ESCOAMENTO DO AR EM ARMAZÉM GRANELEIRO DE GRANDE PORTE COM SISTEMA DE AERAÇÃO

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RESUMO
Foi desenvolvido um modelo matemático de escoamento de ar em armazém graneleiro com sistema de aeração para condições não-uniformes da massa de grão. Para profundidades de camada de grãos diferentes foram obtidos experimentalmente: a) a relação entre velocidade de ar e gradiente de pressão e b) a porosidade de massa de grãos. Foi elaborado o software para determinar a intensidade de fluxo de ar e carga necessária de pressão no armazém com ventilador e eletro-motor escolhidos. Foi utilizado o método de elementos finitos com processo iterativo para cálculo dos termos não-lineares no modelo considerado. Os experimentos e as simulações numéricas mostraram a necessidade de considerar a não-uniformidade de camadas de massa de grãos em armazém para avaliação de desempenho do sistema de aeração.

PALAVRAS-CHAVE: Aeração, Modelagem matemática, Armazenamento de grãos com aeração, Método de elementos finitos.

SIMULATION OF AIR FLOW IN LARGE AERATED GRAIN STORAGE

ABSTRACT
A mathematical model of airflow in an aerated grain storage system was developed for non-uniform conditions of the grain mass. The relationship between airflow velocity and pressure gradient and the values of the porosity factors for different grain layer depths were obtained. It was elaborated the software to determine the airflow rate and initial pressure head in the grain storage for chosen fan and electro-motor. The finite element method with iterative process for calculation of the nonlinear terms was used. Experiments and numerical simulations showed the need to considerate the non-uniformity grain mass in grain storage, in order to choose the estimated performance of the aeration system.

KEYWORDS: Aeration, Mathematical modeling, Aerated grain storage, Finite-element method

1. INTRODUCTION

Aeration, representing the forced air movement through a particulate medium formed by cereal grains, together with drying and sanitary phyto-control, is widely used to minimize the crop losses after harvest. The resistance to the airflow in an aeration system depends on the airflow parameters, on the characteristics of the surface of the product (rugosity), on the form and size of any extraneous impurity in the mass, on the configuration, and on the size of the interstitial space in the mass, on the size and amount of broken grains and on the product layer depth. The works accomplished by Shedd (1953), Bunn and Hukill (1963), Brooker (1969), Pierce and Thompson (1975), Haque *et al*. (1981), Maier et al. (1992), and Khatchatourian *et al*. (2000), examine the influence of some of these parameters on airflow pattern in grain storage.

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With increasing depth of grain storage, the grain mass can no longer be assumed as homogeneous. Non-homogeneity alters significantly the physical parameters involved in the aeration process, such as air velocity and static pressure drop. At the same time, there are no results in recent research related to the compaction factor of soya beans and the airflow pattern under these conditions.

The principal objectives of the present work are: to create a mathematical model, an algorithm and software for the calculation of static pressure, streamlines and airflow velocity distribution in non-homogeneous conditions of air stream in aerated grain store; to study the relationship between the air velocity and the pressure gradient as a function of the compaction factor; to accomplish numerical simulations of actual and virtual grain stores with aeration to detect the operational risk areas.

2. MATHEMATICAL MODEL

In this article, we examine the mathematical model of the airflow in soya beans mass for three-dimensional case proposed by Khatchatourian *et al*. (2001) consisting of a nonlinear partial differential equation:

$$\frac{\partial}{\partial x}\left(-k\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(-k\frac{\partial P}{\partial y}\right)+\frac{\partial}{\partial z}\left(-k\frac{\partial P}{\partial z}\right)=0 \qquad (1)$$

where: P is pressure; $k=\exp\left(\ln 10\left(\left\{\left[\ln\left(1+U^2\right)-2U\,\mathrm{arctg}(U)\right]/\pi+3U\right\}/4a+C\right)\right)/\left|\mathrm{grad}\,P\right|$;
$U=a\lg\left(\left|\mathrm{grad}\,P\right|\right)+b$ is the intermediate argument; a and b are empirical constants.

