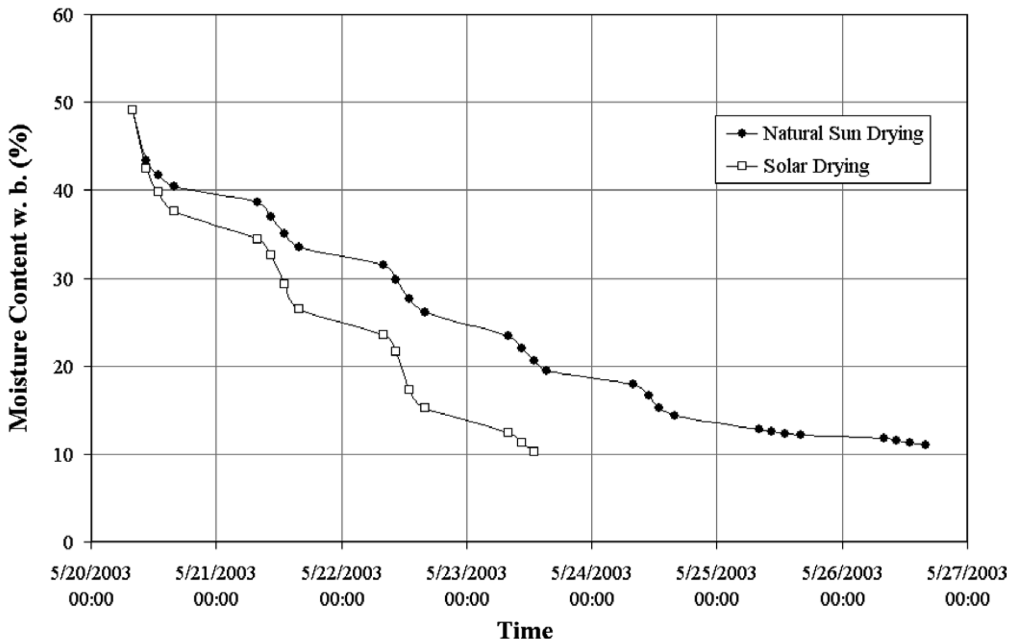

Fig. 7. Drying curve of coffee bean dried using the solar chimney and natural sun drying.

exposed to the sun, while the time required in the solar chimney was only 76 h, approximately half of the time required for natural sun drying. For the coffee grains, the initial moisture content in wet basis was 50 ± 3%, whereas the final moisture content was 11.0 ± 0.7%. During the tests performed, the solar energy incident on the cover was 63 ± 4 MJ/m^2, the average mass flow was 1.28 ± 0.08 kg/s, the average airflow temperature was 21 ± 1°C and the average ambient air temperature was 32 ± 1°C. Mwithiga and Kigo (2006) built a small solar dryer, used to dry coffee grains. When compared to natural sun drying, the drier reduced the time required to dry the coffee grains by 60%, reaching a final moisture content of 13% (w. b.). The solar chimney allowed a reduction of 50%. Nevertheless, the solar chimney allows a greater drying capacity, rendering it more suitable to drying the amount of grains produced in Brazil.

Fig. 8 compares the banana's drying curves inside the solar dryer with natural sun drying (to a final moisture content of 25% in a wet basis). The natural sun drying was completed in 193 h, while the drying inside the chimney was completed in 139 h (72% of the time spent for the natural sun drying). During the tests the solar energy incident on the cover was 84 ± 5 MJ/m^2, the average mass flow was 1.36 ± 0.08 kg/s, the average airflow temperature was 20 ± 1°C and the average ambient air temperature was 30 ± 1°C. Schirmer et al. (1996) dried slices of bananas (1 cm thick) in a tunnel solar drier and compared the results with natural sun drying. To achieve a final moisture content of 30% (w.b.), the banana slices required 84 h in the tunnel solar drier and 110.5 h exposed directly to the sun (for a daily incident solar energy of 23.8 MJ/m^2 day). Despite different drying conditions (bananas shape, final moisture content, and incident solar radiation), it is important to note that the solar chimney presented a greater reduction in drying time. The time required for natural sun drying of the products to desired moisture content was reduced by 72%, in contrast to the 76% reduction required for the tunnel solar dryer created by Schirmer et al. (1996). Purohit et al. (2006) developed a framework to facilitate the comparison of the financial feasibility of the solar drying of any agricultural product for potential users of natural sun drying. The study performed by Purohit et al. (2006) showed that the comparison of the drying times (solar chimney vs. natural sun drying) represents a suitable methodology to assess solar driers.

