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COFFEE GRAIN ROTARY DRYING OPTIMIZATION

OPTIMIZACIÓN DEL SECADO DE GRANOS DE CAFÉ EN UN SECADOR ROTATORIO

W.N. Hernández-Díaz[1*], F.J. Hernández-Campos[1], Z. Vargas-Galarza[1], G.C. Rodríguez-Jimenes[2] and M.A. García-Alvarado[2]

[1] *Depto. Ingeniería Química y Bioquímica y Depto. De Posgrado e Investigación del Instituto Tecnológico de Zacatepec. Calzada Tecnológico 27, Col. Centro, Zacatepec, Morelos, 62780, México.*

[2] *Unidad de Investigación y Desarrollo en Alimentos del Instituto Tecnológico de Veracruz, M.A. de Quevedo.2779, Veracruz, Veracruz, 91987, México.*

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Abstract

The objective of the present work was to determine the coffee bean Guardiola dryer operating conditions that minimized the energy consumption (Q) and maximized the process thermal efficiency. A mechanistic coffee bean drying model was solved for a complete mixed assumption to simulate the drying. The simulated results reproduced the experimental results obtained with a 7.60 m^3 Guardiola dryer loaded with 2675 kg of wet green coffee grains. The thermal second law efficiency of the drying was calculated with an expression that takes into account the exergy air carries before entering the dryer. For the same coffee load, and with restrictions on grain's temperature (T_β <45°C), final water content (X_β <11%) and water activity (a_w <0.80), the drying was simulated for several air fluxes and temperatures to find the optimum drying conditions (T_γ =80°C and G_γ =6560 kg air.h^{-1}). A 15.80% reduction in energy consumption was achieved when optimization results were compared with the normal operation conditions.

Keywords: optimization, thermal efficiency, drying, exergy, coffee.

Resumen

El objetivo del presente trabajo es determinar las condiciones de operación de un secador de café tipo Guardiola que minimicen el consumo de energía (Q) y maximicen la eficiencia térmica del proceso. Para simular el secado se utilizó un modelo mecanístico para secado de café, resolviéndolo de acuerdo a la suposición de mezclado completo. Los resultados de la simulación reprodujeron la conducta experimental obtenida de un secador tipo Guardiola de 7.60 m^3 cargado con 2675 kg de granos de café verde húmedo. Se calculó la eficiencia térmica de segunda Ley del secado con una expresión que toma en cuenta la exergía que el aire posee antes de entrar al secador. Para encontrar las condiciones óptimas de secado, para la misma carga de café y con restricciones de temperatura (T_β <45°C), humedad final (X_β <11%) y actividad de agua del grano (a_w <0.80), se simuló el secado para diferentes flujos y temperaturas de aire. Al comparar las condiciones óptimas encontradas (T_γ =80°C and G_γ =6560 kg aire.h^{-1}) con las normalmente utilizadas en el beneficio se logro una reducción del 15.80% en el consumo de energía.

Palabras clave: optimización, eficiencia térmica, secado, exergía, café.

[*] *corresponding author. E-mail*: wendynetz@yahoo.com.mx

1 Introduction

There are critical points concerning quality and microbiological safety in the drying of coffee beans. Several researchers have reported Ochratoxin A (OTA) mycotoxin contamination during drying (Bucheli, Kanchanommai, Meyer & Pittet, 2000; Paulino de Morales & Luchese, 2003; Suárez-Quiroz *et al*., 2004). Contamination risk is greater during sun drying due to the bean-soil contact and bean rehumidification under high relative humidity conditions. These problems could be eliminated with artificial drying. However, artificial drying is an operation of high exergy demand and it has been shown that if the bean's temperature exceeds 45°C during drying, the coffee's quality is harmed (Sfredo *et al*., 2002). The solution to this problem is to state optimal drying operation conditions that guarantee minimal energy consumption and maximizes bean's quality and thermal efficiency.

Many research reports that deal with the thermal efficiency of drying process exist (Zvolinschi, Johannessen & Kjelstrup, 2006; Wang & Chen, 2000). One of the most popular drying types (and one of the most exergy demanding) is convective drying either continuous or discontinuous. The causes of its high exergy demand is the fact that the heat transfer is indirect, that is, the heat is transferred to a work fluid (air in many cases) which then transfers the heat to the product thus evaporating the liquid. The amount of exergy used is limited by the saturation of vapor in the work fluid to the enviroment. Moreover, in many industries the work fluid is dissipated to environment with a great amount of exergy (Akpinar, Midilli & Bicer, 2006; Akpinar, Midilli & Bicer, 2005). Ramírez *et al*. (2008) proposed a thermal efficiency expression that takes into account the air's exergy before entering the dryer and strategies for optimization.

To improve the thermal efficiency of coffee grains during drying an adequate mathematical representation of the thermal process is needed. Mathematical representations of convective drying have been widely developed (Spencer, 1969; Bruce & Giner, 1993; Ratti & Mujumdar, 1995; Maroulis, Kiranoudis & Marinos-Kouris, 1995; Giner, Mascheroni & Nellist, 1996; Kiranoudis, 1998; Torrez, Gustafsson, Schreil & Martinez 1998; Barrozo, Murata & Costa, 1998; Luna, Salgado, Rodríguez & García, 2005). The model reported by Luna *et al*. (2005) is particularly useful because it is completely mechanistic and it is applicable for continuous or batch processes, or for fixed or moving beds. Luna *et al*. (2005) a dynamic modeling of a spray dryer considered as a series of well-stirred dryers. That is, a series of dryers in which the output variables are equal to the state variables. The state equations were obtained from the heat and water mass balances in product and air. Additionally, heat and water mass balances in interface jointly with water equilibrium relations between product and air were considered.

