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Simulation of the internal environment of a post-harvest installation and a solar dryer of coffee

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A B S T R A C T

This study aimed to make a simulation of the internal environment of an installations for coffee post-harvest and a parabolic solar dryer, specifically analyzing the effect of natural ventilation on the temperature and relative humidity inside these buildings. The ventilated coffee-processing plant and the solar dryer with the largest natural ventilation area showed the best results to preserve the quality of coffee grain.

Palavras-chave:
ambiência
bioclimática
qualidade de café
beneficiamento úmido de café

Simulação do ambiente interno de instalação de beneficiamento e secador solar de café

R E S U M O

Este trabalho propôs, como objetivo, fazer a simulação do ambiente interno de uma instalação de beneficiamento de café e de um secador solar parabólico analisando especificamente o efeito da ventilação natural sobre a temperatura e a umidade relativa do ar no interior dessas construções. A instalação de beneficiamento de café ventilada e o secador solar com a maior área de ventilação natural apresentaram os melhores resultados para conservar a qualidade do grão de café.

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Introduction

Coffee is the third most important food product in the world after wheat and sugar, and the coffee industry employs 125 million people worldwide (Wintgens, 2009).

Nowadays it is observed that the specialty coffee market presents a continuous demand growth, mainly because the world is increasingly enjoying the good coffee and the highest quality beverages (Fonseca et al., 2009). To preserve the quality of the coffee bean, it is very important to have correct and timely processing (Ribeiro et al., 2011; Carvajal et al., 2012). In Colombia the coffee is wet processed. The wet processing of coffee includes depulping, fermentation, washing and drying the coffee bean.

Drying is considered a critical process step (Borém et al., 2008), in which water activity and metabolic processes are reduced. The coffee is dried in order to maintain its quality and store it for extended periods of time (López, 2005; 2006; Ciro et al., 2011). The main problems in the cup (taste) arise from poor drying and storage (Vilela et al., 2000; Corrêa et al., 2003). Some of these problems bring biological and chemical risks with the product and can lead to a product unfit for human consumption (Puerta, 2008; Oliveros et al., 2013).

Although less than 10% of Colombian coffee growers use mechanical drying, they are responsible for approximately 70% of the volume of coffee that is produced in Colombia (Gonzalez et al., 2010). On the other hand, solar drying of coffee, which is used by 90% of Colombian coffee producers and uses a renewable energy source, is also highly appreciated in the specialty coffee market.

More specifically, with respect to the construction, the humid environments and high temperatures in storage are risk conditions that can physically damage the grain, decompose and deteriorate the quality and safety of the product (Puerta, 2008). For example, temperatures higher than 50 °C can kill the seed of coffee. Sharma et al. (1990) found that the temperature of solar dryers without load can reach up to 80-85 °C during the noon hours.

To analyse and suggest solutions for bioclimatic and other problems in the internal environment of the agro-industrial buildings, the application of mathematical and computational modeling is increasingly used and becoming important (Norton et al., 2009). According to Bre et al. (2013), simulation is a very interesting tool in the design stage (and valuation) of buildings, since the buildings involve very complex issues such as transient energy flows, stochastic occupancy patterns, etc.

Most of the internal environment analysis of rural buildings was made with software based on CFD, but there are other programs that may be used. One of the most popular computer programs for energy and bioclimatic simulation for buildings is the EnergyPlus™ (DoE, 2012). This program calculates the energy efficiency, bioclimatic variables and air quality within buildings, through balances of mass, energy and chemical composition.

This study aimed to make a simulation of the thermal environment in EnergyPlus™ software for a coffee-processing plant and a parabolic solar dryer coffee, with different areas of natural ventilation in order to compare and analyse the internal bioclimatic conditions to preserve the quality of the coffee bean.

Material and Methods

This study was conducted during the month of May 2014, coinciding with the first crop in Colombia. The building is located in the municipality of Barbosa (Antioquia-Colombia) at coordinates 6° 26' 15" N, 75° 19' 50" W, at an altitude of 1700 m, and with an average temperature during the month of May of 23 °C. The cultivation of coffee is between 1650 and 1800 m of altitude and corresponds to a farm with an approximate production of coffee cherry of 125,000 kg $year^{-1}$.

