ROBINSON OSORIO HERNANDEZ

# ENVIRONMENTAL ASSESSMENT AND OPTIMIZATION OF FACILITIES FOR COFFEE PROCESSING

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Engenharia Agrícola, para obtenção do título de *Doctor Scientiae*.

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APROVADA: 13 de junho de 2016.

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(Orientadora)

*This thesis is dedicated to all coffee growers in Colombia who, with tireless efforts, have contributed to the development of rural Colombia and have raised high the name of Colombia in the world. I hope that the studies presented here and the included findings contribute towards the progress of the countryside and its producers.*

## ACKNOWLEDGMENTS

Special thanks to Professor Ilda, Ambiagro and Brazilian people, for giving me a new opportunity and for all the assistance during this stage in Brazil.

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My last, but not least and perhaps the thank fondest, is for my family: my son Martin, my wife Marcela, my fathers, my sister, my nephews and my friends, thanks for your love, constant and unconditional support.

# BIOGRAPHY

ROBINSON OSORIO HERNANDEZ, the son of Juvenal de Jesus Osorio Sanchez and Luz Stella Hernandez Osorio, was born in Medellin, Antioquia - Colombia, April $13^{th}$, 1981.

He received a BSc. Eng. in Agricultural Engineering in 2006 from the Universidad Nacional de Colombia - Medellin, Colombia.

From 2006 to 2010, he worked for the National Federation of Coffee Growers of Colombia, in Medellin, within the area of post-harvest and quality of coffee.At the same time, from 2007 to 2010, he worked for the Universidad Nacional de Colombia, as occasional professor of electrotechnics and rural buildings.

He received anMSc. degree in Agricultural Engineering in 2012 from the Universidade Federal de Viçosa, Brazil.

In 2012, he worked again for the Universidad Nacional de Colombia, as occasional professor of electrotechnics and rural buildings, and from 2012 to 2014 he worked for the National Federation of Coffee Growers of Colombia, in the area of quality assurance of coffee, as an analyst in building design for the wet processing of coffee.

In August 2014, he became a doctoral student in the Graduate Program of Agricultural Engineering of the Federal University of Viçosa (Viçosa, Minas Gerais state, Brazil), and defended his Doctoral Thesis in June of 2016.

**CONTENTS**

# RESUMO

OSORIO-HERNANDEZ, Robinson, D.Sc., Universidade Federal de Viçosa, junho de 2016. **Avaliação ambiental e otimização de instalações para processamento de café**. Orientadora: Ilda de Fátima Ferreira Tinôco. Coorientadores: Jairo Alexander Osorio Saraz e Iván Dário Aristizábal Torres.

Esta tese foi preparada como uma tentativa de abordar a ambiência interna de instalações naturalmente ventiladas para processamento úmido, especificamente avaliando os efeitos do calor e o vapor gerados pelo processo de secagem mecânica de café no interior destas construções, e a área de ventilação natural sobre a temperatura e a umidade relativa em estas instalações, com o fim de garantir as condições de ambiência adequadas para conservar a qualidade do café sob as condições ambientais, tipologias construtivas e manejo da Colômbia. Os principais objetivos que levaram à elaboração desta tese foram: (1) Fazer uma análise bioclimática das principais tipologias de construção para processamento úmido do café, a partir de arquivos climáticos anuais, padrões de uso e geração de energia e de vapor no interior dessas instalações; (2) Analisar a relação de área de ventilação natural com respeito à capacidade de secagem mecânica, para garantir as condições bioclimáticas adequadas para preservar a qualidade do café; (3) Analisar a área e localização das aberturas de ventilação natural para otimizar o ambiente bioclimático das instalações para processamento úmido do café. Três estudos foram feitos considerando-se instalações naturalmente ventiladas para processamento úmido de café na Colômbia. O Capitulo 1 intitulado "Bioclimatic analysis of three buildings for wet processing of coffee in Colombia", foi submetido para publicação na revista: *Ingeniería e Investigación;* o Capitulo 2 intitulado *"Bioclimatic modeling for determining the minimum area of natural ventilation in buildings for the wet processing of coffee", foi submetido para publica*ção *na revista: Ingeniería e Investigación; e finalmente o* Capitulo 3 intitulado "Effect of different configurations of openings for natural ventilation on the bioclimatic environment of a facility for the wet processing of coffee", foi submetido para publicação na revista: DYNA. Considerando-se os resultados obtidos com o presente trabalho, ficou evidente a influência da área de ventilação natural, a localização das aberturas e o efeito chaminé sobre as variáveis temperatura e umidade relativa do ar no interior de instalações para processamento de café por via úmida, e que

com o adequado design da ventilação natural podem ser alcançadas as condições bioclimáticas necessárias para a preservação da qualidade do café.

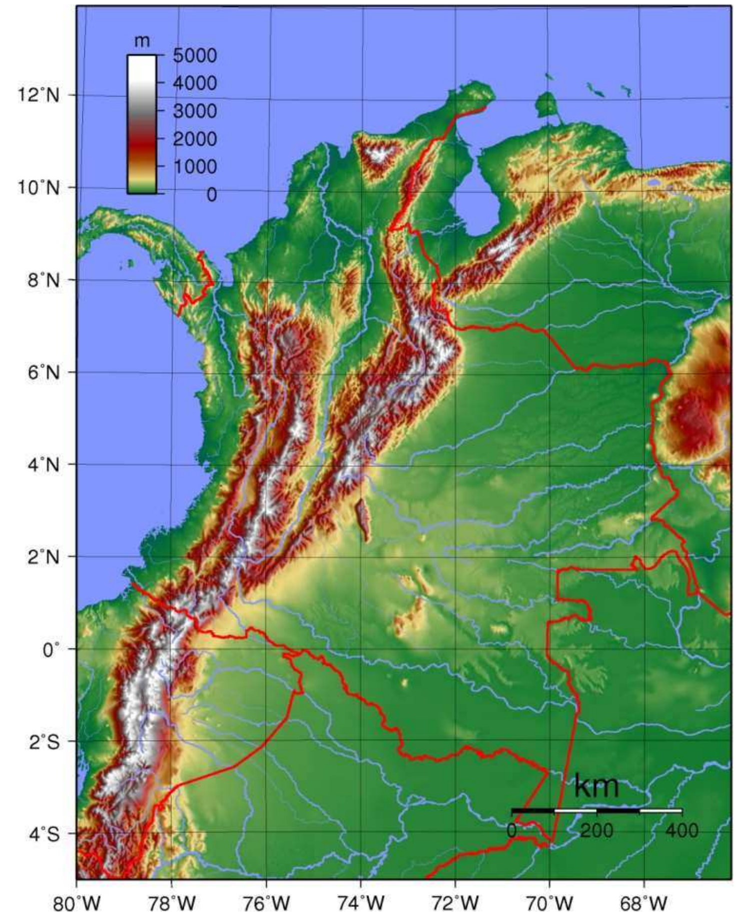
# ABSTRACT

OSORIO-HERNANDEZ, Robinson, D.Sc., Universidade Federal de Viçosa, June, 2016. **Environmental assessment and optimization of facilities for coffee wet processing**. Adviser: Ilda de Fátima Ferreira Tinôco. Co-advisers: Jairo Alexander Osorio Saraz and Iván Dário Aristizábal Torres.

This thesis was prepared as an attempt to address the internal ambience of naturally ventilated facilities for coffee wet processing, specifically assessing the effects of the heat and steam generated by the mechanical drying process of coffee inside these buildings, and the area of natural ventilation, on the temperature and relative humidity in these facilities, to ensure the proper ambience conditions to preserve the quality of coffee, under the environmental conditions, building typologies and management of Colombia. The main objectives that led to the preparation of this thesis were: (1) to perform a bioclimatic analysis of the main building typologies for the wet processing of coffee, from annual climate files, usage patterns and power and steam generation inside these facilities; (2) to analyze the natural ventilation area ratio regarding mechanical drying capacity to ensure the appropriate bioclimatic conditions for the preservation of the quality of coffee, and (3) to analyze the area and location of openings for natural ventilation to optimize the bioclimatic environment of buildings for the wet processing of coffee. The three articles were conducted in naturally ventilated facilities for the wet processing of coffee in Colombia. Chapter 1 is entitled "Bioclimatic analysis of three buildings for the wet processing of coffee in Colombia", and was submitted for publication to *Ingeniería e Investigación.* Chapter 2 is entitled "Bioclimatic modeling for determining the minimum area of natural ventilation in buildings for the wet processing of coffee", and was submitted for publication to *Ingeniería e Investigación*. Finally, Chapter 3 is entitled "The effect of different configurations of openings for natural ventilation on the bioclimatic environment of a facility for the wet processing of coffee", which was submitted for publication to *DYNA*. This thesis shows the influence of natural ventilation area, the location of openings and the chimney effect on the variables of temperature and relative humidity inside of facilities for coffee wet processing; with adequate natural ventilation design, the necessary bioclimatic conditions for the preservation of coffee quality can be achieved.

# GENERAL INTRODUCTION

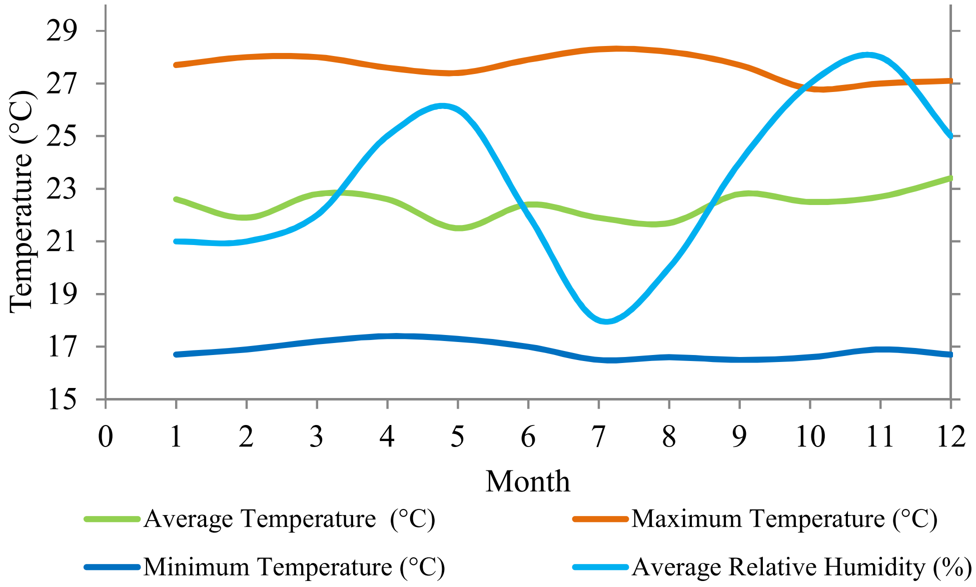
The coffee-growing region of Colombia is located in the Andean equatorial zone (Perez et al., 2016), between 1,000m and 2,000m above sea level. It is characterized by being a relatively warm and humid zone; the rainy season in this area is bimodal, with annual rainfall between 1,500mm and 4,000mm (Oviedo Escobar; Torres, 2014).




Source: http://www.zonu.com/detail/2011-08-16-14292/Mapa-topogrfico-de-Colombia-2007.html.

Figure 1 - Topographic map of Colombia.

The coffee harvest coincides with the rainy season (two crops a year). The fact of being located in the equatorial zone means the temperature range is low (Pérez et al., 2016). During the harvest season the outside temperature ranges between 16°C and 28°C, with an average temperature of 21.5°C.Average relative humidity is between 60% and 80%, and conditions of low direct solar radiation because of clouds means 1,600 and 2,000 hours of sunshine per year, or 4.5 to 5.5 hours of sunshine per day (Cenicafé, 2016).




Source: Adapted from Cenicafé (2016).

Figure 2 - Temperature and relative humidity in time.

