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Use of the CFD Tool to Analyze the Aeration Comportment in a Horizontal Silo

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ABSTRACT

Storage in vertical and horizontal silos is commonly used worldwide, and its better understanding is essential to acquire and maintain product quality of the stored products. Environmental temperature inside the silos is the main factor that drives mass loss, grain biological activity, pest development and product respiration. Thus, the study of temperature behavior at several layers of the product throughout time is necessary to diminish loss and achieve higher storage time with minimum quality loss, profit, and yield. Aeration is a formidable tool that allows the maintenance of temperature and consequently becomes an important preventive method to avoid the problems stated before. Direct measurement of temperature in all directions inside the silo requires numerous expensive equipment and labor force and requires a large amount of time to provide valuable and trusty data. For these reasons, CFD (computational fluid dynamics) was utilized to solve this problem. CFX software satisfactory demonstrated velocity behavior within the horizontal silo containing wheat; however, the aeration ducts configuration did not offered support to the correct silo aeration.

Keywords
Air flow, Heat and mass transfer, Porous media, Storage, Temperature.

Introduction
Grain storage, with the successive productivity increase, turned into a subject of great importance among the grain production chain. Storage aims the product preservation for a sufficient period capable to maintain the product characteristics, as well the maintenance of regulatory stocks, to prevent eventual periods of environment catastrophes, war, and price fluctuation in the market.

Agricultural products, even after their harvest, are living materials and, thus, are susceptible to several processes that may affect its quality and thus their price. Depending onto the environmental conditions of storage ecosystem, grain can be submitted to losses due to respiration of themselves, pest attack and microorganisms' growth. Since these losses can be correlated to environmental factors, the correct management and knowledge of these factors are of fundamental importance in the quest of quality maintenance of stored grain. Temperature and relative humidity are the major factors concerning storage procedures; simultaneously, they act directly over the postharvest processes of grain, influencing the drying process and all metabolic reactions inside the grain, pests, and microorganisms.

By means of temperature and relative humidity control is possible, for instance, to avoid the grain absorption of moisture during storage, which would allow an increase of respiration rate, insect attack and fungi proliferation. At a certain temperature and relative humidity of the air, grain tend to reach an equilibrium with these conditions, presenting either a higher or lower moisture content that the one before the climate change inside the silo.

The main objective of aeration is to maintain the temperature uniformity within silos, with the scope to keep the grain and seeds quality through the longest time possible, avoiding moisture migration, heat spots, pest propagation, etc. In addition, aeration is also used to remove undesired odors and to apply fumigants.

Due to high costs and attainment difficult of temperature, velocity, pressure, and several other data to the study of heat and mass transfer, software's are needed to predict the distribution of these parameters that affects the aeration system. Nowadays, the computational fluid dynamics (CFD) is largely used, being an important tool to study the behavior of parameters (temperature, velocity, pressure) that affects the products during storage. There is a relationship among CFD, and the procedures associated to the food industry such as mixture, drying, cooking, sterilization, and cold storage. Such processes are regularly used to transform and maintain quality, safety, and shelf life of feedstuff [1].

CFD may solve a high number of problems by means of equations from laws that drives mass, heat, and moment conservation [2]; however, the software must be customized whether if velocity, temperature, and moisture distribution must or not be calculated, in the case of stored grain.

Being that stated, the objective of the present work was to develop a tridimensional model in CFD to analyze the velocity and pressure distribution inside a horizontal silo of commercial dimensions storing wheat grain.

Materials and Methods

A horizontal silo located at Maringá city, state of Paraná, Brazil, property of Cooperativa Agroindustrial – COCAMAR, with a bottom shape type of semi "V", with total capacity of 22,400 tons of wheat, was utilized to evaluate the velocity distribution during aeration. It possesses 95 meters of length, 30 meters of width and 17 meters of height, being that the air entrance is situated at the bottom of the silo with an air flow of 0.2 m^3 min^{-1} t^{-1}.

