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COFFEE BEANS INDUSTRIAL VIBROFLUIDIZED BED DRYING OPTIMIZATION (*Coffea arabica L.*)

OPTIMIZACIÓN DE UN SECADOR INDUSTRIAL DE LECHO VIBROFLUIDIZADO, PARA SECAR CAFÉ (*Coffea arabica L.*)

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Abstract

Drying is one of the most important operations in the coffee processing industry, which consists of removing moisture content in the grain, from 55% to 10 or 12%. In the present paper, an industrial dryer of vibrofluidized bed of coffee beans (*Coffea arabica L.*) was optimized, which until the year 2017 presented losses in the drying process about 19% of total coffee beans treated. An analysis of the hydrodynamic and vibrational operation parameters of the dryer was carried out, as well as considerations on the physical properties and drying kinetics of coffee beans. The process operated continuously with a mass flow of coffee beans (m_{s1}) of 3800 kg/h, an initial bed height (L_f) of 5 cm and a total drying time (t_T) of 1.3 h. The optimum temperature was 225 ºC, which allowed to obtain a light green color, named in the color scale as Pantone 5803C, which denotes a high quality for the type of coffee bean processed in the industry, with a final humidity of 0.131 kg of H_2O/kg SS and maintaining a drying speed of 9.6 kg de H_2O/m^2 h.

Keywords: vibrofluidized dryer, optimization , drying kinetics, temperature.

Resumen

El secado es una de las operaciones más importantes en la industria procesadora de café, que consiste en eliminar parte del agua del grano, desde 55% de contenido de humedad hasta un 10 a 12%. En el presente trabajo se realizo la optimización de un secador industrial de lecho vibrofluidizado de granos de café (*Coffea arabica L.*), el cual hasta el año 2017 presentaba pérdidas en el proceso de secado de hasta un 19% de total de granos de café tratados. Se realizo un análisis de los parámetros de operación hidrodinámicos y vibracionales del secador, además de consideraciones sobre las propiedades físicas y la cinética de secado de los granos de café. El proceso opero en continuo con un flujo másico de granos de café (m_{s1}) de 3800 kg/h, una altura inicial del lecho (L_f) de 5 cm y un tiempo total de secado (t_T) de 1.3 h. La temperatura óptima resulto de 225 °C, lo que permitió obtener un color verde muy claro, denominado Pantone 5803C, que denota un alta calidad del grano de café procesado, con una humedad final de 0.131 kg de H_2O/kg SS y manteniendo una velocidad de secado de 9.6 kg de H_2O/m^2 h.

Palabras clave: secador vibrofluidizado, optimización, cinética de secado, temperatura.

1 Introduction

In food industry, drying is one of the oldest methods of preserving food by reducing the amount of moisture in the food matrix to reduce enzymatic activity that deteriorates the product quality (Madiouli *et al.*, 2012; Sabarez, 2015) The drying process involves the elimination of water from food by the application of heat, in order to facilitate product handling, reduce storage and transportation costs, improve appearance, maintain nutritional value and preserve organoleptic properties (Tinoco and Ospina 2010, Hernandez-Diaz *et al.*, 2013).

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In recent years, fluidized-bed drying has been one of the most widely methods used for processing agricultural products, due to performance and quality, and the preservation of physical and chemical properties, Gas-solid fluidization, which is the operation whereby gas is passed through a bed of solid particles thereby suspending particles into a fluid-like state. The minimum fluidization velocity is the gas velocity at which the drag force of the upward moving gas becomes equal to the weight of the particles and is one of the most important parameters (Sivakumar *et al*., 2016; Daud, 2008; Rahman, 2008). One of the variants of fluidized-bed drying is the vibrating bed.

In fibrous materials, such as coffee beans, they shrink greatly as moisture is lost, causing variation in the material surface per unit weight, the development of a hardened surface layer (moisture flow barrier), and shrinkage cause cracking of the material and changes in its structure (Jokanović *et al*., 2012). The dry coffee bean must meet certain physical quality specifications based on moisture and color to ensure that there will be no significant loss of moisture or breakage during the roasting process (Kwak *et al*., 2007).

A study of the operating parameters of the vibrofluidized bed dryer was carried out, it was observed that the bad control temperature caused a shrinkage effect in the coffee beans causing a loss by breaking of 2.4% (wich represents 1,267 kg/day) In addition, a variable humidity of 10.2% dry base in the coffee beans was recorded, which had a significant effect on the total weight of the production, since the 65 tons/day that were programmed, only 52.8 tons/day were produced. In order to reduce losses, the purpose of this study was to optimize the coffee bean drying process through modifications of operating parameters of the vibrofluidized bed dryer, based on calculations of the material and energy balances, drying kinetics and hydrodynamics studies, to ensure a moisture value and an olive green - Pantone 5773C color of high quality coffee beans.

2 Materials and methods

The present work was carried out in the production area of soluble coffee processing industry, the optimization was focused on the drying process of coffee beans (*Coffea arábica L.*) in a vibrofluidized bed dryer, for this purpose a survey was carried out of the operating conditions such as: drying air temperature, system pressure, air volumetric flow, air mass flow and minimum fluidization speed, the measurement of these parameters made it possible to evaluate the quality problem of the final product, represented by the moisture content below the established value (see Table 1).

