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EXPERIMENTAL DRYER DESIGN FOR AGRICULTURAL PRODUCTS

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ABSTRACT: This study consisted of designing and building an experimental dryer that allows working with different temperatures and velocities of the air, aiming to perform studies on thin- and thick-layer drying of agricultural products. The project was divided into three stages: heat source designing, dryer geometric parameters, and fan selection to meet operational demand. Heating was made by a set of six electrical resistances totaling 12 kW and the drying bed in thin layer was composed of two trays with diameter of 0.20 m. Operational demands were met using a centrifugal fan with a power rating of 735.5 W. The used methodology was able to size the experimental dryers for thin- and thick-layer drying working at distinct temperatures and air velocities.

KEY WORDS: thin layer, electrical resistance, temperature, air velocity.

INTRODUCTION

Drying equipment designed for agricultural products, known as dryers, are built in different internal and external geometric shapes to obtain different ways of air flow and product during the drying process, in addition to different ways of operation, aiming process efficiency and product quality maintenance during and after drying.

Dryers of agricultural products can be classified into three types considering the product flow: stationary, intermittent, and continuous dryers (DALPASQUALE et al., 1991). The dryers called stationary or fixed layer or also fixed bed are characterized by resemble to cylindrical silos, not necessarily having the same height as a conventional silo. The drying bed of those dryers includes a bottom composed of drilled plates through which the air is blown, keeping the product resting on the drilled plates during the drying process (GARCIA et al., 2004; SILVA, 2008).

Drying in a stationary or fixed layer consists in forcing the drying air flow through a product layer that remains static in the dryer (GARCIA et al., 2004). Among the artificial drying methods, stationary dryers are the ones that allow drying with unheated air, which depends on the hygroscopic equilibrium between product and the drying air, which in its turn depends on the temperature and relative humidity of the ambient air.

The drying system in fixed layer is widely used by researchers to study the drying kinetics of agricultural products and make simulations of the drying process by means of mathematical models. In order to study the drying kinetics of agricultural products, researchers submit thin layers of them to drying in a fixed bed and monitor their mass weight variation during the process, thereby describing their drying curve.

The drying in thin layer is defined as that with a thickness of only one product unit; on the other hand, a thick layer consists of a succession of superposed thin layers (KASHANINEJAD et al., 2007). When combined the equation that describes the drying of a product in thin layer with the representative equations of other specific physical properties of the product, it is formed a set of mathematical relationships that assist in calculating and understanding the drying process in thick layer (MARTINAZZO et al., 2010).

The simulation by means of mathematical models of the drying process in dryers that operate

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at high temperatures has become an important tool for engineers who work in the area of grain drying and storage (QUEIROZ et al., 1999). Thus, the simulation of various processes has been widely used to assist in the development of more efficient equipment.

Many researchers study the drying kinetics in thin layer of different agricultural products, and many of these studies are conducted in forced air circulation ovens (COSTA et al., 2011; MADUREIRA et al., 2011; SOUSA et al., 2011; OLIVEIRA et al., 2012; SIQUEIRA et al., 2012; DIÓGENES et al., 2013; SANTOS et al., 2013; PEREZ et al., 2013; SIQUEIRA et al., 2013; GONELI et al., 2014a, GONELI et al., 2014b, MARTINS et al., 2015), in which it is only possible to control the drying air temperature during the process. The air flow in greenhouses is fixed, not allowing changes for different tests, being the air flow one of the variables that directly affects the drying process of agricultural products.

The main factors affecting the drying process are the temperature and velocity of the air, directly influencing on the drying time and final product quality. The higher the temperature and velocity of the air is, the lower the product drying time, as well as the possibility of loss in quality due to water stress generated by the high drying rate (CARLESSO et al., 2005).

Due to the need of studying the drying process of agricultural products with controlled temperature and velocity of the air, and even the interaction between these two variables, many researchers have used experimental dryers of fixed bed in laboratory conditions, achieving greater control and dominance of these variables (CARLESSO et al., 2005; RODRIGUES et al., 2008; SANTOS et al., 2010; REIS et al., 2011; FARIA et al., 2012; FERREIRA et al., 2012; PRATES et al., 2012; MORAIS et al., 2013; OLIVEIRA et al., 2013; SOUSA et al., 2014).

