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THREE-DIMENSIONAL SPECIFIC AIRFLOW RATE SIMULATION FOR PERFORMANCE EVALUATION OF LARGE STORAGE BIN AERATION SYSTEMS

Oleg Khatchatourian
Department of Exact Sciences and Engineering, Regional University of the Northwest of the State of Rio Grande do Sul, Ijuí, RS, Brazil
olegkha@unijui.edu.br

Manuel Osório Binelo
Department of Exact Sciences and Engineering, Regional University of the Northwest of the State of Rio Grande do Sul, Ijuí, RS, Brazil
manuel.binelo@gmail.com

Vanessa Faoro
Department of Exact Sciences and Engineering, Regional University of the Northwest of the State of Rio Grande do Sul, Ijuí, RS, Brazil
vanefaoro@yahoo.com.br

Nelson Toniazzo
Department of Exact Sciences and Engineering, Regional University of the Northwest of the State of Rio Grande do Sul, Ijuí, RS, Brazil
toniazzo@unijui.edu.br

Saul Winik
Department of Exact Sciences and Engineering, Regional University of the Northwest of the State of Rio Grande do Sul, Ijuí, RS, Brazil
saul.winik@gmail.com

Abstract. *Aeration systems are of vital importance for maintaining the quality of the grains stored in large storage bins. This work uses the local airflow rate as the evaluation criteria of an actual aeration system. Experimental data consisting of air pressure distribution were obtained for a large storage bin facility, and these data were compared to a three-dimensional simulation of the air flow trough the grain bulk. A specialized mathematical model using the finite element method was used to carry out the simulations in three dimensions, which presented good agreement with the experimental data. The analysis of air distribution was made using the specific airflow rate criteria identifying possible improvements in the aeration system.*

Keywords: *aeration systems, airflow rate, FEM*

1. INTRODUCTION

Due to the hot and humid climate in Brazil, a long-term storage in grain stores is possible only with the use of aeration systems. In order to compensate the storage capacity deficiency in the country, the building and exploitation of large horizontal storage bins reaching significant dimensions (length to 180 m) is widely adopted. Simultaneous ventilation throughout the all grain mass in these conditions is difficult, and sometimes impossible. Therefore, the ventilation is carried out in sections: by opening different valves of the ventilation system at each time session. During the storage time, the amount of the stored product is not constant (part of the grain mass may be extracted or added), which changes the air flow conditions.

Furthermore, the presence of non-homogeneity of the grain mass due to the compaction and anisotropy due to deviations from the spherical shape of seeds, makes the problem of optimum distribution of air in the storage bin more difficult. An inefficient aeration process might cause problems such as grain humidity migration, grain overheat due to biological activity, and the proliferation of fungi and insects (Weber, 1995).

There are various factors that affect the airflow distribution in grain bulks, for example, the filling method, the depth of grain, the grain morphology, the air velocity, etc. In works of Shedd (1953), Brooker (1961 and 1969), Brooker et al. (1982), Bunn and Hukill (1963), Pierce and Thompson (1975), Haque et al. (1981), Jayas et al. (1987), Maier et al. (1992), Weber (1995), Navarro and Noyes (2001), Khatchatourian and Savicki (2004), Crozza and Pagano (2006), Khatchatourian and Oliveira (2006), and Oliveira et. al. (2007) the airflow through grain mass under the influence of some of these characteristics was studied. In large storage bins, non-homogeneity (Khatchatourian and Binelo, 2008) and anisotropy of grain mass (Hood and Thorpe, 1992; Neethirajan et al., 2006 and 2008) significantly affects the airflow field. If the area of cross-section, and consequently airflow direction, practically does not vary (in a silo), these effects can be neglected. However, for large grain storage bins with variable area, especially if the aeration is carried out separately in different segments, the effect of anisotropy can be highly significant (Khatchatourian et al., 2009). It should be noted that in the literature there are no publications on experimental study of the distribution of air for ventilation of large horizontal storage bins.