2.1 *Raw material*

For this study, coffee beans of Veracruz and Oaxaca states in Mexico were used, which before entering the production process must comply with certain characteristics and quality parameters (Table 1), according to the supplier's specifications; if the moisture content is high, the green color of the bean changes its tonality to dark green, when the storage time is prolonged, the color of the coffee bean is very light green and when it is subjected to thermal treatments the color of the beans tends to darken because they are very susceptible to high temperatures.

The colour of the coffee beans was determined according to the colour scale shown in Figure 1, which is indicative of good manufacturing practices because factors such as temperature, storage and moisture content in the beans result in different bean tones.

Table 1. Quality parameters of raw coffee beans.

Coffee bean features	**Parameter**
% coffee bean wash	100% Washing
Odour	Clean and without contamination
Size	50% above shank 5.95 mm, and 5% under 5.55 mm
Colour	Olive green (80% homogeneous or greater)
Moisture	10 to 12.5% on dry basis
Acidity	From very good to excellent
Number of defects	Up to 15 grains in 100 grams of coffee

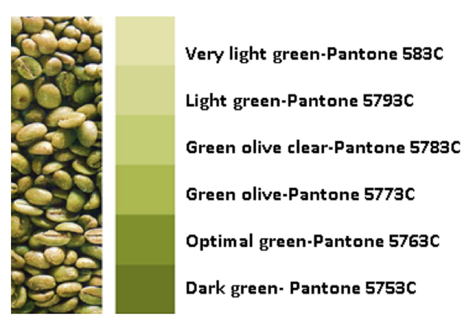

Fig. 1. Classification of coffee beans by colour.

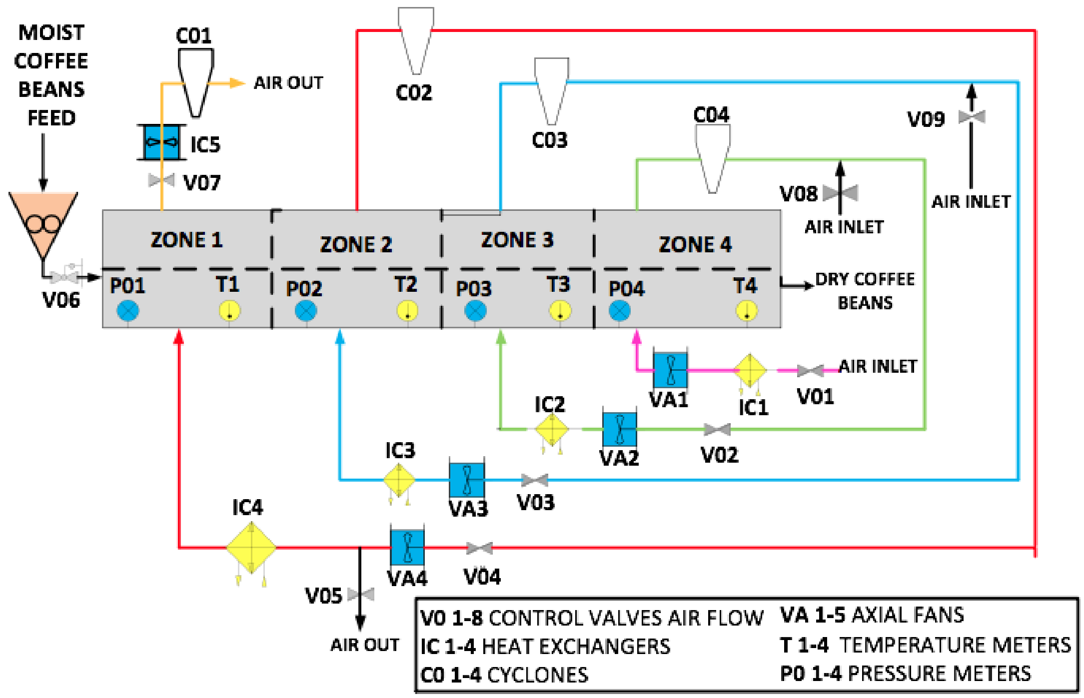

Fig. 2. Process diagram of the URBAR vibrofluidized dryer.

2.2 Operation of the vibrofluidized bed dryer

The industrial vibrofluidized bed dryer used in this study was the URBAR brand (Figure 2) it consists of a rectangular section of stainless steel with an area of 41.5 m^2. It is divided in four zones, three drying zones (zone 1, zone 2 and zone 3), and one cooling zone (zone 4), zone 1 (Z1) measures 4.1×1.82 m, zone 2 (Z2) 7.6×1.82 m, zone 3 (Z3) 7.6×1.82 m, and zone 4 (Z4) 3.5×1.82 m, all with a height of 1.5 m isolated thermally. Each zone has a distributor plate with different number of holes in a triangular design that allows a homogeneous distribution of air in the fluidization chamber with orifice diameters of 0.003 m, 0.0023 m, 0.002 m and 0.0018 m from Z1 to Z4 respectively.

Each zone has a number of holes of different sizes to regulate the air flow to chamber for fluidization. The temperature and velocity of the air in the four zones is different to carry out the fluidization, the reduction of the diameter in the orifices causes the velocity of fluidization to increase.