Previous coffeee drying reports (Sfredo, Finzer & Limaverde, 2005; Varadharaju, Karunanidhi & Kailappan, 2001; Pérez-Alegría, Ciro & Abud, 2001) could not be applied to this study because of the geometry and composition differences between the coffee's cherry and its grain. Hernández-Díaz *et al*. (2008) proposed a 3D expression for heat and mass transfer during coffee grain drying which provides valuable information about the moisture distribution profiles inside the grain during drying. This predicted the zones more susceptible to contamination or to mechanical stress and cracking. The obtained integrated drying kinetic equation, along with the estimated water effective diffusivity and the mass and energy coefficients, reproduced the experimental drying kinetics of a monolayer fixed bed of coffee beans.

In this work Luna *et al*. (2005) model was solved for complete mixed assumption to simulate coffee bean Guardiola drying. The thermophysical properties estimated by Hernández-Díaz *et al*. (2008) were used to simulate the process conduct. The exergy transfered to drying air and process thermal efficiency was calculated according to Ramírez *et al*. (2008). The resulting simulator was then used to determine the optimum drying conditions. In order to optimize the drying process, drying temperature, and air flow operation conditions should be monitored and adjusted according to the designed optimum path. The response surface method (RSM) is a powerful tool for process optimization. It uses quantitative data from an appropriately planned experiment to solve multivariable optimization problems. Madamba & Liboon (2001), Madamba & Lopez (2002), Villalpando-Guzman *et al*. (2011), González-Rentería *et al*. (2011), Téllez-Mora *et al*. (2012) applied RSM to find the optimum operating region for celery (*Apium graveolens*) and mango (*Mangifera indica* L.) drying. Guerrero *et al*. (1996) used the same approach to determine the optimum values of three variables for banana dehydration to obtain minimal discolorization. In this study to minimize energy consume, RSM was applied to construct a second-order polynomial surface response and, to obtain the optimum values of two operation variables (drying temperature, and air flow) for coffee bean rotary drying.

2 Mathematical formulation

2.1 Model building

The model by Luna *et al*. (2005) was rewritten for only one ideal mixed step in the dryer ($N = 1$) and no solid mass flow ($G_\beta = 0$) to represent a cylindrical rotary batch dryer (commonly used in coffee drying called Guardiola), the resulting model is described as follows:

$$\frac{dX_\beta}{dt} = \frac{k_{c\beta} a \left(X_{\beta i} - X_\beta\right)}{(1-\varepsilon)} \tag{1}$$

$$\frac{dX_\gamma}{dt} = \frac{k_{c\gamma} a \left(X_{\gamma i} - X_\gamma\right)}{\varepsilon} - \frac{G_\gamma \left(X_\gamma - X_{\gamma 0}\right)}{\rho_\gamma \varepsilon V} \tag{2}$$

$$\frac{dT_\beta}{dt} = \frac{h_\beta a \left(T_\gamma - T_\beta\right) V}{\rho_\beta (1-\varepsilon)\left(Cp_\beta + Cp_w X_\beta\right)} - \frac{T_\beta Cp_w}{\left(Cp_\beta + Cp_w X_\beta\right)} \frac{dX_\beta}{dt} \tag{3}$$

$$\begin{aligned} \frac{dT_\gamma}{dt} = &- \frac{h_\gamma a \left(T_{\gamma i} - T_\gamma\right) V}{\rho_\beta (1-\varepsilon)\left(Cp_\gamma + Cp_w X_\gamma\right)} \\ &- \frac{k_{c\beta} a \rho_\beta \left(X_{\beta i} - X_\beta\right) \lambda}{\rho_\gamma \varepsilon \left(Cp_\gamma + Cp_w X_\gamma\right)} \\ &- \frac{h_{out} A_{out} \left(T_{\gamma i} - T_{out}\right)}{\rho_\gamma \varepsilon \left(Cp_\gamma + Cp_w X_\gamma\right) V_\gamma} \\ &- \frac{G_\gamma}{\rho_\gamma \varepsilon \left(Cp_\gamma + Cp_w X_\gamma\right) V_\gamma} \\ &\times \left\{ \begin{array}{l} \left[Cp_\gamma T_\gamma + \left(H^0_{wv} + Cp_{wv} T_\gamma\right) X_\gamma\right] \\ -\left[Cp_\gamma T_{\gamma 0} + \left(H^0_{wv} + Cp_{wv} T_{\gamma 0}\right)\right] \end{array} \right\} \end{aligned} \tag{4}$$

where:

$$k_{c\gamma} \rho_\gamma \left(X_{\gamma i} - X_\gamma\right) = k_{c\beta} \rho_\beta \left(X_\beta - X_{\beta i}\right) \tag{5}$$

$$h_\gamma \left(T_\gamma - T_{\gamma i}\right) = h_\beta \left(T_{\beta i} - T_\beta\right) + k_{c\beta} \rho_\beta \left(X_\beta - X_{\beta i}\right) \lambda \tag{6}$$

