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Minimization Entropic Applied to Rotary Dryers to Reduce the Energy Consumption

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***Abstract*—**The drying process is an important operation in the chemical industry and it is widely used in the food, grain industry and fertilizer industry. However, for demanding a considerable consumption of energy, such a process requires a deep energetic analysis in order to reduce operating costs. This paper deals with thermodynamic optimization applied to rotary dryers based on the entropy production minimization, aiming at to reduce the energy consumption. To do this, the mass, energy and entropy balance was used for developing a relationship that represents the rate of entropy production. The use of the Second Law of Thermodynamics is essential because it takes into account constraints of nature. Since the entropy production rate is minimized, optimals conditions of operations can be established and the process can obtain a substantial gain in energy saving. The minimization strategy had been led using classical methods such as Lagrange multipliers and implemented in the MATLAB platform. As expected, the preliminary results reveal a significant energy saving by the application of the optimal parameters found by the procedure of the entropy minimization It is important to say that this method has shown easy implementation and low cost.

***Keyword*—**Drying, entropy minimization, modeling dryers, thermodynamic optimization.

I. Introduction

DRYING is a technique used since antiquity, the evolution of this operation was developed in parallel with the evolution of the humanity and currently it is widely used in various industries. The objective of the drying is to remove the excess of moisture present in the solid, aiming at, for instance, the conservation and durability of grains. Although it may seem simple, it is a complexly operation, in the drying simultaneously occurs the mass and heat transfer in the stream. This operation requires a high consuming of energy. In grain industry, 60% of all energy used are directed to drying. This is one of reasons that drying is an important operation and it is always being reviewed to become more sustainable.

The basic theory and calculations for drying operations serve the chemical engineers as a guide for evaluating and selecting drying processes and equipment [7].

There are many types of the dryers for different products. The rotary dryers are usually employed to dry large volumes of products of high economic value, like granulated materials.

The drying process is used essentially for reducing the moisture of the grains, increasing the storage time. Increasing the time of storage is important because the production of grains in Brazil reached record harvests (about 209.5 million tons [6]) and care are necessaries to avoid losses.

For grains, the use of rotary dryers is a new technique because generally the drying is in towers. But, according to [1], rotary dryers have shown significant results to corn, with a better performance of efficiency and quality.

The modelling of a rotary dryer includes mass and energy balance applied to a process that exhibits the combined effect of mass and heat transfer [2].

The entropy minimization has been used for obtaining the better set of parameters to operate the system. According to [5], by minimizing the entropy production rate directly, it is possible to determine the optimal operating conditions as well as some key constructive parameters for the system.

Since the analysis based on the First Law of Thermodynamics generates suboptimal results, the Second Law should be used to obtain superior results, that is, the entropy balance must be taken into account in the modelling of the drying system.

This paper aims to apply the entropy minimization in the drying process of corns in a rotary dryer to obtain the optimal operating conditions. Since the optimal parameters were established, an analysis of energy efficiency can be done and the energy expense can be then compared to the usual data.

II. Modelling and Case Study

According to [3], a mathematical model is the representation of the essential aspects of a system in a usable form. So, mathematical modeling is the attempt to describe an actual process using mathematical equations, or an equation to represent a set of them or an observed phenomenon.

The presented model describes how a rotary dryer works for corn grains, using mass, heat and entropy balances for better understanding the process and to propose an optimized dryer. Fig. 1 represents the scheme of the rotary dryer used to reduce the moisture of grains.

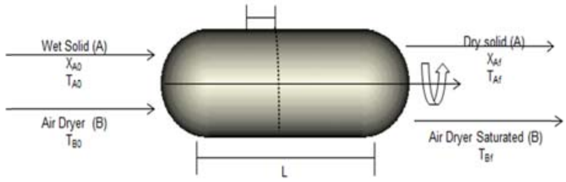

Fig. 1 Design of a rotary dryer

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Some considerations were done about system, like:

- ✓ Adiabatic dryer;
- ✓ Velocity constant;
- ✓ Parallel flow
- ✓ Negligible mass and heat transfer in the r and θ directions;
- ✓ Friction will be not applicable;
- ✓ Dryer rotation gives homogeneity of the stream;
- ✓ Conductivity and diffusivity will be considered constant throughout the dryer;
- ✓ Constants physical proprieties;

Table I shows some information about the drying process of the corn [1].

TABLE I
INFORMATION ABOUT THE DRYING PROCESS OF CORN

Moisture initial	20% b.u.
Final Moisture	12,5% b.u.
Temperature initial of the corn	296 K
Temperature final of the corn	327K
Temperature of the air dryer	373K
Flow of the corn	1250kg

A. Mass Balance

The mass balance has been used to establish the humidity profile on the dryer length. To describe the mass transfer in the rotary dryer the Fick's Law [4] was used.

