COBEM-2017-0726
SOYBEAN STORAGE BIN AERATION SYSTEM OPTIMIZATION

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Abstract. *Aeration is the process used to maintain the quality of grain in storage bins. The optimization of the aeration design and operation is very important in order to have a safe and cost effective storage. In this work a mathematical model and simulation software were developed to predict the airflow distribution in horizontal storage bin with grain mass under non homogeneous and anisotropic conditions. The model incorporates a criterion for airflow distribution evaluation and optimization. Experimental data from an actual horizontal storage bin were collected, the airflow distribution was simulated and an optimal inlet pressure profile was proposed. The results show that the proposed inlet profile greatly improves the airflow distribution and can serve as a guide to better aeration projects.*

Keywords: *Mathematical Modeling, Aeration, Airflow Optimization, Storage Bins.*

1. INTRODUCTION

With the advance of agricultural field and harvests, the rural production has become an important topic. When it comes to finding improvements in production, investing in storage is imperative. The grain production is stored in vertical or horizontal storage bins in different sizes where the important issue is to keep the quality of the grains and to reduce losses. The main technique applied to preserve stored grains is aeration because it seeks to keep the grains mass at a proper and homogeneous temperature in order to obtain an efficient and safe storage.

To compensate for the deficiency of storage capacity in the country, it is widely adopted the construction and operation of large horizontal bulk storage bins, reaching significant dimensions. Uniform ventilation throughout the grain mass under these conditions is difficult and sometimes impossible. An inefficient aeration system can cause problems such as migration of grain humidity, grain overheating due to biological activity, and fungal and insect proliferation Weber (2005).

EThere are several factors that affect the distribution of airflow in grain storage bins, such as filling method, grain depth, porosity and grain humidity, among others. InWeber (2005); Shedd (1953); Brooker (1961, 1969); Brooker *et al.* (1982); Haque *et al.* (1981); Jayas *et al.* (1987); Maier *et al.* (1992); Khatchatourian and Savicki (2004); Khatchatourian and Oliveira (2006); Khatchatourian *et al.* (2007); Crozza and Pagano (2006); Silva *et al.* (2009) othe airflow through the grain mass under the influence of some of these characteristics was studied. In large storage bins, the non-homogeneity was studied in the work of Khatchatourian and Binelo (2008) and grain mass anisotropy in Hood and Thorpe (1992); Neethirajan *et al.* (2008). Khatchatourian *et al.* (2017)) studied the thermal state of the grain mass in vertical storage bin with aeration system. In order to the aeration system to be efficient, the aeration process must be controlled so that airflow uniformity occurs in all regions of the storage bin. Considering that there are regions where this uniformity of airflow does not occur, it is sought to compensate with the increase in total flow, causing an increase in energy consumption, which makes the system more economically costly. In addition, failures in the aeration system can cause excessive drying in one part of the grain mass and inefficient aeration in other domains.

The main objectives of this work were: a) to collect data from a real grain storage system (object of study); b) to develop a mathematical model and simulation software to predict the distribution of airflow in horizontal bulk storage bins, under non-homogeneous and anisotropic conditions; c) incorporate in the model a criterion of evaluation and optimization of the aeration system; d) evaluate the performance of the aeration system of the storage bin studied and propose an optimized air inlet pressure profile.

2. THE OBJECT STUDY DESCRIPTION

The object of study of this work is a real grain storage system owned by Três Tentos Agroindustrial Company, located in the city of Ijuí, state of Rio Grande do Sul, Brazil. Table 1 shows the characteristics of the bulk storage bin and Fig. 1 shows its structure.

Table 1. Characteristics of the object of study.

Type of grain	Soya bean
Tye of store	Below ground, V-shaped
Storage capacity	60 tons
Number of inlets for central aeration	12 registers
Central aeration input number	14 fans DYNT 04, 20 CV
Side aeration input number	8 registers
Number of fans for lateral aeration	2 centrifugal fans RFS 800, 40 CV
Side entry aeration side end	8 registers
Number of lateral aeration fans ends	8 centrifugal fans RLS 450, 4 CV
Pressure value of central aeration	2060 Pa
Pressure value of lateral aeration	3138 Pa
Pressure value of lateral aeration end	1471 Pa
Depth	13,4 m