$$X_{\gamma i} = \frac{18}{29} \left[\frac{a_w p_w / p}{1 - a_w p_w / p}\right] \tag{7}$$

$$a_w = f\left(T, X_{\beta i}\right) \tag{8}$$

Equations (1) and (2) represent the moisture variation with time or rate of moisture loss in solid and air. Equations (3) and (4) represent the food and air temperature variation with convective term for air, internal and external heat transfer, the latent heat required for water evaporation, and variations in the heat capacities. Equation (5) expresses the continuity of mass transfer at the interface. Equation (6) shows how at the interface, the heat flow from air is split in the heat required for water evaporation and the heat transferred to the food interior. Finally, equations (7) and (8) are the thermodynamic relation for water equilibrium between phases. In a convective dryer the environmental (or feedback air) is heated by increasing its potential of water evaporation.

Because the objective of the present work is to minimize the energy consumption (Q) increasing the thermal efficiency, the following equations for instantaneous first law and second thermal efficiencies of the drying process were added to the above equations as presented in Ramírez *et al*. (2008):

$$\eta_1 = \frac{m_\beta \lambda \frac{dX_\beta}{dt}}{Q} \tag{9}$$

$$\eta_2 = \frac{\eta_1}{\eta_{\max}} \tag{10}$$

Where m_β is the coffee grain's mass, which gradually diminishes when the drying progresses because of the water lost; Q is the energy added to the air mass to bring it from ambient temperature ($T_{\gamma out}$) to the drying one ($T_{\gamma 0}$) , it is calculated as follows:

$$m_\beta = V \rho_\beta (1-\varepsilon) \tag{11}$$

$$Q = G_\gamma \left(H_{\gamma 0} - H_{\gamma out}\right) = G_\gamma C p_\gamma \left(T_{\gamma 0} - T_{\gamma out}\right) \tag{12}$$

$H_{\gamma out}$ and $H_{\gamma 0}$ are the air's enthalpy at ambient ($T_{\gamma out}$) and drying (T_γ) temperature respectively. ε is the bed's porosity (which is a function of the change in moisture content) and G_γ is the mass air flux which was kept constant during the drying.

Equation 9 is usually referred as first law thermal efficiency. It is defined as the ratio between the energy transmitted to the solid and the energy incorporated in the drying air. Not all the energy provided by the drying air is available to perform work and therefore first law efficiency values are lower than 1.

Equation 10 is referred as Exergy efficiency or Second Law thermal efficiency. This expression considers the process Exergy, which is defined as the fraction of systems energy that can be used for spontaneous transformation to mechanical work, heat transfer, momentum transfer, mass transfer or chemical reactions. Then, the efficiency energy approach of any process must be in terms of exergy efficiency. The exergy efficiency provides a true measure of the performance of the drying system from the thermodynamic viewpoint. The exergetic efficiency can be defined as the ratio of the products exergy to exergy inflow for the drying.

Equation 10 is a function of the maximum efficiency (η_{max}). The maximum efficiency is a function of the system's exergy, which is expressed as:

$$\eta_{\max} = \frac{Ex}{Q} = \frac{G_\gamma Cp_\gamma \left(T_{\gamma w0} - T_{\gamma wout}\right)}{Q} \qquad (13)$$

Where $T_{\gamma w0}$ and $T_{\gamma wout}$ are the air's drying and ambient wet bulb temperatures respectively. In equation (13), $T_{\gamma 0}$ is used as the air's final condition and $T_{\gamma out}$ as the initial and not as a reference value as Kavak *et al*. (2005) proposed. In this way, the air's exergy before entering the dryer is taken into account. This was also considered by Prommas *et al*. (2010) for exergetic efficiency calculation.

The following expressions were used to evaluate the overall process efficiencies and energy consumption:

$$\eta = \frac{\int_0^\tau \eta(t)dt}{\int_0^\tau dt} \qquad (14)$$

$$Q = G_\gamma \int_0^\tau \left(H_{\gamma 0} - H_{\gamma out}\right) dt \qquad (15)$$

where τ is the drying time.

3 Materials and methods

3.1 Materials

Fermented washed arabica coffee beans were obtained from a local green coffee producer (Huatusco, Veracruz, México).The coffee is cultivated at 1600 m over the sea level. Its size was measured with a Vernier. The dimensions were characterized in agreement with coordinate system used, that is, the focal distance a was calculated in order that the half prolate spheroidal coordinates approximate the coffee beans shape with $R = 1$ (where R = focal distance/diffusion characteristic length). The beans initial moisture content was evaluated according to the AOAC (1990) method No. 22.013 at 60 °C and 13.30 kPa in a vacuum stove. The beans bulk density was calculated by water displacement in a graduated tube. The specific surface area was calculated with the numbers of beans in the drying bed and with surface area and volume equations for a prolate spheroid.

The Guardiola cylindrical rotary batch dryer used in coffee processing has cylindrical walls made out of perforated steel to allow wet air to get out. The cylinder is mounted on a hollow axis inside which hot drying air circulates through axial conducts. The conducts are connected to radial perforated arms from which air comes out and makes contact with the wet coffee beans. The Guardiola drier also has loading and discharge windows. The drier is batch operated and the total drying time (τ) varied according to the beans initial moisture ($X_{\beta 0}$) and load (m_β), as well as the air drying flux (G_γ) and temperature (T_γ). The Guardiola dryer used had a volume of 7.60 m^3 .