The air used for the vibrofluidized bed dryer was supplied from the atmosphere before a filtering process and was recirculated to each zone with axial fans (VA1, VA2, VA3 and VA4). To cool and heat the air by radiators heat exchangers (IC1, IC2, IC3, IC4). The temperature conditions for the air in each zone (Z1 to Z4) were: 250 °C, 220 °C, 120 °C and 32 °C. The hot air circulation ducts are made of galvanized steel with asbestos coating to obtain thermal efficiency and have a dust collector cyclone at the outlet of each zone of the dryer. The air flow to each zone is controlled by means of pneumatic control valves (V01, V02, V03, V04, V07 and V08) to prevent the equipment from being pressurized to a maximum of 124 Pa valves V07 and V08 were controlled.

2.3 Determination of the physical properties of the coffee bean

Average unit volume. The average unit volume of the beans was determined by the method of displacement of a fluid for irregularly shaped particles (Mohsenin, 1970). 100 coffee beans were added to a graduated cylinder with edible vegetable oil and the volume of oil displaced was measured, which is related to the number of beans.

$$V_c = \frac{level\ displaced}{number\ of\ specks} \tag{1}$$

The equivalent diameter. Corresponds to the diameter of a sphere with the same volume of grain (Kunii and Levenspiel, 1991); this was calculated using the expression where (V_c) is the unit volume according to equation (2):

$$d_{eq} = \left[\left(\frac{6V_c}{\pi}\right)\right]^{1/3} \tag{2}$$

Density packed. Coffee beans up to a known volume were placed in a test tube. Mass particles ((M_C), equivalent to the volume particles (V_T) weighing on an analytical balance, the mass was divided by volume to determine the packed density.

$$\rho_e = \frac{(M_C)}{V_T} \tag{3}$$

Apparent density. The coffee beans were placed in a test tube up to a known volume, the coffee mass filling the volume was weighed on an analytical balance and the corrected volume, which is the total volume minus the volume of the gaps between the beans introduced into the tube, was then measured.

$$\rho_a = \frac{unit\ \ mass}{unit\ \ volume} \tag{4}$$

Sphericity. It was calculated with the relation of the dimensions of the coffee bean, a random sample of 100 coffee beans was taken and length (a), width (b) and high (c) of each grain where measurements to obtain an average (Mohsenin, 1970).

$$\phi = \frac{(a \cdot b \cdot c)^{1/3}}{a} \tag{5}$$

The porosity of the bed. The porosity of the packed bed (ε_0) was calculated once the apparent (ρ_a) and packed (ρ_e) density were known (Kunii and Levenspiel, 1991).

$$\varepsilon_0 = 1 - \frac{\rho_e}{\rho_a} \tag{6}$$

2.4 Determination of hydrodynamic parameters

Fluidized bed porosity: The fluidized bed was determined using experimental data of the studies carried out by Sánchez *et al*. (2008) who works with a similar beans and operating conditions, because the measurement involved entering the dryer to perform the observations and this was not possible because vibrofluidized dryer is industrial scale, and it remained in operation.

$$\frac{1}{\phi \varepsilon_{mf}^3} \cong 14 \tag{7}$$

Fixed bed height: This parameter was determined taking into account the sphericity, bulk density, total area of the fluidized bed (41.5 m^2) as well as controlling the initial height of the bed to achieve fluidization of the particles, the initial conditions were determined considering a coffee mass of 1267 kg.

$$L_f = \frac{n_c}{(1-\varepsilon_0)\rho_a A_L} \tag{8}$$

Height of the bed under minimum fluidization conditions. This parameter was determined from the initial height of the bed (L_f) which is the bed height under conditions of minimum fluidization, bed porosity (ε_0), as well as the minimum fluidization porosity (ε_{mf}).

$$L_{mf} = \frac{L_f(1-\varepsilon_0)}{1-\varepsilon_{mf}} \tag{9}$$

Minimum fluidization rate. The minimum fluidization rate (V_{mf}) was calculated in each zone of the dryer, because each one has different operating parameters. ρ_g was calculated according to local atmospheric pressure, air inlet temperature and fan design parameters.

$$V_{mf} = \frac{(\rho_s - \rho_a) g d_{ed}^2 \varepsilon_{mf}^3}{\mu_a 180(1-\varepsilon_{mf})} \tag{10}$$

Once the physical and hydrodynamic properties of the coffee bean had been determined and the initial parameters which the dryer operated had been taken into account, the theoretical pressure drop for each zone (Eq. 11) was determined, as well as the pressure drop in the distributor (Eq. 12) and the total pressure drop (Eq. 13).

$$\Delta pB = (1-\varepsilon_{mf})(\rho_s - \rho_a) g L_{mf} \tag{11}$$

$$\Delta P_g = 0.3 \Delta pB \tag{12}$$

$$\Delta P_T = \Delta pB + \Delta P_g \tag{13}$$

2.5 Determination of the vibration parameters

Vibration frequency. A stroboscope (Strobe Lamp skf N 021) was used to measure the speed of the motor which, in conjunction with the concentric pulleys, induces the vibrations, a beam of light was passed with the stroboscope to the motor rotor to measure the vibration frequency and convert it to revolutions per minute (r.p.m.) as shown in Eq. 14.

