STUDY OF THE APPLICATION OF A NUMERICAL MODEL OF SIMULATION OF THE DRYING PROCESS FOR DIMENSIONING OF ROTARY DRYERS

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Abstract. *The drying has a fundamental part in most areas of the industry in the world. Perhaps one of the most common and older industrial operations, however still not completely understood. The calculation and dimensioning methods of dryers, specially rotary dryers, are very old and has being transformed very slowly. Initially they were basically experimental models and with the technological advances, they had in such a way started to be as empirical as experimental methods. Actually there isn't a single theory or project methodology in open literature or any manual that can be used for the description of the drying process. Due to extensive application of the techniques of drying and its importance in different manufacture processes, many theoretical and experimental studies on drying techniques, effect of the involved parameters and on mathematical and numerical models for simulation of the drying process has been carried through and published. Such mathematical models can in such a way be used for dimensioning as much as the forecast of variations of the final product as a function of the variation of the inlet process parameters, and, because of its singularities, those methods return results of very distinct precision. The present work studied the application of a simplified model of simulation of rotary dryers, developed and published in another work (Soares et. al., 2004), for the dimensioning of these type of dryers, comparing its results with the ones of other described models in literature, from real cases of the sugar industry.*

Keywords: *Sugar Drying, Mathematical Models, Numeric Simulation, Dimensioning, Rotary Dryers.*

1. Introduction

The operation of a rotary dryer is a complex process that not only involves heat and mass transfer, but also the particle movement inside the dryer. Many authors had made inquiries concerning the modeling of steady state in the process of rotary dryers. Baker (1983) supplied a detailed review of literature on cascade rotary dryers, covering all the topics related to this equipment, for example, the design of flights, particles transport, heat and mass transfer and the simulation of this kind of dryer. Many publications about particles transport have followed the empirical approach, and deals with the hold-up and residence time.

Most often, rotary dyers have been treated as simple direct contact heat exchangers, and the exchanger has been treated in terms of a volumetric global heat transfer coefficient. Friedman & Marshall (1949) and McCormick (1962) followed this approach. They've correlated the global coefficient with the gas flow rate W_B.

These correlations presented interesting results for steady state conditions, but they can't predict anything about the drying process inside of the dryer for the unsteady conditions, since they aren't able to predict the effect of the material flow rate variations induced by a change in the rotation of the shell, or retention of solid material in the dryer, which should cause a variation of the heat transfer area and, and consequently, in the volumetric heat transfer coefficient. Friedman & Marshall (1949a) had considered a correlation capable to perceive the dynamic behavior of the process.

Strumillo & Kudra (1986) presented as general principles of dryer design, the approach of drying kinetics, based in the experimental procedure, and a mathematical modeling of drying processes. In the first way, it describes the drying process as two distinct periods. The first has a constant drying rate, and the second has a variable drying rate. A differential mass balance provides an equation that permits to calculate the drying time, with the experimental moisture rate values. Perry et. al. (1999) had presented a model for both periods. It consists of equations integrated from the mass balance differential equation. For the drying rate constant period it was integrated between initial and critical content (the content limit between these periods), and between critical and the equilibrium content, at the end of drying process. In the falling rate period they presented correlations for different mechanisms of fluid internal transport.

Douglas et. al. (1993) had applied a mathematical model based on the differential heat and mass balance to the dynamic control of a countercurrent rotary dryer for the granulated sugar.

Wang et. al. (1993) had presented a model for the process of drying in rotating driers based on the model presented by Douglas et. al. (1993), considering the non-steady condition. The model consists in a set of partial differential equations, where different methods had been used to determine the heat transfer. Studies of static and dynamic simulations had been made.

2. Drying Process

Sugar drying is a complex unity operation that involves transient heat and mass transfer in a addition to many processes, such as physical or chemical transformations, that can cause changes in the quality of product as well as in the mechanisms of heat and mass transfer. The physical changes that can occur include: shrinking, crystallization, glass-transitions. In some cases, chemical or biochemical reactions, desirable or undesirable, can occur leading to the changes in the color, texture, smell or other properties of the solid product.