3.2 Numerical methods

Equations (1) to (15) were programmed in Fortran and Matlab R2009a and the ordinary differential equations were solved using fourth order Runge Kutta method. Then simulation was carried out according to the operating conditions specified in Table 1 for a three level arrangement of the independent variables T_γ and G_γ.

The dryer volume (V) and coffee load (m_β) correspond to a real Guardiola dryer used in the coffee factory "La Cuchilla" located in Huatusco, Veracruz, Mexico. T_γ =60°C and G_γ = 14000 kg.kg^{-1} correspond to the operation drying conditions used in the factory. For the simulations, the specific surface area, beans bulk density, bed porosity and size change were obtained from Hernández-Díaz *et al*. (2008). As well as the expressions shown in Table 2.

3.3 Response surface modeling and optimization

To establish de dependence between variables, the simulation results were analyzed using Response Surface Methodology (RSM). RSM is used to model

Table 1. Levels of independent variables simulated

Independent variable levels			
Independents Variables (x)	-1	0	+1
x_1, G_γ (kg/h)	5000	7200	14000
x_2 , T_γ (°C)	60	70	80

General variables: V=7.65 m^3; $M_{\beta o}$=2675 kg; ε = 0.4; $X_{\beta 0}$=1,1 kg.kg^{-1}; $X_{\beta \tau}$=0.136 kg.kg^{-1}; $X_{\gamma 0}$=0.018 kg.kg^{-1}

Table 2. Thermophysical properties used for model solving

a_w	1-exp(-100.103$T_{\beta 1}$7.75$X_\beta^{0.88}$)	Hernández-Díaz *et al.* (2008)
k_β (W m^{-1} s^{-1})	0.49-0.443exp(-0.206X_β)	Pérez-Alegría *et al.* (2001)
k_γ (W m^{-1} s^{-1})	8.4044x10^{-5}T+4.63x10^{-5}, T en K	Geankoplis (1982)
ΔH_{w0} (J kg^{-1})	2.501 x10^6	Geankoplis (1982)
ΔH_w (J kg^{-1})	2.501 x10^6-2.26x10^{3}T-1.7T^2, T en °C	Geankoplis (1982)
$C_{p\beta}$ (J kg^{-1} K^{-1})	1652.2+5835X$_\beta$/(1+X$_\beta$)	Pérez-Alegría *et al.* (2001)
$C_{p\gamma}$ (J kg^{-1} K^{-1})	1000	Geankoplis (1982)
$C_{p\omega\omega}$ (J kg^{-1} K^{-1})	1608.92	Geankoplis (1982)
$C_{p\omega}$ (J kg^{-1}K^{-1})	4185	Geankoplis (1982)
ρ_ω (kg m^{-3})	352.961/T, T en K	Ideal gas law
μ_γ (kg m^{-3})	5.87x10^{-6}+4.25x10^{-8}T, T en K	Geankoplis (1982)
$C_{p\omega}$ (J kg^{-1} K^{-1})	4185	Geankoplis (1982)
$D_{\omega\gamma}$	$\frac{1.86X10^{-7}T^{3/2}}{p\sigma_{w\gamma}^2\Omega_{D,w\gamma}}\left(\frac{1}{M_w}+\frac{1}{M_\gamma}\right)$	Ecuación de Chapman-Enskog
α	$891.6\left(0.36+0.64\frac{X_{\beta prom}}{X_{\beta 0}}\right)$	Hernández-Díaz *et al.* (2008)
ε	$0.4\left(0.5+0.5\frac{X_{\beta prom}}{X_{\beta 0}}\right)$	Hernández-Díaz *et al.* (2008)
$k_{c\gamma}$	ShD$_{w\gamma}$/LD	Herman-Lara *et al.*, (2005)
h_γ	Nuk$_\gamma$/ LD	Herman-Lara *et al.*, (2005)
ρ_{lecho}	$580.56\left(1.58-0.58\frac{X_{\beta prom}}{X_{\beta 0}}\right)$	Hernández-Díaz *et al.* (2008)
Nu	$0.79\left[\frac{20.4}{\varepsilon}\mathrm{Re}^{0.185}Sc^{1/3}\right]$	Geankoplis (1982)
Sh	$0.79\left[\frac{20.4}{\varepsilon}\mathrm{Pr}^{0.185}Sc^{1/3}\right]$	Geankoplis (1982)
Re	$L_D v\rho_\gamma/\mu_\gamma$	Geankoplis (1982)
Sc	$\mu_\gamma/D_{w\gamma}\rho_\gamma$	Geankoplis (1982)
Pr	$C_{p\gamma}\mu_\gamma/k_\gamma$	Geankoplis (1982)
$k_{c\beta}$	$\frac{\pi^2 D_\beta}{4L_D^2/L_D}$	Hernández-Díaz *et al.* (2008)
h_β	$\frac{12.3k_\beta}{L_D^2 a}$	Hernández-Díaz *et al.* (2008)
D_β	$\exp\left(2.7085-\frac{66857.4}{RT}+1.74\frac{X_{\beta avg}}{X_{\beta 0}}\right)$	Hernández-Díaz *et al.* (2008)