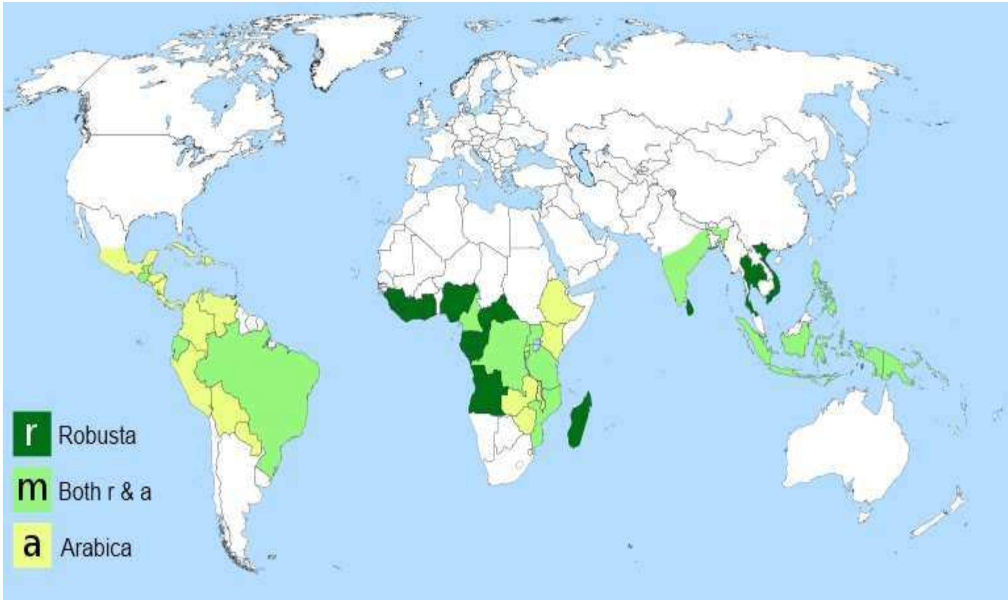
Coffee is the third most important food product in the world, after wheat and sugar. It is one of the most popular beverages in the world and has great economic and social importance (López, 2005; López, 2006). Coffee is the world's second most valuable traded commodity (Garcia et al., 2014), behind only petroleum. In addition, global coffee consumption has risen at an average annual rate of 1.9% over the past 50 years (ICO, 2016).

Coffee plants are grown in tropical and subtropical regions of Central and South America, Africa and South East Asia, mainly in regions with temperate and humid climates (Garcia et al., 2014). Nearly 25 million households in 50 countries around the world depend on coffee for a significant part of their livelihood (Wintgens, 2009). Latin America produces more than half the world's coffee, with Brazil and Colombia as the first and third highest producers, respectively (ICO, 2016).

In recent years, it is observed that the specialty coffee market presents a continuous demand for growth, mainly because the world is increasingly enjoying good coffee and the highest quality beverages (Fonseca et al., 2009; ICO, 2016).

High-quality coffee requires special care, from the pre-harvest phase, through harvest, to post-harvest. In these phases, several factors may cause changes that may affect the future drink. Producing coffees of better quality means a good differential of product price and hence more profit for the producer (Pereira et al., 2010). Specifically, the post-harvest coffee process is one of the primary points for the preservation of the quality of the coffee bean (Ribeiro et al., 2011; Carvajal et al., 2012).

In regions such as Colombia, Central America and Hawaii, Arabica coffees are processed via the wet method, where only mature coffee cherries are harvested and pulped to remove the exocarp and mesocarp. Subsequently, the thin mucilaginous layer surrounding the coffee seeds is removed, either via a natural fermentation process or mechanically. Finally, the processed coffee beans are then mechanically dried or sun-dried to a moisture content of 11% to 12% to achieve microbial stability (Borém et al., 2007; Ciro et al., 2010; Ciro et al., 2011; Ghosh; Venkatachalapathy, 2014; Wei et al., 2015).




Source: http://quaffee.co.za/pages/xtras/ArabicaVSRobusta.aspx.

Figure 3 - World coffee growing regions showing Robusta and Arabica areas.

In the post-harvest treatment of coffee, drying occupies one of the most important roles from an energy effort point of view. If this process is badly performed, microorganisms can grow on the coffee bean surface, exposing it to biochemical reactions that could affect the sugar content (Kleinwächter; Selmar, 2010). The main problems in the cup (taste) arise from poor drying and storage. The development of microorganisms is a factor in the ecosystem that arises only when adverse storage conditions permit excessive moisture accumulation in the grain bulk or when grain is stored initially above the permissible safe moisture content required for its preservation (Puerta, 2008; Oliveros et al., 2013).

Microbial contamination can occur in the cherries and during harvesting, fermentation, drying, and storage of the coffee beans (Silva et al., 2008). Bacteria, yeasts and filamentous fungi have already been reported in the pulp and beans of coffee processed in Brazil, India, Hawaii, Congo, Argentina, Colombia, Costa Rica, Ethiopia, and Mexico (Silva et al., 2008). In terms of the flavor and aroma of the beverage, filamentous fungi predominate at the end of the processing period and during storage, but also present a safety risk to the final product, due to the production of toxic secondary metabolites, the mycotoxins, which can be harmful to consumers at certain concentrations (Taniwaki, 2006; Paterson et al., 2014).

The bioclimatic conditions of the place where the parchment coffee is stored are very important. Fungi live and reproduce best between 70% and 80% relative humidity, whereas yeast and bacterial development require a humidity higher than 85% in the intergranular air (Navarro; Noyes, 2001). The biological risk is latent in facilities' wet processing of coffee; for example, according to Puerta (2006), *aspergillus ochraceus* (a leading producer of Ochratoxin A) was found in 70% of the facilities tested in Colombia, in the facilities' post-harvest coffee, solar dryers, coffee parchment, and green coffee. This author argues that only when adequate conditions of humidity, temperature, time, and unhygienic conditions occur, can these microorganisms proliferate.

On the other hand, temperatures above 50°C can kill the coffee seed and begin its process of decomposition. Sharma et al. (1990) found that the temperature of solar dryers without load can reach up to 80°C to 85°C during the midday hours. In the tropical zone, with relative humidity above 70% and temperatures higher than 27°C, freshly harvested and processed grains can be attacked by insects common in storage (Navarro; Noyes, 2001).

In general, facilities for the wet processing of coffee in Colombia are closed for safety reasons and climate conditions and, to prevent further biological risk, contact with the product is not permitted from personnel and animals.

On the other hand, according to (Salazar et al., 2013), most coffee farmers in Colombia are small producers and small farms owners, i.e., the wealth of this agribusiness is distributed among a large population. For this reason, most of the facilities are of a small size.

Figure 4 - Typical facilities for coffee processing in Colombia.

Farmers and, in particular, the more remote farmers, often store parchment stage or green-bean coffee for long periods before it can be transported to a sale point (Osorio et al., 2016). In the warm and humid/rainy conditions, moisture can build up in stored beans, promoting fungi and bacteria development (Navarro; Noyes, 2001).

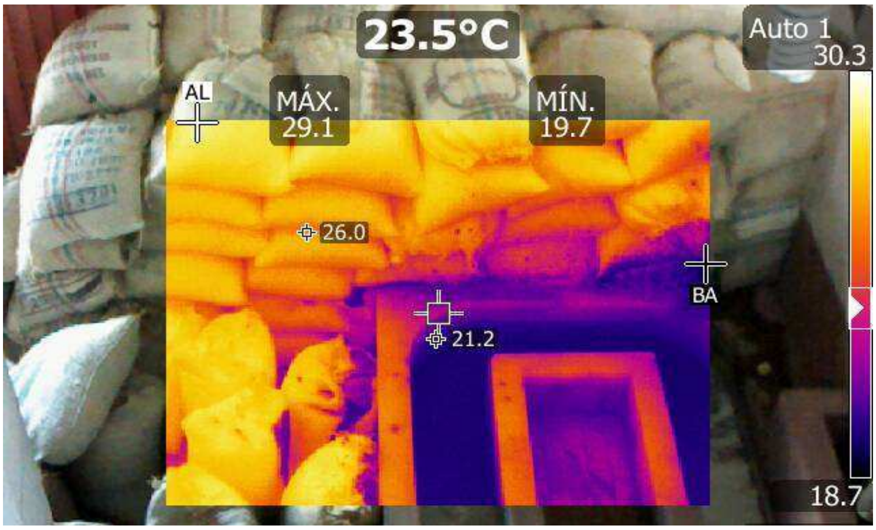



Figure 5 - Thermographic image of storage coffee in facility for coffee processing.

The fact that the facilities are closed, and that the harvest coincides with the rainy season, coupled with poor control and design of buildings for the wet processing of coffee, can compromise product quality due to inadequate bioclimatic environments (Osorio et al., 2015). The bioclimatic approach of buildings in tropical warm and wet regions requires previous bioclimatic work, analyzing the envelope of the building to limit the power contributions and to optimize the flow of air from natural ventilation (Bastide et al., 2006).

Approximately 70% of the volume of coffee that is produced in Colombia is dried mechanically (Gonzalez et al., 2010). This process usually generates a lot of steam and heat in the facilities where the coffee is dried. In the post-harvest coffee stage, the largest power consumption occurs in the mechanical drying process, with efficiencies of 50% (Oliveros et al., 2009). The fact that machines are generating heat inside agroindustrial buildings reinforces the importance of natural ventilation and its beneficial effect on the removal of the water vapor (Baêta; Souza, 2010) generated from the perspiration of the occupants and particularly the drying process, which can lead to biologically dangerous conditions for the preservation of quality coffee.

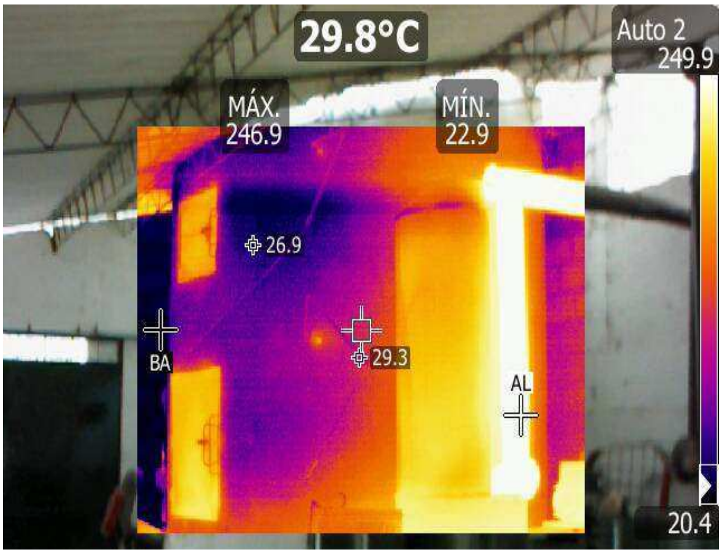



Figure 6 - Thermographic image of mechanical dryer inside of facility for coffee processing.

Natural ventilation is an effective method for improving indoor air quality and reducing energy consumption in buildings, especially when the indoor temperature is close to, or higher than, the temperature of the external environment (Lomas, 2007; Wang et al., 2014; Aflaki et al., 2015). The natural ventilation strategy in design is often disregarded as there are no standards available to support designers in the design of natural ventilation openings (Schulze; Eicker, 2013).

In engineering, all models are a simplified representation of reality and of complex physical or chemical phenomena in the world (Marlin, 1996). Computational modeling of natural ventilation related to energy consumption and thermal comfort has been carried out using different methods: for example, fuzzy control algorithms have been used, combining indoor air quality that is acceptable to thermal comfort with good results (Schulze; Eicker, 2013), as well as computational fluid dynamics modeling (CFD) to analyze the flow field and turbulence (Norton et al., 2009). Zonal and network models have also been used, in programs such as EnergyPlus$^{TM}$ (Oropeza; Ostergaard, 2014).

This is the context in which this thesis originated. There is an urgent need to develop research related to the bioclimatic conditions necessary to preserve the quality of coffee in naturally ventilated buildings for the wet processing of coffee, with drying machines inside, and with the help of computer modeling and simulation.