2.1. Rotary Dryers

The principal part of a Rotary dryer is a horizontal cylinder with a small inclination through which the material flows, and during the drying is heated by the hot airflow through the cylinder. In this process, the some heat is lost for heat conduction through the walls of the cylinder. In some cases, the cylinder rotates and in others the cylinder is stationary and a flight or a screw rotates inside the cylinder making the material flow completely. An example of rotary dryer is shown in Fig. 1.

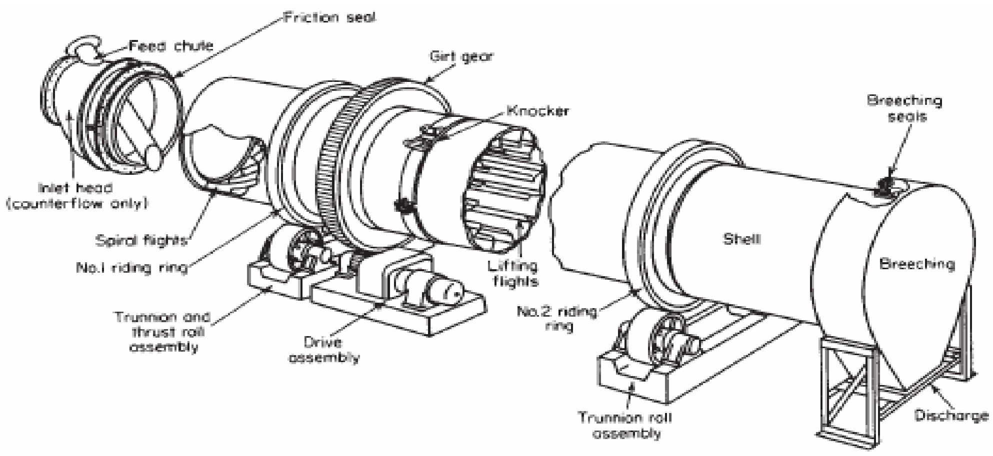

Figure 1. Component arrangement of a countercurrent direct-heat rotary dryer - ABB Raymond/Bartlett-Snow TM (Perry et. al., 1999).

Rotary dryers could have relative flow direction between the material and air streams in three ways: parallel, countercurrent and cross flow. The parallel flow dryers are widely used and particularly appropriate for drying of materials with high water content, sensible to the heat or have trend to break or to harden. The countercurrent rotary dryers are more appropriate for materials that need to be dried to very low a moisture levels, where the remaining humidity are very difficult to remove or when a product with high temperature is desired. Also they are effective used as combined dryers / pre-heaters.

The typical temperature profiles curves of gas and material in the interior of the dryer with parallel and countercurrent arrangement are shown in Figs. 2a and 2b, respectively.

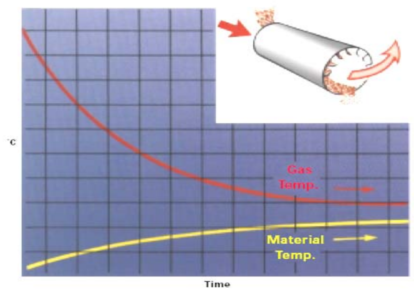

Figure 2a. Parallel flow.

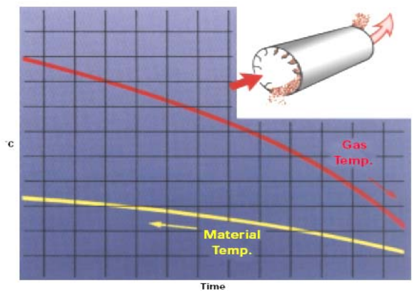

Figure 2b. Countercurrent flow.

In cross flow dryers, the material is supported and moved through a set of flights mounted in the shell of the dryer. Hot air is insufflating through channels in a cylinder of double wall and is deflected to pass through the solid, as shown in Fig. 3. The rotation of the cylinder makes the material roll and mix, promoting a bigger contact with the drying air. The constant movement of the solid assures a contact uniform with hot air for heat and mass transfer.