By studying the drying of passion fruit seeds in thin layer, CARLESSO et al. (2005) used a prototype of a fixed bed dryer in which the drying bed was constituted by a circular tray with perforated bottom drilled plate with an internal diameter of 0.25 m and height of 0.10 m, having a centrifugal fan with power of 1.0 hp and using as air heating source a set of electrical resistances with total power of 5 kW.

Although several researchers make use of experimental dryers in their researches, which have different configurations of drying bed in thin layer and constructive forms, there is no established methodology for the sizing and construction of them.

Considering the mentioned above, this study aimed to size and build an experimental dryer that allows working with different temperatures and velocities of the air, aiming drying studies of agricultural products in thin layer and, secondarily, in thick layer.

DESCRIPTION OF THE SUBJECT

The methodology presented below was used to size and build an experimental dryer, which was carried out at the Laboratory of Pre-Processing and Storage of Agricultural Products of the School of Agricultural Sciences, Federal University of Grande Dourados, in Dourados - MS, Brazil. Figure 1 shows a sketch of the experimental dryer project developed according to the methodology to be presented, in which will be discussed each design and construction stage.

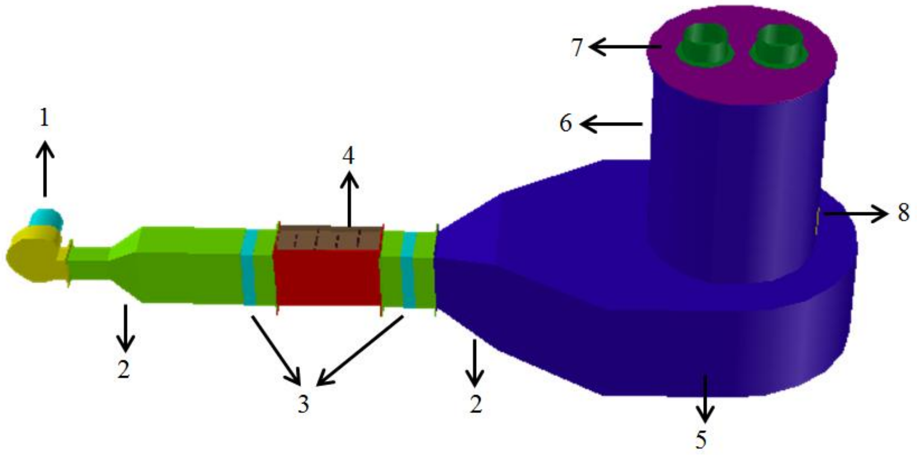

FIGURE 1. Three-dimensional representation of the designed experimental dryer.

where,

1 – Centrifugal fan: it has the function to provide adequate air flow for drying tests and to overcome the static pressure imposed by agricultural products when the drying in thick layer is carried out;

2 – Expansions: their function is to join the dryer structures with different dimensions in order to standardize the air flow in it and prevent head loss;

3 – Air homogenizers: their function is to homogenize the distribution of air in the duct and provide better contact between the air and the electrical resistance, favoring the heat exchange;

4 – Electrical resistances: their function is to provide thermal energy to the air for drying;

5 – Plenum: its function is to provide a good distribution of air to the drying bed in thick layer;

6 – Drying bed in thick layer;

7 – Trays for drying in thin layer, and

8 – Opening for unloading the product from the drying bed in thick layer.

The experimental dryer designing and designing were divided into five parts: sizing of the electric power required for heating the air, sizing of the drying bed in thin and thick layer, expansions, plenum air homogenizers and fan selection to meet the operational demands of the dryer.

Sizing of electric power required for heating the air and the drying bed in thin layer

As a heat source of drying air, it was chosen electrical resistances of heat exchange with the air due to their simple operation, allowing automates the temperature control for various electronic control logics. The set of electrical resistances has been designed to transfer thermal energy to the drying air so that it reached the temperature of 90 °C and air velocity in each drying tray in thin layer with maximum value of 2 m s^{-1}.

The sizing of the electric power of resistances for generating sufficient heat to the drying air influenced the configuration of the drying bed in thin layer (number and diameter of trays). The electric power required for heating the drying air was calculated according to [eq. (1)].

$$P = \frac{\dot{Q}}{V_s} \Delta h \tag{1}$$

In which,

P is the electric power (kW);

$\dot{Q}$ is the air flow ($m^3\ s^{-1}$);

V_s is the specific volume of moist air ($m^3\ kg_{dry\ air}^{-1}$) and,

Δh is the variation of air enthalpy ($kJ\ kg_{dry\ air}^{-1}$).