the behavior of response variables (Q, η_1 and η_2) to process variables modification, generating predictive equations which correlate this response with variables studied in the process. The polynomial models of the three response variables as a function of independent variables are shown below:

$$Q = \alpha_0+\alpha_1 G_\gamma+\alpha_2 T_\gamma+\alpha_{11}G_\gamma^2+\alpha_{22}T_\gamma^2+\alpha_{12}G_\gamma T \quad (16)$$

$$\eta_1 = \alpha_0+\alpha_1 G_\gamma+\alpha_2 T_\gamma+\alpha_{11}G_\gamma^2+\alpha_{22}T_\gamma^2+\alpha_{12}G_\gamma T_\gamma \quad (17)$$

$$\eta_2 = \alpha_0+\alpha_1 G_\gamma+\alpha_2 T_\gamma+\alpha_{11}G_\gamma^2+\alpha_{22}T_\gamma^2+\alpha_{12}G_\gamma T_\gamma \quad (18)$$

Usually a second order polynomial is sufficient to model the process and perform the optimization (Villalpando-Guzman *et al.*, 2011; González-Rentería *et al.*, 2011). These predictive equations (models) can be used to optimize the process and to estimate the expected response to combinations of factors not directly tested. For each treatment, the dependent variables were evaluated and the data submitted to a multivariate regression analysis, whose model contained linear, quadratic and interacting terms for the two independent variables. To prepare the adjusted models and its respective surfaces, only the statistically significant parameters for acceptance of the null hypothesis were considered. This for a probability value p <0.05. The validity of the models was evaluated by means of the multiple regression tool of the Microsoft Office Excel software as a function of their respective coefficients of determination as well as by an ANOVA.

After RSM was applied and the second order polynomials obtained, optimization was carried out according to Luna *et al.* (2005) using the Complex algorithm programmed in Matlab R2009a and Fortran. The optimization criteria was to determine the value of the independent variables (x) that minimized the energy consumption (Q), and maximized the process first and second law thermal efficiencies (η_1 and η_2); fixing as (m) restrictions: a_w <0.80 (to prevent mycotoxin formation), final water content< 11% or $X_\beta = 0.13$ kg (kg of dry matter)$^{-1}$, grains temperature < 45°C. Production size was fixed at 2675 kg of wet green coffee beans for all the treatments in Table 1, this production size was established because it accounts for 60% volume of the simulated Guardiola drier. The optimization problem was established as follows:

$$\text{Find the } x \in R^n = \begin{Bmatrix} T_\gamma \\ G_\gamma \end{Bmatrix}$$
$$\text{that } Q(x) \rightarrow \min$$
$$\text{that } \eta(x) \rightarrow \max$$
$$\text{with restrictions of}$$
$$m = \begin{Bmatrix} X_\beta \leq 0.136\text{kg(kg of dry matter)}^{-1} \\ \mathrm{T}_\beta < 45°C \end{Bmatrix}$$

4 Results

4.1 Simulation Results and Thermal Efficiency estimation

Figures 1 and 2 show the instantaneous first and second law thermal efficiencies behaviors, which can be divided accordingly to the drying periods as follows:

Constant drying rate period: As shown in Figure 2 the grains temperature (T_β) increases rapidly until it equilibrates at a temperature close to $T_{\gamma w0}$. At this point the constant rate drying period begins (see Figure 1), and dX_β/dt, η_1 and η_2 reach their highest value. This coincidence can be explained by eqs. 9 and 10, both thermal efficiencies are directly proportional to drying rate. During this period most of the non bound water is eliminated and T_β remains constant. The air-grains moisture gradient is gradually reduced and so is the dX_β/dt and thermal efficiency values.

Falling drying rate period: After critical moisture content is reached (0.17 kg of water/kg of dry solid) more energy is needed to remove the remainder bound water and therefore the thermal efficiency drops. The grains structure collapses and the grain and its cuticle separate, which becomes an extra barrier to heat and mass transfer. The thermal efficiency drops to its lower level when the grain reaches its final water content and T_β increases.