$$f = \frac{1}{\theta} = \frac{\omega}{2\pi} = \frac{rpm}{60s} \quad (14)$$

Amplitude. Using a digital vernier in perpendicular position to the distributor plate of the dryer to measure the displacement in each concentric pulleys. The equipment was subjected to vibrations and with a stroboscope, the maximum displacement reached by the plate with respect to its static position was visualized. With these two data the angular frequency (ω) and the vibrational intensity (τ), equations 15 and 16 respectively, were determined

$$\omega = 2\pi f \quad (15)$$

$$\tau = \frac{Am\omega^2}{g} \quad (16)$$

Minimum vibration fluidization speed. This value was measured by regulating the air flow for fluidization by means of pneumatic control valves and the pressure drop in the bed was recorded in equipment control panel, starting from the maximum permissible air flow in the dryer, the flow was gradually reduced to zero, and this measurement was carried out for each dryer zone.

2.6 Determination of drying kinetics in continuous operation

To construct the drying kinetic curves, work was carried out at temperatures of 225, 185, 75 and 25 ºC for each zone, 1-4 respectively, and the moisture content was determined on a dry basis (X_0) as a function of time (t) related to the drying speed (kg of H_2O/h·m^2) as a function of time (t). For this, sampling points were placed in each zone of the dryer as shown in Figure 3 and the necessary samples were taken from each zone to build the drying curve, this procedure was expedited to avoid stopping the coffee production process for a long time.

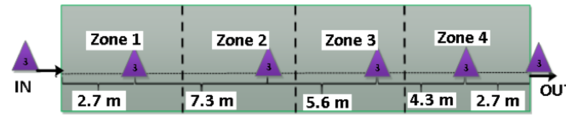

Fig. 3. Sampling points in the vibrofluidized dryer.

2.7 Initial moisture measurement on a wet basis

It was calculated using a thermobalance with an operating range from 0.01 to 100% humidity and a temperature range of 50-200 °C. The critical humidity and equilibrium was determined from the drying curve (Colina, 2010).

$$X_{bh} = \frac{Mass\ of\ water\ in\ a\ product}{Total\ mass\ of\ wet\ product} \quad (17)$$

2.8 Coefficient of heat transfer by convection

The coefficient of heat transfer by convection of Eq. (18) is used to determine the drying time at the constant and decreasing speed stage in each zone of the dryer according to the minimum fluidization rate (Colina, 2010; Treybal, 1968).

$$h_c = 24.2G^{0.37} \quad (18)$$

2.9 Determination of the total drying time

To calculate the total theoretical drying time in each zone of the vibrofluidized bed dryer the following equations were used considering that on decreasing stage the moisture is eliminated by capillarity. Drying speed was calculated in the constant speed stage $\left(\frac{dW}{dt}\right)_c$ and in the decreasing velocity stage $\left(\frac{dW}{dt}\right)_d$ using equations 19 and 20, respectively (Colina, 2010).

$$\left(\frac{dW}{dt}\right)_c = -\frac{h_c A'_T (T_a - T_s)}{\lambda \rho_s} \quad (19)$$

$$\left(\frac{dW}{dt}\right)_d = -\frac{h_c A'_T (T_a - T_s)(X_f - X_e)}{\lambda \rho_s (X_c - X_e)} \quad (20)$$

From the constant and decreasing speed, the increasing drying time (t_c), decreasing (t_d) and total (t_T) in each stage was determined with equations 21, 22 and 23, respectively (Colina, 2010).

$$t_c = \frac{\lambda \rho_s (X_0 - X_c)}{h_c A'_T (T_a - T_s)} \tag{21}$$

$$t_d = \frac{\lambda \rho_s (X_c - X_e)}{h_c A'_T (T_a - T_s)} \ln\left(\frac{X_c - X_e}{X_f - X_e}\right) \tag{22}$$

$$t_T = t_c + t_d \tag{23}$$

2.10 *Balance of matter and energy*

For the material and energy balance (Figure 4), it was considered that solids entered with a velocity of m_{s1} (kg solids/h) a moisture x_{s1} (kg of H_2O/kg S.S.) and a temperature T_{s1} (°C) and that it goes out to x_{s2} and T_{s2}. The gas enters at m_{a1} (kg dry air/h) with moisture of x_{a1} (kg of H_2O/kg dry air) and temperature T_{a1}, the gas exits at T_{a2} y x_{a2} (Colina, 2010).

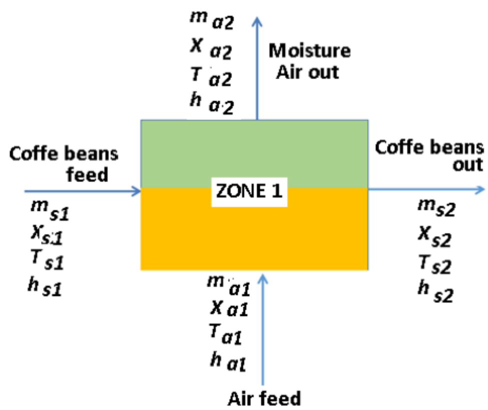

Fig. 4. Representative block for matter and energy balance.