The main objectives of the present work were: to create a mathematical model and software, to calculate the static pressure, streamlines, and airflow velocity distribution in two and three dimensions under non-homogeneous and anisotropic conditions; to incorporate a software criteria for aeration quality evaluation in each point of the grain storage bins; to measure the static pressure distribution at different depths of the real grain store; and to accomplish numerical simulations of real and virtual grain stores with aeration to validate the developed model and to detect the operational risk areas.

2. MATHEMATICAL MODEL

To simulate the three-dimensional airflow in particulate media in this study, the mathematical model described by the system of equations of continuity Eq. (1) and motion Eq. (2) was used:

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

$$gradP = aV + b|V|V \tag{2}$$

where V is the velocity in m s^{-1}, P is the pressure in Pa, a and b are constants that depend on the type of grain forming the particulate medium.

Equation (2) is similar to the equation proposed by Bachmat (1965) and presented in Bear (1988):

$$K{\cdot}J = \frac{\gamma}{g}\left(1 + \frac{q\beta}{\gamma}\right)q \tag{3}$$

where K is permeability tensor, β is a geometrical coefficient, J is the hydraulic gradient, q is the specific flux vector, γ is the specific weight of fluid, ε is the particulate medium porosity.

Equation (2), which is used where the Navier - Stokes equation typically would be, and implicitly determines the non-linear dependence $V = f(gradP)$, can be presented in the form:

$$V = -KgradP \tag{4}$$

where K is permeability tensor for anisotropic medium. For one-dimensional case K can be presented as:

$$K = \frac{1}{a + b|V|} \tag{5}$$

Substituting Eq (4) in the continuity equation Eq. (1), the nonlinear partial differential equation for pressure is obtained:

$$\frac{\partial}{\partial x}\left(-K_x\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(-K_y\frac{\partial P}{\partial y}\right) + \frac{\partial}{\partial z}\left(-K_z\frac{\partial P}{\partial z}\right) = 0 \tag{6}$$

where K_x , K_y and K_z are the permeability coefficients in the principal directions.

The boundary conditions for this problem have the following form:

$$P = P_e \text{ (Dirichlet condition for air entrance and exit)} \tag{7}$$

$$nKgradP = 0 \quad \text{(Neumann condition on the silo walls and floor)} \tag{8}$$

where n is unit vector normal to the wall or floor surface.

Eq. (6) and the boundary conditions Eq. (7) and Eq. (8), describe the steady-state pressure distribution in a cross-section of an aerated grain storage under non-uniform and anisotropic conditions. Knowing this distribution, it is easy to find the velocity distribution using Eq. (4).

3. METHODS

To validate the proposed mathematical model, the empirical relationship between the velocity and the air pressure was obtained for different layers at different grain depths. In this paper it is assumed that: a) the coefficient K_z corresponding to the vertical direction is given by equations Eq. (5) and Eq. (6); 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 is considered not homogeneous and the permeability coefficient and the pressure gradient varie according to the depth at which the grain layer is 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_x , K_y and K_z) was taken into account in accordance with the work Khatchatourian et.al. (2009).

The coefficients a and b in Eq. (5) were obtained experimentally for soybeans, maize, rice and wheat. Experimental equipment and procedure of the experiment are described in Khatchatourian et.al. (2009).

The results obtained allow to calculate the permeability coefficient K_z in Eq. (6) corresponding to the vertical movement of the air. 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. The simulations showed significant influence of anisotropic properties of the particulate medium on airflow distribution.

3.1 Brief software description

The finite element method (Segerlind, 1976) was used to solve the nonlinear partial differential equation Eq. (6). The matrix of permeability coefficients *K* was calculated at each node of the finite element mesh, using an iterative process.

The software, developed in ANSI C++ and Pascal, uses free software tools when possible and consists of tools for: a) geometry construction; b) mesh generation with dynamic adaptive refinement (Liu and Joe, 1996); c) generation of system matrix by the finite element method (Segerlind, 1976); d) solver of obtained system of linear algebraic equations using the successive over-relaxation method (Hageman and Young, 1981); and e) results post-processing and analysis using Paraview software (Ahrens, Geveci, & Law, 2005). A more detailed description of the software can be found in Khatchatourian and Binelo (2008).