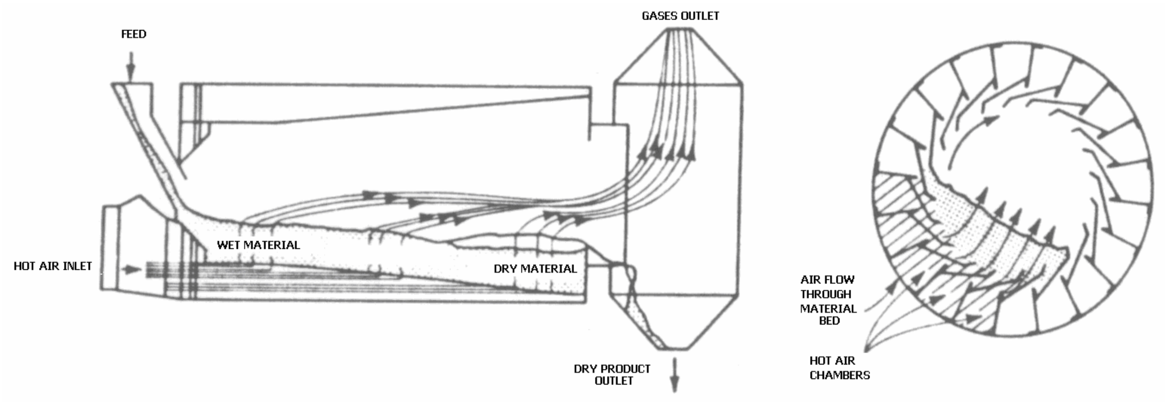

Figure 3. Dryer details.

The roto-louvre dryer is one of most important kind of continuous dryers. This type of cross flow dryer is appropriate to processes granulated solid, that don't offer much resistance to the passage of air, requires high contact with air. For example, materials such as sugar, rice, coffee, etc.

2.2. Physical Problem Description

In the Brazilian sugar industry, it is usual using models of total balance for dryers design. Such models don't shows good results, because they are based only in the inlet and outlet conditions of the product. Since changes in material properties occur during the drying process, this approach does not predict appropriately the drying process.

The model presented by Soares et. al. (2004) is composed of a set of mass and energy differential equations, and constitutive equations for heat and mass transfer. It can be described as a static model, that discards any dynamic effect, considers an outlet steady condition and the properties variations in function of the displacement in the dryer.

3. Simulation Models

This work uses the model presented by (Soares et. al., 2004) to dimensioning and predict the specific consumption of air of a dryer, using cases found in literature, to compare the results with some other methods, like the empiricist (Hugot's method) and the partially empirical (total balance method).

3.1. Method from Hugot

Hugot (1969), which first edition of his book has been published in 1950, presents a method to design a rotary sugar dryer. Basically, this is a method for required air flow rate determination.

This method starts with the desired value of material water content and calculates the necessary air flow rate based on the saturated air humidity in the outlet temperature, as it shown the Eq. (1).

$$W_B = \frac{W_S (X_1 - X_2)}{c(Y_{sat,2} - Y_{sat,1})} \quad (1)$$

where W_B is the air flow rate, W_S the material flow rate, X is the material water content, subscripts 1 and 2 are related to the inlet and outlet, respectively, c is a coefficient, Y_{sat} is the air saturation humidity, and subscripts 1 and 2 are related to the temperature that the humidity is evaluated, inlet and outlet, respectively.

Usually the outlet saturation humidity is calculated by thermodynamical correlations or some other method, as total balance method, that will be described in topic 3.2.

This method considers that, for a countercurrent flow, air absorbs about 2/3 of the water that could have absorbed if it was saturated in the exit of the dryer. To parallel flow, this amount would be of 1/3. In other words, coefficient *c* of the Eq. (1) has the value of 1/3 for the parallel flow and 2/3 for the countercurrent flow.

The drying calculations methodology proposed by Hugot, considers the length and diameter of the dryer as having pre-established values, independent of its demand. Accordingly to Hugot (1969) the length of the sugar dryers varies from 8 to 10 m, and its diameter from 1 to 4 m.