The variation of enthalpy (Δh) is the difference between the drying air enthalpy (after passing through the electrical resistances) and the inlet air in the dryer (ambient air). The psychometric properties of the ambient and drying air, considering the elevation of 463 m in Dourados, MS, Brazil, were calculated by using the software Grapsi 8.1.1.

The total volumetric flow in the drying process in thin layer was obtained according to [eq. (2)] considering an air velocity of 2 m s^{-1} for drying in thin layer.

$$\dot{Q}_{THIN} = n_t\ v\ A_t \qquad (2)$$

In which,

$\dot{Q}_{THIN}$ is the demanded air flow in the drying in thin layer ($m^3\ s^{-1}$);

n_t is the number of trays;

v is the drying air velocity in thin layer (m s^{-1}), and

A_t is the area of each drying tray in thin layer (m^2).

To calculate the electric power required for heating was necessary to know the variation of enthalpy (Equation 1), which is dependent on the ambient air conditions and heated air. After analyzing the study by SCHNEIDER & SILVA (2012) on the climate dynamics of Dourados, MS, Brazil, it was possible to adopt as average temperature and relative humidity the values of 20 °C and 70%, respectively.

Table 1 shows the psychometric properties of the inlet (ambient) and drying air involved in calculating the electric power required for heating the air. It is possible to note that the variation of enthalpy for heating the inlet air at 90 °C is 71.76 kJ $kg_{dry\ air}^{-1}$.

TABLE 1. Psychometric properties of the ambient and drying air for Dourados, MS, Brazil, considering the local altitude of 463 m.

	Inlet air (ambient air)	Outlet air (drying air)
Temperature (°C)	20	90
Relative humidity (%)	70	2.34
Specific enthalpy ($kJ\ kg_{dry\ air}^{-1}$)	47.52	119.28
Specific volume ($m^3\ kg_{dry\ air}^{-1}$)	0.89	1.10

Table 2 shows the electric power values demanded by the electrical resistances for different settings of the drying bed in thin layer considering a final temperature of 90 °C and an outlet velocity of the drying air of 2 m s^{-1} in each tray, being analyzed two diameter combinations of trays with four different quantities. To calculate the electric power required for heating the air (Equation 1), it was used the specific volume of inlet air.

TABLE 2. Simulation of the electric power demanded by the electrical resistances based on the number and diameter of trays for drying in thin layer.

Velocity (m s^{-1})	Diameter (m)	Number of trays	Air flow (m^3 s^{-1})	Power (kW)
2.0	0.25	4	0.39	31.66
2.0	0.25	3	0.29	23.75
2.0	0.25	2	0.20	15.83
2.0	0.25	1	0.10	7.92
2.0	0.20	4	0.25	20.26
2.0	0.20	3	0.19	15.20
2.0	0.20	2	0.13	10.13
2.0	0.20	1	0.06	5.07

By analyzing Table 2, it is observed that the variation in number and diameter of trays has a strong influence on the demanded electric power for heating the drying air. The experimental dryer was designed to be placed in a research laboratory for drying and storage agricultural products in which there are various equipment (forced air circulation ovens, climate chambers, air conditioners, etc.) with different electric power demands. Thus, there was the need to observe the electric power in order not to cause risks of overloading the electrical installation of the laboratory. Another important point in selecting the configuration of the drying bed in thin layer is that the higher the electric power is, the higher the component costs for assembling the control panel of the experimental dryer.

Taking into account the considerations made previously and the configuration that meets the research needs, it was chosen a drying bed in thin layer that presented a set of two trays with 0.20 m of diameter each, corresponding to a power of at least 10.13 kW (Table 2). Thus, it reduced considerably the number of times that a condition (temperature and velocity of the air) must be tested to obtain a satisfactory number of repetitions. Another possibility to have a reasonable number of repetitions on a single condition was to construct a set of four trays (Figure 2). The use of this bed with four trays is possible when it comes to drying with a combination of temperature and velocity of the air that do not extrapolate the power supplied by the set of electrical resistances.

FIGURE 2. Drying bed in thin layer with two (left) and four (right) trays.