4. EXPERIMENTAL STUDY

The aquisition of data was carried out in a real horizontal grain storage bin of V-form floor (characteristics are given in Tab. 1) belonging to the Cooperative Society Cotrirosa located in the city of Santa Rosa, in the Rio Grande do Sul state, Brazil. The structural layout of the studied storage bin which has a width of 40 m and maximum length of 180 m is shown in Fig.1. There are two air inlet systems: a central inlet system with eight inlet pipes and a lateral inlet system with six lateral pipes (Fig. 1).

Table 1. Characteristics of studied grain storage bin

Type of grain	Soya bean
Type of store	Below ground, V-shaped
Storage capacity	30 000 000 kg
Number of inlets for central aeration	8 inlet pipes
Number of fans for central aeration	8 fans with electromotor of 60 CV/1730 RPM
Number of lateral inlets	6 inlet pipes
Number of fans for lateral aeration	2 fan with electromotor of 60 CV/1730 RPM
Input pressure for central aeration	2942 Pa
Input pressure for lateral aeration	981 Pa

All experiments were carried out when the storage bin was filled with soya bean as of September 2013. At first, the position of the free surface of the grain mass was measured in order to determine the geometry of the grain bulk, i.e., to obtain the integration domain for the considered problem. During the experiments, the ventilation was carried out only for one third of the grain mass (air was supplied only through three lateral inlet pipes and four central inlet pipes at the left part of a silo, shown in Fig. 1). The static pressure was measured at depth of 1 m and 2 m from the grain mass free surface, in 28 points for each depth. The pressure sensor consisted of a rigid steel tube of 15 mm in diameter and of 2.0 m length, with a set of lateral orifices of 2 mm in diameter, located at the bottom to receive the airflow. The measurement of pressure in inlet pipe was carried out by Pitot tube. The value of the initial pressure of the air entering the storage bin supported P_e = 2942 Pa, which provided an acceptable accuracy of the measurement of static pressure at selected points at a depth of 1 m and 2 m from the free grain surface. To increase accuracy of the measurements of static pressure it was used the inclined-tube manometer with its measuring leg inclined to the horizontal axis by an angle of 30°. Experimental results are shown in Figs. 6 and 7 (closed points).

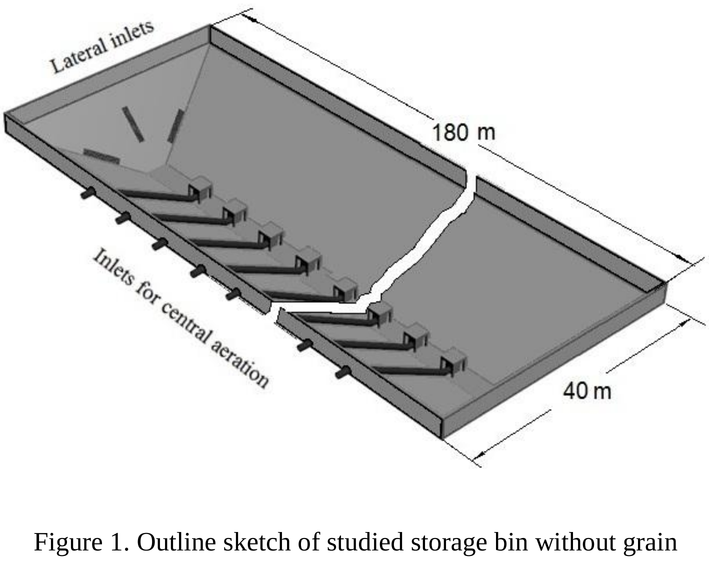

Figure 1. Outline sketch of studied storage bin without grain

5. NUMERICAL SIMULATIONS

For the problem under consideration, one mesh was used, with the number of tetrahedrons of approximately 300,000. The initial mesh was generated using Tetgen software (Hi, 2015), and the developed software applied adaptive refinement in order to have a higher grid density in regions with greater pressure gradient. The pressure, velocity and streamline distributions in the studied storage bin were solved using the developed software (Figs 2, and 3).