Optimizing bioclimatic performance and contributing to filling this gap in the field of scientific knowledge is the main objective of this thesis. In order to meet this general goal, the following specific objectives were raised: (1) To perform a bioclimatic analysis of the main building typologies for the wet processing of coffee, from annual climate files, usage patterns and power and steam generation inside these facilities; (2) To analyze the natural ventilation area ratio regarding the mechanical drying capacity, to ensure the appropriate bioclimatic conditions for the preservation of the quality of coffee; (3) To analyze the area and location of openings for natural ventilation to optimize the bioclimatic environment of buildings for the wet processing of coffee.

This thesis has been prepared in journal manuscript format and includes three manuscripts that meet the objectives of this thesis. The three research studies were conducted in naturally ventilated facilities for coffee wet processing in Colombia.

Chapter 1 is entitled "Bioclimatic analysis of three buildings for the wet processing of coffee in Colombia", and was submitted for publication to *Ingeniería e Investigación.* Chapter 2 is entitled "Bioclimatic modeling for determining the minimum area of natural ventilation in buildings for the wet processing of coffee", and was submitted for publication to *Ingeniería e Investigación.* Chapter 3 is entitled "The effect of different configurations of openings for natural ventilation on the bioclimatic environment of a facility for the wet processing of coffee", and was submitted for publication to *DYNA*.

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**CHAPTER 1 - BIOCLIMATIC ASSESSMENT OF THREE BUILDINGS FOR WET PROCESSING OF COFFEE IN COLOMBIA**

**ABSTRACT**: This study aimed to perform a bioclimatic comparison of wet processing facilities of coffee in Colombia, with three typical types of Colombian coffee zone, through computer simulation in EnergyPlus$^{TM}$ program, specifically evaluating the effect of heat and steam generated by mechanical drying machines, and natural ventilation area on the temperature and relative humidity within these facilities. The following statistical tests were performed: means test (Tukey) and box plots, to compare different types, plus an analysis of percentage of number of hours that the indoor environment was with relative humidity conducive to the development of microorganisms. The effect of natural ventilation areas in the buildings that generate steam was observed on the highest area of natural ventilation, minor temperature and relative humidity; i.e. whether type *b* performed better than *a* bioclimatically was observed. However, type *c* presented the most appropriate bioclimatic environment in terms of temperature and relative humidity to preserve the quality of the coffee bean, as this was the only type that discharges steam from the drying process outside.
**Keywords**: Bioclimatic simulation; biological risk; quality coffee; architectural typology; coffee drying.

## 1. INTRODUCTION

Coffee is the third most important food product in the world after wheat and sugar. The coffee industry employs 125 million people in 50 countries in tropical and subtropical regions of Asia, Africa and Latin America (Wintgens, 2009; FNC, 2015).

In recent years, it can be observed that the specialty coffee market is experiencing continuous growth in demand (Fonseca et al., 2009). Various factors determine the formation of the flavors and aromas of the coffee beverage, the final appearance of the grain and thus the value of the final product. These factors include the genetic strain, variety, edaphological factors, and crop and climatic factors, but harvest and postharvest management are key issues (Ribeiro et al., 2011).

The postharvest coffee process is one of the primary points for the preservation of coffee quality bean (Ribeiro et al., 2011; Carvajal et al., 2012). In Colombia, coffee is produced with wet processing. The wet process of coffee includes depulping, fermentation, sorting, washing and drying the coffee bean.

Drying is considered a critical step of the process. The coffee is dried in the interest of maintaining quality and storing it for extended periods of time (Borém et al., 2007; Ciro et al., 2010; Ciro et al., 2011).

The main problems in the cup (taste) arise from poor drying and storage. The development of microorganisms is a factor in the ecosystem that arises only when adverse storage conditions permit excessive moisture accumulation in the grain bulk or when grain is initially stored above permissible safe moisture contents required for its preservation (Puerta, 2008; Oliveros et al., 2013).

Consequently, the main reason for drying or reducing the moisture content of grain is to prevent the activity of microflora. These organisms consist of fungi, yeasts, and bacteria. Fungi live and reproduce best from 70 to 80% relative humidity, whereas yeast and bacterial development require humidities higher than 85% in the intergranular air (Navarro; Noyes, 2001).

The biological risk is latent in facilities that perform the wet processing of coffee; for example, according to Puerta (2006), Aspergillus ochraceus (the leading producer of Ochratoxin A) was found in 70% of the facilities tested in Colombia, in coffee postharvest facilities, as well as solar dryers, coffee parchment and green coffee. This author argued that when adequate conditions of humidity, temperature, time and poor hygiene occur, these microorganisms can proliferate.

Approximately 70% of the volume of coffee that is produced in Colombia is dried mechanically (González et al., 2010). This process usually generates a lot of steam and heat in the facilities where the coffee is dried. In the coffee post-harvest process, the largest power consumption occurs in the mechanical drying process, which, having an efficiency of 50% (Puerta, 2006), added large amounts of steam and thermal energy to the building, which increases the temperature and moisture inside. Consequently, the biological risk is increased.

Poor control and design of buildings for the wet processing of coffee can compromise product quality due to inadequate bioclimatic environments (Osorio et al., 2015). Humid environments and high temperatures during storage are risk conditions that can physically damage the grain, causing decomposition and deterioration of the quality of the product (Puerta, 2008).

Temperatures higher than 50°C can kill the coffee seeds and start the decomposition process. In the tropical zones with relative humidity above 70%, freshly harvested grains are often at a temperature that is favorable to the development of common insects (temperatures above 27°C) (Navarro; Noyes, 2001).

To analyze and suggest bioclimatic and air quality solutions within agro-industrial buildings, the application of mathematical and computational modeling and simulations is increasingly used (Norton et al., 2009). Simulation is a very interesting tool in the design and evaluation of buildings, as the bioclimatic conditions of the buildings involve complex aspects such as energy flows, transient weather variables, stochastic occupancy patterns, etc., that traditional design methods based on experience or experimentation cannot satisfactorily quantify (Bre et al., 2013).

One of the most popular computer programs for energy and bioclimatic simulation for buildings is EnergyPlus™ (DoE, 2012), which is a free open source software developed by the US Department of Energy (DoE). This program was used by Osorio et al. (2015) and Osorio et al. (2016) for the bioclimatic and energy analysis of post-harvest coffee facilities with good results.

Its main input variables are: 3D building design, physical and thermodynamic properties of building materials, internal equipment, and climate of the site where the building is located. This program can calculate the energy efficiency, bioclimatic variables and air quality within buildings, across balances of mass, energy and chemical composition.

This study aimed to simulate the thermal environment of three typical installations of the Colombian coffee postharvest, through computer simulation, in order to compare and analyze the internal bioclimatic conditions, in terms of temperature and relative humidity in order to preserve grain quality.

## 2. MATERIAL AND METHODS

The three buildings are located in the department of Antioquia – Colombia. For these simulations, the climate file was used for the capital Medellin (at coordinates 6°14’41”N 75°34’29”W, altitude of 1500 m), which has a representative climate for coffee of this zone (average conditions of temperature of 16 to 28°C and relative humidity of 60 to 80%). The three farms produce the same amount of coffee, with a coffee cherry production of about 156250 $kg.year^{-1}$ (31250 $kg.year^{-1}$ of parchment coffee). This study was conducted during the month of November (main harvest of 2015).

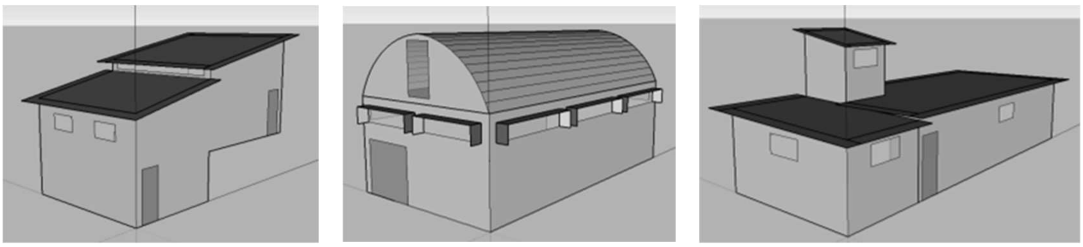
The area was drawn in the 3D geometry SketchUp® program, for each of the three buildings (Figure 1). The first geometry, type *a*, has two floors (of equal size) in a stepped form. On the first floor was the mechanical drying area, while the second floor contained the area for pulped and fermented coffee. The dimensions of this building are: 5.50 m wide x 9.50 m long x 4.0 m high.

Type *b* has two separate floors: the first floor is the area for pulping, fermentation and mechanical drying of the coffee and has dimensions of 11.0 m long x 6.0 m wide x 3.5 m high. The second floor consists of a parabolic solar dryer with plastic covering, measuring 11.0 m long x 6.0 m wide x 2.3 m high. Between the first and second floor, there is a lightweight concrete and brick slab.

Type *c* has two rooms: the main room is the area for the pulping and fermentation of coffee, while the second room is a mechanical dryer for the coffee. Type *c* has dimensions of 10.40 m long x 5.0 m x wide x 2.7 m high. The second room has dimensions of 2.0 m long x 2.0 m wide x 4.60 m high. Unlike types *a* and *b*, in type *c*, as its mechanical drying machine protrudes of the building, expels the vapor and heat produced in the drying process to the external environment.

Each floor of type *b*, as well as the room for the wet processing of coffee and mechanical drying machine of typology *c*, were analyzed as an independent thermal area, while type *a,* was analyzed as a single thermal zone. The thermal zones were created using the plug-in Open Studio (EnergyPlus$^{TM}$), to generate an idf file for each type. In each thermal zone, the thermal characteristics of the materials and other details of each patterned surface are described (DoE, 2014).

The three types were built with 15cm unplastered brick, and the windows of all buildings were open all the time. Types *a* and *c* had a fiber cement roof, whereas type *b* had *a* lightened slab between the first floor and the solar dryer (second floor).



a) b) c)

Figure 1 - 3D geometries of three buildings for the wet processing of coffee types *a* (a), *b* (b) and *c* (c).

In the three types, there were concrete stairs, fermentation tanks, and a coffee hydraulic classifier inside; to these models, one layer of concrete and other of ceramic were added at the bottom, with a volume of 3.5 m$^3$ in order to account for the effect of thermal inertia of this mass. Also, it were measured the volume and natural ventilation area of each building of each type.

The second floor of type *b* corresponds to the parabolic solar dryer of the coffee, which has a polyethylene plastic cover and a coffee layer with an average humidity of 33% wb and a 0.03m thick slab. The solar dryer has two openings of 1.6 $m^2$ each for natural ventilation during the day. For the night conditions, it is assumed that the solar dryer was closed.

For all three types, there are lights, a humidity processing module to peel and sort coffee with a capacity of 2000 kg of coffee cherry per hour, and a mechanical drying machine with a capacity of 1125 kg of parchment coffee per day.

For the thermal properties of the washing coffee, we used equations 1 and 2 proposed by Montoya et al., (1990), for the specific heat ($C_p$, $J.kg^{-1}.°K^{-1}$ ) and density of the coffee ($\rho_C$, $kg.m^{-3}$). These properties are functions of the moisture content of the product on a dry basis ($M_{db}$, decimal dry basis).

$$C_p = 1.3556 + 5.7859M_{db} \quad (1)$$

$$\rho_C = 365.884 + 2.7067M_{db} \quad (2)$$

To calculate the thermal properties of composite materials and the thickness and equivalent thermal resistance of the various construction materials (INMETRO, 2013), it used the method of simplification layers of materials (LabEEE, 2015).