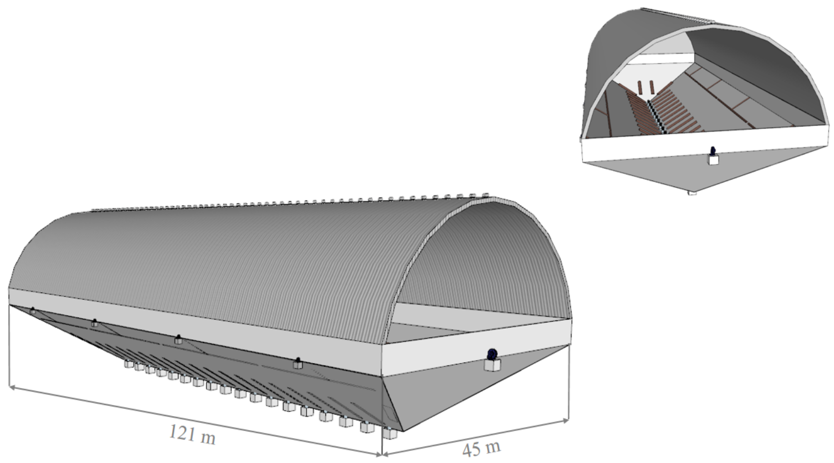

Figure 1. Sketch of the structure of the object of study.

The storage bin has a deep V structure, 121 meters long and 45 meters wide. The aeration system consists of three air inlet systems: 1) Central Aeration, 2) Lateral Aeration, and 3) Aeration at the Extremities. Figure 2 mostra a localização the location of the air inlets of the aeration system.

To perform the simulation of the airflow of the real system, the grain mass height map was obtained for the entire domain of the study object. It was possible to approximate the position of the points of the grain mass (x, y, z), by means of a laser distance meter with an accuracy of $\pm 1,5$ millimeters, measuring $0,05$ to 50 meters away. Experimental data was also collected from the study object, referring to air pressure and speed and grain mass temperature, which will be used in future work.

3. MATERIALS AND METHODS

3.1 Mathematical Modeling

In order to simulate three-dimensional airflow in particulate medium, the mathematical model described by Khatchatourian and Binelo (2008), was used. It describes the airflow in particulate medium, consisting of a system of two equations:

$$divV = 0 \tag{1}$$

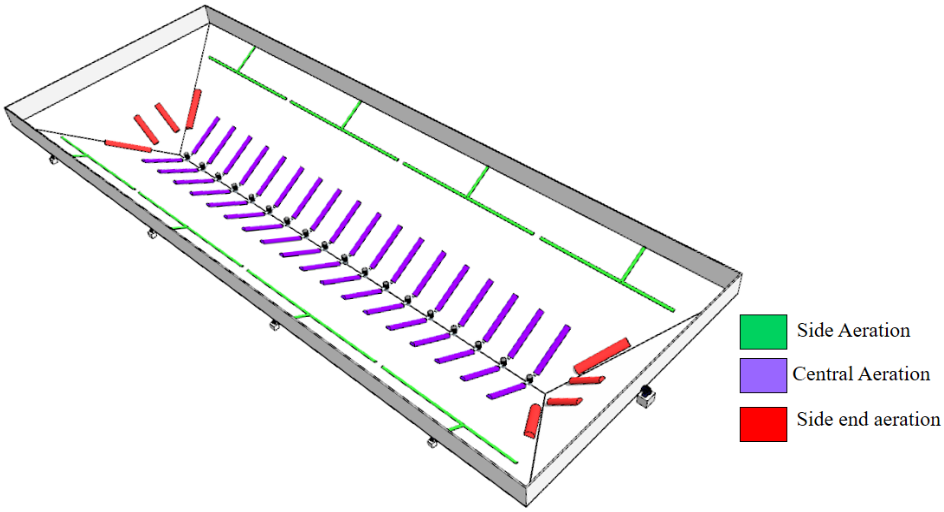

Figure 2. Location of the air intakes of the aeration system of the object of study

$$V = -\frac{gradP}{|gradP|} exp\left(\left\{\left[\left(1+U^2\right) - 2Uarctan\left(U\right)\right]/\pi + 3U\right\}/4a + C\right) \tag{2}$$

where V is the speed vector in ms^{-1}; $gradP$ is the pressure gradient in Pa; a and b are constants that depend on the type of grain; where $U(P) = aln\,|gradP| + b$ s an intermediate argument, corresponding to laminar and turbulent flow; C is the integration constant.