Equations from 24 to 28 are derived from the respective material and energy balance with the moisture (x_a) shown in Figure 4:

$$m_{a1} x_{a1} + m_{s1} x_{s1} = m_{a1} x_{a2} + m_s x_{s2} \tag{24}$$

$$h_{a1} = c_s (T_{a1} - T_0) + x_{a1} \lambda_0 \tag{25}$$

$$C_s = 1.005 + 1.88 x_{a1} \tag{26}$$

$$h_{s1} = C_{ps}(T_{s1} - T_0) + x_{a1} C_{pa} (T_{s1} - T_0) \tag{27}$$

$$m_{a1} h_{a1} + m_{s1} h_{s1} = m_{a1} h_{a2} + m_{s1} h_{s2} + Q \tag{28}$$

where h_{a1}, h_{s1}, h_{s2}, c_s, C_{ps}, C_{pa}, T_{a1}, T_0, λ_0 and Q where considered in an adiabatic process, $Q = 0$, and if heat is added, Q is negative, the units of measurement were kJ, kg and °C.

3 Results and discussion

Optimum temperatures were assessed from the balance of matter and energy for the best performance of fans installed in the vibrofluidized bed dryer.

Table 2. Operating parameters in each zone of the vibrofluidized dryer.

Parameter	Zone 1	Zone 2	Zone 3	Zone 4
Mass flow of evaporated water (kg / h)	543	477	189	0
Mass flow of coffee at the entrance (kg / h)	3800	3257	2780	2591
Mass flow of coffee at the outlet (kg/h)	3275	2780	2591	2591
Volumetric flow of air at the entrance (m3/h)	19664	14923	11927	33125
Input air moisture (kg of H2O/kg of dry air)	0.0518	0.0466	0.0278	0.0161
Output air moisture (kg H2O/kg dry air)	0.0812	0.0831	0.0466	0.0161
Moisture of coffee at the entrance (kg of H2O/kg of dry solid)	0.4	0.3	0.18	0.12
Moisture of the coffee at the exit (kg of H2O/kg of dry solid)	0.3	0.18	0.12	0.12
Inlet Air temperature (ºC)	225	185	75	25
Output Air temperature (ºC)	70	140	60	35
Coffee beans inlet temperature (ºC)	40	120	90	70
Coffee beans output temperature (ºC)	120	90	70	25

Table 3. Physical properties of coffee beans.

Physical characteristics	**Mean**	**n***
Length of the coffee beans (a) m	9.56×10^{-3}	100
Coffee beans width (b) m	7.13×10^{-3}	100
Height of the coffee beans (c) m	6.41×10^{-3}	100
Unitary average volume (V_c) m^3	1.733×10^{-7}	10
Apparent density (ρ_a)kg/m^3	1,384	10
% final moisture on dry basis (X_f)	10.2	30
Colour	Dark coffee	30

Table 4. Hydrodynamic parameters of the coffee beans.

Physical characteristics	**Amount**
Height of the bed in a state of minimum fluidization L_{mf} (m)	0.7
Initial bed height L_f (m)	0.05
Total pressure drop in the bed ΔP_T (Pa)	169
Packed density ρ_e (kg/m^3)	609
Equivalent diameter d_{eq} (m)	6.92×10^{-3}
Sphericity ϕ	0.71
Porosity of the bed ε_0	0.56
Porosity of the bed in the state of minimum fluidization ε_{mf}	0.64

Table 2 shows the values of the parameters that should work with each area according to the balances. Table 3 shows the mean values (n * number of grains) of the physical properties of the coffee beans, these values were similar to the ones of the coffee beans used by Moreno *et al*. (2007) and Ramirez *et al*. (2007) who reported to *Coffea arabica L.* y *Coffea arabica L. var. typical*, values of 9.6×10^{-3}, 6.4×10^{-3} and 4×10^{-3} m for its dimensions of length, width and height respectively to 11% grain humidity, the only value that showed a difference was the height of grain that was lower (0.4 cm) to the ones measured during this investigation (0.6 cm). Bulk density was 1,384 further to those reported by Ramírez *et al*. (2007).

The average values of the hydrodynamic parameters of the coffee bean for an initial humidity of 40% on the dry basis coffee are shown in table 4, according to these values and compared with the classification made by Geldart (1990). The sphericity of 0.71, was similar to the value reported in other studies in which the temperature that was used was a temperature of 220° C, close to the proposal in this article (225° C), this value is closely linked with the mechanism of the water removal, if the grain water is removed by diffusion this value varies considerably (Ramírez *et al*., 2007; Colina, 2010).

While the values corresponding to the equivalent diameter (6.917×10^{-3} m) and porosity of the bed (0.56) are similar to those reported by Ramírez *et al*. (2007) which are (6.917×10^{-3}m) and 0.5, respectively for the equivalent diameter and porosity, which are indicated by increasing the temperature to 240 °C, these values were higher, this is explained by the expansion suffered by the structure of the grain by the formation of internal pores. The parameters mentioned directly influence the minimum fluidization speed.