A 3D geometry of a two-story coffee-processing plant was designed in the SketchUp® program (Figure 1): the first floor for wet processing and mechanical drying of coffee, 11 m wide x 6 m long x 3.5 m high; the second floor is composed of a parabolic solar dryer of coffee with plastic cover, 11 m wide x 6 m long x 2.30 m high. There is a concrete slab and brick between the first and second floors.

Each floor was analysed as an independent thermal zone. The thermal zones were created with the help of the plugin Open Studio EnergyPlus™, thus forming an idf file. These zones have group objects (Zone, BuildingSurface), which describe the thermal characteristics of the zone, as well as the details of each surface modeled (DoE, 2014).

The first floor has brick walls 0.15 m thick, without plaster, in the initial 2 m. Between 2 and 3.5 m in height, there are perforated brick walls, in the form of 10 windows. It was calculated air exchange area of the perforated brick windows and interference to the passage of light. To simplify the geometric model, 10 windows were made with the effective area of the perforated brick, and shading devices were inserted to simulate the interference with the light. The calculated area of the simplified windows was 1.92 m^2 for each of the windows of the north and south walls, and 1.5 m^2 for each window of the east and west walls.

The first floor inside the building has scales, fermentation tanks, and a coffee hydraulic classifier was added to the concrete at the bottom of the western wall, with a volume of 3.5 m^3 in order to have the effect of thermal inertia of this mass.

Within the first floor, there are lamps, a humid processing module to peel and sort coffee, with capacity for 2000 kg of coffee cherry per hour, and a mechanical drying machine with capacity for 262.5 kg of parchment coffee (1312.5 kg cherry coffee) per day. The coffee processing plant was simulated in two conditions: fully enclosed and with the perforated brick openings.

A. B. C.

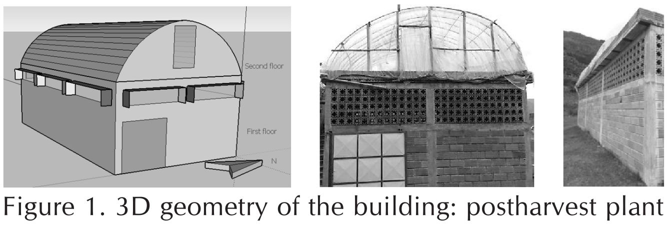

Figure 1. 3D geometry of the building: postharvest plant (first floor) and solar dryer of coffee (second floor) (A), front facade (B), side facade (with windows in perforated brick) (C)

The second floor corresponds to the parabolic solar dryer of coffee, which has a polyethylene plastic cover and a coffee layer with an average humidity of 33% w.b. and it is 0.03 m thick on the slab. The solar dryer has two openings for natural ventilation: one in the front and another in the back. It was simulated with four conditions: (1) fully enclosed, (2) with two openings of 0.6 m^2 each, (3) with an opening of 1.6 m^2 and another of 0.05 m^2, and (4) with two openings of 1.6 m^2 each.

To calculate the thermal properties of composite materials and the thickness and equivalent thermal resistance of the construction materials, the method of simplification for the layers of materials was used (INMETRO, 2013; LabEEE, 2015). Table 1 shows the thermal properties of the building materials used as part of the boundary conditions of the computational model.

Table 1. Thermal properties of materials

Material	ρ (kg m^{-3})	K (W m^{-1} K^{-1})	C_p (kJ kg^{-1} K^{-1})
Mortar	2000	1.15	1.00
Concrete	2200	1.75	1.00
Brick	2200	0.95	0.84
Ceramics	1600	0.90	0.92
Polyethylene plastic	920	0.04	1.59
Steel - Iron	7800	55	0.46

Source: Adapted from INMETRO (2013) and ABNT-NBR 15220-2 (2003)
ρ - Aparent density, K - Thermal conductivity; C_p - Specific heat