A Eq. (1)is the continuity equation for incompressible fluid whose density remains constant (very small air speed) and isothermal. The proportionality K is expressed by the permeability coefficient for anisotropic medium:

$$K = \frac{exp\left(\left\{\left[ln\left(1+U^2\right) - 2Uartan(U)\right)\right]\pi + 3U\right\}/4a + C\right)}{|gradP|} \tag{3}$$

Using Eq. (1) the components of velocity u, v and w for the 3D case, we have:

$$u = -K_x\frac{\partial P}{\partial x}; v = -K_y\frac{\partial P}{\partial y}; w = -K_z\frac{\partial P}{\partial z} \tag{4}$$

By combining Eq. (4) with Eq. (1), the non-linear partial differential equation is obtained for the general case of the airflow in granulated medium, given by:

$$\frac{\partial}{\partial x}\left(-K_x\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(-K_y\frac{\partial P}{\partial y}\right) + \frac{\partial}{\partial z}\left(-K_z\frac{\partial P}{\partial z}\right) = 0 \tag{5}$$

where K_x, K_y and K_z in $m^3kg^{-1}s$, are the permeability coefficients in the main directions.

Considering the problem, we have the boundary condition:

1. Dirichlet condition for input and output of air are considered constant values for the pressure, Eq. (6).

$$P = P_e \tag{6}$$

2. Condition of the natural boundary of the problem or boundary value problem of Neumann, Eq. (7).

$$\mathbf{n}gradP = 0 \tag{7}$$

where: P_e is the pressure at the air inlet and outlet at Pa; $\mathbf{n}$ n is the unit vector normal to the storage bin wall surface.

A Eq. (5), together with the Dirichlet boundary conditions Eq. (6) and Neumann Eq. (7), describe the airflow distribution in bulk grain medium with an aeration system under non-uniform and anisotropic conditions.

In this paper it is assumed that: a) the coefficient K_z corresponds to the vertical direction; b) the coefficients belonging to the horizontal plane are equal, i.e. $K_x = K_y$; c) the ratio between the coefficients in the vertical and horizontal direction (degree of anisotropy) is constant at all points of the storage bin. In large storage bins, due to compaction, grain mass was not considered to be homogeneous and the permeability coefficient and the pressure gradient varied according to the depth at which the grain layer was located. The results obtained in Khatchatourian and Binelo (2008) were used to account for the influence of the grain bulk compaction factor on the permeability coefficient. The anisotropy of the grain mass (the difference between K_z and K_x or K_y) was taken into account in accordance with the work Khatchatourian *et al.* (2009).

The coefficients a and b in Eq. 1 were obtained for soya bean, maize, rice and wheat using experimental data provided in Khatchatourian *et al.* (2009). These results allow the permeability coefficient K_z corresponding to the vertical movement of the air to be calculated. In order to calculate the permeability coefficients corresponding to the horizontal airflow the relations between horizontal and vertical streams obtained by Khatchatourian *et al.* (2009) for various types of grains were applied.

3.2 Brief Software Description

The finite element method, (Segerlind, 1976) was used to solve Eq.(5), being necessary to establish an integration domain of smaller elements. The software, developed in ANSI C ++ and Pascal, uses free software tools whenever possible and consists of the following steps:

- Geometry construction: The geometry was built in *OpenSCAD*, defining all the boundary information of the object of study.
- Mesh generation with dynamic adaptive refinement (Liu and Joe, 1996):): The geometry was discretized in smaller tetrahedra volumetric elements in *NetGen*, software, which contains modules for optimization and refinement of mesh.
- Generation of the matrix of the system by the finite element method (Segerlind, 1976).
- System solver obtained from linear algebraic equations using the successive over-relaxation method.
- Post-processing results and analysis using *Paraview* software.

The permeability coefficient matrix K was calculated at each node of the finite element mesh by means of an iterative process. A more detailed description of the software can be found in the work of Khatchatourian and Binelo (2008).

