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Effect of the Outlet Air Reuse on Thermal Efficiency of a Pilot Plant Spray Dryer with Rotary Atomizer

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The thermal efficiency of a spray drying process is related to operating parameters such as the temperature and the mass flow rate of the inlet air of the dryer and the increase of these values will result in higher energy costs. The objective of this work was to evaluate the effect of recycling the outlet air of a pilot plant spray dryer with rotary atomizer on the thermal efficiency of the drying process. The results showed that the thermal efficiency is related to inlet air properties and it can be improved with the recirculation of the outlet air.

1. Introduction

According to Oi (2011), the green banana biomass (processed green banana), insipid and odorless, is an option to be used as a substitute for the traditional thickeners in nourishments, such as heat, soy, potato starch and corn starch, with the advantage of improving their nutritional value.The green banana commercialization is mainly made with the product in powder due to easier handling, transportation, storage and consumption. The method most used for the obtainment of this form of the green banana biomass is spray drying. The efficiency of the spray dryer operation is strongly related to the nature of the spray dried material and to spray drying conditions

This method is preferred for drying a lot of materials with thermal sensibility, such as foods or pharmaceutical products. An uniform distribution of the particle size is the reason for what spray dryer is usually used in industries, like catalysts. (Keey, 1992)

The efficiency of the drying process by spray dryer can be evaluated by several ways. However, by a general way, it’s possible to define the efficiency of the process as the rate between the heat used in the evaporation and the total heat used for heating the drying air.

According to Mujumdar (2006), the energetic efficiency of drying equipment can be defined by the volumetric rate of evaporation, the superficial heat loss, steam consume and thermal efficiency.

Once the drying chamber capacity is directly related with the difference between inlet and outlet air temperature, it’s desirable to reach a higher temperature difference, which means, a higher inlet temperature and a lower outlet temperature. However, the rise of the inlet temperature can damage the product and, on the other hand, low outlet temperatures implies in a final product with high moisture content.

Two types of efficiency are used to measure the spray dryer performance: the thermal efficiency and the evaporative efficiency, showed on Eq. (1) and (2) (Hall and Hedrick, 1971).

$$\eta_{thermal} = \left(\frac{T_{in}-T_{out}}{T_{in}-T_{\infty}}\right) \times 100\ (\%) \tag{1}$$

$$\eta_{evaporative} = \left(\frac{T_{in}-T_{out}}{T_{in}-T_{sa}}\right) \times 100\ (\%) \tag{2}$$

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The thermal or energy efficiency of a dryer is defined as the ratio between the energy required to evaporate moisture and the energy supplied to the dryer and it can be calculated according to Eq (3) (Kaminski et al., 1989).

$$TE = \frac{W\Delta H}{MC_{pa}(T_{a,in} - T_{a,atm})} \qquad 3)$$

According with the methodology proposed by Kajiyama and Park (2008), from the mass balance, the water evaporation flow can be related with the inlet mass flow according to Eq (4) and (5) (Canovas and Mercado, 2000):

$$W = F\left(\frac{X_0 - X_f}{1 - X_f}\right) \qquad (4)$$

$$W = M(Y_f - Y_0) \qquad (5)$$

The energy required to heat the drying air can be calculated from the Eq (6):

$$PG_{aq} = M(H_{aq} - H_{atm}) \qquad (6)$$

Considering Eqs (3) and (4), the thermal efficiency can be expressed by Eq (7) (Kajiyama and Park, 2008):

$$TE = \frac{W\lambda_{wb}}{M\left(H_{aq} - H_{atm}\right)} = \frac{EG_{ev}}{EG_{aq}} \qquad (7)$$

From this definition, it’s noticed that the efficiency of the process it’s directly related with the operational parameters, such as temperature and air mass flow rate in the feed air of the dryer, being this raise of the numbers associated with higher energy costs. At the same time, the increase of the air temperature makes the simultaneous mechanisms of heat and mass transfer more efficient. So, it’s necessary to know the effect of drying parameters in a spray dryer process on the energetic efficiency, with the goal to reduce the energy cost and raise the evaporative efficiency.

Depending on the operational conditions, the drying air, before the contact with the product, leaves the dryer with high temperatures. Thus, the reuse of this air can be a way to minimize the energy necessary to heat the inlet air.

The objective of this work was to evaluate the effect of drying parameters and of the outlet air reuse on the thermal efficiency of a green banana biomass drying process in a pilot plant spray dryer with rotary atomizer through a computational simulation.

2. Methodology

2.1 Thermal efficiency evaluation

The effect of drying process parameters and of the outlet air reuse on the thermal efficiency of the drying process in a spray dryer was made by computational simulation, considering the methodology proposed by Kajiyama and Park (2008).