The boundary conditions for the problem considered consist of Dirichlet condition P=P_e for air entrance and exit and of Neumann condition $\boldsymbol{n}\cdot\mathrm{grad}P = 0$ on the silo walls and floor,

where P_e is air entrance or exit pressure in Pa; and $\boldsymbol{n}$ is unit normal to surface.

Equation (1) was solved by the finite element method with iterative process for calculation of the coefficient k in each point of the domain of integration using the pressure distribution in the immediately previous iteration step. The software developed consists of a generator of finite element mesh, a program for resolution of the system of linear algebraic equations (conjugate gradient method) and a graphical plotting program for two-dimensional case.

The airflow lines $\Psi(x,y)$=const were calculated solving the non-linear partial differential equation of the function-current:

$$\frac{\partial}{\partial x}\left(\frac{1}{k}\frac{\partial \Psi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{k}\frac{\partial \Psi}{\partial y}\right)=0 \qquad (2)$$

where k was calculated, knowing the pressure distribution after the resolution of Eqn (1).

3. IDENTIFICATION OF THE MATHEMATICAL MODEL

To simulate the characteristics of an aerated grain storage, an equipment was developed to determine, experimentally, the grain mass compaction factor, due to the weight force action of superior layers, and the compaction influence on relationship between the airflow velocity and the static pressure drop. To model the conditions in the bottom of grain storage, a compacting device was developed with a lever, which made it possible to apply moderate forces to simulate the depth up to 50 m.

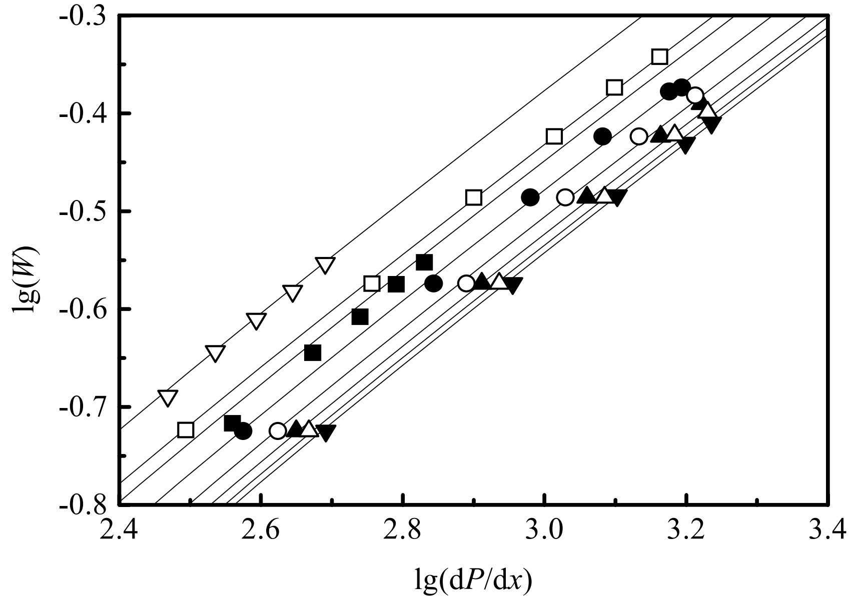

FIGURA 1: Influence of the soya bean layer depth (H) in m on the airflow (W) in m/s (one-dimension grain storage): ─, predicts; 4, H = 2.74 m, Shedd (1953); □, 1 m; ●, 10 m; ○, 20 m; ▲, 30 m; Δ, 40 m; ▼, 50 m; ■, 3 m, Khatchatourian et al. (2000).