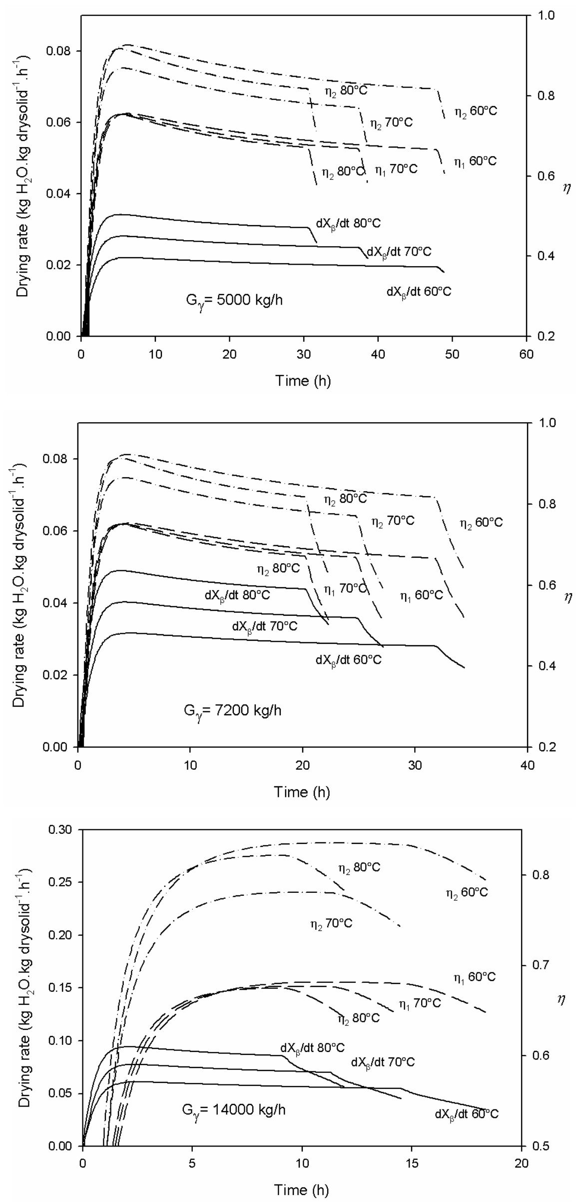

Fig. 1. Instantaneous first (η_1) and second (η_2) law thermal efficiencies simulations at different air fluxes and temperatures.

η_2 values are significantly higher than η_1 values in all drying conditions. This behavior was expected because thermal efficiencies are calculated dividing the energy transferred to the solid to the energy provided by the drying air, but η_2 considers that only a fraction of this energy is available to perform work obtaining higher thermal efficiencies. $(T_{\gamma 0} - T_{\gamma out})$ values are inversely proportional to η_1 and $(T_{\gamma w0} - T_{\gamma wout})$ to η_2. For all treatments η_2 values are higher than η_1 because $(T_{\gamma 0} - T_{\gamma out})$ is always higher than

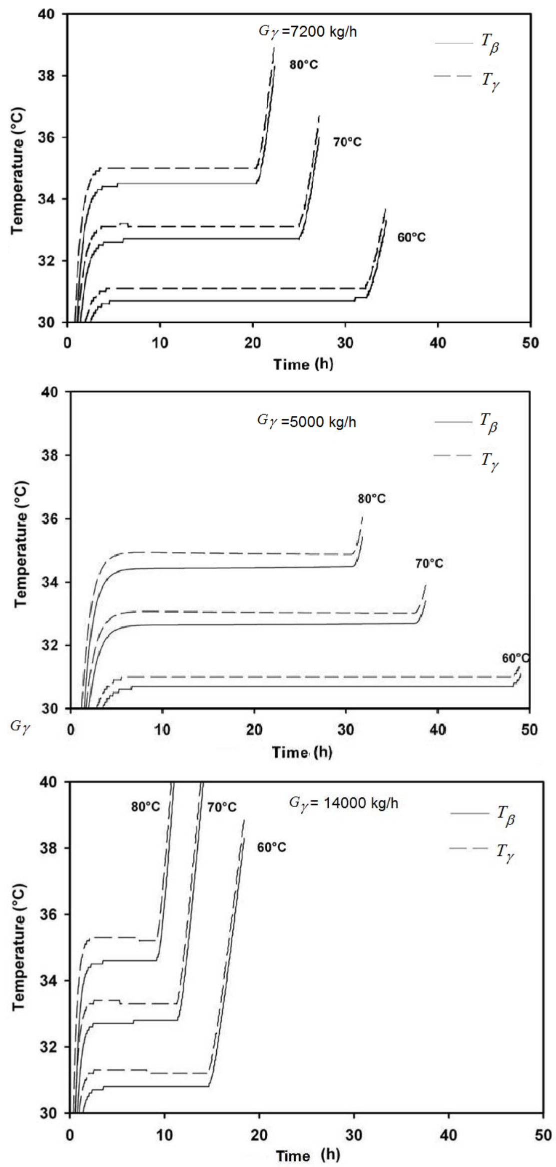

Fig. 2. Air (T_γ) and grains (T_β) temperature during drying simulation at different conditions.

$(T_{\gamma w0} - T_{\gamma wout})$.

Figure 1 shows lower η_1 values for higher drying temperatures. This can be explained by eq. 12, $(T_{\gamma 0} - T_{\gamma out})$ and Q values increase with drying temperature, and because Q is inversely proportional to η_1 (see eq. 9) first law thermal efficiency decreases.

For all drying conditions the higher η_2 values are obtained at 60°C and 80°C. At 60°C less energy is provided to the solid (Q) and the ratio between transmitted and provided energy increases (η_2). At 80°C although more energy is required to heat air (Q), the increment in drying rate is higher (0.016 kg H_2O.kg dry solid^{-1}.h^{-1}). First law thermal efficiency fails to measure the effect of T_γ on thermal efficiency, all the η_1 trajectories overlap. Although 60°C and 80°C have similar η_2 values, the drying time for the highest temperature is at least 20% smaller.

In Figure 2 it can be observed air flux and temperature are inversely proportional to the drying time. Nevertheless, this does not mean that the process is more efficient at higher temperatures, especially considering the effect on the sensorial quality of the grain. The higher thermal efficiencies are reached at low air fluxes. This behavior is easily explained by the fact that when the air flux is increased Q increases too, and according to equation (9) Q is inversely proportional to thermal efficiency.