The thermal efficiency was calculated through Eq (1) considering different combinations of drying parameters, by using the software MATLAB^{TM}. The process parameters considered for the thermal efficiency evaluation were the inlet air temperature (Ta_{in}), the air mass flow (M) and the feed flow (F). The responses considered were the thermal efficiency (Eq 1) and the outlet air moisture content. The analysis of the independent variables’ effects on the thermal efficiency was assayed with a Nonlinear Estimation Package using the software Statistica (Statsoft, 2001), according to a mathematical model of second order (Eq. 8).

The real values corresponding to codified levels of experimental design are presented in Table 1. These values were defined according to experimental data of a green banana biomass drying in a rotative disc spray dryer, located in the Unit Operations Laboratory from the Santa Cecília University, located in Santos, São Paulo, Brazil.

$$Y = b_0 + b_1x_1 + b_{11}x_1^2 + b_2x_2 + b_{22}x_2^2 + +b_3x_3 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad 8)$$

Table 1 Real values of experimental design levels corresponding to Eq (8)

Variables	Levels				
	-1.68	-1	0	1	1.68
Ta_{in} (ºC)	106.4	120	140	160	173.6
M (kg/s)	0.066	0.01	0.015	0.02	0.0234
F (mL/s)	0.0160	0.05	0.1	0.2	0.268

2.2 Effect of air reuse on thermal efficiency

To study the effect of the outlet air reuse on thermal efficiency of the spray drying process, different mixing proportions of the outlet air with the drying air, between 10 and 90 %, were considered, according to what is represented in Figure 1. The effect of this mixture on the thermodynamic properties of the inlet air was considered.

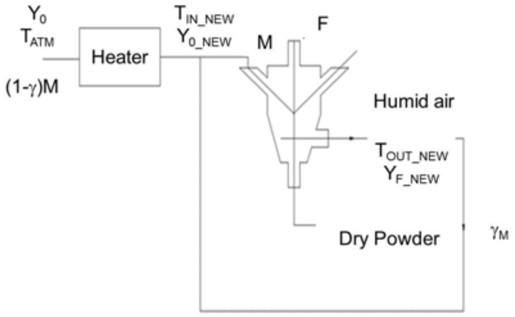

Figure 1: Schematic representation of the outlet air reuse

For each proportion of outlet drying air mixture on the inlet air, the thermodynamic properties of the air were determined and the thermal efficiency of the drying process was calculated through Eq (1), considering the combination of different values of the inlet air temperature (Ta_{in}), the air mass flow (M) and the feed flow (F). The outlet air temperature was considered as 90°C and the moisture content was calculated according to Eq (5) (Kajiyama and Park, 2008).

2.3 Drying process simulation

The program was developed using the software MATLAB^{TM} with the objective of interact with the user.

Even for the case that there is no an air reuse, the user must inform: a vector of temperature; a vector of air mass flow; a vector of green banana biomass volumetric flow.

The user is still required to inform: initial moisture content; final moisture content; environment air moisture content; environment air temperature;

- Statistical test: table containing only the points that will be used on the statistical treatment.
- Complete test: table containing all possible combinations.

The properties of green banana biomass considered for the evaluation of the thermal efficiency were (Gonçalves et al., 2010): Liquid density: 1000kg/m^3; Initial moisture content: 0.79; Final Moisture content: 0.047. The environment conditions considered were: air temperature: 25°C; air moisture content: 0.6

3. Results

3.1 Thermal efficiency evaluation

The results obtained for the outlet air moisture content (Y_o) and for the thermal efficiency (TE) for each combination of the inlet air temperature (Ta_{in}), air mass flow (M) and feed flow (F) are presented in Table 2. The results presented in Table 2 were analyzed according to response surface methodology. Considering the outlet air moisture content at a confidence level of 95 %, the codified mathematical model that represents the effect of the independent variables is presented in Eq (9). The R^2 value corresponding to the adjustment of the experimental data to this model was approximately 0.995

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$$Y_o = 0.0197 + 0.0042Ta_{in} + 0.0008Ta_{in}^2 - 0.0025M + 0.0009M^2 - 0.0014Ta_{in}M \tag{9}$$

According to the results presented in Eq (9), at a confidence level of 95 %, the inlet air temperature and the air mass flow had a positive effect on the outlet air moisture content. The feed flow had not significant effect on outlet air moisture content. The response surface corresponding to Eq (9) is presented in Figure 2. According to Figure 2, the increase of inlet air temperature and of the air mass flow results in higher values of outlet air moisture contents. Considering the thermal efficiency at a confidence level of 95 %, the codified mathematical model that represents the effect of the independent variables is presented in Eq (10). The R^2 value corresponding to the adjustment of the experimental data to this model was approximately 0.936.