This method is based on the experience of the operator, who knows the equipment and for many time was considered with sensitivity enough to know a good configuration, predicting the length and diameter of the drum of the dryer.

3.2. Total Balances Based Method

A model based on total balances couldn't gives a good approach of the drying process, since is only taken in account the inlet and outlet states, not allowing to any deeper analysis nor the process optimization. This model can be used as the base for comparisons with other refined models. Basically, the model based on total balances consists of, as the proper name says, mass and energy balances between the initial and final states. The inlet parameters for the model are:

- Temperature of the material (T_m) in the entrance and the exit of the dryer;
- Material water content (X) in the entrance and the exit of the dryer;
- Material flow rate (W_S);
- Inlet air temperature (T_g);
- Inlet absolute air humidity (Y);
- Air flow rate (W_B).

3.3. Model Used in this Work

Using the developed model in Soares et. al. (2004), that considers the mass and energy balances in a control volume of a differential volume, as well as a balance on the air-material interface. The outlet moisture content and temperature of air and material on each differential volume are calculated using empirical correlations and properties experimentally determined.

Applying the same hypotheses described in Soares et. al. (2004) to simplify the equations and express the differential forms in terms of finite differences, the described system of equations for the method is as shown in Eqs. (2) to (5).

$$(I_{m,i} - I_{m,i-1}) + \left(\frac{W_B}{W_S}\right)(I_{g,i} - I_{g,i-1}) + q_l = 0 \tag{2}$$

$$(X_i - X_{i-1}) + \left(\frac{W_B}{W_S}\right)(Y_i - Y_{i-1}) = 0 \tag{3}$$

$$UaV(T_{g,i} - T_{m,i}) = W_S(I_{m,i} - I_{m,i-1}) + k_y aV(Y_{eq} - Y_{i-1})I_{Av} \tag{4}$$

$$W_S(X_i - X_{i-1}) + k_y aV(Y_{eq} - Y_{i-1}) = 0 \tag{5}$$

where I represents enthalpy, subscripts m and g means material and air, respectively, q_l represents the heat losses. The subscript i is the actual node of the mesh and i-1 indicates the prior node. V is the volume of the dryer and $k_y a$ is the mass transfer coefficient. Y_{eq} is the equilibrium humidity, which is calculated from the sorption isotherm. The enthalpy I_{Av} is the heat enthalpy of vaporization of the water transferred from the material to the air.

Here the equations are presented in a simplified form, where the term (W_B/W_S) appears, which represents the dry air consumption in function of the mass of dry product. It is an important parameter in the industry and normally can be used to performance comparison of industrial dryers.

Determination of the global volumetric heat transfer coefficient, *Ua*, was made, in this work, according to the correlation proposed by Friedman & Marshall (1949a):

$$Ua = \psi \left(\frac{m_S}{\rho_S V} \right)^{\beta} W_B^{0.16} \tag{6}$$

where m_S is the mass of dry product inside each node of the mesh, ρ_S is the material density and β and ψ are coefficients which depends on the material.

For the calculation of the residence time, T_R, a correlation proposed by Friedman & Marshall (1949b) was used, shown in the Eq. (7).

$$T_R = k \left(\frac{0{,}23L}{\tan(\alpha) N^{0,9} D} \pm \frac{0{,}6LBW_B}{W_S} \right) \tag{7}$$

where L, D, N and α are length, diameter, rotation and inclination of the dryer, respectively. The parameter B is function of grain's diameter, D_p, of the material being dried, thus, $B = 5D_p^{-0.5}$, and k is a constant of the process.

4. Methods Comparison

To compare the results of the described methods, nine cases of drying for the sugar had been used, using the data and results published by Douglas et. al. (1993), that used the data of industrial dryers supplied by Shield (1990), and simulated his dynamic model, comparing its results with the real values. Table 1 shows the characteristics of the simulated dryer used by Douglas et. al. (1993) and Tab. 2 shows the real inlet and outlet conditions of the cases used.

Table 1. Dryer dimensions (Douglas et. al., 1993).