For the thermal properties of the stripped coffee, equations proposed by Montoya Restrepo et al. (1990) were used for the specific heat (C_p) and density of the coffee (ρ_c). These properties are functions of the moisture content of the product on a dry basis (M_{db}).

$$C_p = 1.3556 + 5,7859 M_{db}$$

$$\rho_c = 365.884 + 2.7067 M_{db}$$

Table 2 shows the values of the power of coffee processing equipment to calculate the heat generated within the building; highlighting that, the largest proportion of adding energy into the building is introduced by the heat-exchanger mechanical dryer of coffee. Specifically, this heat-exchanger mechanical drying machine uses coffee husks as fuel; according to Oliveros et al. (2009), drying has a peel consumption of 0.352 kg kg^{-1} of dry parchment coffee with a calorific power of 17,936 kJ kg^{-1}.

The metabolic energy that the human body uses during the performance of physical activity (metabolic rate) varies with the person, activity and working conditions carried out, among other factors. The metabolic rate values can be determined using Eq. 3, proposed by ASHRAE (2001), where M is the metabolic rate (W m^2), Q_{Oz} is the volumetric consumption rate of oxygen at 0 °C and pressure 101.325 kPa (L s^{-1}), A_d is the DuBois area (m^2), W is weight (kg) and H is height (cm).

Table 2. Power of coffee processing equipment

Equipment	Power	Unit
Luminaries	10	W m^{-2}
Engine module processing	1118	W
Engine mechanical dryer	746	W
Heat-exchanger mechanical dryer	30690	W

Source: Direct measurement

$$M = \frac{21(0.23RQ + 0.77)Q_{O_z}}{A_d}$$

$$A_d = 0.202 W^{0.425} H^{0.725}$$

Table 3 shows the usage patterns of the coffee processing plant model with mechanical drying and solar drying, their patterns of occupation (by workers), hours of pulping, mechanical drying and using luminaires. Specifically, the solar dryer is only open during the day to encourage the exchange of mass of water, and it is closed at night to retain heat, prevent moist air and protect from the cold external environment. The coffee processing plant works from Monday to Friday, and solar drying worked all day.

The internal environment of the building was simulated for the month of May, which represents the first harvest of the year; the second harvest starts in October, coinciding with the bimodal behavior of rainfall in this part of Colombia (Oviedo Escobar & Torres, 2014).

Coffee processing simulations were performed in two situations: fully enclosed or without natural ventilation (PHP_unventilated), and with the openings of the perforated brick or naturally ventilated (PHP_ventilated). Four conditions were considered for the solar dryer: without natural ventilation or fully closed (SD_unventilated), with two openings of 0.6 m^2 each (SD_ventilated1), with one opening of 1.6 m^2 and another of 0.5 m^2 (SD_ventilated2), and with two openings of 1.6 m^2 each (SD_ventilated3). An analysis was performed for temperature and relative humidity, in addition to the energy storage rate for the heat balance.

Finally, from hourly data of temperature and relative humidity, a box plot was made for the temperatures during the month of May, for the external environment, the coffee-processing plant and solar coffee dryer, for each of the experimental conditions. In addition, analysis of variance and test of means were performed for the analysis of relative humidity.

Table 3. Usage patterns

Hours	OFF	OSF	MD	SD	PC	L
00:00-06:00	0	0	0	0	0	0
06:00-07:00	2	0	1	0	0	1
07:00-07:30	0	1	1	1	0	0
07:30-09:00	0	0	1	1	0	0
09:00-10:00	1	0	1	1	0	0
10:00-10:30	0	1	1	1	0	0
10:30-12:00	0	0	1	1	0	0
12:00-13:00	2	0	1	1	1	0
13:00-13:30	0	1	1	1	0	0
13:30-14:00	0	0	1	1	0	0
14:00-15:00	0	0	1	1	0	0
15:00-15:30	1	1	1	1	0	0
15:30-16:00	1	0	1	1	0	0
16:00-17:30	0	0	1	1	0	0
17:30-18:00	0	0	1	1	1	1
18:00-19:00	1	1	1	0	1	1
19:00-20:00	2	0	1	0	0	1
20:00-21:00	2	0	1	0	0	1
21:00-24:00	0	0	0	0	0	0