The drying beds in thin layer of experimental dryers used in researches are very diverse with respect to size, number and shape. Most dryers are radially arranged with circular trays as the experimental dryer used by CARLESSO et al. (2005), which had as drying bed in thin layer a circular tray with a diameter of 0.25 m and a height of 0.10 m. On the other hand, the experimental dryer used by MORAIS et al. (2013) had three circular trays with a diameter of 0.09 m and that used by OLIVEIRA et al. (2013) also had three trays, but with a diameter of 0.23 m and height of 0.05 m.

After selected the configuration of the drying bed in thin layer (two trays of 0.2 m in diameter each), a set of six finned electrical resistances of 2000 W each was assembled for heating exchange with the air, totaling 12 kW of power, wherein each component has a length of 0.30 m and voltage supply of 220 V. The set of finned electrical resistances (12 kW) presented a power 18.5% higher than the sized (10.13 kW), providing to the heating system a safety margin regarding the electric power availability for heating the drying air.

Drying bed in thick layer

The cylinder diameter that constitutes the drying bed in thick layer must be enough to dispose the drying bed in thin layer because it is assembled on the drying bed in thick layer (Figure 1).

The average layer thickness recommended for drying in fixed bed dryer at high temperatures for most agricultural products lies in the range from 0.40 to 0.60 m. Drying in a fixed bed at high temperatures requires revolving the product mass in order to avoid water content gradients and over drying the layer close to the drilled plate (SILVA, 2008). Therefore, to facilitate the manual product turn over when drying in thick layer, it was adopted a height of 1.00 m for the drying bed.

Since the drying bed in thin layer is composed of two or four trays with diameter of 0.2 m, the minimum diameter of the drying bed in thick layer to properly arrange the trays that compose the drying bed in thin layer could be 0.60 m. With regard to the drying quality in thick layer, which is mainly influenced by the product layer thickness, it was adopted a diameter of 0.8 m, which results in a lower layer thickness when compared to the two diameters for the same product mass. In Figures 3 and 4 are shown the front and top views of the experimental dryer with all its components (drying bed in thin and thick layer, expansions, plenum chamber and air homogenizers).

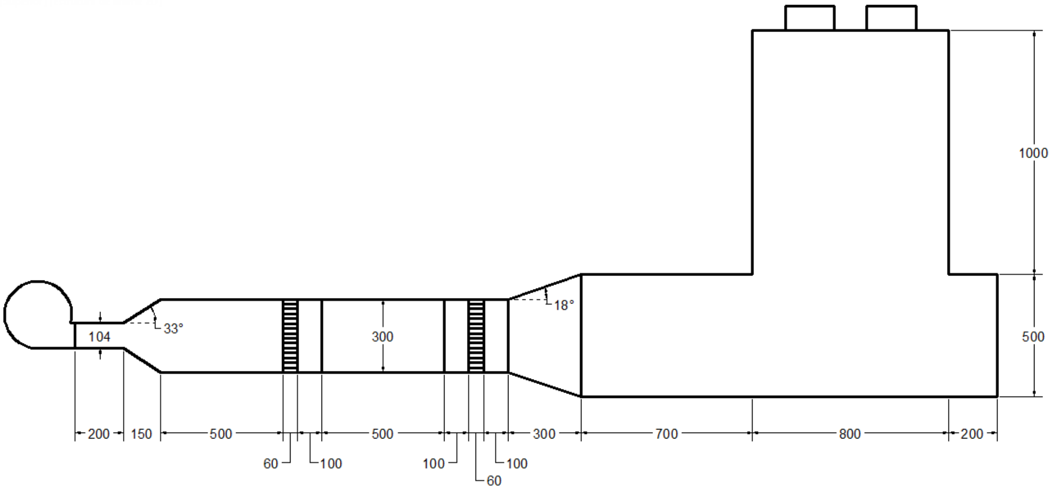

FIGURE 3. Front view of the experimental dryer (dimension values in millimeters or × 10^{-3} m).