Dimension	**Value**	**Unit**
Length	9.75	m
Diameter	3.05	m
Inclination	2.5	degree
Rotation	3.3	rpm

Table 2. Inlet dryer conditions.

Case	**Sugar Flow Rate (kg/s)**	**Inlet Sugar Moisture Content (kg/kg)**	**Inlet Sugar Temp. (°C)**	**Air Flow Rate (kg/s)**	**Air Humidity (kg/kg)**	**Inlet Air Temp. (°C)**	**Outlet Sugar Moisture Content (kg/kg)**	**Outlet Sugar Temp. (°C)**
1	23.45	0.0178	56.43	11.34	0.0110	23.26	0.0100	41.0
2	17.39	0.0148	54.95	8.11	0.0120	23.54	0.0090	38.0
3	12.07	0.0175	60.66	8.40	0.0130	21.06	0.0068	39.0
4	17.34	0.0215	54.23	8.59	0.0123	26.23	0.0132	45.0
5	23.23	0.0099	40.09	8.29	0.0100	24.42	0.0057	27.0
6	17.29	0.0082	37.12	8.31	0.0100	24.86	0.0055	27.5
7	11.92	0.0111	40.37	8.88	0.0115	16.06	0.0082	22.0
8	17.17	0.0131	38.12	8.76	0.0063	12.54	0.0112	25.5
9	17.86	0.0220	57.81	8.59	0.0086	26.23	0.0132	38.0

Two comparison studies were made on the present work with the model proposed by Soares et. al. (2004). The first one, considering the Hugot's method and the second one considering the total balance method. The method presented by Hugot, basically calculates the air consumption, considering preset values of length and diameter, and the total balance method considers just length and diameter of the dryer.

Detailed examples of calculations of case 1 of Tab. 2 for each method are shown in Figs. 5 and 6, after that it is shown the results of all simulations in Tabs. 3 and 4.

For the air consumption calculation in the dryer of case 1, shown in table 2, using the model considered for Soares et. al. (2004), was made an abacus, presented in Fig. 5, that shows the behavior of the system when simultaneous variations of material and air flow-rates occur. Figure 5 shows the selection of the air flow rate using this abacus.

Figure 5 shows the selection of the air flow rate using this abacus. In this case, when the material flow rate is set, a combination of material outlet moisture content and temperature with the desired values isn't possible to reach. Thus, it was selected another condition that was satisfactory. In this case the priority was the outlet moisture content, since it is the main objective of the drying. In other words, it was chosen the outlet moisture content slightly below of the real one and, consequently, a slightly bigger temperature.

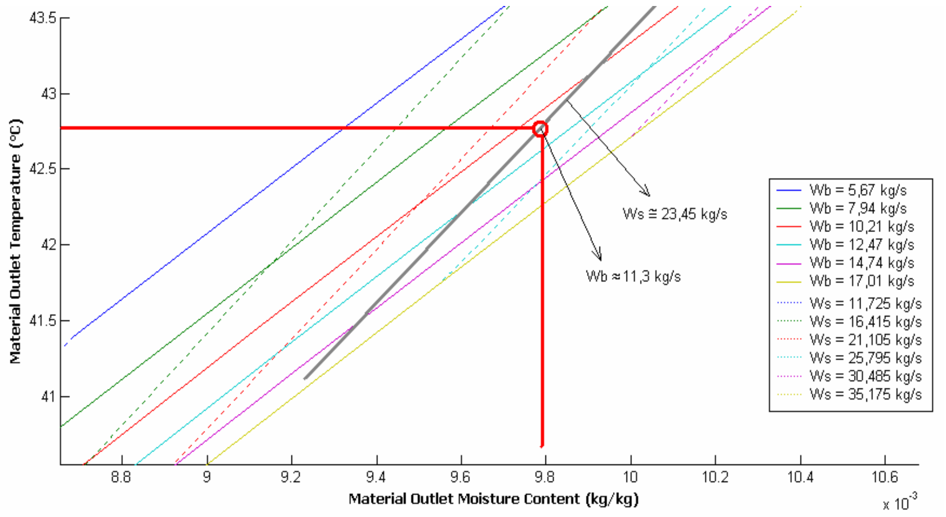

Figure 5. Air flow rate selection for case 1.