Figure 3 shows experimental and simulated values of first and second law overall thermal efficiencies. As can be seen simulated η_2 values exhibit less error predicting thermal efficiency and adequately represent the experimental conduct (higher efficiency values correspond to 60°C and 80°C). Most of simulated η_1 values are overestimated and don't follow the experimental conduct.

One of the optimization restrictions was that the grains temperature (T_β), should be kept under 45°C during drying to avoid harming the sensorial quality of the drink according to Sfredo *et al*. (2002). During the drying simulation at the different air temperatures (T_γ = 60°C, 70°C and 80°C) the grain's temperature was monitored to verify that constraints were complied by. As can be observed in Figure 2 the grain's temperature (T_β) was kept under 45°C at a value close to the air's water bulb temperature.

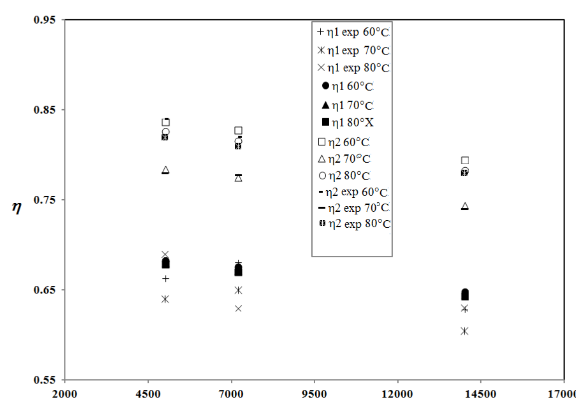

Fig. 3. Experimental and simulated values of overall thermal efficiency for different drying conditions.

Table 3. Regression coefficients of the final regression models and ANOVA.

Source	Q	p value	η_1	p value	η_2	p value
α_0	2.78766	0.002	0.747217069	9.4773×10^{-6}	3.12555	1.1563×10^{-6}
α_1	1.506×10^{-5}	0.000	-4.2395×10^{-7}	0.389171*	-5.71764×10^{-7}	0.56027*
α_2	0.001	0.003	-1.4742×10^{-3}	0.023376	-0.0660583	2.7817×10^{-6}
α_{12}	6.5170×10^{-8}	0.5987*	-1.5363×10^{-8}	0.025127	-1.7375×10^{-8}	0.1076383*
α_{11}	-1.45×10^{-10}	0.7956*	-1.010×10^{-10}	0.009474	-1.22×10^{-10}	0.0408097
α_{22}	1.70333×10^{-5}	0.8321*	9.5166×10^{-6}	0.03	4.685×10^{-4}	2.7957×10^{-6}
Total df	8		8		8	
SSR	0.03062		0.001653		0.006920	
SSE	0.00032		3.5×10^{-7}		1.5436×10^{-6}	
Regression MS	0.00612		0.00033		0.00138412	
Residual MS	0.00010		1.1 X10-7		5.1454×10^{-7}	
LOF error	0.02		0.0013		0.00620329	
Pure error	0.01042695		0.00034		0.00071732	
Total SS	0.030952		0.001654		0.00692215	
F_0	56.3395		2765.35		2690.00335	
F_{signif}	0.00363		0.0000108		1.1304×10^{-5}	
R^2	0.98946		0.9997830		0.999777	
R^2_{adj}	0.97190		0.9994215		0.999405	

* Not statistically significant for $p < 0.05$.

4.2 *Response surface analysis*

An ANOVA was conducted to determine the significant effects of process variables on the response. The estimated regression coefficients of the two independent variables, along with the corresponding p- significance values were displayed in Table 3.

A p-value for the statistic F minor to 0.05 indicates that there is significant statistical evidence to reject the null hypothesis Ho ($Ho : \alpha_0 = \alpha_1 = \alpha_2 = \alpha_{11} = \alpha_{22} = \alpha_{12} = 0$). This implies that at least one of the independent variables contributes significantly to the model. Only the coefficients with p-values less than 0.05 were used to model the response.

Meanwhile, coefficient of determination (R^2) is defined as the ratio of the explained variation to the total variation and is a measurement of the degree of fitness (Wang *et al.*, 2008). A small value of R^2 indicates a poor relevance of the dependent variables in the model (Sin *et al.*, 2006). By analysis of variance, the R^2 values of the models were higher to 0.98 in all cases, which showed that the regression models represented adequately the behavior of the system.

All independent variables showed a significant influence on the final energy consume but not their interactions. The $\alpha_2 T$ term showed the most significant effect on the three responses (Q, η_1 and η_2) in all cases with $p < 0.02$. The positive sign of the $\alpha_2 T$ term indicates that the best strategy to reduce the energy consumption is to reduce the airs temperature, as can be seen in Figure 4. Nevertheless, although the negative sign of the $\alpha_2 T$ term shall lead to the supposition that a reduction in the airs temperature would achieve higher thermal efficiencies; the positive sign of the $\alpha_{22} T^2$ term contra rests this effect. Figure 6 show that higher η_2 correspond to higher temperatures, which contradict the results of η_1 in Figure 5. Meanwhile, according to $\alpha_1 G$ and $\alpha_{11} G^2$ terms, the air mass flow shall be reduced to minimize the process Q and increase thermal efficiencies.