$$TE = 9.7761 - 4.0950Ta_{in} - 3.5161M + 5.9718F - 2.6971Ta_{in}F - 2.1681MF \tag{10}$$

Table 2. Outlet air moisture content (Yo) and thermal efficiency

Trial	Ta_{in} (°C)	M (kg/s)	F (mL/s)	Yo (kg_{water}/ $kg_{dry\ air}$)	TE
1	120	0.01	0.05	18.3	8.18
2	120	0.01	0.20	18.3	32.72
3	120	0.02	0.05	16.3	4.09
4	120	0.02	0.20	16.3	16.36
5	160	0.01	0.05	30.0	3.38
6	160	0.01	0.20	30.0	13.54
7	160	0.02	0.05	22.2	1.69
8	160	0.02	0.20	22.2	6.77
9	140	0.015	0.10	19.6	6.96
10	106.4	0.015	0.10	15.2	15.22
11	173.6	0.015	0.10	28.3	3.36
12	140	0.007	0.10	26.2	15.81
13	140	0.023	0.10	17.7	4.46
14	140	0.015	0.02	19.6	1.11
15	140	0.015	0.7	19.6	18.64

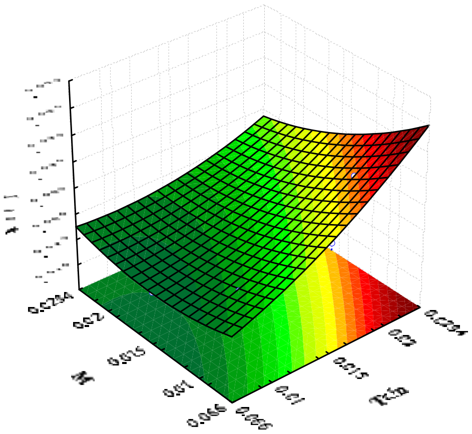
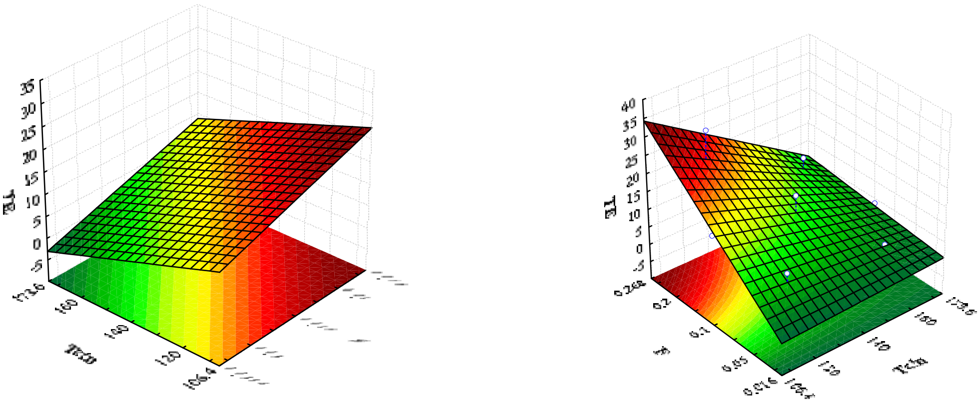


Figure 2: Response surface for outlet moisture content in function of inlet air temperature and air mass flow, obtained from Eq (9)

The response surface corresponding to Eq (10) can be seen in Figure 3. According to Eq.10, at a significance level of 95 %, the inlet air temperature and the air mass flow had a negative effect on the thermal efficiency. It means that increasing the drying temperature and the air mass flow, the thermal efficiency was lower. This effect was expected, once lower drying temperatures and air mass flows results in less energy requirement to heat the inlet air, what results in higher energy efficiency. By the other side, the increase of feeding rate led to higher thermal efficiency values.



(a) Ta_{in} x M

Ta_{in} x F

Figure 3: Response surfaces for thermal efficiency in function of inlet air temperature, air mass flow and feed flow, obtained from Eq (10)

Inside the considered range of process parameters values, the thermal efficiency varied from 1.69 to 32.72%. The highest value was obtained at a combination of the lowest levels of inlet air temperature and air mass flow with the highest level of feed flow. Toneli et al. (2010) and Goula and Adamapoulos (2003) studied the effect of the inlet air temperature and of the air mass flow on the thermal efficiency of inulin and tomato pulp spray drying processes, respectively, and both observed the same effects.

Kajiyama and Park (2011) studied the effect of feed flow, initial and final moisture contents on thermal efficiency and observed no significant effect. According to the authors, the increase in initial moisture content (or decrease in final moisture content or increase in feed flow) increased the evaporating water portion, that increased the vaporization energy, which in turn, was supplied by the drying air. In this study, however, the initial and final moisture contents do not change. So, the vaporization energy is always the same and the drying parameters affect only the energy requirement to heat the inlet air.