Fig. 9 shows the tomato's drying curve in the sun and in the solar dryer. The natural sun drying occurred over a period of 195 h, while the drying of the tomatoes inside the solar chimney occurred in 67% of this time (130 h). The tomato's drying process occurred under the same conditions of the banana's drying process.

Microbiological contamination of the dried products was not observed. All dehydrated products presented acceptable flavor, texture and color.

Despite obtaining a shorter drying time using the solar chimney, a global analysis of the energy absorbed by the airflow, as compared to the solar incident energy, resulted in a low efficiency for the device (approximately 7%). This low efficiency can be attributed to significant heat losses, occurring mainly due to the inner layers of the ground, as indicated by local energy balances. It can be observed that a considerable amount of the absorbed solar radiation and of the stored energy in the ground does not return to the flow at night. The use of a plastic material at the cover also contributes to significant energy losses. The plastic used in the cover presents a low transmittance for solar radiation (72 ± 5%) and a high transmittance for infrared

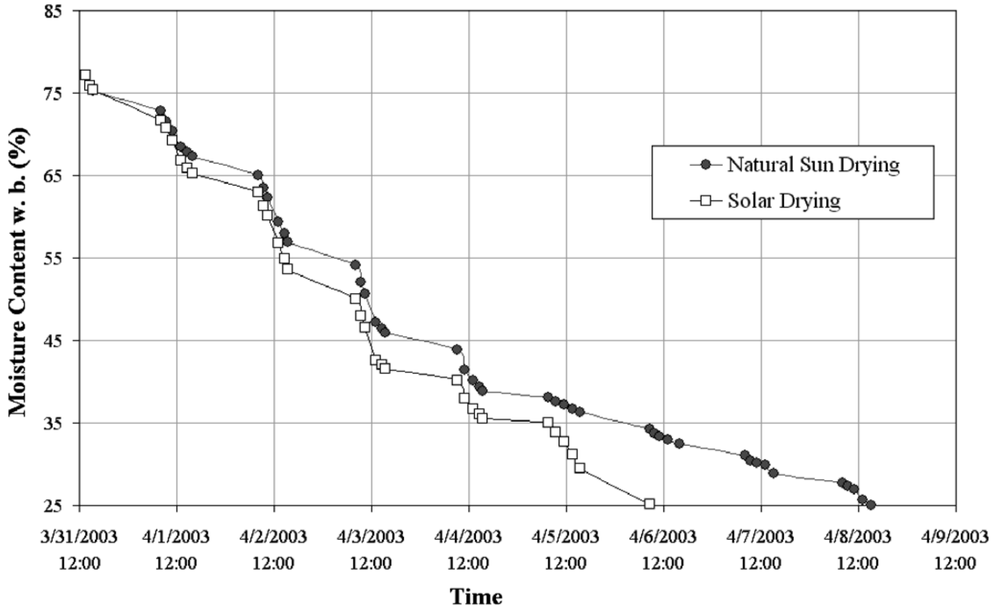

Fig. 8. Drying curve of bananas dried using the solar chimney and natural sun drying.