Table 1 - Thermal properties of materials

| Material | $\rho$ | $k$ | $C_p$ |
|---|---|---|---|
| Mortar | 2000 | 1.15 | 1.00 |
| Concrete | 2200 | 1.75 | 1.00 |
| Brick | 1800 | 1.05 | 0.92 |
| Ceramics | 1600 | 0.65 | 0.84 |
| Polyethylene plastic | 920 | 0.40 | 1.90 |
| Steel - Iron | 7800 | 55.00 | 0.46 |
| Fiber cement | 1600 | 0.65 | 0.84 |

Source: Adapted from NBR-15220 (ABNT, 2003). $\rho$: density, kg $m^{-3}$; $k$: thermal conductivity, $W.m^{-1}.K^{-1}$; $C_p$: specific heat, $W.kg^{-1}.K^{-1}$.

For calculation of the energy balance, it is necessary to calculate the heat generated within each building (heat generated by machines, luminaries and human metabolism). Table 2 shows the power values of the machines and lighting.

For the three types, simulations were performed with heat exchanger drying machines using coal (anthracite) as fuel, which, according to Oliveros et al. (2009) has a consumption of 0.224 kg of coal per kg of dry parchment coffee, with a calorific value of 33440 $kJ.kg^{-1}$.

Table 2 - Power of coffee processing equipment

| Equipment | Power | Unit |
|---|---|---|
| Lighting | 10 | $W.m^{-2}$ |
| Engine of processing module | 3357 | W |
| Engine of mechanical dryer | 2238 | W |
| Mechanical dryer heat exchanger | 130044 | W |

The metabolic rate, i.e., the metabolic energy that the human body expends while performing physical activities, varies from person to person, according to the activity and working conditions performed. The value of 423 $W.person^{-1}$ was used in this study for the metabolic rate as, according to ASHRAE (2001), this value corresponds to heavy work activity and the handling of 50 kg sacks.

Table 3 shows the usage patterns of the three coffee processing plant models, that is, when the machines are operating, and how many workers are into facilities and in that schedule. Mechanical drying and pulping require the same working hours for three typologies. The solar dryer (in type *b*) is only opened during the day to encourage the mass exchange of water, and is closed at night to retain thermal energy, prevent condensation and prevent the ingress of moist air from outdoors.

The internal environment of the buildings was simulated for the month of November, during the main harvest of the year, which coincided with the second season rainfall in this part of Colombia (Oviedo; Torres, 2014).

Table 3 - Usage patterns in facilities for coffee wet processing

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

MD: Mechanical drying; PC: Pulping coffee; L: Luminaries; O: Occupants.

A statistical analysis of variance ($p < 0.001$) and test media (Tukey, $p < 0.050$) was performed for the analysis of temperature (hourly), and a boxplot was used for the analysis of relative humidity, with four treatments: outdoor, type *a*, *b*, *c* and outdoor as a witness.

Also, an analysis of the number percentage of hours that facilities remained with a relative humidity between 90 and 100%, 70 and 90% and less than 70% was performed, in order to assess the bioclimatic environment and biological risk for the preservation of the quality of parchment coffee.

## 3. RESULTS AND DISCUSSION

Table 4 shows that the type *c* building has the smallest area of natural ventilation (1.44 $m^2$) and a lower ratio of natural ventilation area to volume built, followed by the type *a* (2.82 $m^2$).

Table 4 - Volume built and natural ventilation area for typologies *a*, *b* and *c*

| GN | V ($m^3$) | VA ($m^2$) | VA/V ($m^2m^{-3}$) |
|---|---|---|---|
| Type *a* | 209 | 2.82 | 0.0135 |
| Type *b* | 231 | 17.40 | 0.0753 |
| Type *c* | 140 | 1.44 | 0.0103 |

GN: Group name, V: Volume, VA: Ventilation area

However, although typology *c* had the smallest ventilation area, because the steam and heat of the mechanical drying process is removed out the building, and its average temperature (23.55°C) was lower and statistically different from other types (Table 5), typologies *a* and *b*, with steam and heat generation inside, the effect of ventilation on lowering the internal temperature was observed, agreeing with Osorio et al. (2015) and Osorio et al. (2016). The type *a* building had greater temperature variance (indicative of scattering data), also presenting the highest maximum temperature (44.49°C) and lowest minimum temperature of the three buildings.

In tropical zones with a relative humidity above 70%, freshly harvested grains are often at a temperature favorable to the development of common insects (temperatures above 27°C) (Navarro; Noyes, 2001); this means that typology *a* presents a biohazard for its indoor environment with a high average temperature.

Table 5 - Statistical data of mean temperature for typologies *a*, *b* and *c*

| Group name | N | Mean | Minimum | Maximum | Standard Deviation |
|---|---|---|---|---|---|
| Outdoor | 720 | 21.88a | 13.06 | 29.63 | 2.96 |
| Type *a* | 720 | 27.46b | 15.41 | 44.49 | 7.49 |
| Type *b* | 720 | 24.96c | 15.70 | 35.06 | 4.11 |
| Type *c* | 720 | 23.55d | 16.52 | 32.90 | 3.56 |

Means followed by the same letters do not differ by the Tukey test at 0.05 probability. N: number of data.

Figure 2 presents the statistical data of relative humidity content. As in the case of temperature (Table 5), type *a* had the highest and most variable content of relative humidity, with a median value of 70.60%, and a maximum value of 100%, i.e., condensation occurred within the construction. Type *b* had a median value of 67.44%, and a maximum value of 99.80%, and type *c* had a median value of 65.48%, and a maximum value of 94.02%. As the harvest of coffee occurs in the rainy season in Colombia, some of the time, the external environment has relative humidity above 70%; in the case of natural ventilation, this constitutes a natural bioclimatic limitation.

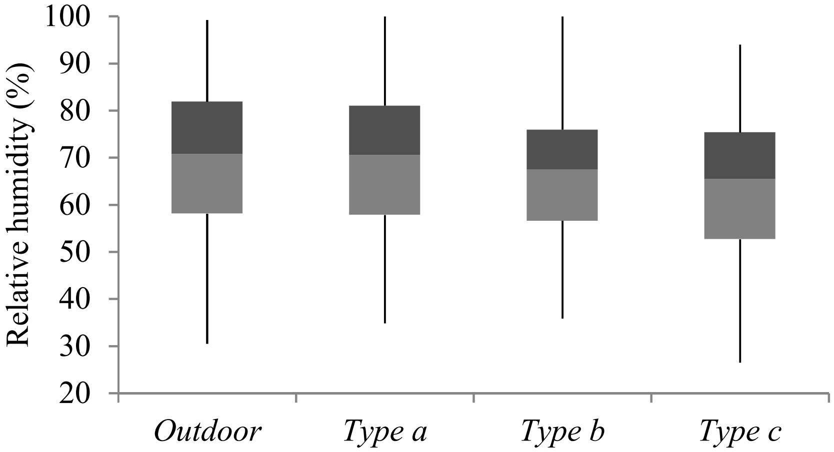



Figure 2 - Boxplot relative humidity of treatments.

The grain moisture contents that are in equilibrium with the surrounding air containing a lower relative humidity than 70% are considered safe (Navarro; Noyes, 2001; Puerta, 2008). Table 6 shows data of the percentage of time that remains inside the buildings at different relative humidities.

The internal environment of type *a,* was close to saturation most of the time (9.70% of the time), and spent more than half of the time with relative humidity above 70% (51.52% of the time), which leads to a danger of proliferation of fungi and bacteria that are harmful to grain quality.

Table 6 - Percentage of time remaining at different relative humidities

| Group name | N | Percentage of time in the range of relative humidity | | |
|---|---|---|---|---|
| | | 90-100% | 70-90% | < 70% |
| Type *a* | 720 | 9.70 | 41.82 | 48.48 |
| Type *b* | 720 | 5.68 | 38.23 | 56.09 |
| Type *c* | 720 | 0.42 | 28.95 | 70.64 |

N: number of data.

In Colombia, it is common to store dry parchment coffee during the harvest in buildings of processing of coffee for several weeks, in order to increase the volume of dry parchment coffee to transport and save money on freight costs (Osorio et al., 2015). In this context, type *a* had a greater biological risk regarding the creation of fungi and bacteria (hot and humid environment), meaning that the grain may be re-moistened and damaged (Puerta, 2008). In the same context, type c showed the most innocuous bioclimate (safe biologically), with a lower average temperature of 27°C (Table 5), an internal relative humidity less than 70% most of the time, with a humidity close to saturation for almost no time (Table 6).

## 4. CONCLUSIONS

In this study, the buildings of post-harvest coffee with steam and heat generation inside, the effect of ventilation on lowering internal temperature and relative humidity was observed.

typology *a*, showed higher internal temperature and relative humidity, according to literature, can bring biological risk for stored grain, for attack of fungi and bacteria, and re-moistened and damaged of grains.

In type *c*, as its mechanical drying machine protrudes from the building, to expel the vapor and heat produced in the drying process to the external environment, this type showed the most innocuous bioclimate conditions (safe biologically), with a lower average temperature of 27°C and internal relative humidity less than 70% relative humidity most of the time.

## 5. ACKNOWLEDGMENTS

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## CHAPTER 2 - BIOCLIMATIC MODELING FOR DETERMINING THE MINIMUM AREA OF NATURAL VENTILATION IN BUILDINGS FOR THE WET PROCESSING OF COFFEE

**ABSTRACT**: This study aimed to find the minimum area of natural ventilation suitable for coffee processing wet facilities in Colombia that have mechanical drying inside, in order to preserve the intrinsic characteristics of coffee through a bioclimatic environment conducive to biological safety. This study was made with the help of computational simulation in EnergyPlus™ program. It was found that as the drying capacity is increased, and therefore the power of the drying machines, temperature and internal humidity tend to increase. Furthermore an inverse linear correlation was found between the area of natural ventilation and variables temperature, and relative humidity. Finally, it is found relationships between the minimum area of natural ventilation and the drying capacity, in order to obtain a suitable bioclimatic environment for preserving of coffee parchment.
**Keywords**: warm and humid environment; mechanical drying of coffee; biological risk; coffee storage; postharvest of coffee.

### 1. INTRODUCTION

Coffee is the third most important food product in the world after wheat and sugar. It is one of the most popular beverages in the world and has great economic and social importance (López, 2005; López, 2006). Coffee is the world's second most valuable traded commodity (Garcia et al., 2014), behind only petroleum. In addition, global coffee consumption has also risen at an average annual rate of 1.9% over the past 50 years (ICO, 2016).

Coffee plants are grown in tropical and subtropical regions of Central and South America, Africa and South East Asia, mainly in regions with temperate and humid climates (Garcia et al., 2014**)**. Nearly 25 million households in 50 countries around the world depend on coffee for a significant part of their livelihoods (Wintgens, 2009). Latin America produces more than half the world's coffee, with Brazil and Colombia as the first and third highest producers, respectively (ICO, 2016).

High-quality coffee requires special care and handling from the pre-harvest phase, through harvest, to post-harvest. In these phases, several factors may cause changes that may affect the future drink. Producing coffees of better quality means a good differential of product price and hence more profit for the producer (Pereira et al., 2010). Specifically, the post-harvest coffee process is one of the primary points for the preservation of coffee bean quality (Ribeiro et al., 2011; Carvajal et al., 2012).

In regions like Colombia, Central America, and Hawaii, Arabica coffees are processed via the wet method, where only mature coffee cherries are harvested and pulped to remove the exocarp and mesocarp. Subsequently, the thin mucilaginous layer surrounding the coffee seeds is removed either via a natural fermentation process or mechanically. Finally, the coffee beans are sun-dried or mechanically to a moisture content of 11-12% so as to achieve microbial stability (Borém et al., 2007; Ciro et al., 2010; Ciro et al., 2011; Ghosh; Venkatachalapathy, 2014; Wei et al., 2015).

In post-harvest treatment of coffee, the drying occupies one of the most important roles from an energetic effort point of view. If this process is badly performed, microorganism can grow on the coffee bean surface, exposing it to biochemical reactions that could affect sugar content (Kleinwächter; Selmar, 2010). The main problems in the taste of cup arise from poor drying and storage. Development of microorganisms is a factor in the environment that arises only when adverse storage conditions permit excessive moisture accumulation in the grain bulk or when grain is stored initially above the permissible safe moisture contents required for its preservation (Puerta, 2008; Oliveros et al., 2013).