OFF - Occupants first floor; OSF - Occupants second floor; MD - Mechanical drying; SD - Solar drying; PC - Pulping coffee; L - Luminaries

Results and Discussion

The box plot temperatures (Figure 2) shows that the fully enclosed indoor environment of the coffee postharvest plant and solar drying of coffee is warmer and has higher temperature variations. On the other hand, the environment with an increased ventilation area is cooler and more thermally stable. The coffee-processing plant, being naturally ventilated (through the perforated brick), had a similar behavior to the outdoor environment, but was a little warmer.

Table 4 shows the statistical analysis of the relative air humidity, where it can be observed that only the postharvest plant that is naturally ventilated (PHP_Ventilated) and the outdoor environment (Outdoor) presented no statistical difference. It also shows that totally closed indoor environments, without natural ventilation (PHP_Unventilated and SD_Unventilated) had the highest relative humidity, close to saturation. It can also be observed that, specifically in the solar drying, with increase in the area of natural ventilation, there were decreases in the relative humidity (average) of the internal environment, suggesting an inverse relationship between these two variables (area of ventilation and relative humidity).

Figure 3 shows the thermal environment during the first experimental week for the evaluated conditions of the coffee-processing plant (unventilated and ventilated). It is observed that the fully closed coffee-processing plant has the highest temperature (higher than 40 °C). The minimum peaks during the day are due to the door opening when employees come to work in the pulping of coffee or mechanical drying.

The coffee processing plant that is naturally ventilated has a temperature closer to that of the external environment. The coffee-processing plant only operates from Monday to Friday; Saturday and Sunday the machines are turned off. In Figure 3,

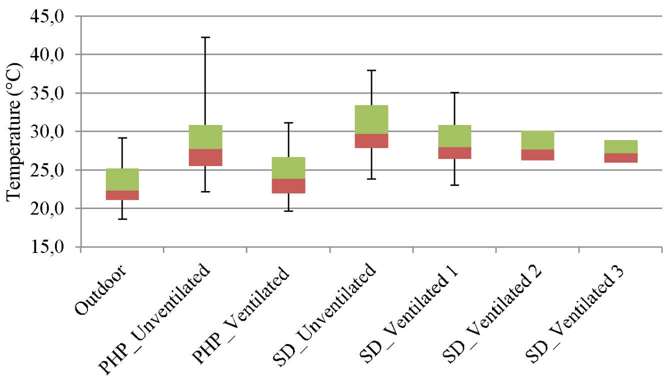

Figure 2. Box plot temperatures

Table 4. Statistical test of means of hourly relative humidity during the month of May

Group name	N	Mean (%)	Std Dev
Outdoor	744	72.2 a	2.464
PHP_Unventilated	744	92.0 b	4.771
PHP_Ventilated	744	73.3 ca	2.755
SD_Unventilated	744	98.2 d	3.408
SD_Ventilated 1	744	86.5 e	2.816
SD_Ventilated 2	744	78.8 f	2.530
SD_Ventilated 3	744	75.3 g	2.158

Means followed by the same letters do not differ by Tukey test at 0.05 probability ($p < 0.001$, F = 448.48)

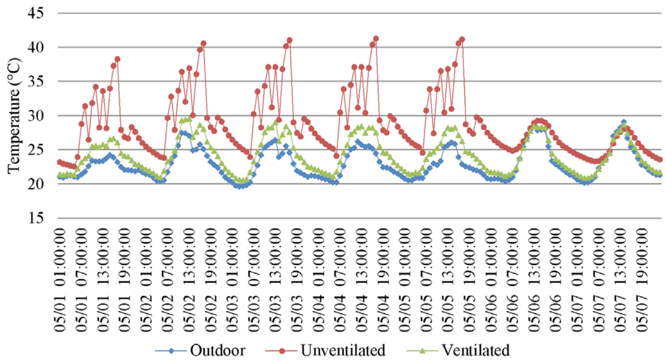

Figure 3. Thermal behavior - coffee processing plant - first floor - first week

one can see the cooling effect on the coffee processing plants opened and closed, where the opened processing plant balances with the external environment, but the closed processing plant is always warmer.