The driving force for mass transfer is typically a difference in chemical potential, which can be defined by means of other thermodynamic gradients. It is clear that the chemical species move from areas of high chemical potential to low chemical potential.

The mass balance in the differential form on an infinitesimal element of ρ density and velocity v in Fig. 1 can be given by:

$$\sum_i^n \rho_e * v_e * A_e - \sum_i^n \rho_s * v_s * A_s \pm R_i = \frac{dm_i}{dt} \quad (1)$$

where the elements with sub index *i* represents the input system and, *f*, the outlet.

By presenting cylindrical features, the development of (2) must be performed in cylindrical coordinates. Since in drying systems no reaction occurs, so the following equation can be formulated:

$$\frac{\partial X_i}{\partial t} = -\left(\frac{1}{r}\frac{\partial(X_i v_i r)}{\partial r} + \frac{1}{r}\frac{\partial(X_i v_\theta)}{\partial \theta} + \frac{\partial(X_i v_z)}{\partial z}\right) - \left(\frac{1}{r}\frac{\partial(J_i r)}{\partial r} + \frac{1}{r}\frac{\partial(J_i)}{\partial \theta} + \frac{\partial(J_i)}{\partial z}\right) \quad (2)$$

Replacing Fick Equation of diffusivity in (2), we have:

$$\frac{\partial X_i}{\partial t} = -\left(\frac{1}{r}\frac{\partial(X_i v_i r)}{\partial r} + \frac{1}{r}\frac{\partial(_i v_\theta)}{\partial \theta} + \frac{\partial(X_i v_z)}{\partial z}\right) + D_{ij}\left(\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial X_i}{\partial r}\right)\right) + \frac{1}{r^2}\left(\frac{\partial}{\partial \theta}\left(\frac{\partial X_i}{\partial \theta}\right)\right) + \left(\frac{\partial}{\partial z}\left(\frac{\partial X_i}{\partial z}\right)\right)\right) \quad (3)$$

where v_i, v_θ, v_z, D_{ij} and X_i respectively corresponding to speed components in axes, diffusivity coefficient and moisture of the component "i".

Applying the considerations about the system in (3), we have (4) that represents the profile of moisture along the dryer length:

$$\frac{dX_i}{dt} = D_{ij}\left(\frac{d^2Xi}{dz^2}\right) \quad (4)$$

B. Energy Balance

Analogous to mass balance, for obtaining the temperature profile along the dryer, the First Law of Thermodynamics differential is applied to both flow of the drying process, by producing the general heat balance shown in (5):

$$\sum_i^n m_e E_e - \sum_i^n m_s E_s + \dot{Q} - \dot{W} = \frac{dE_t}{dt} \quad (5)$$

where E_t corresponds to total energy, E_P is the potential energy, E_C kinetic energy, U internal energy, $\dot{Q}$ denotes the heat transfer and $\dot{W}$ the system work.

Analyzing the behavior of the work in the process, two segments can represent it: The working pressure and work generated in the control volume (*VC*).

$$\delta\dot{W} = \delta W_{VC} + (pvdm) - (p_e v_e dm_e) \quad (6)$$

Developing the energy balance equation, we have:

$$\rho_i \frac{\partial(E_P + E_C + U)}{\partial t} = -\nabla E_c - \nabla E_P - \nabla U + \nabla\dot{q} - \dot{W}_{vc} + \nabla(PV) \quad (7)$$

where;

$$\nabla E_c = -\frac{1}{r}\frac{\partial E_C}{\partial r} - \frac{1\partial E_C}{r\,\partial\theta} - \frac{\partial E_C}{\partial z}$$

$$\nabla E_p = -\frac{1}{r}\frac{\partial E_p}{\partial r} - \frac{1}{r}\frac{\partial E_p}{\partial\theta} - \frac{\partial E_p}{\partial z}$$

$$\nabla U = -\frac{1}{r}\frac{\partial U}{\partial r} - \frac{1}{r}\frac{\partial U}{\partial\theta} - \frac{1}{r}\frac{\partial U}{\partial z}$$

$$\nabla\dot{q} = -\frac{1}{r}\frac{\partial\dot{q}}{\partial r} - \frac{1}{r}\frac{\partial\dot{q}}{\partial\theta} - \frac{\partial\dot{q}}{\partial z}$$

Knowing that dH= dU+Pdv+VdP and considering that *V* is constant we obtain:

$$\rho_i \frac{\partial(\mathrm{Ec} + \mathrm{Ep} + \mathrm{U})}{\partial \mathrm{t}} = -\nabla\mathrm{E_c} - \nabla\mathrm{E_P} - \nabla\mathrm{H} + \nabla\dot{\mathrm{q}} - \dot{\mathrm{W}}_{\mathrm{vc}}$$