Microbial contamination can occur in the cherries and during harvesting, fermentation, drying and storage of the coffee beans (Silva et al., 2008). Bacteria, yeasts, and filamentous fungi have already been reported in the pulp and beans of coffee processed in Brazil, India, Hawaii, Congo, Argentina, Colombia, Costa Rica, Ethiopia and Mexico (Silva et al., 2008). In terms of flavor and aroma of the beverage, filamentous fungi predominate at the end of the processing period and during storage, but also present a safety risk for the final product, due to the production of toxic secondary metabolites, the mycotoxins, which can be harmful to consumers at certain concentrations (Taniwaki, 2006; Paterson et al., 2014).

The bioclimatic conditions of the place where the parchment coffee is stored are very important. Fungi live and reproduce best between 70 and 80% relative humidity, whereas yeast and bacterial development require humidities higher than 85% in the intergranular air (Navarro; Noyes, 2001). The biological risk is latent in facilities' wet processing of coffee; for example, according to Puerta (2006), *Aspergillus ochraceus* (a leading producer of ochratoxin A) was found in 70% of the facilities tested in Colombia, in the facilities' post-harvest coffee, solar dryers, coffee parchment and green coffee. This author argues that only when adequate conditions of humidity, temperature, time and unhygienic conditions occur, can these microorganisms proliferate.

On the other hand, temperatures above 50°C can kill the seed of coffee and begin its process of decomposition. In the tropical zone, with relative humidity above 70% and temperatures higher than 27°C, freshly harvested beans and processed grains can be attacked by insects common in storage (Navarro; Noyes, 2001).

Farmers, particularly to remote farmers, often keep store parchment or green-bean coffee for long periods before it can be transported to a sale point (Osorio et al., 2016). In the humid/rainy conditions, moisture can build up in stored beans, promoting fungi and bacteria development (Navarro; Noyes, 2001).

Approximately 70% of the volume of coffee that is produced in Colombia is dried mechanically (Gonzalez et al., 2010). This process usually generates a lot of steam and heat into the facilities where the coffee is dried. In the post-harvest coffee, the largest power consumption occurs in the mechanical drying process, with efficiency of 50% (Oliveros et al., 2009), The fact that machines are generating heat inside the agroindustrial buildings reinforces the importance of natural ventilation and its beneficial effect on the removal of water vapor (Baêta; Souza, 2010) generated from the perspiration of the occupants and particularly the drying process, which can lead to biologically dangerous conditions for the preservation of quality coffee.

Natural ventilation is an effective method for improving indoor air quality and reducing energy consumption in buildings, especially when the indoor temperature is close to or higher than the temperature of the external environment (Lomas, 2007; Wang et al., 2014; Aflaki et al., 2015). The natural ventilation strategies design is often disregarded as there are no standards available to support designers in the design of natural ventilation openings (Schulze; Eicker, 2013).

A poor control and design of buildings for the wet processing of coffee can compromise product quality due to inadequate bioclimatic environments (Osorio et al., 2015). The bioclimatic approach of buildings in tropical warm and wet regions requires previous bioclimatic work, analyzing the envelope of building to limit the power contributions and to optimize the flow of air from natural ventilation (Bastide et al., 2006).

Computational modeling of natural ventilation related to energy consumption and thermal comfort has been carried out using different methods: for example, fuzzy control algorithms have been used, combining indoor air quality that is acceptable to thermal comfort with good results (Schulze; Eicker, 2013), as well as computational fluid dynamics modeling (CFD) to analyze the flow field and turbulence (Norton et al., 2009).

Zonal and network models have also been used, in programs such as EnergyPlus™ (Oropeza; Ostergaard, 2014).

Osorio et al. (2015) and Osorio et al. (2016) performed bioclimatic analysis for a parabolic solar dryer and wet mill of coffee facilities through simulations in the EnergyPlus™ program. These authors were found that the greater the area of natural ventilation, is lower temperature and relative humidity inside these facilities, but in the no such relationship has been found, nor is there any recommendation for the minimum natural ventilation area necessary to maintain a suitable bioclimatic environment for different scales of coffee production.

Taking into consideration facilities that varied in the size of production, and using computational simulation, this study aimed to find the minimum area of natural ventilation suitable for coffee processing wet facilities in Colombia that have mechanical drying inside, in order to preserve the quality of coffee through a bioclimatic environment conducive to biological safety.

## 2. MATERIAL AND METHODS

This study was conducted taking into account the conditions of the coffee region of Antioquia, Colombia. For these simulations the climate file of its capital Medellin (at coordinates 6°14′41″N 75°34′29″W, an altitude of 1500 m) – which has a climate representative of this coffee zone was used. The internal environment of the buildings was simulated for the month of November, during the main harvest of the year, which coincides with the second rainfall season in this part of Colombia (Oviedo; Torres, 2014).

Using the program EnergyPlus™, which is one of the most popular bioclimate simulation programs in the world (DoE, 2012), 118 computer simulations were performed for different sizes of production and different areas of ventilation, with mechanical drying inside with power (of heat exchanger) ranging from 26 kW to 1625 kW, and ventilation areas of 0 $m^2$ to 120 $m^2$, and with facilities with building volumes ranging from 28 $m^3$ to 3200 $m^3$. Data on drying power and volumes of buildings for wet coffee processing were provided by Comité de Cafeteros de Antioquia.

In engineering, all models are a simplified representation of reality, of complex physical or chemical phenomena in the world (Marlin, 1996). In this case, for the modeling, simple geometries of the buildings were assumed, orientation east–west, and drawn in the 3D geometries SketchUp® program, for each of the 118 different cases (Figure 1).

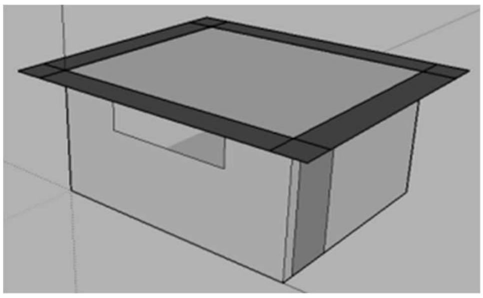

Figure 1 - Simple geometry of the building.

For the thermal properties of the washing coffee, it was used equations 1 and 2 proposed by Montoya et al. (1990) for the specific heat ($C_p$, J.kg$^{-1}$.°K$^{-1}$ ) and density of the coffee ($\rho_C$, kg.m$^{-3}$). These properties are functions of the moisture content of the product on a dry basis ($M_{db}$, decimal dry basis).

$$C_p = 1.3556 + 5.7859M_{db} \quad (1)$$

$$\rho_C = 365.884 + 2.7067M_{db} \quad (2)$$

To calculate the thermal properties of composite materials and the thickness and equivalent thermal resistance of the various construction materials (INMETRO, 2013), we used the simplified method of generating layers of materials (LabEEE, 2015).

Table 1 - Thermal properties of materials for facilities for coffee wet processing

| Material | $\rho$ | $k$ | $C_p$ |
|---|---|---|---|
| Mortar | 2000 | 1.15 | 1.00 |
| Concrete | 2200 | 1.75 | 1.00 |
| Brick | 1800 | 1.05 | 0.92 |
| Ceramics | 1600 | 0.65 | 0.84 |
| Steel – Iron | 7800 | 55.00 | 0.46 |
| Fibercement | 1600 | 0.65 | 0.84 |

Source: Adapted from NBR-15220 (ABNT, 2003). $\rho$: density, kg m$^{-3}$; $k$: thermal conductivity, W.m$^{-1}$.K$^{-1}$; $C_p$: specific heat, W.kg$^{-1}$.K$^{-1}$.

For the calculation of the energy balance, it is necessary to calculate the heat generated within each building (heat generated by machines, lighting, and human metabolism). Table 2 shows the power values of the machines and lighting.

It was assumed that the heat exchangers of the drying machines used coal (anthracite) as fuel, which, according to Oliveros et al. (2009), has a consumption of 0.224 kg of coal per kg of dry parchment coffee, with a calorific value of 33440 $kJ.kg^{-1}$.

Table 2 - Power of coffee processing equipment

| Equipment | Power | Unit |
|---|---|---|
| Lighting | 10.00 | $W.m^{-2}$ |
| Engine of processing module | 0.37–44.76 | kW |
| Engine of mechanical dryer | 0.37–45.52 | kW |
| Mechanical dryer heat exchanger | 26.00–1625.60 | kW |

Metabolic rate, i.e. the metabolic energy that the human body expends while performing physical activities, varies from person to person, according to the activity and working conditions performed. The value of 423 $W.person^{-1}$ was used in this study for the metabolic rate; according to ASHRAE, (2001), this value corresponds to heavy work activity and handling 50 kg sacks.

A statistical analysis was performed with a linear correlation matrix to observe the existence of a linear correlation between variables: Drying capacity (kg of coffee parchment per day), building volume, natural ventilation area, mean temperature and mean relative humidity inside the facilities.

Also, a mapping of the temperature and relative humidity variables related to the power drying machines and natural ventilation area was performed, applying the Kriging gridding method using the Surfer program. Finally, from the relationships drawn from these maps, a minimum area of natural ventilation was proposed to maintain the facilities with an adequate bioclimatic environment to preserve the quality of coffee.

## 3. RESULTS AND DISCUSSION

Table 3 shows the linear correlation matrix. It can be seen that there is a linear correlation between the capacity of the machines for drying coffee and the volume of the construction (building size) and the area of natural ventilation. This result is expected, since the power of the machines, volume of the buildings and ventilation areas of actual installations were used.

Also, a direct linear correlation was observed between the internal temperature and capacity of the drying machines, and an inverse correlation between the capacity of the drying machines and the relative humidity inside the facilities. This is because, since the efficiency of these machines is 50% (Oliveros et al., 2009), this means that when the power increases, the thermal energy gain increases inside these buildings.

Furthermore, it is observed that the building volume didn't have a significant linear correlation with the variables temperature and relative humidity; however, the area of natural ventilation presented a strong inverse linear correlation with temperature and relative humidity variables. This fact suggests that as the area of natural ventilation is increased, the temperature and relative humidity decreases, because facilitates the transfer of heat and steam (produced by drying process) to the outside.

Table 3. Matrix linear correlation of different variables in facilities for coffee wet processing

| | CD | V | NVA | T | RH |
|---|---|---|---|---|---|
| CD | 1.00 | 0.86 | 0.80 | 0.69 | -0.43 |
| V | 0.86 | 1.00 | 0.74 | -0.06 | 0.10 |
| NVA | 0.80 | 0.74 | 1.00 | -0.92 | -0.83 |
| T | 0.69 | -0.06 | -0.92 | 1.00 | -0.46 |
| RH | -0.43 | 0.10 | -0.83 | -0.46 | 1.00 |

CD: capacity of the machines for drying, V: volume, NVA: natural ventilation area, T: temperature, RH: relative humidity.

Figure 2 shows a map of isolines of temperature (°C) within the wet coffee processing facilities, in function of drying capacity of machines, and area of natural ventilation. A pattern can be observed showing that when the drying capacity increases, so the internal temperature of these facilities increases; on the other hand, as the area of natural ventilation increases, so the internal temperature decreases. Osorio et al. (2016) found a similar result for a parabolic solar coffee dryer.