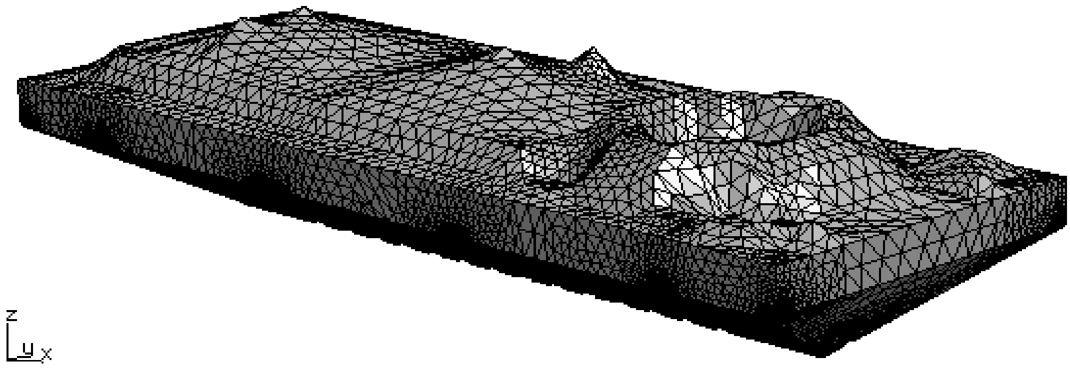

Figure 3. Surface wireframe of the tetrahedral mesh

3.3 Critério de Eficiência da Aeração

In order to analyze the efficiency of the aeration system in agricultural storage, one important information is the analysis of the air velocity field, but this alone is not enough, because regions where the airflow travels through a large layer of product, need higher pressure and air speed, so in regions where the flow travels through a smaller layer of the product, they need a lower speed.

In order to evaluate the aeration system, the most used indicator is the specific airflow, determined by the ratio of the total airflow to the total mass of the product. However, if the variation in the geometry of the storage bin is significant or the distribution of the air inlets is complex, this criterion is difficult to apply.

In order to evaluate the efficiency of the aeration system in bulk storage bins with complex geometry or with the complex distribution of air inlets, the criteria created by Khatchatourian and Binelo (2008), called local specific flow rate, was used. This criterion allows to evaluate the specific flow at any internal point of the storage bin with a variable cross-sectional area at any internal point $X = X(x, y, z)$, daccording to Khatchatourian and Binelo (2008),can be presented as:

$$q_L(X) = \frac{V(X)}{\rho(X)L_X} \tag{8}$$

where: $q_L(X)$) is the local specific airflow at point $X(x, y, z)$ in $m^3\ s^{-1}\ kg^{-1}$; $V(X)$is the speed at point X in $m\ s^{-1}$; $\rho(X)$) is the grain mass density at point X in $kg\ m^{-3}\ s^{-1}$; $L_(X)$ is the total length in m of the trajectory of air passing through the point X, shown in Fig. 4.

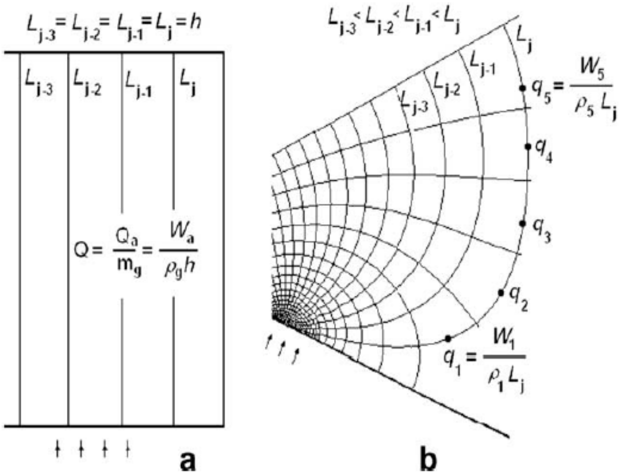

Figure 4. Schematic model for the determination of the airflow rate of the local specific flow source
Fonte: Khatchatourian and Binelo (2008)

For Khatchatourian *et al.* (2015), the local specific flow rate proved to be a good parameter to analyze the efficiency of the aeration system. With this parameter it is also possible to perform several analyzes with the individual activation of the air inlets and also with different aeration time distributions for each input.

3.4 Airflow Optimization Criteria

For a proposal to improve airflow distribution in bulk storage bins, the criteria created by Khatchatourian *et al.* (2015), which proposes an optimized pressure profile, is called by the authors "recommended profile". The study shows that the almost optimal results correlate well with a function proportional to the square of grain mass depth, given by the equation:

$$p_x = \frac{h_x^2}{h_{max}^2} p_{max} \tag{9}$$

where: $p_x$is the inlet pressure to the point x dat the bottom of the storage bin; h_x is the height of the product layer at point x; h_{max} the height of the maximum product layer of the storage bin; p_{max} is the maximum pressure required to maintain the airflow rate.