Two different situations were considered to study and compare the temperature distribution within the silo: the first one consists in the consideration that the silo is using its maximum capacity of wheat; and the second one is considering that the slope created by the angle of repose of the product is zero, in other words, that the product after its filling up inside the silo is flattened in its surface.

Software

Software ANSYS CFX® version 11.0 was used to predict the studied phenomenon through the boundary conditions established. The mesh was created through the same software, being constituted by more than 20,000 tetrahedral to obtain a higher representativeness of the phenomenon occurring within the silo. This mesh represented a fraction of the silo length, and by symmetry it was acquired the simulation of the entire silo, disregarding the board effect.

CFD software employs different procedures to solve the problems. The most used techniques include finite difference, finite elements, and finite volumes. Finite difference is of limited use in engineering due to difficult in its handling and complex geometries; thus, the use of finite elements and finite volumes increased considerably, in which these use mesh structures to properly evaluate the geometry of the problem.

Commercially, there are few software that works with finite elements, usually being used the finite volume method. When global equations are expressed by means of finite volume, they form an intuitive physical method to obtain mass, moment, and energy changes while the fluid passes through the partial volumes inside the computational domain [3].

Several CFD models are used to calculate heat transfer, and other studies [4-6] report that the k-ε turbulence models are poor to predict the solutions to confront with experimental data. This fact is related to the lack of representativeness of the flow near the walls due to standard wall functions and suggested that this treatment was abandoned to heat transfer calculation [5]. The velocity profile in porous media is approximated to a flow in a reduced diameter duct, therefore this profile is laminar.

Considerations

Wheat (*Triticum aestivum*) was used with porosity (ε) of 41 % [7] and sphericity of 62 %. In the case of porous media, it is necessary to know some parameters to the correct simulation of the real condition, and thus the permeability (k) and loss coefficients (K_{loss}) were calculated.

Ergun equation (Equation 1), usually utilized at chemical engineering literature, is an expression of Darcy's equation, in which the permeability (Equation 2) and loss (Equation 3) coefficients were obtained [8]. Permeability coefficient was 3.512 x 10^{-8} m^2 and loss coefficient was 5,691 m^{-1}. It was considered the reference pressure as being 1 atm and the air velocity of the aeration duct being 0.3 m s^{-1}.

$$-\frac{\Delta P}{L} = 150\frac{(1-\varepsilon)^2 \mu q}{\varepsilon^3 (D_P\phi)^2} + 1.75\frac{(1-\varepsilon)Pq^2}{\varepsilon^2 (D_P\phi)} \quad (1)$$

$$k = \frac{D_p^2 \phi^2 \varepsilon^3}{150(1-\varepsilon)^2} \quad (2)$$

$$K_{loss} = 2\left(\frac{0.14}{\varepsilon^{1.5}\sqrt{k}}\right) \quad (3)$$

In which,

P: pressure, Pa; *L:* length of grain layer, m; ε : porosity, decimal; μ: air viscosity, kg m^{-1} s^{-1}; *q:* air velocity, m s^{-1}; D_p: particle diameter, m; ϕ : sphericity, decimal; k: permeability coefficient, m^2; K_{loss}: loss coefficient, m^{-1}.

Global Equations

Equations that govern the fluid flow and heat transfer can be considered as mathematical formulations derived from conservation laws of fluid mechanics and are referred as Navier-Stokes equations [9]. These laws may be divided in three: mass conservation or continuity equation (Equation 4), moment conservation equation or Newton's second law (Equation 5) and energy conservation equation or first law of thermodynamics (Equation 6).

$$\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)+\frac{\partial \rho}{\partial t}=0 \quad (4)$$

$$\frac{\partial}{\partial t}(\rho u)+\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}=-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (5)$$

$$\rho c\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=K\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 t}{\partial y^2}\right)+\dot{q} \quad (6)$$

In which:
ρ: bulk density, kg m^{-3}; t: time, s; x, y: cartesian coordinates; u, v: velocity components, m s^{-1}; c: specific heat, W kg^{-1} K^{-1}; T: temperature, K; K: thermal conductivity, W m^{-1} K^{-1}; and q : heat flow, W m^{-3}.