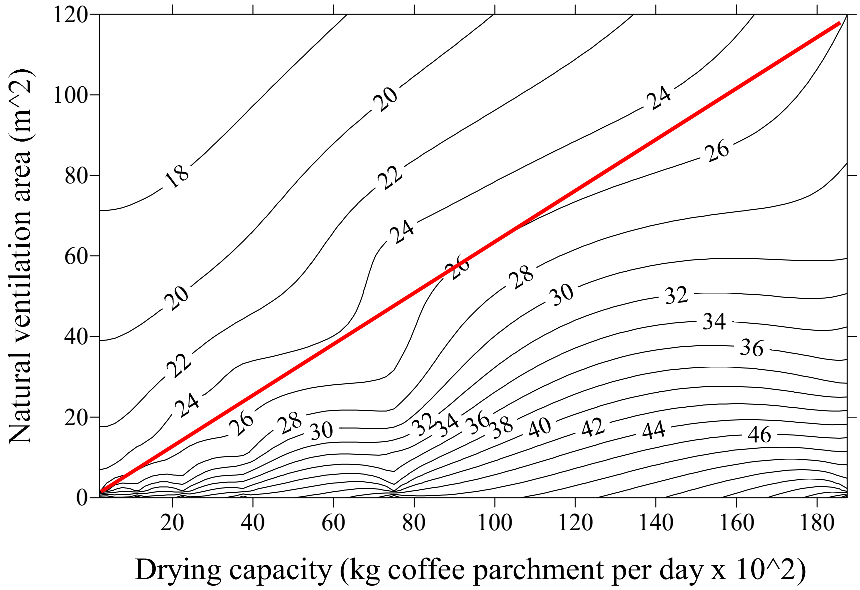


Figure 2 - Map of isolines of temperature inside of facilities for wet processing of coffee.

In Figure 2 a straight diagonal line separating the lower internal temperatures at 27°C can also be seen, which it is the limit for safekeeping grains from insect attack (Navarro; Noyes, 2001). This line is defined by equation 3, and suggests the minimum area of natural ventilation in function of the drying capacity of the machines inside the coffee processing facilities.

$$\mathrm{NVA_m} = 0.64\mathrm{DP} \quad (3)$$

Where:

$\mathrm{NVA_m}$: Minimum area of natural ventilation ($m^2$).

DP: Drying capacity (kg of coffee parchment per day x $10^2$).

Figure 3 shows a map of isolines of relative humidity (%) inside the coffee processing facilities in function to the drying capacity of the machines, and the area of natural ventilation. Similar to the temperature variable, a pattern can be observed, which shows that as the drying capacity increases, so too does the internal relative humidity of these facilities increase. On the other hand, the area of natural ventilation increases, so the internal relative humidity decreases. Osorio et al. (2016) found a similar result for a parabolic solar coffee dryer.

It can be observed in general that the facilities may be more prone to fungal attack when there is a relative humidity of between 70 and 80% (Navarro; Noyes, 2001); this is consistent with the study of Puerta (2006) and Gamboa (2012).

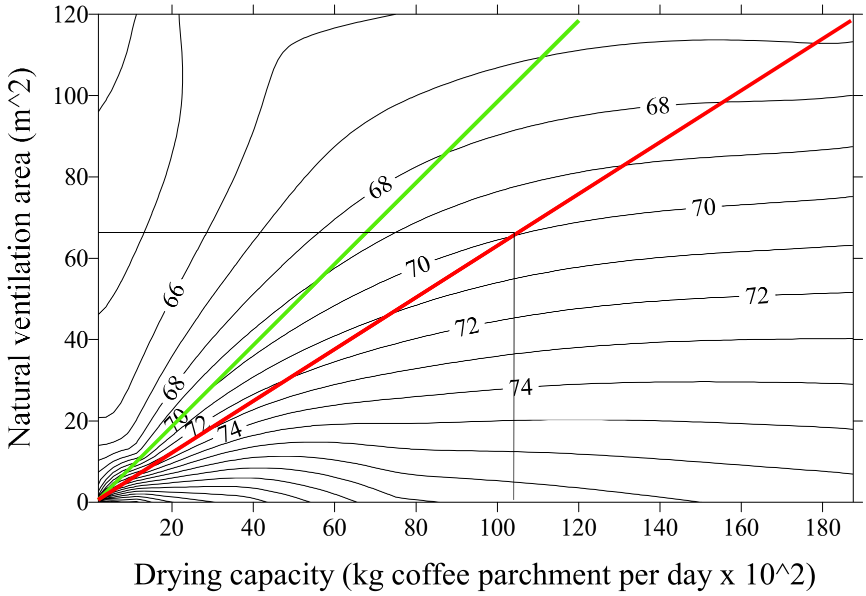


Figure 3 - Map of isolines of relative humidity inside of facilities for wet processing of coffee.

In Figure 3, two straight diagonal lines can also be observed separating relative humidities greater than 70%, in order to maintain safety in the grains (Navarro; Noyes, 2001): the red line is defined by equation 3, and its application range is to higher capacities of up to 10500 kg dry parchment coffee per day. For smaller capacities (green line), the minimum area of natural ventilation is defined by equation 4.

$$\mathrm{NVA_m} = 1.00\mathrm{DP} \tag{4}$$

With a higher drying capacity the slope of the isolines relative humidity within the facilities decreases, and this can be explained by the fact that although the increasing drying capacity of the machines increases the emission of water vapor, it also increases its addition of thermal energy, and so the temperature and pressure saturation vapor, and thus the relative humidity trends to decrease.

The dimensions of natural ventilation openings are very important, but so is its location (Baêta; Souza, 2010). Because within in buildings for wet processing of coffee is generated large amount of heat and steam, it is recommended to take advantage of dynamic and thermal ventilation, using air inlets located on the bottom of the building, and air outlets located on top of the facility, in order to direct the airflow (Lomas, 2007) warm and steam laden outside of the building. It is recommended future studies in CFD in this regard.

## 4. CONCLUSIONS

In facilities used for the wet processing of coffee, with drying machines inside, as the capacity of such machines is increased, so the internal temperature and relative humidity tends to increase, due to the addition of heat and steam inside.

There is an inverse linear correlation between the natural ventilation area in facilities used for the wet processing of coffee with drying machines inside, and the temperature and relative humidity inside.

In this study it was found equations that relate the minimum area for natural ventilation and capacity of drying machines for facilities for coffee wet processing. It is possible, by using the capacity of the coffee drying machines, to calculate the required minimum area of natural ventilation to reduce the biohazard inside coffee processing facilities.

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# CHAPTER 3 - EFFECT OF DIFFERENT CONFIGURATIONS OF THE OPENINGS FOR NATURAL VENTILATION ON THE BIOCLIMATIC ENVIRONMENT OF A FACILITY FOR COFFEE WET PROCESSING

**ABSTRACT**: This study aimed to analyze the effect of the area and location of openings for natural ventilation on the temperature and relative humidity inside a facility for coffee wet processing with mechanical drying inside, using modeling in computational fluid dynamics modeling (CFD), in order to preserve the quality through bioclimatic conditions suitable for the coffee parchment. A significant effect was found regarding the area and location of the openings for natural ventilation on the internal hygrothermal environment, but no significant effect was found on the temperature. It was also found that the chimney effect played a decisive role in the mass transfer of steam (in terms of reducing the relative humidity) and heat to the outside of this building, and helped to maintain a suitable internal environment for the preservation of coffee parchment.
**Keywords:** CFD modeling, coffee quality, mechanical drying of coffee, biological risk, hygrothermal environment.

## 1. INTRODUCTION

Coffee is one of the most popular beverages in the world (López, 2005; López, 2006). Behind petroleum, coffee is the world's second most valuable traded commodity (Garcia et al., 2014). Global coffee consumption has also risen at an average annual rate of 1.9% over the past 50 years (ICO, 2016). Coffee plants are grown in tropical and subtropical regions of Central and South America, Africa, and South East Asia, mainly in regions with temperate and humid climates (Garcia L. et al., 2014). Nearly 25 million households around the world depend on coffee (Wintgens, 2009). Latin America produces more than half the world's coffee, with Brazil (world's largest producer) and Colombia (third largest producer) these two countries, with approximately 40% of production of coffee in the world (ICO, 2016).

Producing coffees with better quality represents good differentials in product price and hence more profit for the producer (Pereira et al., 2010). Specifically, the post-harvest coffee process is one of the primary points for the preservation of coffee bean quality (Ribeiro et al., 2011; Carvajal et al., 2012; Clemente et al., 2015). It is estimated that the post-harvest process and storage affect more than 50% the quality of the final product (Giomo, 2012).

In regions like Colombia, Central America and Hawaii, Arabica coffees are processed via the wet method, where mature coffee cherries are harvested, the pulped to remove the exocarp and mesocarp. Then, the thin mucilaginous layer surrounding the coffee seeds is removed via a natural fermentation process or is removed mechanically. Finally, the coffee beans are sun-dried or mechanically to a moisture content of 11-12%. The coffee is dried in the interest of maintaining its quality and storing it for extended periods of time (Borém et al., 2007; Ciro et al., 2010; Ciro et al., 2011; Ghosh; Venkatachalapathy, 2014; Wei et al., 2015).

On the other hand, microbial contamination could occur in the cherries and during the harvesting, fermentation, drying and storage of coffee beans (Puerta, 2008; Silva et al., 2008; Kleinwächter; Selmar, 2010; Oliveros et al., 2013). Bacteria, yeasts and filamentous fungi have been reported in the pulp and beans of coffee processed in Brazil, India, Hawaii, Congo, Argentina, Colombia, Costa Rica, Ethiopia and Mexico (Silva et al., 2008). Filamentous fungi predominate at the end of processing and during storage, with effects in terms of the flavor and aroma of the beverage, but fungi also present a safety risk to the final product, due to the production of toxic secondary metabolites, i.e. mycotoxins, which can be harmful to consumers at certain concentrations (Taniwaki, 2006; Paterson et al., 2014).

The indoor environment conditions of the place where parchment coffee is stored (warehouse of storage or facilities for processing of coffee) are very important. Fungi live and reproduce best between 70 to 80% relative humidity, whereas yeast and bacterial development require humidity higher than 85% in the intergranular air (Navarro; Noyes, 2001). The biological risk is latent in facilities carrying out the wet processing of coffee; for example, according to Puerta, (2006), *Aspergillus ochraceus* was found in 70% of the facilities tested in Colombia, including coffee postharvest facilities, solar dryers, coffee parchment and green coffee. These authors also claimed that these microorganisms can proliferate only when adequate conditions of humidity, temperature, time and unhygienic conditions occur.

With respect to the temperature variable, temperatures above 50°C can kill the seed of coffee and begin a process of decomposition. In the tropical zone, with temperatures higher than 27°C and relative humidity above 70%, freshly harvested beans, and processed grains can be attacked by insects common in storage (Navarro; Noyes, 2001).

Farmers often keep store parchment stage or green-bean coffee for long periods before it can be transported to a sale point (Osorio et al., 2016), particularly more remote farmers. In the humid/rainy conditions, moisture can build up in stored beans, promoting the development of fungi and bacteria (Navarro; Noyes, 2001).

In Colombia, approximately 70% of the volume of coffee is dried mechanically (Gonzalez et al., 2010). This process generates a lot of steam and heat into the facilities. In post-harvest coffee processing, the greatest power consumption occurs in the mechanical drying process, which has an efficiency of 50% (Oliveros et al., 2009). The fact that machines generate heat inside agroindustrial buildings for processing of reinforces the importance of natural ventilation and its beneficial effect on the removal of water vapor (Baêta; Souza, 2010) during the drying process.

Natural ventilation is very important to improve indoor air quality and to reduce energy consumption in buildings, especially when the indoor temperature is close to or higher than the temperature of the external environment (Lomas, 2007; Wang et al., 2014; Aflaki et al., 2015). The strategic design of natural ventilation is often disregarded, since as there are no standards available to support designers in the project of natural ventilation openings (Schulze; Eicker, 2013). The size and location of the openings for natural ventilation, and their correct orientation are important factors to consider in the control of air streams (Baêta; Souza, 2010; Ralegaonkar; Gupta, 2010).

Design errors and poor control of coffee processing facilities can compromise the quality of the coffee beans due to an inadequate bioclimatic environment (Osorio et al., 2015; Osorio et al., 2016). The bioclimatic approach of buildings in warm and wet tropical regions requires previous bioclimatic work, analyzing the envelope to limit the power contributions and optimize the flow of air from natural ventilation (Bastide et al., 2006).