3.2 Air reuse evaluation

The thermal efficiencies corresponding to trials 1 to 15 by considering air reuse mixing proportions from 0 to 90% are presented in Figure 4. The results presented in this Figure show that, independent of the proportion of air reuse, the maximum thermal efficiency was obtained with the combination of low values of inlet temperature and air mass flow with high feed flow, as it was observed for thermal efficiency without outlet air reuse.

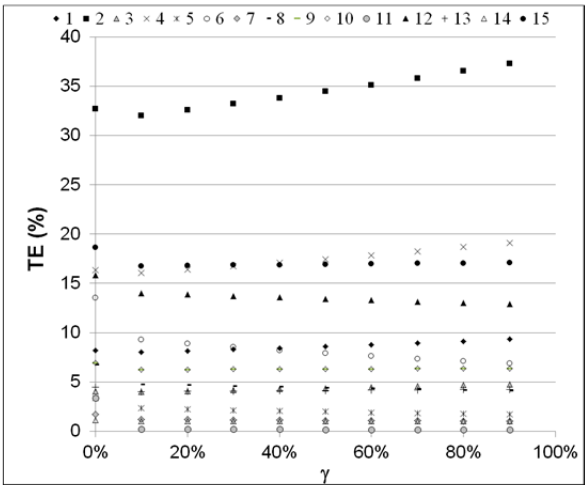


Figure 4: Effect of the mixing proportions of outlet air reuse on thermal efficiency of spray drying process for trials 1 to 15

Considering the results obtained for the best drying conditions (Trial 2), it can be seen that the air reuse in mixing proportions superior to 10 % increased the thermal efficiency. With outlet air reuse proportions lower than 10 %, the energy required to heat the ambient air and remove its moisture content is higher. So, it is not enough to equalize the energy required to evaporate the moisture content.

Table 3: Regression coefficients for thermal efficiency codified mathematical model (Eq 8) with different mix proportions of air reuse

	γ			
Coeff.	0.2	0.4	0.6	0.8
b_o	8.75	8.89	9.06	9.26
b_1	-5.16	-5.56	-5.98	-6.43
b_2	-3.08	-3.04	-3.01	-2.99
b_3	5.38	5.45	5.53	5.63
b_{12}	1.87	2.04	2.19	2.34
b_{13}	-3.32	-3.58	-3.84	-4.12
b_{23}	-1.92	-1.92	-1.93	9.26
R^2	0.958	0.957	0.956	0.931

The effect of the inlet air temperature, the air mass flow and the feed flow on the thermal efficiency was evaluated according to response surface methodology. Considering a confidence level of 95%, the coefficients of the codified mathematical models that represent the effect of the independent variables for each air reuse mixing proportion are presented in Table 3. The behavior was the same for all proportions of outlet air reuse in such a way that, at a significance level of 95%, the inlet air temperature and the air mass flow had a negative effect on the thermal efficiency while the feeding rate had a positive effect on thermal efficiency values.

4. Conclusions

The inlet air temperature and the air mass flow had a negative effect on thermal efficiency, once lower drying temperatures and air mass flow results in less energy requirement to heat the inlet air, what results in higher energy efficiency. By the other side, the increase of feeding rate led to higher thermal efficiency values. The outlet air reuse improved the thermal efficiency fat the best drying conditions, when the proportion of mixture was higher than 10 %.

Nomenclature

TE	thermal efficiency of the drying process		x_1	air inlet temperature	ºC
W	water evaporation flow	kgs^{-1}	x_2	air mass flow	kgs^{-1}
ΔH	vaporization enthalpy	kJkg^{-1}	x_3	dryer feed mass flow	kgs^{-1}
M	air mass flow	kgs^{-1}	Y	dependent variable	
Cpa	specific heat at constant pressure	kJkg^{-1}°C^{-1}	x	dependent variable	
T	temperature	°C			
F	dryer feed mass flow	kgs^{-1}	**Greek Letters**		
X	humidity from product, dry basis	kgkg^{-1}	λ	latent heat	kJkg^{-1}
Y	air humidity	gg^{-1}			
PG	heating potency	kW	**Subscripts**		
H	enthalpy	kJkg^{-1}	a, in	inlet air	
EG	specific energy consum	kJkg^{-1}	a, atm	atmospheric air	
M	air mass flow	kgs^{-1}	i	index from the variable	
b_i	constant obtained experimentally that represents the effect of the variable x over the answer y		wb	Wet basis	
			ev	evaporation	

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