4.3 *Optimization conditions*

The response model obtained for Q and η_2, with the constrains established in point 3.3, were introduced to the optimization algorithm programmed in Matlab R2009a and Fortran. The response model obtained for η_1 was not included because as is shown in Figure 3 η_2 represents better the experimental conduct.

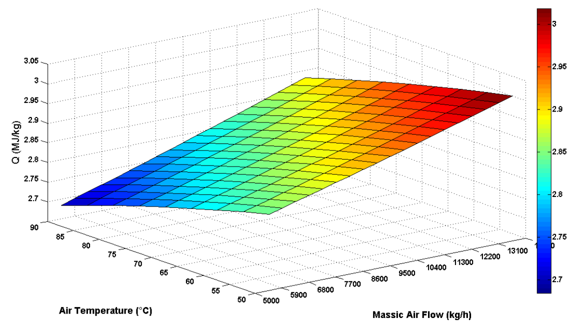

Fig. 4. Energy Consumption (Q) Response surface.

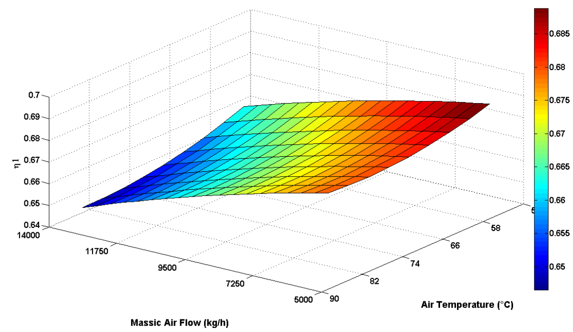

Fig. 5. First Law thermal Efficiency (η_1) Response surface.

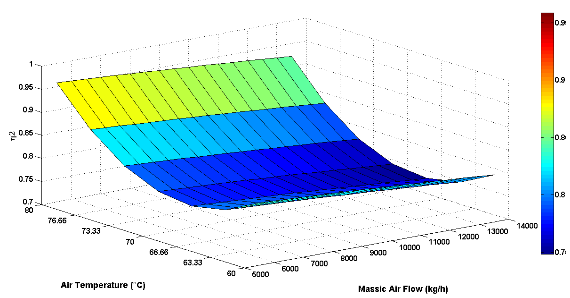

Fig. 6. Second Law thermal Efficiency (η_2) Response surface.

The minimum and maximum values of each response variables (Q and η_2) that met the criteria were: Q = 2.96 MJ/kg and η_2 = 0.82, obtained for process conditions: T_γ = 80°C , G_γ = 6560 kg air/h. In the coffee benefit T_γ = 60°C , G_γ = 14000 kg air/h process conditions are traditionally used. The response variables for these conditions are: Q = 3.53 MJ/kg and η_2 = 0.78. Implementing the optimized process conditions, a 15.80% reduction in Q is achieved. The strategy of using low drying temperatures with high mass flows to reduce the products humidity without harming the grains temperatures is thermally inefficient. The grains saturation air flow is reached at 6560 kg/h, higher mass flows have no effect on drying velocity and only increase energy consumption. Meanwhile, increasing the airs temperature the water diffusion inside the grain is increased with a positive effect of drying velocity without exceeding the grains temperature restriction of 45°C.

Conclusions

The simulation results of the coffee bean Guardiola drier showed that reducing the mass air flow and using high air temperatures, the dryings global η_2 increase as a result of drying time and Q reduction. This results confirm that the traditional strategy used in the coffee processing sector of drying beans using high mass air flows and low air temperatures is very energy demanding and thermally inefficient. The approach of keeping low air temperatures to protect the grains sensorial quality is also unnecessary, simulation results show that at all the process conditions evaluated the grains temperature was kept under 45°C which complies with the sensorial quality restrictions of the grain.

The use of RSM to model the behavior of the responses to process variables G_γ and $T_{\gamma 0}$ generated a predictive models which were later used to optimize the drying minimizing the process energy consume. This study revealed that using the optimum conditions resulted in 15.80% reduction of the energy consumption.

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Nomenclature

A	specific surface area between phases (m^2 m^{-3})
a_w	water activity
Cp	specific heat (J kg^{-1} K^{-1})
D	effective diffusivity (m^2 s^{-1})
Ex	exergy (J)
G	mass Flow (kg s^{-1})
H	heat transfer coefficient (W m^{-2} K^{-1})
H	enthalpy (J kg^{-1})
K	thermal conductivity (W m^{-1} K^{-1})
k_c	internal mass transfer coefficient (m s^{-1})
L_D	characteristic length (m)
M	mass (kg)
P	total or partial pressure (Pa)

Q	energy consumption (MJ/kg)
T	temperature (°C)
t	time (s)
V	volume (m^3)
x	independent variables
X	water content (kg water (kg dry matter)$^{-1}$)
Y	predictive response

Greek symbols

ΔH^0_{wv}	water latent heat at reference value(J kg^{-1})
α	regression coefficients
β	indicate solid phase (coffee)
ε	porosity
γ	indicate gas phase (air)
η_1	first law thermal efficiency
η_2	second law thermal efficiency
η_{max}	maximum Thermal efficiency
τ	drying time (s)
μ	viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
λ	water latent heat (J kg^{-1})

Subscripts

Wv	indicate water vapor
Out	indicate ambient conditions
I	indicate interface
W	indicate water
0	indicate reference state

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