In practice, it is not technically possible to create an air inlet system with these characteristics since the inlets are distributed in some points of the storage bin and have a discrete distribution of pressures. However, this profile can serve as a guideline for the design of the aeration system

4. RESULTS AND DISCUSSION

Next, the problem of optimum air distribution in agricultural storage will be discussed. The aeration system was simulated, with the real characteristics of the object of study, considering the different pressures of the system current air inlets. The cross-section in the center of the storage bin is shown in Fig. 5, Fig. 6 and Fig. 7, depicts the flow of air in the grain mass. The air from the aeration system is supplied for the entire length of the storage bin. For this purpose, the optimization profile of the air inlet according to Eq. 9, was used, keeping the value of the global specific flow constant $Q = 8,12m^3h^{-1}t^{-1}$.

Figure 5A shows the current aeration system, we can note the central and lateral air inlets, where the pressure is significantly higher. The optimization of the recommended profile is shown in Fig. 5B, where aeration was performed throughout the bottom of the storage bin. In the optimized profile it is noticed that the maximum pressure is greater, to maintain the same flow rate of the current profile of $Q = 8,12m^3h^{-1}t^{-1}$.

Figure 6, shows the flow stream lines in the grain mass of the current profile (Fig. 6A) and the optimized profile (Fig. 6B). It is verified that the optimized profile allows a better distribution of the airflow. The stream lines are varying due to pressure at each point of the object of study. In the lateral domain, the stream lines (dashed lines) slope progressively along the storage bin, showing that the pressure at a given point is continuously changing direction.

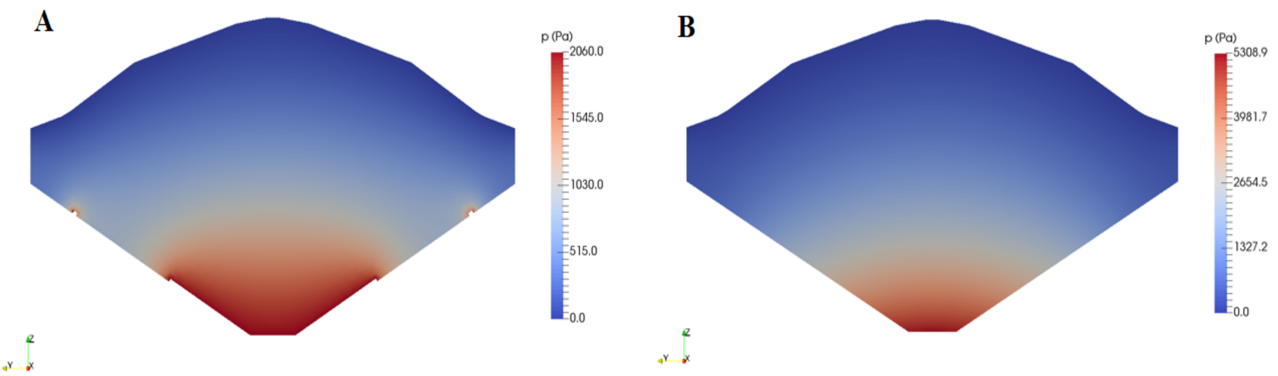

Figure 5. Distribution of airflow of the study object (a cross-section view). A: current profile; B: optimized profile. The global specific airflow rate $Q = 8,12 m^3 h^{-1} t^{-1}$