Computational modeling of natural ventilation related to energy consumption and thermal comfort has been carried out using different methods (Norton et al., 2009; Schulze; Eicker, 2013; Oropeza; Ostergaard, 2014). Computational fluid dynamics modeling (CFD) modeling has been widely used in rural buildings, specifically in the bioclimatic analysis of greenhouses and livestock facilities (Norton et al., 2009). The most complete approach in bioclimatic building simulation is the CFD method. Software using the CFD model are essentially based on the resolution of the Navier-Stokes equations (Tu et al., 2007). The CFD method is mainly employed for its ability to produce a detailed description of the different flows inside buildings. It is based on the decomposition of each building zone in a large number of control volumes with homogeneous or heterogeneous global mesh. Thus, it allows one to study very complex geometries of the building by locally minimizing the mesh of specific parts (Foucquier et al., 2013). Specifically, so far not is reported in the literature, studies about bioclimatic CFD analysis, applied to coffee processing facilities.

The aim of this study was to analyze the effect of the area and the location of openings for natural ventilation on the temperature and relative humidity inside a facility for coffee wet processing with mechanical drying coffee inside, using computer modeling in CFD, in order to preserve the quality of coffee by establishing bioclimatic conditions suitable for coffee beans.

## 2. MATERIAL AND METHODS

This study was conducted in Barbosa city (Antioquia-Colombia) at coordinates 6°26'15"N, 75°19'50"W, 1700 m altitude, average temperature of 22°C (in November), in a typically facility for wet processing of coffee, oriented east-west, with a coffee cherry production of about 156250 $kg.year^{-1}$ (31250 $kg.year^{-1}$ of parchment coffee). The internal environment of the building was simulated for the month of November, during the main harvest of the year, which coincides with the second rainfall season in this part of Colombia (Oviedo et al., 2014), that is the most critical situation for operability conditions of the coffee buildings.

Figure 1 shows a sketch of installation for processing coffee. This facility has two floors (of equal size) in stepped form. On first floor is a mechanical drying area, and second floor is an area for pulped, fermented, and classified coffee. The dimensions of this building are: 5.50 m wide x 9.50 m long x 4 m high. The building has 15 cm of unplastered brick cladding, with two windows on western side of 1.15 m x 0.6 m, and a window in roof discontinuity of 4.80 m x 0.30 m. These windows remain open all time (unglazed). The roof is made of fiber cement tiles (slope of roof 20%).

The heat exchanger drying machine uses coal (anthracite) as fuel, which, according to Oliveros et al. (2009), has a consumption of 0.224 kg of coal per kg of dry parchment coffee, with a calorific value of 33440 $kJ.kg^{-1}$. The mechanical dryer of this building has a drying capacity of 1125 kg of parchment coffee per day. The mass flow of steam produced was 0.05 kg of $water.sec^{-1}$, and its temperature was 30°C. Floor temperature was 20°C and average outdoor temperature 22°C.

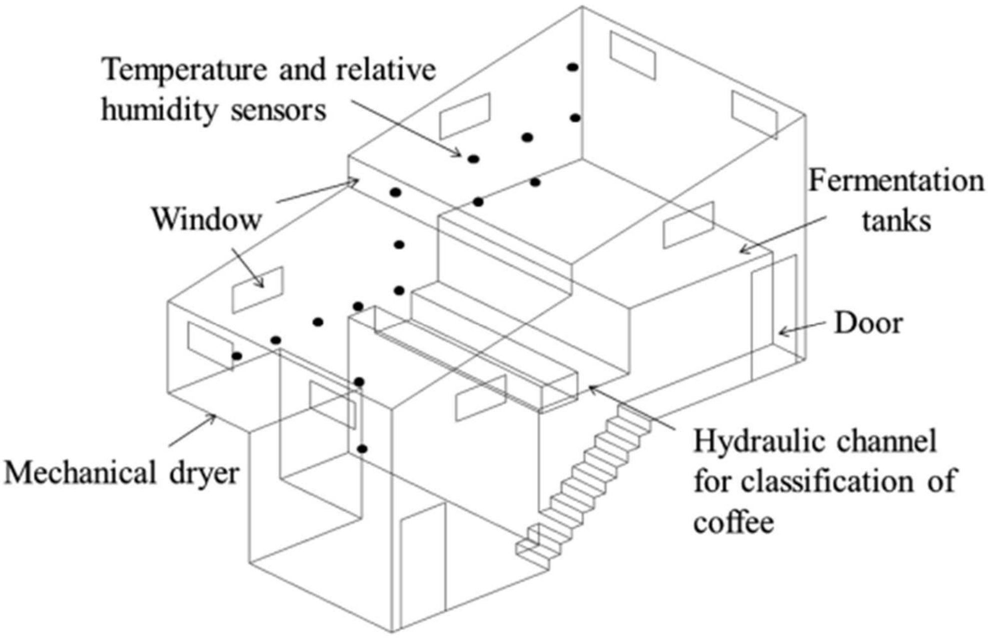
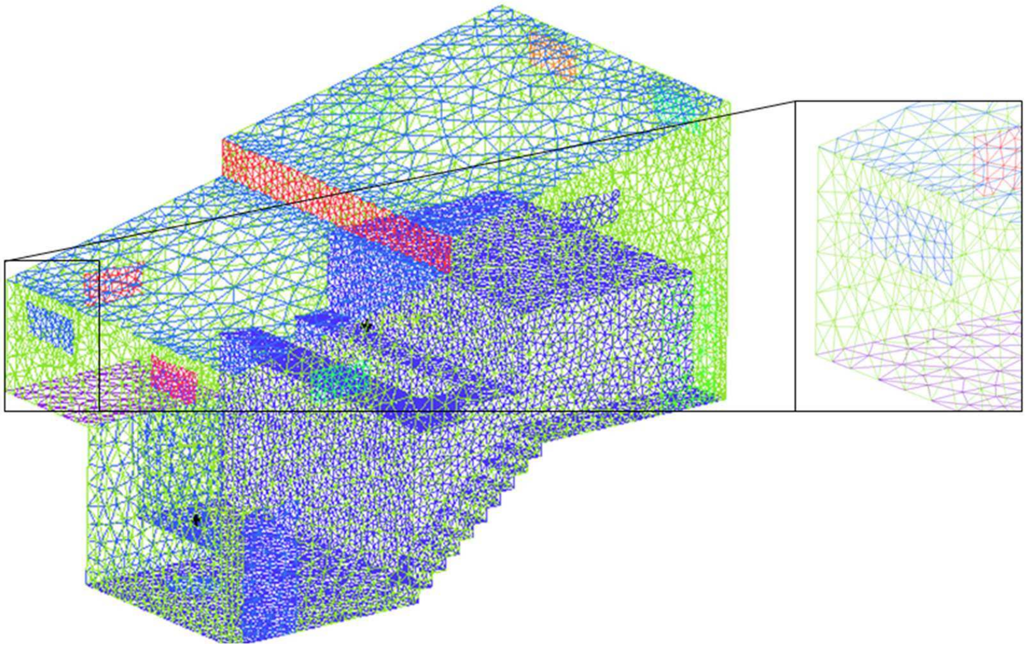


Figure 1 - 3D geometry of the facility for wet processing of coffee.

To collect the experimental data of temperature and relative humidity, 15 temperature sensors DS18B20 (0.5°C accuracy in the temperature range of -10°C to 85°C), and 15 relative humidity sensors HIH400 (measuring range 0 to 100%, ± 2% accuracy) were installed in this facility, as shown in Figure 1. Data on temperature and relative humidity were acquired by Arduino™ micro-controllers. Building surfaces temperature were taken with a thermal imaging (infrared) camera (measuring range -20°C to +1200°C, ± 2°C or 2% accuracy).

The 3D geometry (1:1 scale) of the facility for coffee wet processing was developed in computational domain using a CAD tool. The geometry was then imported into software ANSYS® ICEM CFD (version 13) for development of a tetrahedral mesh consisting of 15287 nodes and 74514 elements (Figure 2).

CFD-based computer models help with the visualization of scalar and vector fields of indoor environments by means of solving a set of equations that describe fluid flow, commonly known as the Navier-Stokes equations (Tu et al., 2007). Turbulence was modeled using the standard k-ε turbulence method, which evaluates the viscosity ($\mu_\tau$) from a relationship between the turbulent kinetic energy (k) and the turbulent kinetic energy dissipation (ε). It was used as a criterion to define solution convergence, i.e. a mean square error (MSE) of the smallest solution of $10^{-4}$.



Source: the authors.

Figure 2 - Building for coffee wet processing with a tetrahedral computational grid.

The model that describes non-isothermal fluid flow is described by the simplified equations (1, 2, 3 and 4) of mass, continuity, energy and species (Tu et al., 2007; Kim et al., 2008; Rocha et al., 2013); where: $C_A$: concentration of species, g.m$^{-3}$; $C_p$: specific heat, W.kg$^{-1}$.K$^{-1}$; D: diffusion coefficient, m$^2$.s$^{-1}$; $\rho$: density, kg m$^{-3}$; $k$: thermal conductivity, W.m$^{-1}$.K$^{-1}$; $\vec{m}$: velocity component, m.s$^{-1}$; $T$: temperature, K; T: transposition operator; $U$: velocity vector; $\mu_\tau$: dynamic viscosity of the fluid, kg.m$^{-1}$.s$^{-1}$.

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \quad (1)$$

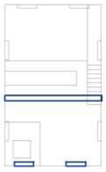
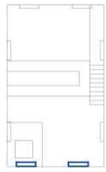
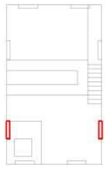
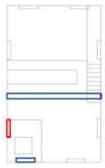
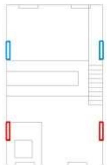
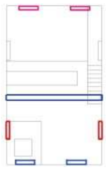
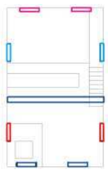
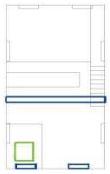
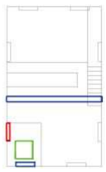
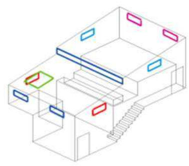
$$\frac{\partial(\rho U)}{\partial t} + \nabla.(\rho U U) = \nabla p + [\mu_\tau(\nabla U + \nabla U^{\mathrm{T}})] \quad (2)$$

$$\frac{\partial(C_p T)}{\partial t} + \nabla.\left(-k\nabla T + \rho C_p T U\right) = 0 \quad (3)$$

$$\frac{\partial C_A}{\partial t} + \vec{m}.\nabla C_A = \nabla(\mathrm{D}\nabla C_A) \quad (4)$$

Different options for natural ventilation openings were simulated in order to determine the influence of vent area and the location of the openings on the temperature and relative humidity inside the facility. The different treatments can be seen in Table 1. Treatment 1 had the actual configuration of natural ventilation, while other treatments were different options of area and location of the openings for natural ventilation, including the use of a skylight of 1.0m x 1.0m with an opening of 10 cm on the roof over the drying machine (treatments 8 and 9).