Boundary Conditions

Vertical and horizontal silos can contain regions of laminar, turbulent and transition behavior of air flow. This information, allied to several factors that interfere at the resistance of air passage through the grain mass, such as the geometric shape of grain, zones with limited porosity, heterogeneity of particle surfaces, grain mass compaction, moisture content variation and impurity presence, leads to errors in the simulation of the air flow among grain mass using solely the continuity and Navier-Stokes equations, not generating compatible solutions with the reality [10].

To large storage silos, especially with aeration system, there are regions with velocity increase and regions in which the air velocity is practically zero. In this case, to velocity distribution calculations, the variation at the flow conditions has high influence.

Equations 7 and 8, additionally with boundary conditions (Equations 9 and 10), are sufficient to satisfactory describe the velocity distributions in an aerated horizontal silo [10)]

$$u=-k\frac{\partial P}{\partial x};v=-k\frac{\partial P}{\partial y};w=-k\frac{\partial P}{\partial z} \quad (7)$$

$$\frac{\partial}{\partial x}\left(-k\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(-k\frac{\partial P}{\partial y}\right)+\frac{\partial}{\partial z}\left(-k\frac{\partial P}{\partial z}\right)=0 \quad (8)$$

$$P=P_i \quad (9)$$

$$n\bullet\nabla P=0 \quad (10)$$

In which:
z: cartesian coordinate; w: velocity component, m s^{-1}; P_i: inlet of air or pressure exit, Pa; n: vector normal to the wall or the silo floor.

These boundary conditions reflect that the fluid velocity at the walls is zero and the variation at the y direction does not occur. Furthermore, as the aeration goal is to maintain the temperature within the silo more homogeneously possible, the fluid density variation (air) can be discarded, meaning dρ/dx=0; therefore, the natural convection can be also discarded at the calculation procedures due to its minor value in comparison with the forced convection (fan action). The system was permanent and tridimensional, with the fluid properties being constant.

The software utilization to the study of velocity behavior into the silo was accomplished by means of a mesh that represents a fraction of the silo length, and through symmetry it was obtained the simulation for the entire silo, not considering the edge effect.

Results and Discussion

Figures 1 and 2 illustrate the velocity flow lines at the first study situation of the present work. It can be noticed that there is a satisfactory air distribution in all silo length (z axis), however the aeration does not affect a small portion of the silo close to the sides (x axis), leading to significant losses during the wheat storage. Due to the lack of proper aeration at these regions, they become a propense local to occur hot spots or heat zones, because of the temperature increase, leading to pest propagation, subsequent formation of toxic products and finally contaminating the remaining product stored.

Figures 3 and 4 demonstrate the velocity flow lines at the silo for the second situation. It is noticed that in this case, the aeration is also suitable at all silo length, however the silo sides are not properly aerated. This trend can be explained by the aeration ducts configuration, in which solely the air input at the silo bottom is not sufficient to homogenize and maintain the grain mass temperature at a safe range. Therefore, installation of additional air ducts is required alongside the bottom at all silo width to the silo laterals can be able to receive the aeration air.

Theoretically, to store grain, the silos require to flat the surface grain, otherwise, the cone formed by the repose angle of the product is hardly aerated. This trend is due to the higher distance required for the air to pass and by a higher resistive force because of the weight of these additional grain mass. However, at the present work, it was observed that without flattening the grain and therefore with a higher pressure at the silo bottom due to this grain mass, a higher resistance to air flow over the height direction occurred, and consequently obtaining better results at the width silo direction (x axis). Flattening the grain mass, the mentioned additional pressure was removed, facilitating the air flow through the wheat due to the aeration ducts configuration. If aeration ducts were installed alongside the silo bottom, a better aeration situation would be expected at case 2.