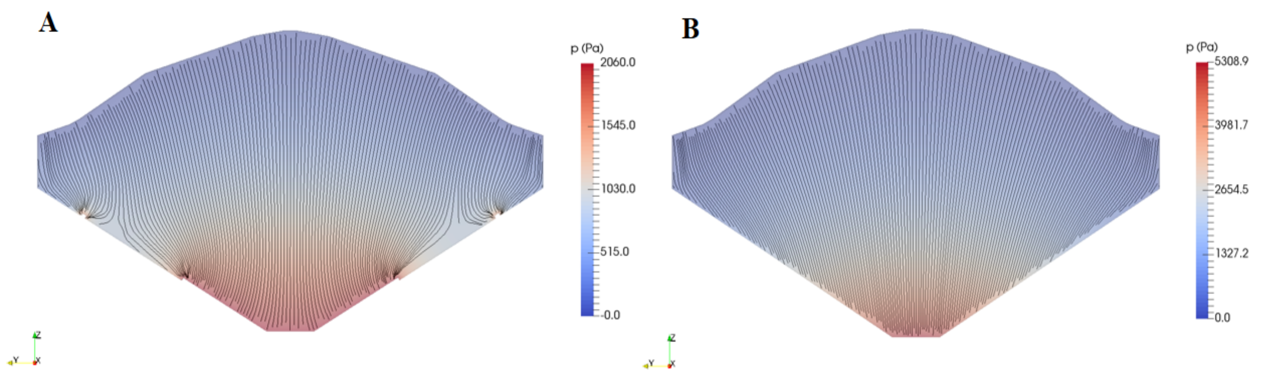

Figure 6. Pressure distribution and airflow streamlines of the study object (a cross-section view). A: current profile; B: optimized profile. The global specific airflow rate $Q = 8,12 m^3 h^{-1} t^{-1}$

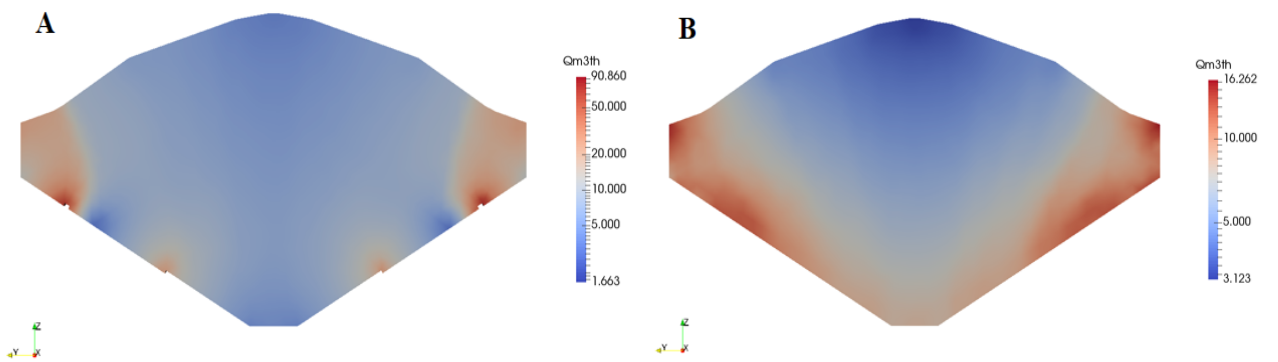

Figure 7. Local airflow rate distribution of the study object (a cross-section view). A: current profile; B: optimized profile. The global specific airflow rate $Q = 8,12 m^3 h^{-1} t^{-1}$

With the local specific airflow criterion (q_L) it is possible to evaluate the airflow in m^3 of air per hour per ton of grain at all points in the central cross-section of the storage bin. The optimization criterion of the airflow produced a significant improvement in this distribution.

Figure 7, shows the airflow distribution for both cases. It is verified that in the present profile (Fig. 7A) nat the bottom of the storage bin, there are areas where the airflow of the air is very low, resulting in areas with little aeration. In the optimized profile (Fig. 7B) the airflow is much better distributed with a considerably smaller difference between the lowest and highest local specific airflow, which means better aerated areas.

5. CONCLUSIONS

This work presented a mathematical modeling and software capable of simulating the distribution of airflow in horizontal bulk storage bins, under nonhomogeneous and anisotropic conditions. The simulation was performed in a real grain storage system. Visualization of the results through the criterion of the specific airflow rate demonstrated that airflow can be optimized, reducing the energy spent in the aeration and bringing a better benefit to the storage. The optimization criterion was used and an evaluation of the airflow performance of the current profile and the optimized profile was performed, in which it was verified, through the criterion of the specific airflow, that the airflow distribution was significantly improved. Although the proposed profile can not be technically adopted in practice since it is not possible to implement a variable continuous inlet system for the entire lower surface of the storage bin, this profile can be used as a guideline for a more economical and efficient aeration system design.

6. ACKNOWLEDGEMENTS

We thank UNIJUÍ for the opportunity, and the Três Tentos Agroindustrial Company, for their help and availability in collecting the experimental data.

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