The calculated and experimental values of static pressure for the depth of 1 m and 2 m from the free surface of the grain mass are shown in Figs. 4 and 5. A satisfactory agreement between the calculated and experimental data, confirmed by high values of the Pearson correlation coefficient (R = 0.8910 for depth of 1 m and R = 0.9769 for 2 m) indicates the accuracy of the developed method and computer program.

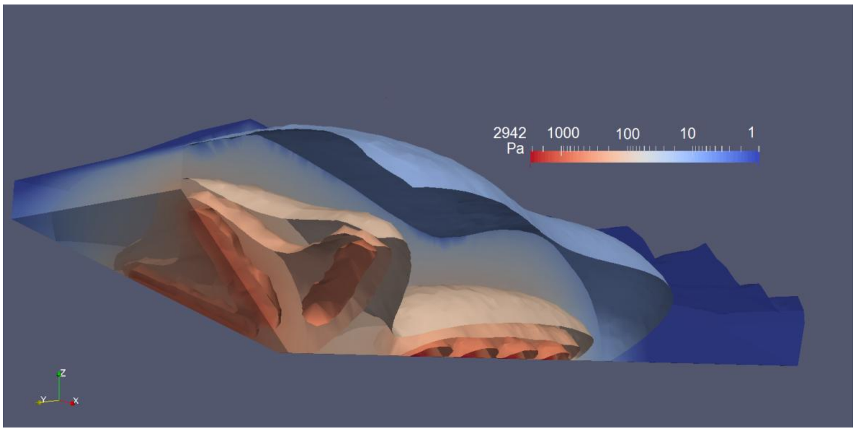

Figure 2. Predicted isobaric surface in studied storage bin

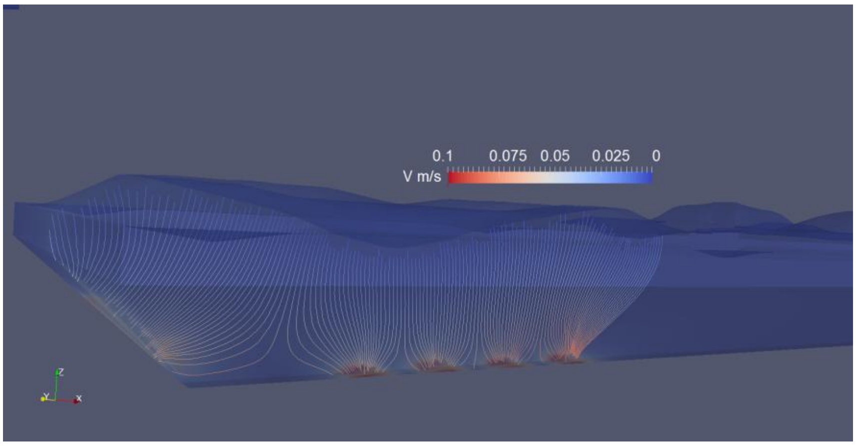

Figure 3. Predicted streamlines and velocity levels in longitudinal section of studied storage bin