Conclusions

CFD tool satisfactory described the velocity behavior inside the horizontal silo in both cases. The aeration is more effective including the flat procedure of wheat grain at the top of the silo, however in the present work with this procedure, it is still not advised the utilization. Aeration velocities ranged from 2.694 x 10^{-3} to 0.4958 m s^{-1} and 1.171 x 10^{-3} to 0.5122 m s^{-1} without and with flat procedure of wheat mass, respectively. To future

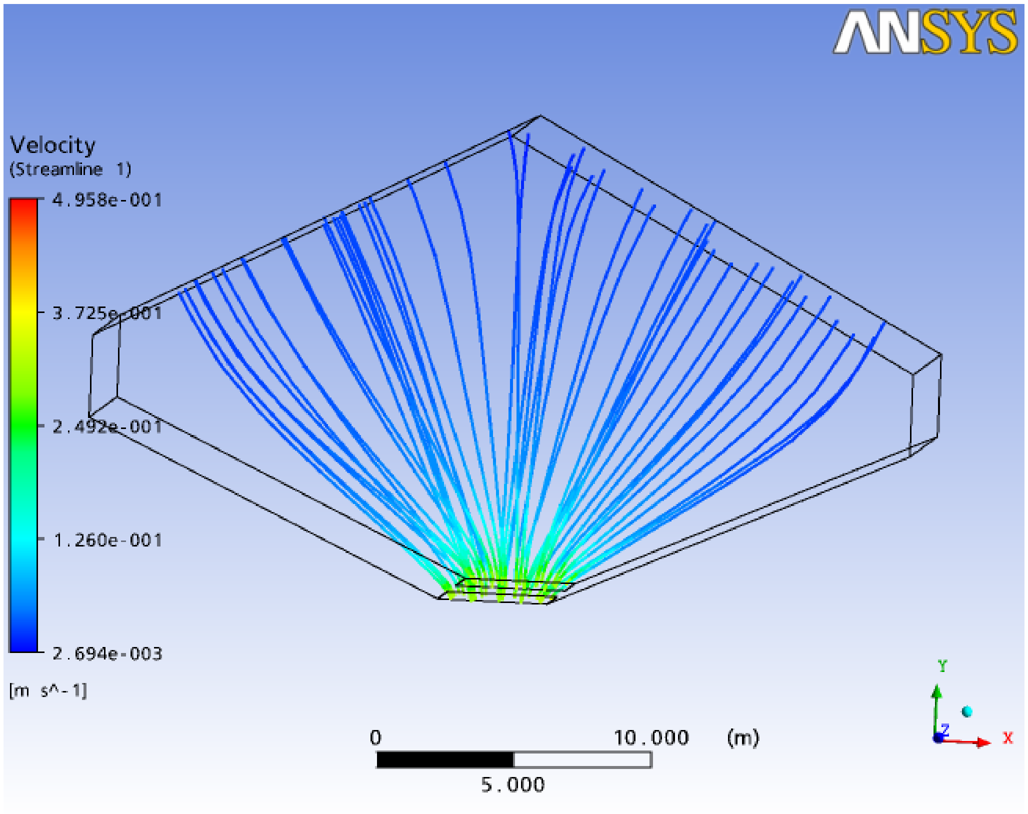

Figure 1: Velocity flow lines in a silo with bottom shape type of semi "v", frontal view.