If kinetic and potential energy are constants in the drying, and the work in the control volume is disregarded we have:

$$\rho_i \frac{\partial(\mathrm{U})}{\partial \mathrm{t}} = -\nabla\mathrm{H} + \nabla\dot{\mathrm{q}} \quad (8)$$

The conduction is the mechanism of heat transfer that prevails in the drying. The law that describes this process is Fourier 'Law. Therefore, substituting the Fourier Law in (8) we will have:

$$\rho_i \frac{\partial(\mathrm{U})}{\partial \mathrm{t}} = -\nabla\mathrm{H} + \mathrm{K}\nabla^2 T \quad (9)$$

where;

$$\nabla^2 T = -\frac{1}{r}\frac{\partial^2 T}{\partial r^2} - \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} - \frac{\partial^2 T}{\partial z^2}$$

The enthalpy and internal energy are functions of the temperature and theirs derivate can be replaced. Doing the substitutions and the considerations in (10), we will have the equation that describe the profile temperature of the dryer in function of the time and length of the dryer.

$$\frac{dT_i}{dt} = \alpha\left(\frac{d^2Ti}{dz^2}\right) \quad (10)$$

where;

$$\alpha = \frac{K}{\rho_i c_{pi}}$$

C. Entropy Balance

The entropy is a feature of the system and is related to the measurable properties of their components [8]. Analogous to the heat and mass balance, the entropy balance can be applied in an element of de volume v and density ρ of Fig 1.

A new term, called entropy generation rate, is added in the entropy balance and represents the irreversibility of the system.

The general entropy balance can be expressed by:

$$\sum \dot{m}_s\, s_s - \sum \dot{m}_e\, s_e \pm \frac{Q}{T} + \frac{dS}{dt} = \dot{S_{ger}} \geq 0 \quad (11)$$

where there are the contributions to variation of entropy by the flow, heat and generation entropic.

With the equation of the balance entropy, the generation entropy rate can be minimized. Knowing that entropy is function of the temperature, pressure and components numbers and with pressure constant in the system, we have:

$$S = f(T, \sum n_i)$$

Now,

$$\frac{ds}{dt} = \frac{\partial S}{\partial T}\frac{dT}{dt} + \sum \frac{\partial S}{\partial n}\frac{dn}{dt} \quad (12)$$

Realizing the change of the term dS/dt in (11), assigning that the moisture corresponds to the propriety to contribution of the components and isolating the term to be minimized:

$$\sum \dot{m}_s\, s_s - \sum \dot{m}_e\, s_e \pm \frac{Q}{T} + \frac{dT}{dt} + \frac{dX}{dt} = \dot{S_{ger}} \quad (13)$$

The minimization was done with restrictions of temperature once the quality of the corn is sensitive to the high temperature, so:

$$\textit{Minimized } \dot{S_{ger}}$$

$$\textit{Restriction } T < T_{Drying}$$

The simulations were developing to find the optimal values to drying temperature and to get better the process.

III. Analysis and Discussions

The equations that describe the drying behavior were simulated using Matlab platform. The implementation was done using techniques boundary value problems for analysis point to point along the dryer.

With the application of the data's about drying corns on (4), we obtained the profile of moisture for the grain and the air shown in Fig. 2.

An adiabatic system was taken into account, ie, all the heat lost by the drying means is absorbed by the grain. In other words, the sensible heat lost by the air is passed to water evaporation from the grain so that the total heat system remains the same.