The optimal vibrational parameters for the drying process are shown in table 5, this data was achieved by keeping the vibrational frequency constant and taking two amplitude values to characterize the process. When the vibrational intensity was higher than the unit, the vibrations favored the fluidization of the coffee bean and a lower amount of air (35%) was required in the vibrofluidized bed.

The minimum speed of vibrofluidización (V_{mv}) obtained for each zone of the vibrofluidized bed is shown in Figure 5. The minimum fluidization speed (V_{mf}) was higher according to the minimum vibrofluidization velocity, this being the effect of the hydrodynamics of the coffee beans inside the dryer, however the difference is notable in figure 5a.

Table 5. Vibrational parameters for optimal operation.

Parameter		**Amount**				
Turning speed		315 (r.p.m.)				
Vibrational frequency (Fr)		5.25(Hz)				
Angular frequency (ω)		32.9 (1/s)				
Amplitude (Am)		Vibration intensity (τ)	V_{mv} (m/s) Z1	V_{mv} (m/s) Z2	V_{mv} (m/s) Z3	V_{mv} (m/s) Z4
Less	0.0180 (m)	1.99	8	9	11	12
Higher	0.0254 (m)	2.80	7	8	10	10.5

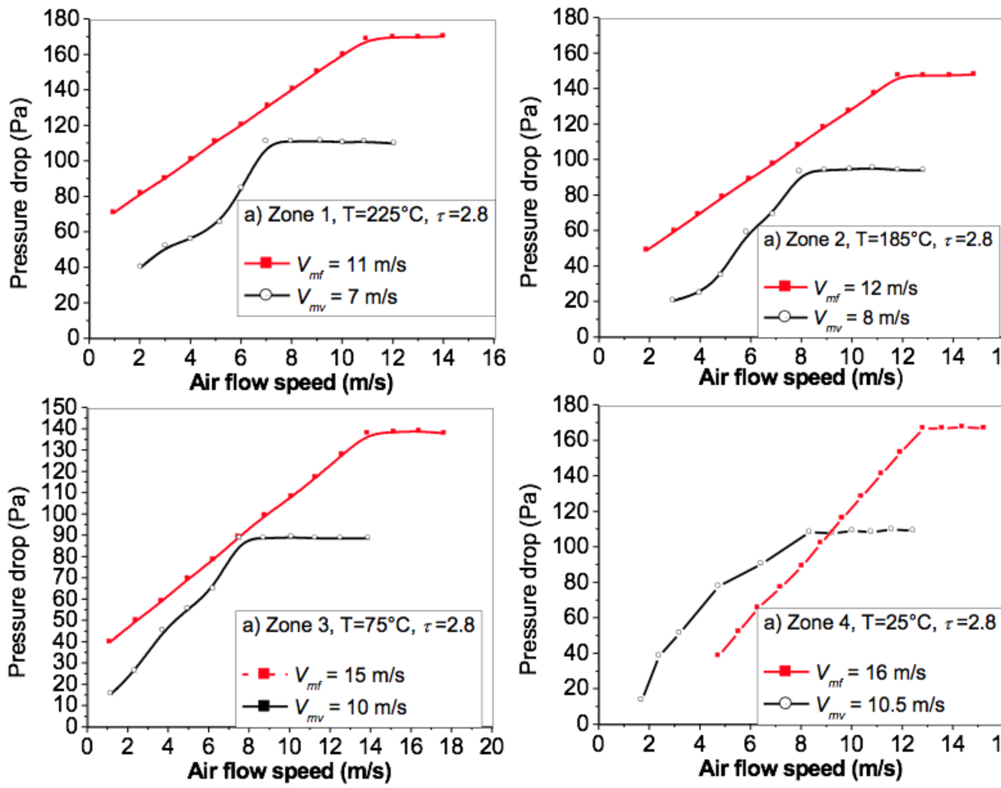

Fig. 5. Minimum fluidization speed.

The theoretical velocity of minimum fluidization was 11 m/s while the vibrofluidization was 7 m/s, this is because the vibration allows the passage of air through the grains more effectively by decreasing the work required by the fans due to the decrease of the operating pressure drop. The drying kinetics were evaluated before modifying the operating parameters of the dryer to identify the periods of constant speed and decreasing speed of the drying curve, the results are shown in table 6.

The theoretical parameters of drying kinetics were calculated, heat transfer coefficient (h_c), drying time in the constant and decreasing speed stage (the sum of both determine the total drying time and the drying speed). The results obtained from the drying curve if compared with the drying speed vs. humidity, figure 6, they show the behavior of the drying profile of the coffee bean, the initial humidity was 0.666 kg of H_2O/kg SS.

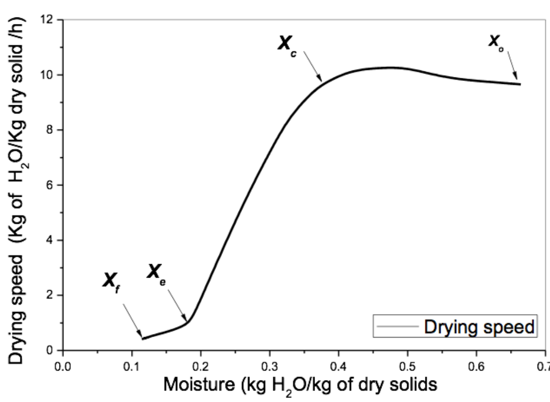

Fig. 6. Kinetic for coffee beans.