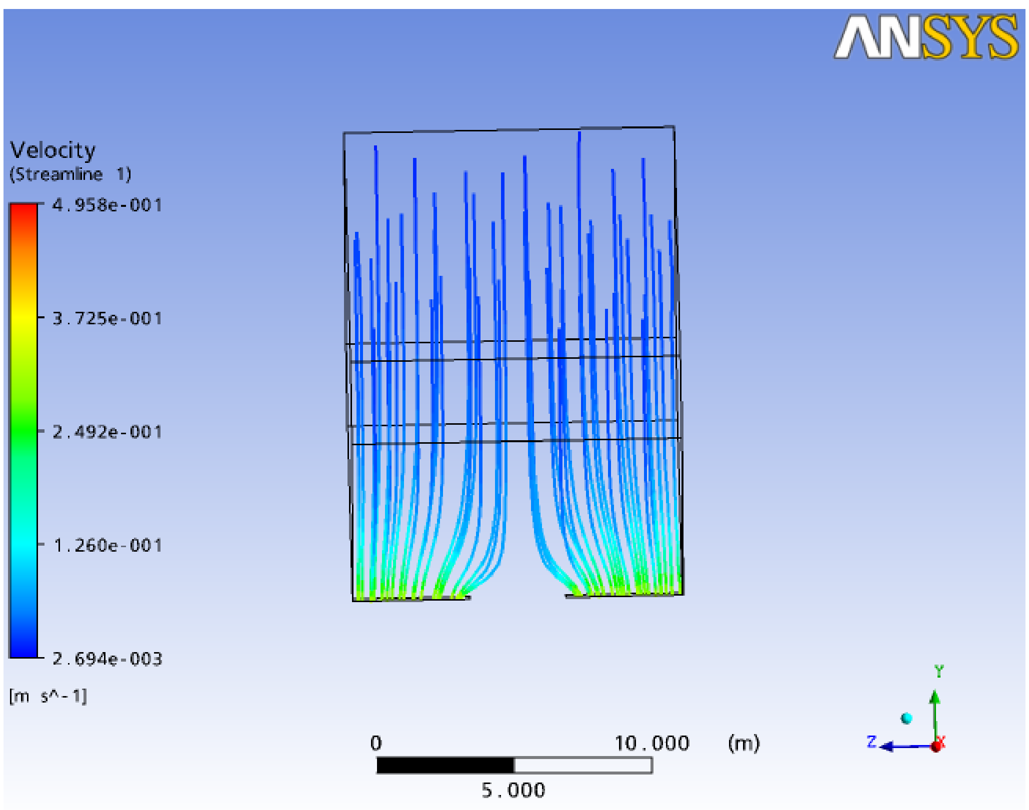

Figure 2: Velocity flow lines in a silo with bottom shape type of semi "v", lateral view.