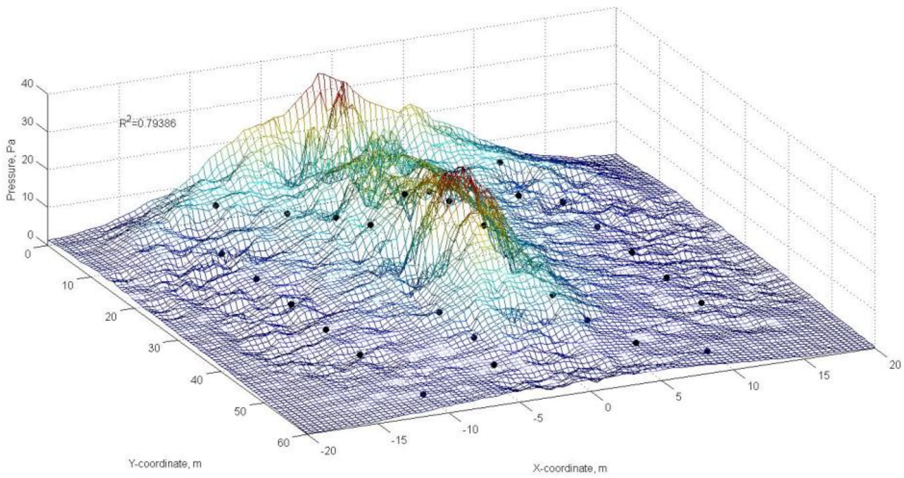

Figure 4. Pressure distribution in the grain layer located at a depth of one meter from the free surface of the grain mass: simulation and data experimental (points), coefficient of determination $R^2 = 0.7939$

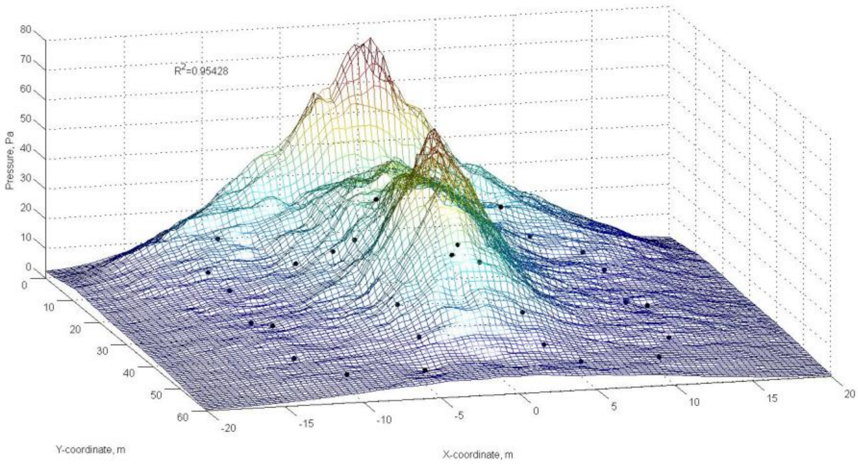

Figure 5. Pressure distribution in the grain layer located at a depth of two meters from the free surface of the grain mass: simulation and data experimental (points), coefficient of determination R^2 = 0.9543

5.1 Analysis of the effectiveness of the air distribution storage

To estimate the efficiency of an aeration system for storage bin with constant cross-sectional area, the specific airflow rate is usually used which represents the ratio between the total airflow rate and the total grain mass, and expresses a volume of air that passes through unit of grain mass in a unit of time:

$$Q = \frac{Q_a}{m_g} = \frac{VA}{\rho_b HA} = \frac{V}{\rho_b H} \tag{10}$$

where Q_a is total air flow rate in $m^3\ s^{-1}$; m_g is total grain mass in kg; V is air velocity in ms^{-1}; ρ_b is product bulk density in $kgm^{-3}\ s^{-1}$; A is the cross-sectional area in m^2; H is the grain mass depth in m.

However, for a silo with a variable cross-section, this criterion is not appropriate. Besides, in Khatchatourian and Binelo (2008) it is shown that it is very difficult to evaluate the effectiveness of the ventilation in the silo with a variable cross-section according to the distribution of velocities or the flow lines. Therefore, a local specific airflow rate was proposed as a criterion for describing the efficiency of aeration system in each point of the silo, instead of the specific airflow rate, that is a global characteristic.

The local specific airflow rates for all internal points $X(x, y, z)$ of storage bin can be presented as:

$$q_L(X) = \frac{V(X)}{\rho(X)\ L(X)} \tag{11}$$

where $q_L(X)$ is the local specific airflow rate in point $X(x, y, z)$ in $m^3\ s^{-1}\ kg^{-1}$; $V(X)$ is the air velocity in point X in $m\ s^{-1}$; $\rho(X)$ is product density in point X in $kg\ m^{-3}\ s^{-1}$; $L(X)$ is the full length in m of a trajectory on which the point X is located.