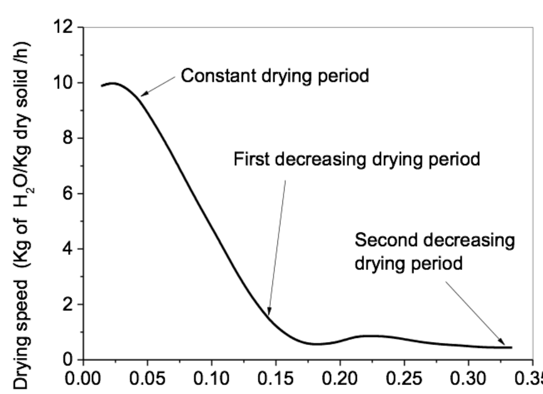

Fig. 7. Speed profile for the drying process.

Table 6. Parameters for drying kinetics.

Parameter	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
h_c (kcal/h m^2 ºC)	27.13	37.75	94.00	139.66
Theoretical drying time (h)	0.023	0.118	0.110	0.068
Total theoretical dry time (3800 kg)	60.23 min			
$\left(\frac{dW}{dt}\right)_c$	4.1 kg of H_2O/h·kg of dry air			
$\left(\frac{dW}{dt}\right)_d$	1.08 kg of H_2O/h·kg of dry air			

The water evaporation speed is constant 9.6 kg H_2O/m^2h, and the phase of the decreasing period starts from a critical humidity of 0.378 kg H_2O/kg SS and ends with a humidity of 0.131 kg of H_2O/kg SS. In determining the drying speed as a function of time, Figure 7, it was found that the constant speed period 0.05 h, at this stage the free water is eliminated and the surface of the product is kept moist and this could be a factor by which two periods of decreasing drying are present, the first occurring from 0.05 to 0.15 h where the diffusivity allows the internal humidity to move towards the surface of the grain as fast as it evaporates.

Table 7 shows the average values of the operating parameters of the vibrofluidized bed dryer before (a) and after (b) the proposed changes for the drying process. The proposed air temperature was 225 °C, this value compared to the previous one presented a lower variability, which indicated an improvement in temperature control, this trend was consistent for temperature in the other areas (Z2, Z3 and Z4), which were periodically declining to 25 °C in the Z4.

Another objective was to increase the percentage of humidity in the coffee bean until reaching 12% b.s. that was expected according to the quality requirement of the company, an increase of 10.2% b.s. to 11.4% b.s. was achieved, although it was relatively small this increase was sufficient to decrease the percentage of breakdown loss from 2.4 to 1.1%, which in terms of losses represents in total production of 1.267 kg/day up to a total of 660 kg/day of coffee beans that were rejected.

Table 7. Vibrofluidized dryer operating parameters a) before and b) after optimization.

Operating condition	**Parameter**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
(a)	Pressure (Pa)	1976	1104	1978	2100
	Air speed (m/s)	3.5	4.2	4.8	6.1
	Air temperature (°C)	250	220	120	32
	% final moisture (X_f)	10.2% dry basis			
	% of lose by breaking	2.4% (1267 kg/day)			
	Colour	*Dark coffee, not registered in the color scale*			
	Dry time	1.3 hours			
(b)	Pressure (Pa)	1169	1244	2488	2737
	Air speed (m/s)	7.0	8.0	10.0	10.5
	Air temperature (°C)	225	185	75	25
	% final moisture (X_f)	11.4% dry basis			
	% of lose by breaking	1.1% (660 kg/day)			
	Colour	*Very light green-Pantone 5803C acceptable on the colour scale*			
	Dry time	0.97 hours			

Conclusions

Optimization of the process of drying of coffee bean obtained a very clear green grain-Pantone 5803C, with a humidity of 11.4% b.s. The period of decreasing drying speed was greater than the constant speed period, which caused a long residence time. The color change in the coffee beans was attributed to a high and variable temperature in the drying air, and the time of residence in each drying area that was very prolonged. The drying time was reduced from 1.3 h to 0.97 h.

The minimum vibrofluidization velocity achieved was: Z1, 7 m/s; Z2, 8 m/s; Z3, 10 m/s and Z4, 10.5 m/s, operating with a vibrational intensity of 2.80 for fluidization, this allowed the darkening and cracking of the coffee beans (Coffe arábica L.) to be avoided in the drying process when they were in contact with the distribution plate. The increase of the vibrations reduces the time of residence; therefore, it is important to check the values of the theoretical time of residence necessary for the drying in each zone.

It was possible to reduce the percentage of loss by breaking from 2.4 to 1.1%, which represents a reduction in losses of 1,267 kg/day up to a 660 kg/day of coffee beans that were rejected.