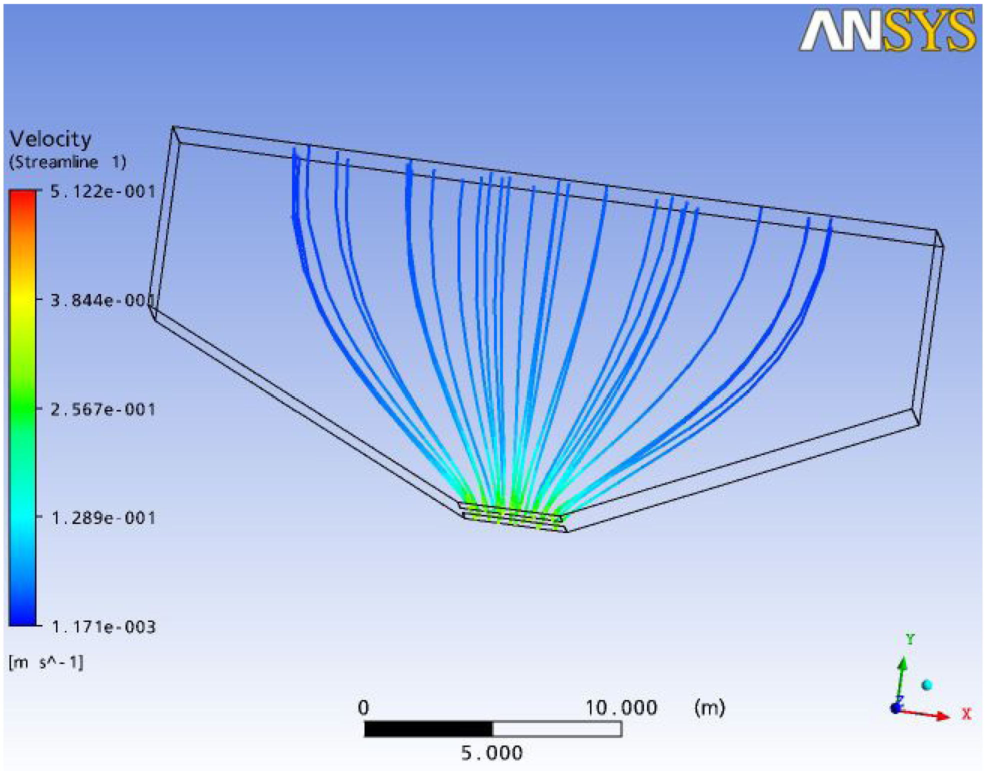

Figure 3: Velocity flow lines in a silo with bottom shape type of semi "v" with grain surface flattened, frontal view.

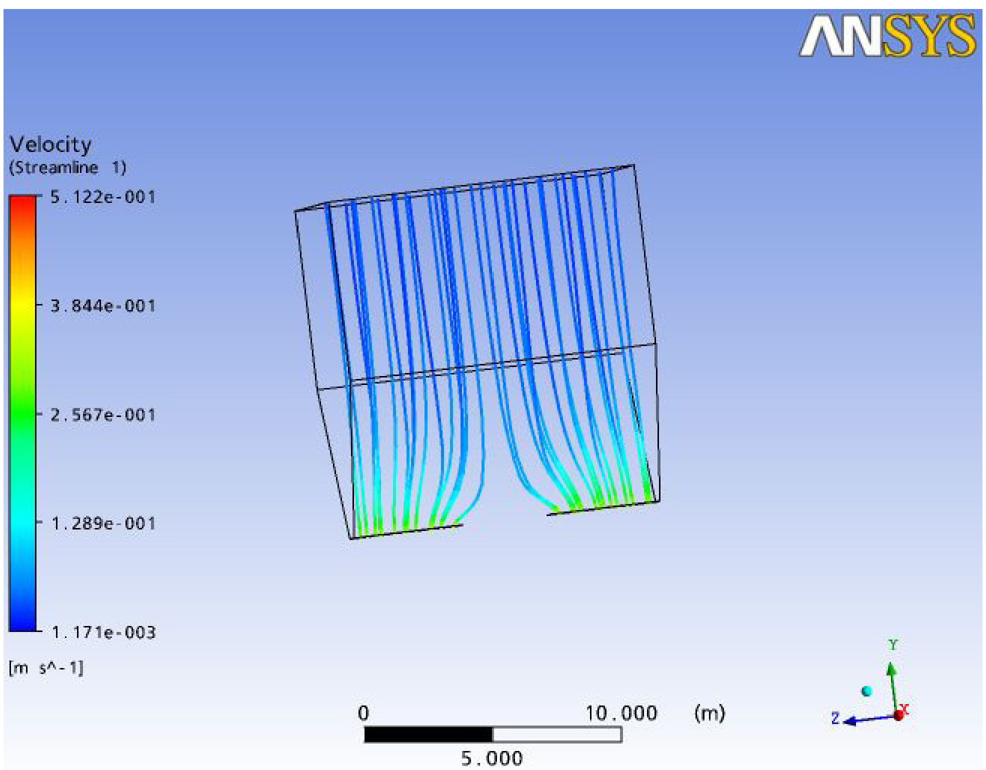

Figure 4: Velocity flow lines in a silo with bottom shape type of semi "v" with grain surface flattened, lateral view.

research, the installation of additional aeration ducts alongside the silo bottom, not solely at the semi "v" base.

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