Figure 4 shows the behavior of the relative humidity inside the coffee processing plant during the first experimental week, relative to the different conditions. The closed construction reaches saturation, reducing the relative humidity only when the door is opened by employees. The saturation of the air muffles the environment for the worker, making for an uncomfortable environment. This is a dangerous environment for coffee quality, since it is conducive to biological risk because of the development of fungi and bacteria (hot and humid environment), making the grain re-moisten and damaged (Puerta, 2008).

The environment of construction naturally ventilated at times is close to saturation, but not saturated, having a more suitable environment for the quality of the coffee bean. But the external environment, which is moist and warm, is a limiting internal bioclimatic for naturally ventilated buildings, as in this case. In this regard, Vilela et al. (2000) suggested that coffee must not be stored for more than eight days in an indoor environment with relative humidity higher than 52% and a temperature above 20 °C. In other words, the processing plant is not suitable to store more than one coffee per week.

Figure 5 shows the thermal environment inside the solar dryer in conditions without natural ventilation or fully closed (unventilated), and the different conditions of natural ventilation with two openings on the east and west walls for

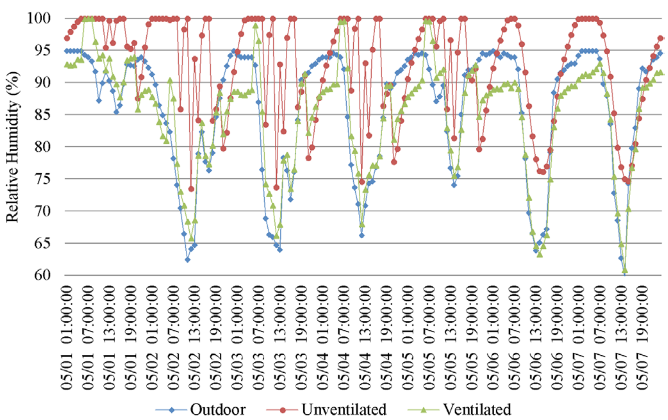

Figure 4. Relative humidity air - coffee processing plant - first floor - first week

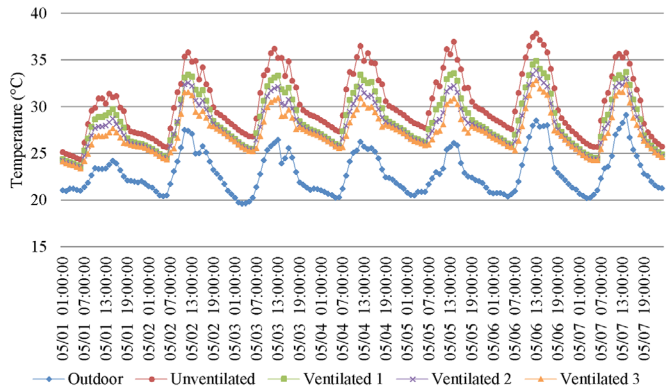

Figure 5. Thermal behavior - solar dryer of coffee - second floor - first week

steam mass transfer during the day: with two openings of 0.6 m^2 each (ventilated1), an opening of 1.6 and 0.5 m^2 for another (ventilated2), and two openings of 1.6 m^2 each (ventilated3). Figure 5 shows that inside the solar dryer, for the different conditions of the study, the temperature was higher than that in the outdoor environment, showing that the temperature has been inversely proportional to the size of natural ventilation openings. It also shows that no temperature is dangerous for the coffee seed (not exceeding 50 °C).

Figure 6 shows the behavior of the variable relative humidity inside the solar dryer of coffee; this variable shows the same trend as the temperature, i.e., it is inversely proportional to the area of natural ventilation. The fully enclosed environment (unventilated) during most of the time showed 100% relative humidity (saturated); in this closed environment, the relative humidity decreased when the solar dryer was opened to stir the coffee. This saturation in a tropical climate brings biohazard for the coffee. For less time than in the previous case, the ventilated 1 and ventilated2, reached 100% relative humidity. Only ventilated3 had an internal environment without saturation, with lower relative humidity, increasing the drying capacity and improving vapor exchange with the external environment.