Table 1 - Architectural plan with different options of natural ventilation in terms of area and location of the openings

| | | | |
|---|---|---|---|
| T1 control<br>Ventilation area: 2.8 $m^2$ |  | T2<br>Ventilation area: 1.4 $m^2$ |  |
| T3<br>Ventilation area: 1.4 $m^2$ |  | T4<br>Ventilation area: 2.8 $m^2$ |  |
| T5<br>Ventilation area: 2.8 $m^2$ |  | T6<br>Ventilation area: 5.6 $m^2$ |  |
| T7<br>Ventilation area: 7.0 $m^2$ |  | T8<br>Ventilation area: 3.2 $m^2$ |  |
| T9<br>Ventilation area: 3.2 $m^2$ |  | 3D Sketch |  |

The results from the CFD model (T1 control) were verified and compared to those corresponding to the experimental measurements. Concordance between the measured values and those described by the CFD model were also evaluated by calculating the normal mean square error (NMSE) recommended by the American Society for Testing Materials (American Society for Testing Materials, 2002) (equation 1). For this, the average of the 15 points of temperature data and the 15 points of relative humidity data was calculated. Values with an NMSE less than 0.25 were accepted as good indicators of concordance; as this value approaches zero, the concordance between measured and predicted values is greater. For the statistical comparison of different treatments, a statistical analysis of variance ($p < 0.001$) and post hoc test (Tukey, $p < 0.050$) was performed for the analysis of temperature and relative humidity.

$$NMSE = \frac{\frac{1}{n}\sum_{i=1}^{n}(Y_{pi} - Y_{mi})^2}{Y_{pi}Y_{mi}} \quad (1)$$

Where:

$Y_p$: predicted value

$Y_m$: measured value

## 3. RESULTS AND DISCUSSION

A comparison between the data obtained by the model and the experimental data of the control treatment showed an NMSE of 0.0031 for temperature and 0.0025 for relative humidity, indicating good agreement between the results (Table 2). It was therefore concluded that the proposed model can be used to accurately predict the behavior of temperature and relative humidity in the indoor facility.

Table 2 - Comparison of experimental and modeled data for temperature and relative humidity of control treatment

| | Indoor air temperature (°C) | | Indoor relative humidity (%) | |
|---|---|---|---|---|
| | Experimental | CFD model | Experimental | CFD model |
| Average | 26.1 | 26.2 | 90.1 | 90.3 |
| NMSE | 0.0031 | | 0.0025 | |

NMSE: normal mean square error.

Table 3 shows the ANOVA for comparison of average temperature, and Table 4 shows the average temperature data for the different treatments. It was found that increasing the vent area led to a slight fall in temperature (agreeing with the results of Osorio et al. (2015) and Osorio et al. (2016), as well as with the use of the skylight. However, for the temperature, no differences were found among different treatments, in this case suggesting that there is little effect of the position of natural ventilation openings on the indoor temperature of the building.

Table 3 - ANOVA for comparison of average temperature

| Source of Variation | Degrees of freedom | Sum of squares | Mean square | F-value |
|---|---|---|---|---|
| Between Subjects | 14 | 322.8 | 23.0 | |
| Between Treatments | 8 | 32.3 | 4.0 | 2.2 |
| Residual | 112 | 209.5 | 1.9 | |
| Total | 134 | 564.5 | | |

Table 4 - Statistical data of mean temperature (°C) inside of facility with the different configurations of opening for natural ventilation

| Treatment Name | N | Mean (°C) | Maximum (°C) | Minimum (°C) | Standard Deviation | Ventilation area ($m^2$) |
|---|---|---|---|---|---|---|
| T1 control | 15 | 26.1 a | 28.9 | 22.9 | 1.8 | 2.8 |
| T2 | 15 | 26.4 a | 29.9 | 22.9 | 2.1 | 1.4 |
| T3 | 15 | 26.3 a | 29.9 | 23.9 | 1.8 | 1.4 |
| T4 | 15 | 25.3 a | 28.9 | 22.9 | 1.7 | 2.8 |
| T5 | 15 | 26.3 a | 29.9 | 22.9 | 2.0 | 2.8 |
| T6 | 15 | 25.6 a | 28.8 | 21.8 | 2.0 | 5.6 |
| T7 | 15 | 25.3 a | 28.7 | 21.7 | 2.6 | 7.0 |
| T8 | 15 | 25.1 a | 28.6 | 20.9 | 2.3 | 3.2 |
| T9 | 15 | 25.2 a | 28.7 | 20.9 | 2.4 | 3.2 |

Means followed by the same letters do not differ by the Tukey test at 0.05 probability ($p = 0.036$, $F = 2.157$).
N: number of data.

Table 5 shows the ANOVA for comparison of average relative humidity, and Table 6 presents the statistical analysis of relative humidity inside the facility. It was observed that there was a significant effect of the natural ventilation area on reducing the internal relative humidity. A statistically significant difference was found between treatments, on one hand for T4, T6 and T7, and on the other hand for T8 and T9 with respect to the other treatments. This means that, besides the effect of natural ventilation area, the position of the natural ventilation openings, in this case, had a considerable effect, showing that when they were closer to the source of steam emission (T4), the internal relative humidity decreased.

On the other hand, in T8 and T9, the fact that the skylight was located on the same axis of the emission source of steam and heat (mechanical dryer), the proximity of other openings of the steam emission source, and the chimney effect (process by which air, when heated, becomes less dense and rises) played the most important role in the removal of water vapor, as a considerable decrease in the relative humidity and temperature was observed.

Table 5 - ANOVA for comparison of average relative humidity.

| Source of Variation | Degrees of freedom | Sum of squares | Mean square | F-value |
|---|---|---|---|---|
| Between Subjects | 14 | 531.5 | 38.0 | |
| Between Treatments | 8 | 22984.7 | 2873.1 | 304.6* |
| Residual | 112 | 1056.6 | 9.4 | |
| Total | 134 | 24572.8 | | |

Table 6 - Statistical data of mean relative humidity (%)

| Treatment name | N | Mean | Maximum | Minimum | Standard Deviation |
|---|---|---|---|---|---|
| T1 control | 15 | 90.3 a | 95.0 | 87.9 | 2.1 |
| T2 | 15 | 92.3 a | 95.3 | 90.1 | 1.3 |
| T3 | 15 | 92.9 a | 95.5 | 92.2 | 1.0 |
| T4 | 15 | 75.9 b | 94.0 | 68.9 | 7.9 |
| T5 | 15 | 90.4 a | 95.0 | 89.0 | 1.9 |
| T6 | 15 | 87.9 c | 94.0 | 78.8 | 4.1 |
| T7 | 15 | 86.9 c | 93.5 | 75.9 | 4.6 |
| T8 | 15 | 58.9 d | 61.1 | 58.1 | 0.8 |
| T9 | 15 | 58.7 d | 60.9 | 57.9 | 0.8 |

Means followed by the same letters do not differ by the Tukey test at 0.05 probability ($p < 0.001$, $F = 304.56$). N: number of data.

Under the bioclimatic conditions of T1, T2, T3 and T5 on the one hand, and of T6 and T7 on the other hand, the biological risk was latent (Puerta, 2006), as these conditions presented a relative humidity above 85%, which can increase the risk of bacterial growth (Navarro; Noyes, 2001).

Although, treatment T4 presented conditions with less relative humidity (mean of 75.9%) than configurations T1, T2, T3 and T5, this relative humidity constitutes a risk to the final product, due to the production and proliferation of filamentous fungi which can adversely affect the quality of the final product, due to the production of toxic secondary metabolites, i.e. mycotoxins, which can be harmful to consumers at certain concentrations (Taniwaki, 2006; Paterson et al., 2014).

Figure 3 shows in more detail the profiles of temperature and relative humidity inside the facility for treatments T1 (control treatment), T4 (two windows near the steam outlet of the drying machine), T8 (original configuration + skylight) and T9 (T4 configuration + skylight). It was observed that, in general, temperatures above 300.15°K (27°C), risking insect attack (Navarro; Noyes, 2001), occurred only near the vapor outlet of the drying machine in all treatments.

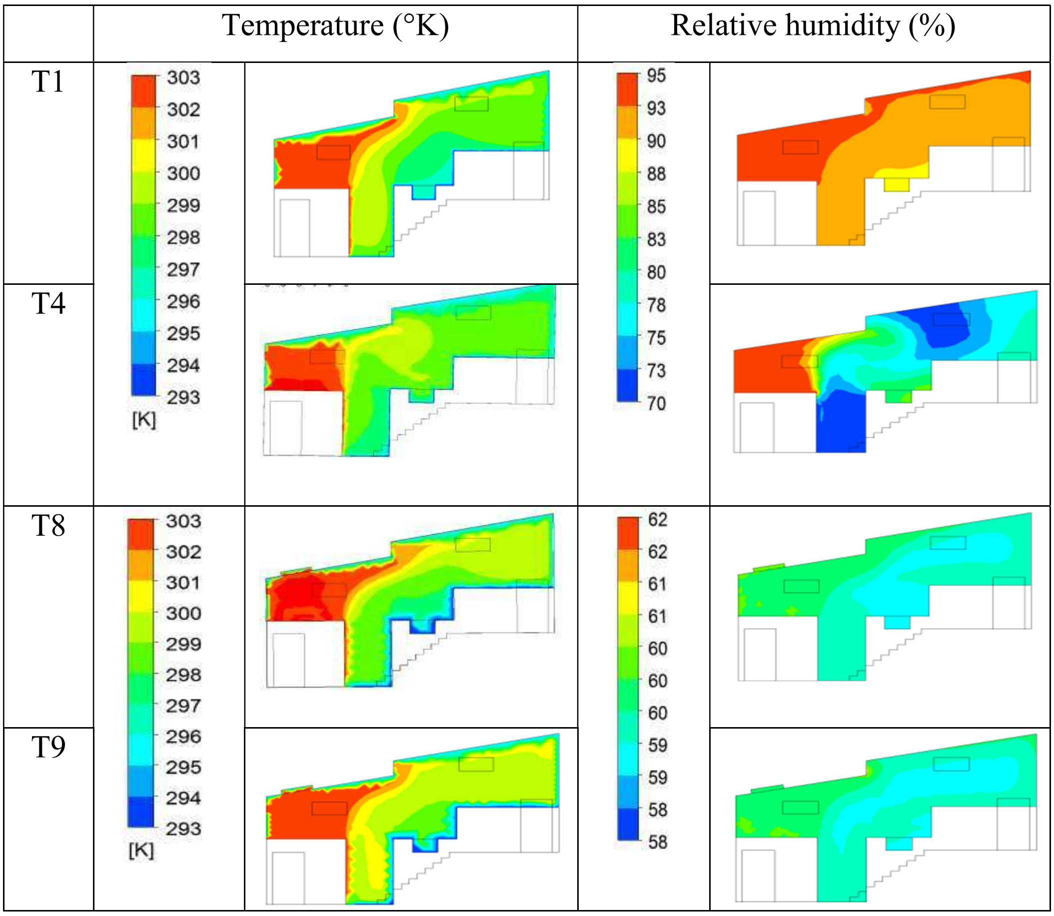



Figure 3 - CFD profiles of temperature and relative humidity of treatments T4, T8, T9 and T1 (control).

Moreover, Figure 3 shows that the T1 configuration presents a relative humidity above 85% throughout its volume, a moisture level that can increase the risk bacterial growth (Navarro; Noyes, 2001). T4 presented a relative humidity greater than 85%, but only around the steam outlet of the coffee drying machine; in some areas, it presented a relative humidity between 70-85%, a moisture level that can promote the development of filamentous fungi (Navarro; Noyes, 2001). However, T8 and T9 showed a relative humidity lower than 70% throughout the entire volume, which makes these configurations the most appropriate to preserve the quality of coffee.

## 4. CONCLUSIONS

CFD modeling proved to be a useful tool for the bioclimatic analysis of facilities for coffee wet processing.

Through CFD modeling, a significant effect of the natural ventilation area was observed in terms of reducing the relative humidity inside the facility investigated in this study.

The location of the openings for natural ventilation play an important role for providing a suitable bioclimatic environment for preserving the quality of coffee, suggesting the need for locating these openings close to emission sources of steam and heat.

In the context of facilities with machines that generate a lot of steam and heat inside, the chimney effect plays a decisive role in vapor mass transfer to outside the building, and thus helps to maintain the internal environment under suitable bioclimatic conditions.

T8 and T9 treatments presented the best bioclimatic conditions, suggesting that make these small changes in the buildings for coffee wet processing of this typology in Colombia could improve conditions to preserve grain quality.

In future studies, CFD models could be developed with this and other constructive typologies, with larger areas of natural ventilation close to the steam outlet of coffee drying machines and the addition of several skylights, in order to find patterns that provide an adequate bioclimatic environment for each constructive typology for facilities for coffee wet processing.

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