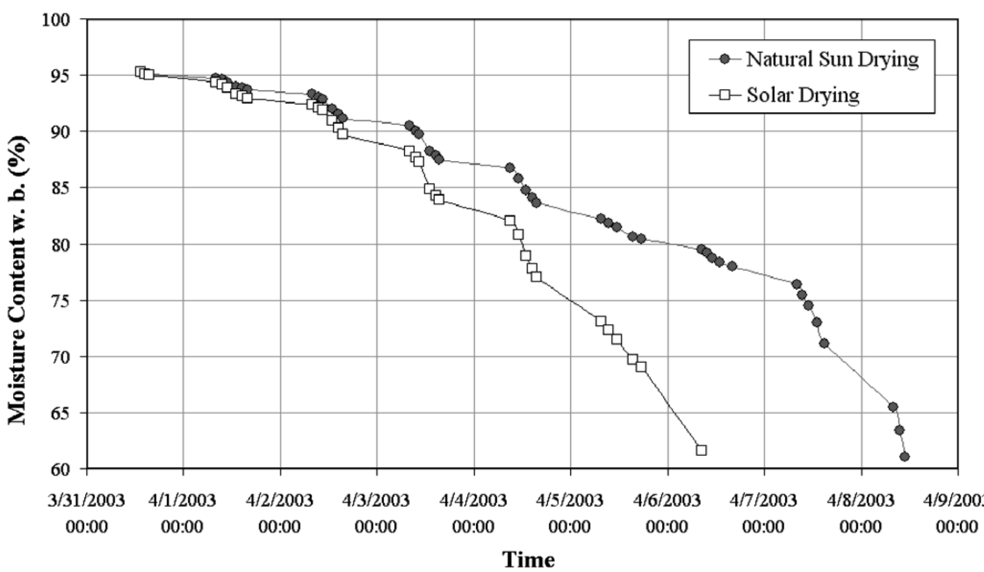

Fig. 9. Drying curve of tomatoes dried using the solar chimney and natural sun drying.

radiation emitted by the warmed ground ($40.0 \pm 1.5\%$). Moreover, the device efficiency can be sensitively increased using a layer of thermal insulation under the ground and replacing the cover material with one with higher transmittance for solar radiation and a lower transmittance for infrared radiation emitted by the warmed ground. A suitable material should be glass.

4. Concluding remarks

This paper presents an experimental study of a solar chimney. To assess its use for food drying, a prototype of a solar chimney was built in Belo Horizonte (Brazil). An experimental simulation of the ambient thermal conditions and thermal fluid dynamics of the hot air flow generated was performed. The solar chimney is a device technically feasible for the drying of food, mainly grains. The performance of the solar chimney can be modified by equipping the device with the proposed improvements, in accordance with each farmer's specific needs.

The tower, made of wood and fiberglass, proved to provide a good thermal insulation. A visual assessment of its physical integrity suggests a great durability for this component. Due to the higher cost required for the tower construction, the replacement of the constructive materials should be studied. The thermal diffuser plastic film presents low weight and reduced costs, and is more suitable to be used in the solar chimney's cover.

The thermal behavior of the flow shows that the drying products must be placed at the center of the device, close to the ground. Drying tests on bananas support these verifications and suggest that drying on wire mesh is more interesting than drying on plastic canvas; however, the use of superposed meshes actually delays the drying process.

The constructed prototype showed a maximum temperature increase of 27 ± 2 °C (related to the ambient air temperature) and a reduction of the flow's relative humidity (in terms of the yearly average) from $63 \pm 4\%$ to $53 \pm 4\%$. This flow temperature increase and the reduction of the flow's relative humidity (related to the ambient relative humidity) ensure the feasibility of the device as a solar dryer, presenting advantages when compared to natural sun drying. During the tests performed in 2003, an average yearly mass flow of 1.40 ± 0.08 kg/s could be observed, allowing one to estimate the drying capacity of the device to be 440 kg of product (320 kg of products per m^3/s of air flow).

The low thermal efficiency observed can be explained mainly by the heat diffusion through the ground, by the low transmittance of solar radiation and by the high transmittance of infrared radiation from the plastic cover. These losses can be minimized by implementing thermal insulation in the ground and replacing the plastic material of the cover.

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