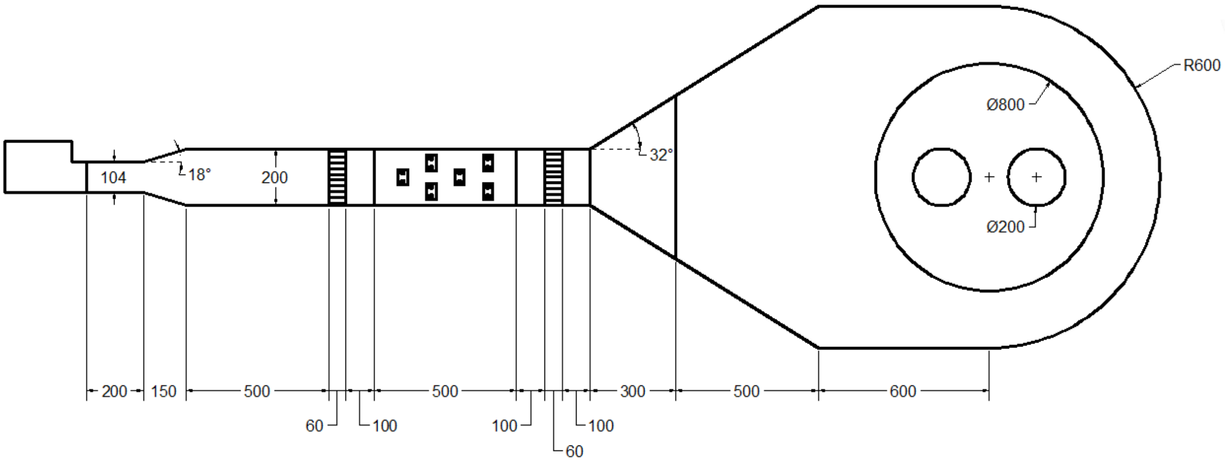

FIGURE 4. Top view of the experimental dryer (dimension values in millimeters or × 10^{-3} m).

The drilled plate of the drying bed in thick layer was constructed from a mesh of circular holes with average diameter of 1.9×10^{-3} m, totaling a drilled area of 33.97%. The drying trays in thin layer were also built with the same mesh (Figure 2).

Expansions and plenum chamber

The transition elements or expansions between the air distribution chamber of a fixed bed dryer and the fan are required to standardize the air flow in the dryer. The expansions between the fan and the air distribution chamber were sized with the opening angle of the transition element in relation to the symmetry axis of the dryer between 15 and 45° in order to have a negligible head loss (DALPASQUALE et al., 1991). Therefore, this recommendation has been implemented in the expansions after the fan and immediately before the plenum, as can be seen in Figures 3 and 4.

DALPASQUALE et al. (1991) recommend for the construction of fixed bed dryers that the air distribution chamber (plenum) have a height of 0.50 m to facilitate the floor maintenance of the drying bed and plenum, in addition to prevent high head losses and enable a good distribution of the drying air. Thus, the plenum of the experimental dryer met this specification (Figure 3).

Air homogenizers

To homogenize the air flow in the duct between the fan and the plenum, flow homogenizers were installed in the dryer before and after the electrical resistances (Figure 1). The homogenizer installed before the electrical resistances has the function to homogenize the air distribution in the duct, so that it makes contact with the entire structure of the electrical resistances, optimizing the heat exchange between the air and the fins of the resistances. After the resistances, the homogenizer has the function of attenuating the turbulence caused during the flow, when the air passes through the set of electrical resistances, so that it reaches a more uniform regime in the air distribution chamber.

The homogenizer was built in alveoli of square section, wherein the dimensions of the edges of them observed a limit from 7.5 to 15% of the air duct diameter in which it was installed. The homogenizer thickness corresponded three times the size of the homogenizer alveolus edge.

Since the section of the dryer air duct was rectangular (Figures 1, 3 and 4), it was necessary to determine the equivalent diameter (Equation 3).

$$D_{eq} = \frac{2\ a\ b}{a + b} \tag{3}$$

In which,

D_{eq} is the equivalent diameter for a rectangular duct (m);

a is the height of the rectangular duct (m), and

b is the width of the rectangular duct (m).

By applying the [eq. (3)], it was obtained the equivalent diameter of 0.24 m for the duct section in which the electrical resistances have been allocated, considering a duct height of 0.30 m and its width of 0.20 m (Figures 3 and 4). Thus, the homogenizer alveoli could have edges from 0.018 to 0.036 m (7.5 to 15% of the duct diameter). However, for construction convenience, it was adopted alveoli edges of 0.02 m. Consequently, the homogenizer thickness was 0.06 m (three times the length of the homogenizer edge) (Figures 3 and 4).