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Nomenclature

a Particle length (m)
A_L Total area bed (m^2)
Am Amplitude (m)
A'_T Product surface area/Product bedding volume (m^2/m^3)
b Particle width (m)
c Particle height (m)
C_P Specific heat (kJ/kg de air °C)
C_{ps} Dry solid heat capacity (kJ/kg Dry solid·K)
C_{pa} Liquid water heat capacity (kJ/kg H_2O·K)
C_s Humid air heat capacity (kJ/kg air °C)
d_{eq} Particle equivalent diameter (m)
$\left(\frac{dW}{dt}\right)_c$ Drying speed at constant speed stage ((kg)/(h))
$\left(\frac{dQ}{dt}\right)_c$ Heat transfer speed at constant speed stage (kcal/h)
$\left(\frac{dW}{dt}\right)_c$ Drying speed in the decreasing speed stage (kg H_2O/kg Dry solids)/h
Fr Vibrational frequency (Hz)
G Air speed mass (kg/m^2s)
g Gravity acceleration (m/s^2)
h_a Specific enthalpy (kJ/kg Dry air)
h_{a1} Air enthalpy to the inlet of the dryer (kJ/kg Dry air)
h_{a2} Air enthalpy to the dryer leakage (kJ/kg Dry air)
h_c Convection heat transfer coefficient (kcal/h m^2 °C)
h_{s1} Solid-humid enthalpy (kJ/kg Dry solid)
H_a Drying air humidity (kg H_2O/kg Dry air)
H_S Air saturation humidity (kg H_2O/kg Dry air)
H_{sp} Moisture on the surface of the product (kg H_2O/kg Dry air)
k_a Air heat transfer coefficient (kcal/h m^2 °C)
k_m Mass transfer coefficient (kg/m^2·h)
L_f Initial height of the bed (m)
L_{mf} Height of the bed in a state of minimal fluidization (m)
m_a Mass flow of air (kg/h)
m_{a1} Mass flow of air at the inlet of the dryer (kg/h)
m_{a2} Mass flow of air at the dryer outlet (kg/h)
m_c Mass of coffee in the bed (kg)
m_{s1} Mass flow of solids in the feed (kg/h)
m_{s2} Mass flow of solids at the output (kg/h)
m_v Air volumetric flow (m^3/h)
m_{v1} Volumetric air flow for drying in zone one (m^3/h)
p Water vapor pressure in a food at a given temperature (kPa)
p_0 Water vapor pressure at the same temperature (kPa)
P_A Steam water partial pressure (kPa)
P_p Weight of bedding particles (kg)
ΔP_T Total pressure drops in the bed (Pa)
ΔP_g Pressure drop in grid (Pa)
ΔpB Pressure drop along the bed (Pa)
P_T Total steam water pressure (kPa)
Q Loss of heat in drying in (kj/h)

r	Product radio (m)
rpm	Revolutions per minute
t	Time (s,min,h)
t_c	Product drying time at constant speed stage (h)
t_d	Drying time of the product in the decreasing speed stage (h)
t_T	Total drying time of the product (h)
T_a	Drying air temperature (°C)
T_{a1}	Air mass flow temperature at the dryer inlet (°C)
T_{a2}	Air mass flow temperature at dryer outlet (°C)
T_s	Surface temperature of the product being dried (°C)
T_{s1}	Temperature of the particles at the entrance (°C)
T_{s2}	Temperature of the particles in the output (°C)
T_0	Air base temperature or steam water (0°C or 32 °F)
v	Air velocity (m/s)
V_c	Unit volume of bedding (m^3)
V_l	Volume of the particle-occupied bed (m^3)
V_{mf}	Minimum fluidization speed (m/s)
V_{mv}	Minimum vibrofluidization speed (m/s)
V_P	Specific volume (m^3/kg Dry air)
x_{a1}	Moisture contained in the inlet air to the drying (kg H_2O/Dry air)
x_{a2}	Moisture contained in the exhaust air of the dryer (kg H_2O/Dry air)
X_{bh}	Moisture content of the particle on wet basis (%) o (kg S.S./kg H_2O)
X_{bs}	Moisture content of the particle in dry base (%) o (kg H_2O/kg S.S.)
X_c	Critical moisture content of the particle on dry basis (kg H_2O/kg S.S.)
X_e	Moisture content of the particle in equilibrium with the air (kg H_2O/kg S.S.)
X_f	Final moisture content of the particle in dry base (kg H_2O/kg S.S.)
X_L	Free particle moisture content on dry basis (kg H_2O/kg S.S.)
x_{s1}	Moisture of feed particles, dry base (kg H_2O/kg S.S.)
x_{s2}	Moisture from particles at output, dry base (kg H_2O/kg S.S.)

Greek symbols

λ	Latent heat from evaporation to (kcal/kg)
λ_0	Latent heat of water at temperature of 0 °C (kJ/kg)
ε_0	Bedding porosity (dimensionless)
ε_{mf}	Porosity of the bed in the state of minimum fluidization (dimensionless)
k	Variable that is depending on the constant speed stage
π	Pi number
ϕ	Sphericity (dimensionless)
ρ_g	Air density (kg/m^3)
ρ_e	Packed density of particles (kg /m^3)
ρ_a	Apparent particle density (kg /m^3)
ρ_s	Dried product density (kg Dry solids/m^3)
π_a	Air viscosity (kg/m·s)
τ	Vibrational intensity (dimensionless)
ω	Angular frequency (s^{-1})

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