With this configuration an approximated value of 11.34 kg/s for the air flow rate was selected, that is the average point between the lines of W_B equals 12.47 and 10.21 kg/s.

The value of the air flow rate, calculated for the Hugot's method, was 14.26 kg/s. Actually, two possibilities were considered: the first one was to consider the outlet air temperature equal to the material outlet temperature for the calculation of the outlet saturation humidity; second was to use the total balance method to calculate the air outlet temperature and then calculate the air flow rate, however this second hypothesis has achieved, in this case, an air flow rate of 43.91 kg/s and average relative errors for all cases were 328%, therefore it were discarded, being considered only the first hypothesis.

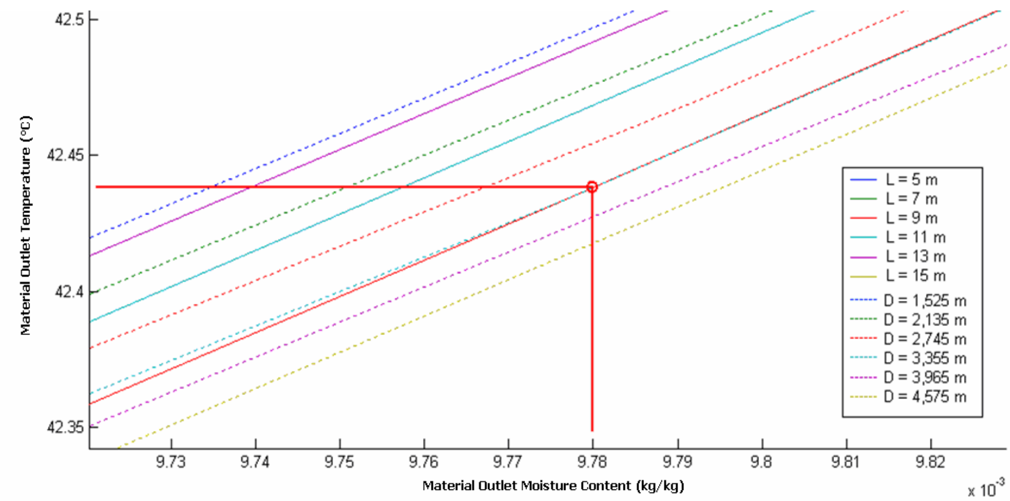

Figure 6. Dryer length selection for case 1.

For the dimensioning of the dryer in case 1, shown in Tab. 2, using the model considered for Soares et. al. (2004), an abacus generated for such was used, as Soares (2004), which shows the behavior of the system with simultaneous variations of length and diameter of the dryer.

Figure 6 shows the use of an abacus for the dimensioning of the above-mentioned dryer. With this abacus it was not possible to combine accurately the given values of outlet temperature and moisture content of case 1. It was decided to reduce slightly the moisture content and, consequently, to increase slightly the desired outlet temperature.

From Fig. 6 it can be seen that the outlet temperature had to be modified to slightly above of 42.4 °C to guarantee that with the supplied flow rate the outlet moisture content could reach the value of 0.00978 kg/kg, close to the desired value. From the graph, the values that was found were L = 9.0 m and $D \cong$ 3.36 m.

Table 3 shows the results for the air consumption for the Hugot's method and the method proposed for the conditions of cases 1 to 9 of Tab. 2.

Table 3. Air consumption methods comparison.