Thermal insulation

The experimental dryer was designed to heat the air up to 90 °C, but it is possible to reach higher temperatures because its adjustments that allow operating it with lower air velocity. Thus, it was necessary to select a thermal insulator that for security reasons could withstand temperatures around 200 °C.

Thermal insulators that withstand temperatures around 200 °C are easy to find on the market, being the most popular the glass wool and rock wool. In this study, it was used a thermal insulator of ceramic fiber, which withstands temperatures up to 1260 °C, with a thickness of 0.051 m and density of 128 kg m^{-3}. This thermal insulator was used due to its characteristics meet handily the project needs, in addition to the relatively low cost and ease of acquisition. For fixing the thermal insulator in the experimental dryer, it was installed between double plates.

Selecting the fan for the dryer

The fan of the experimental dryer was selected according to the maximum flow rate and static pressure demanded for drying in thin and thick layer. The maximum demanded air flow for drying in thin and thick layer is determined by eqs. (2) and (4), respectively.

$$\dot{Q}_{THICK} = A_L \ AFD \tag{4}$$

In which,

$\dot{Q}_{THICK}$ is the demanded air flow in the drying in thick layer ($m^3\ s^{-1}$);

A_L is the drying bed area in thick layer (m^2), and

AFD is the air flow density ($m^3\ s^{-1}\ m^{-2}$).

In order to calculate the maximum air flow demanded for drying in thick layer, it was used the air density value of 0.25 $m^3\ s^{-1}\ m^{-2}$ since according to DALPASQUALE et al. (1991) the air flow density used in drying at high temperatures in fixed bed dryer can vary from 0.12 to 0.25 $m^3\ s^{-1}\ m^{-2}$, being used as a criterion for selecting the fan the increased air flow value determined by the eqs. (2) and (4).

The drop in pressure or static pressure imposed by the dryer structures (expansions, plenum, etc.) was disregarded, and in a fixed bed dryer is expected that the highest drop in pressure, except that imposed by the product to be dried, be caused by the drilled plate. According to SILVA (2008), if the drilled plate presents at least 10% of perforated area, it is disregarded the drop in pressure imposed by this structure. Thus, it was selected a drilled plate that presented more than 10% of perforated area to compose the drying bed in thick and thin layer.

The resistance to the passage of air imposed by the product mass was determined only for the drying in thick layer by means of [eq. (5)] (SILVA, 2008) plus a correction factor, since in thin layer it is negligible.

$$\Delta P_g = \frac{a\ AFD^2\ h_g}{\ln(1 + b\ AFD)}\ CF \tag{5}$$

In which,

ΔP_g is the drop in pressure due to product resistance (mm.c.a.);

AFD is the air flow density ($m^3\ min^{-1}\ m^{-2}$);

h_g is the height of the product mass (m);

a and *b* are constants dependent on the various agricultural products, and

CF is the correction factor (25% for losses not calculated and 25% for the compaction factor).

Table 3 shows the maximum values of demanded flow in the drying process in thick and thin layer determined by eqs. (2) and (4).

TABLE 3. Maximum air flow demanded for drying in thin and thick layer.

Air flow demanded (m^3 min^{-1})		
Thin layer		Thick layer
Set of 2 trays	Set of 4 trays	
7.54	15.08	7.54

By analyzing the drying in thin layer, in the situation that requires higher air flow for drying, it was obtained the flow of 15.08 m^3 min^{-1}; for drying in thin layer the drops in pressure imposed by the dryer structures and the product layer are negligible due to the thickness be the thinnest as possible. Thus, it must be selected a fan that can provide the air flow of up to 15.08 m^3 min^{-1}.

For the drying in thick layer (Table 3), the maximum air flow rate is 7.54 m^3 min^{-1}. However, in the case of a thick layer, it should be considered the resistance to the air imposed by the product mass. Thus, the calculation for drop in pressure was conducted for wheat due to its characteristic in offering the highest resistance to the passage of air, in addition to be one of the main and more traditional agricultural products (SILVA, 2008). The drop in pressure imposed by the wheat was calculated according to [eq. (5)], with the values of the coefficients a and b equal to 0.825 and 0.164, respectively (SILVA, 2008).