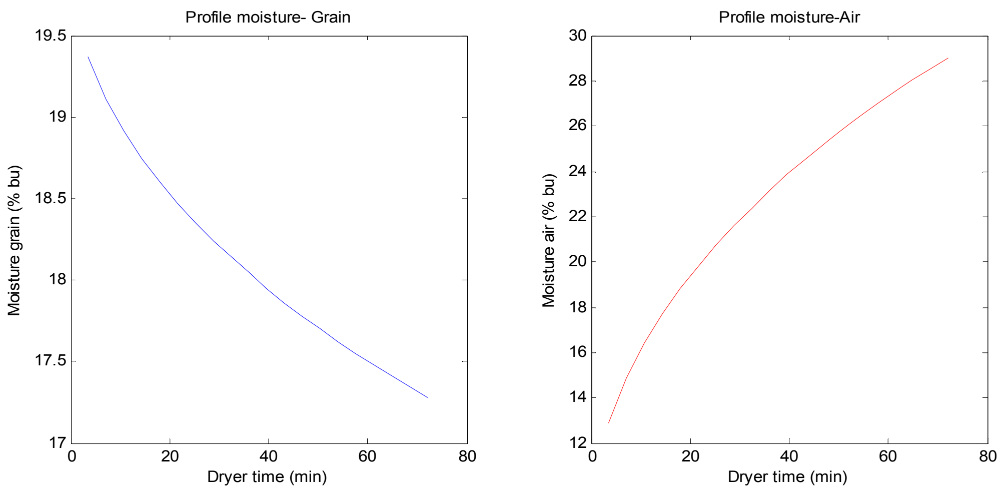

Fig. 2 Moisture profile of the grain and air

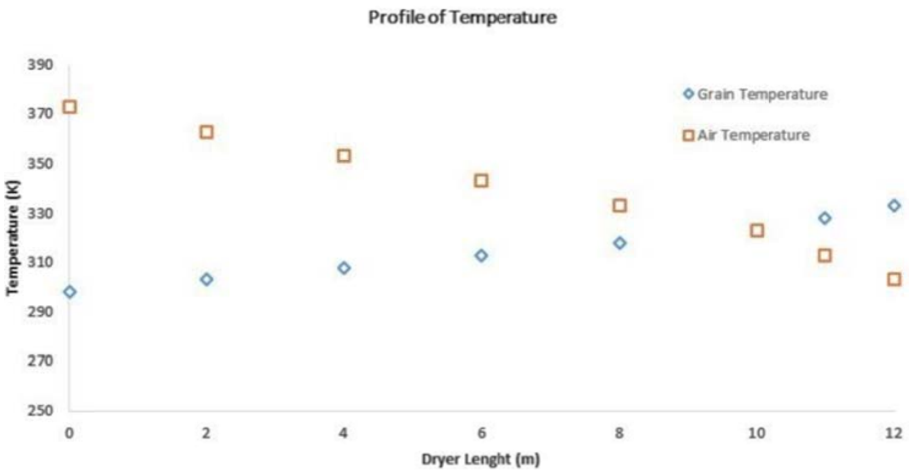

Fig. 3 Profile of Temperature profile of the system's dry

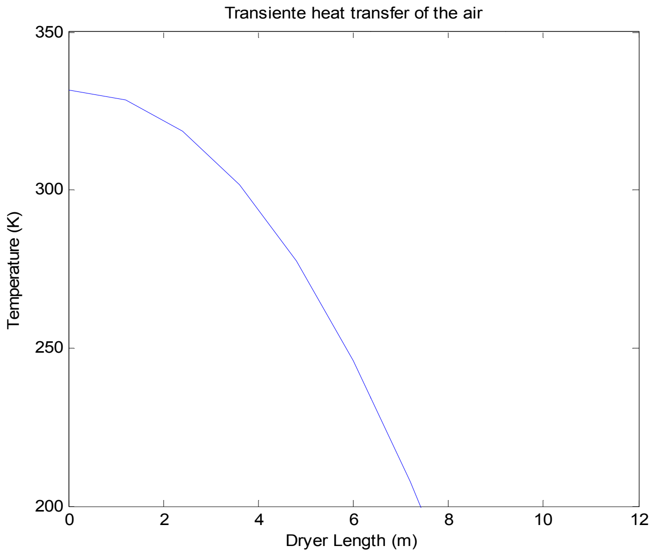

Fig. 4 Profile of temperature of the air

Using (10), we obtained the profile of temperature of the air utilized in the corn drying. Fig. 3 shows how the air lose heat to the grain.

The input air temperature was of 373 K and the corn 298 K. The heat is supplied until the beans reach the temperature drying and, when achieve final humidity, the corn leaves the dryer with 329 K while the saturated steam leave the dryer at 311 K.

Known mass and heat profiles, the minimizing simulations entropy generation rate were conducted with drying temperature restriction:

$$Minimize\ \dot{S_{ger}} = f(T)\ with\ the\ temperature'\ restriction\ T < 350K$$

The optimal drying temperature was obtained by the minimizing the entropy production rate. Equation (13) was used like tool for the simulation. Simulating the equation with temperature restriction, a new temperature for this process was obtained, about 341K. Fig. 4 shows the air heat profile operating with the new drying temperature. It is observed that after reaching the process temperature drying air rapidly loses favoring drying. In this case, the drying temperature was obtained in ¼ of the dryer length, and the final temperature of the air was reached before to complete the total length of it.

With the minimization, we had a new way to procedure the drying. In this case, the drying temperature is about 341 K, reduction of 9 degrees of the tradition process (350 K). The changes in the process can have low cost when the changes are only in processes parameters. Some inexpensive changes can be realized like the enter flow of the grain, dryer velocity and residence time. The assessment of the parameters of the drying during the project of the equipment for questions costs and quality is important.

IV. Conclusion

We can conclude that the application of mass balance equations, energy and entropy combined with thermodynamic conditions can verify the behavior of elements within the dryer.

Concentration and temperature profiles in addition to the loss of moisture behavior throughout the process can provide greater system control and product warranty specifications and guaranteed quality.

The application of minimizing entropy production rate could help draw up action plans for improvement in plants using this process with the aim of reducing energy consumption, and can also be used for projection of rotary dryers.

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