In Figs. 6 and 7 the distributions of local specific airflow rates calculated over the total volume of the storage bin under study (Fig. 6) and in its cross section (Fig. 7) are presented. A very big difference between the maximum and minimum values of this rate, a significant difference between values of the local specific airflow rates and global airflow rate (equal to 13.3) for considerable volumes of grain mass, as well as significant non-uniformity of this parameter inside the storage bin, indicate that the effectiveness of the ventilation in the storage bin should be greatly improved. Opportunities for improving the ventilation of existing storage bin exist, but are very limited. For horizontal storage bin these improvements can be achieved, in particular, by optimization of the locations of the air inlet sections, its sectional areas and of the air pressure at the air inlet of the storage bin.

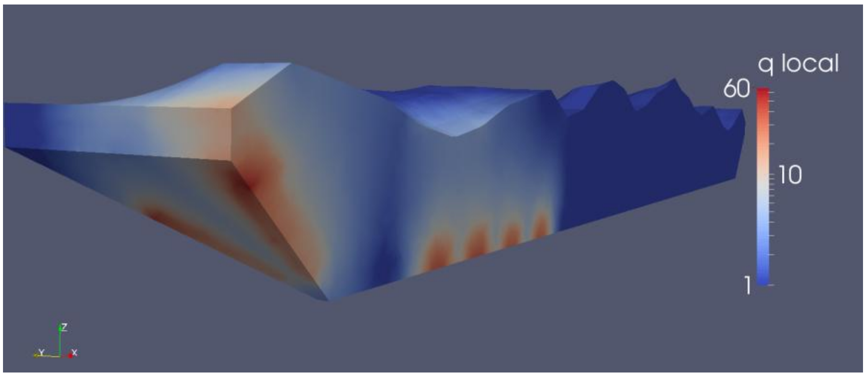

Figure 6. Predicted distribution of the local specific airflow rates in studied horizontal storage bins with real air inlet system

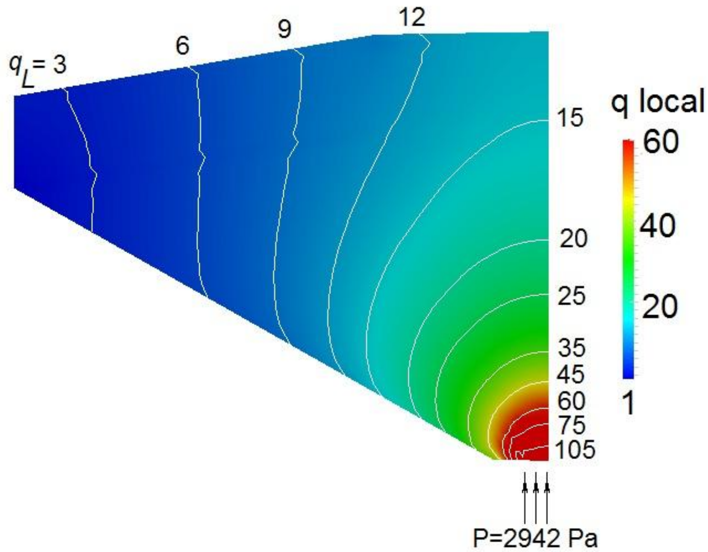

Figure 7. Predicted distribution of the local specific airflow rates in cross-section (y=35 m) of studied horizontal storage bins with real air inlet system. The global specific airflow rate Q = 13.3 $m^3 h^{-1} t^{-1}$

6. CONCLUSIONS

The mathematical model and software for the calculation of large horizontal storage bins were developed. Experimental data on the pressure distribution in the real large horizontal storage bin were obtained. Comparison between experimental and predicted data showed their satisfactory agreement.

Using the criteria proposed by the authors to estimate the effectiveness of the air distribution in storage bins, a performance evaluation of the current system was carried out. The analysis of air distribution in horizontal storage bins was carried out. It was shown that at a constant value of the global specific airflow rate, a small area inlet causes a poor distribution of air. The criteria used by the authors is an important tool to evaluate the efficiency of aeration systems in large storage bins. This method presents an important contribution to the design of more efficient storage bins, for the design of new aeration systems for existing storage bins, and also for a better operation of existing systems.

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