Table 4 shows the value of the drop in pressure calculated for wheat considering some layer thickness values and air flow density recommended for drying agricultural products in stationary dryers (DALPASQUALE et al., 1991).

TABLE 4. Pressure drop (ΔP_g) due to different air flow densities and wheat layer thickness.

AFD (m^3 min^{-1} m^{-2})	Flow rate (m^3 min^{-1})	Layer thickness (m)	ΔP_g (mm.c.a.)
7.20	3.62	0.40	34.23
		0.50	42.78
		0.60	51.34
9.00	4.52	0.40	45.99
		0.50	57.49
		0.60	68.99
12.00	6.03	0.40	68.14
		0.50	85.18
		0.60	102.21
15.00	7.54	0.40	93.32
		0.50	116.64
		0.60	139.97

When studying the resistance to the passage of air through a mass of quinoa grains as a function of the grain layer depth, impurity content and increase of air flow, GRATÃO et al. (2013) found that the static pressure increases linearly with increasing the grain layer depth; also, for the same product layer depth the static pressure increases with the increase of air flow. In addition, the authors reported that other researchers studying different agricultural products have also observed similar behavior, thus reinforcing the behavior of the information presented in Table 4, which were the basis to select the appropriate fan for the experimental dryer.

Based on the maximum flow rate values demanded in the drying process in thin and thick layer (Table 3) and the drop in pressure imposed by the product mass (Table 4), it was selected a fan that would meet the needs of the drying process. The commercial fan was selected based on the catalog of Sirocco fans VSI, manufactured by IBRAM, being selected the model VSI–160. Figure 5 shows the Sirocco fan VSI–160 curve, manufactured by IBRAM.

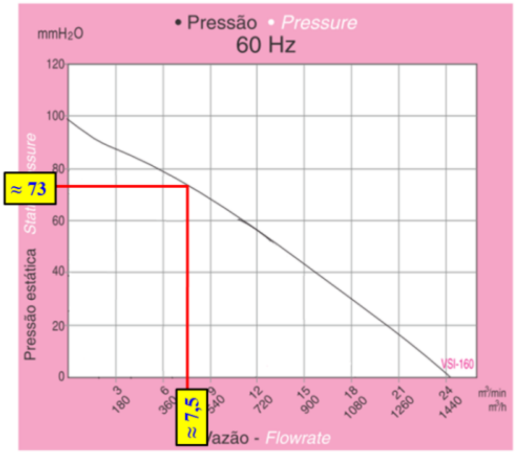

FIGURE 5. Sirocco fan curve, model VSI–160, manufactured by IBRAM. Source: Adapted from IBRAM (2013).

As can be observed in Table 4 and Figure 5, for the air flow density values of 15.00 and 12.00 $m^3\ min^{-1}\ m^{-2}$ for wheat drying, it should be used wheat layers of approximately 0.31 and 0.45 m, respectively, due to the drop in pressure imposed by the product in this air flow. For the other air flux density values shown in Table 4, it is possible to dry wheat by using the thicknesses recommended in this table. For the other agricultural products, which have lower resistance to the passage of the air flow when compared to wheat, it is possible to use thicker layers for higher air flow densities. Thus, the selected fan meets the drying conditions in thick layer, with minimal limitations in the case of drying products that offer high resistance to the passage of air, as in wheat.

It can be observed in Figure 6 the experimental dryer built according to the methodology presented and allocated at the Laboratory of Pre-Processing and Storage of Agricultural Products of the Federal University of Grande Dourados.

FIGURE 6. Experimental dryer for drying agricultural products in thin and thick layer.

The temperature control in the experimental dryer (Figure 6) was performed by means of a power controller manufactured by Novus, model PCW–3P–60, and a temperature controller manufactured by Novus, model N1200, working with a proportional integral derivative (PID) controlling logic. In order to provide different velocities to the drying air, it was installed a frequency inverter model CFW08, manufactured by WEG, in the motor of the centrifugal fan.

CONCLUSIONS

Using the methodology presented, it was possible to size experimental dryers to operate in different ranges of temperature and velocity of the drying air, with different drying bed configurations in thin and thick layer.

The configuration of the drying bed in thick layer (quantity and diameter of trays) and the drying air velocity strongly influences the sizing of the electrical resistances for heating the air; for the fan selection, it is preponderant the influence of thickness and type of product for the drying in thick layer.

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