Real Air Consumption	Present Work		Hugot	
	Air Consumption	Relative Error	Air Consumption	Relative Error
0.4836	0.4836	0.0%	0.6081	25.7%
0.4664	0.4899	5.0%	0.5846	25.3%
0.6959	0.7316	5.1%	1.0289	47.9%
0.4954	0.5202	5.0%	0.5020	1.3%
0.3569	0.3749	5.1%	1.0422	192.0%
0.4806	0.5032	4.7%	0.6351	32.1%
0.7450	0.7844	5.3%	1.7924	140.6%
0.5102	0.5352	4.9%	0.4100	19.6%
0.4810	0.5050	5.0%	0.7960	65.5%

The discrepancies showed on the results obtained by the Hugot's method can be explained by a simple analysis on this method, since it considers that the air absorbs only a fraction of the amount of water that could be absorbed if the outlet air was saturated. In other words, the results generated by this method could be more accurate if the drying take place at a very slow rate, thus the air would be near to a saturation condition. The model presented considers the rate of moisture transfer from the material to the air, instead of a saturation condition. This consideration has a major impact on the results, since even if the fraction proposed by Hugot is accurate, it still depends on the dynamics of moisture transfer. Thus, the model proposed can describe accurately the drying process.

Table 4 show the dimensioning of the dryer for the conditions of cases 1 to 9 of Tab. 2, using the total balance and the considered by Soares et. al. (2004) method.

Table 4. Dimensioning methods comparison.

Present Work				Total Balance			
Length (m)	Relative Error	Diameter (m)	Relative Error	Length (m)	Relative Error	Diameter (m)	Relative Error
9.00	7.7%	3.36	10.2%	20.31	108.3%	3.22	5.6%
9.00	7.7%	2.75	9.8%	21.10	116.4%	2.72	10.8%
10.00	2.6%	3.20	4.9%	14.20	45.7%	2.76	9.4%
10.50	7.7%	3.66	20.0%	19.59	101.0%	2.82	7.5%
10.00	2.6%	4.27	40.0%	27.56	182.7%	2.75	9.8%
10.00	2.6%	2.75	9.8%	20.56	110.8%	2.75	9.9%
11.00	12.8%	3.20	4.9%	13.67	40.2%	2.80	8.2%
9.75	0.0%	3.66	20.0%	20.31	108.3%	2.76	9.6%
9.50	2.6%	3.66	20.0%	20.22	107.4%	2.82	7.6%

The results presented in Tab. 4, for the dimensioning, shows clearly that the total balance method, that is still used in the industry (COOPERSUCAR, 2000), supplies dryers with dimensions, in special the length, much above of that would have to be, becoming the much more expensive project and requiring a bigger space in the plant. The total balance method treats the moisture and temperature variations as linear, since it considers only the initial and final states. Besides, it is also based on observation, since many properties and process data are tabled.

The present method considers the variations throughout the dryer length and determines the properties needed to the calculations. Since the actual method is an ideal one, the outlet values of moisture and temperature were below the real ones, indicating a high efficiency. However, since it wasn't possible to reach the exact desired values, it was chosen combinations of length and diameter, prioritizing the material outlet moisture content.

A summary of the results can be seen in Tab. 5, which shows the minimum, average and maximum relative errors of each method, calculated as shown in Eq. (8).

$$dev = \left| \frac{x_{calculated} - x_{\exp erimental}}{x_{\exp erimental}} \right| \times 100 \quad (8)$$

Table 5. Relative Errors of all methods.

Relative Error	Air Consumption		Length		Diameter	
	Present Work	Hugot	Present Work	Total Balance	Present Work	Total Balance
Minimum	0.0%	1.3%	0.0%	40.2%	4.9%	5.6%
Average	4.5%	61.1%	5.1%	102.3%	15.5%	8.7%
Maximum	5.3%	192.0%	12.8%	182.7%	40.0%	10.8%

5. Conclusions

The total balance and Hugot's models are old. Currently many researches are being developed and because the effort of the scientific community, the knowledge of the drying process technology has been increased continuously, becoming possible the development of new methods.

The methods used for dimensioning and to determine the air consumption in a dryer, described in this work had been pioneering as a simple, fast and easy way to calculate such properties, avoiding to purchase equipments at a high cost or the consulting of specialized companies to the maintenance of the activities of the sugar industry.

The model developed by Soares et. al. (2004) and presented in this work can be used for the creation of abacuses that could guide the selection of parameters of operation and constructive details of the dryer, showing that, although being a simplified model, it can be of great utility in the industry and for research.

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