In the tests, the soya beans were used, with moisture content of 13% and impurity of 2% (the recommended storage values), determined in the Laboratory of Analysis of Seeds of the Department of Agrarian Studies of the Regional University of the Northwest of the State of Rio Grande do Sul - UNIJUI. The experimental results presented in *Fig. 1*, establish dependence between airflow velocity and static pressure drop in compacted soya bean mass for several layer depths of grain storage. There is significant influence of the considered layer depth at grain storage on aerodynamic resistance of grain mass in the studied interval (of 1 m up to 50 m). The treatment of these data permitted to determinate the relative pressure gradient increment as function of the depth *H.* Comparison between results obtained by the developed model and the experimental data presented by Holman (Puzzi, 1986) for simple grain storage layouts showed satisfactory coincidence.

4. NUMERICAL SIMULATIONS

Three types of real grain storage, used in the state of Rio Grande do Sul (Brazil), were analyzed: V-form floor, semi-V form floor and vertical grain storage. The aeration simulations in silos, for different layouts, were generated using the airflow rate of 9 $m^3h^{-1}t^{-1}$ (2.5×10^{-6} $m^3s^{-1}kg^{-1}$), which is the most recommended values in an aerated grain storage. As an example, Figure 2 displays the relative superathmospheric pressure *p* and airflow lines distribution in the V-form floor silo with air ducts on the lateral walls. It is necessary to note that the aeration system with lateral ducts equalized essentially the airflow in comparison with the same silo without lateral ducts.

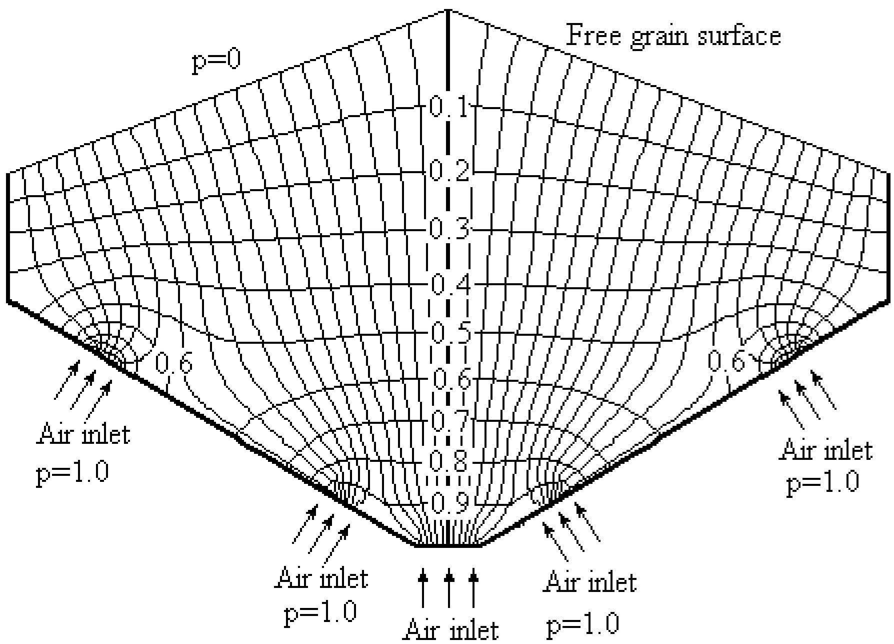

FIGURA 2: Airflow and isobar lines for a V-form floor silo with lateral ducts.

5. CONCLUSIONS

1. A mathematical model of airflow in an aerated grain storage system was developed for non-uniform conditions of the grain mass.
2. Experimental study allowed to obtain the relationship between airflow velocity and pressure gradient and the values of the porosity factors for different grain layer depths.
3. It was elaborated the software to determine the airflow rate and initial pressure head in the grain storage for chosen fan and electro-motor.
4. Experiments and numerical simulations showed the need to considerate the non-uniformity grain mass in grain storage, in order to choose the estimated performance of the aeration system.
5. The aeration system efficiency of several real grain storages was analyzed (the airflow distribution uniformity and the static pressure head values to generate the appropriate airflow rate for a safe storage).

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