The solar dryer of coffee as postharvest plant has an internal environment with relative humidity greater than 52% and temperature above 20 °C, indicating that it is not a suitable environment for storing or maintaining coffee for periods longer than eight days (Vilela et al., 2000). This is especially important, because it suggests that, for biosafety, the drying time in this type of solar dryer should be less than eight days.

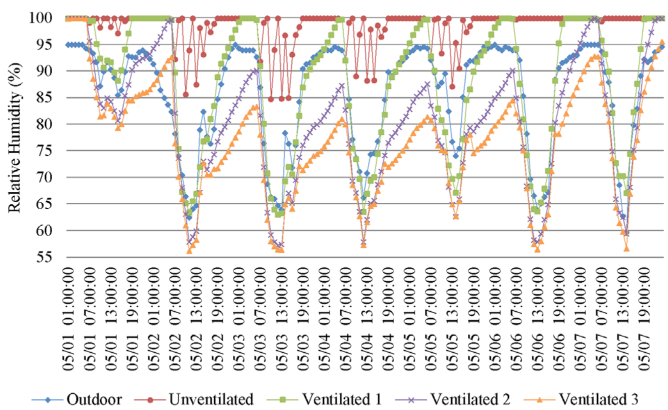

Figure 6. Relative humidity air - solar dryer of coffee - second floor - first week

In Colombia, solar dryers totally enclosed and with little movement of coffee may exceed three weeks in drying time.

Drying is defined as the moisture removal process using simultaneous heat and mass transfer (El-Sebaii & Shalaby, 2012). In this context, energy is needed to optimize drying, as well as optimal conditions for mass exchange; in the case of naturally ventilated solar dryer of coffee, during the day (where there is availability of solar energy), sufficient natural ventilation area should be maintained to facilitate mass exchange (vapor water) with the purpose of increasing efficiency.

The above-mentioned factors can be confirmed in Figure 7, which shows the energy balance of the experimental month for the different opening conditions of the solar dryer. The Figure 7 shows that, for smaller openings for air exchange, there were greater storage of energy and higher mean level of relative humidity, and on the contrary, for larger area of natural ventilation, there were lower energy storage and lower mean level of relative humidity. In the second case, the energy is used for drying and mass transfer, i.e., the solar dryer with the largest area of natural ventilation is the most energy efficient and appropriate for the coffee drying process.

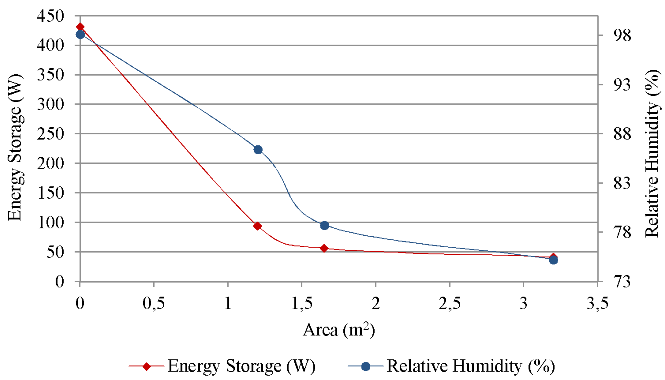

Figure 7. Energy balance and relative humidity for different openings for natural ventilation

Conclusions

1. The largest area of natural ventilation has a lower internal temperature and lower internal relative humidity in both the processing plant and the solar dryer, which improves the bioclimatic conditions to preserve the quality of coffee bean.

2. The solar dryer of coffee with the largest natural ventilation area (case ventilated3) is the most energy efficient and the most appropriate to preserve the quality of coffee. It has lower drying temperatures and lower relative humidity that does not reach the saturation.

3. Given the local environmental conditions (hot and humid), neither the processing plant nor the solar dryer are able to store coffee for a period longer than eight days.

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