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Modeling airflow in outdoor grain pile aeration systems

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Abstract

Numerous aeration system designs exist to aerate large outdoor grain piles (up to 50,000 tonnes) in North America. Suction airflow is used to hold tarps covering these piles in place. Airflow through the peaked grain mass is presumed to be non-uniform. A computational fluid dynamics package (CFD), FLUENT, was used to model non-uniform suction airflow in one commercial outdoor maize pile. The material properties of maize including moisture content, porosity and bulk density were specified and boundary conditions of air mass inflow rates based on an airflow rate of 0.085 m^3/min/tonne were used. A procedure was established to estimate the percentage of grain volume having a flow velocity above a critical value needed for ozonation. A comparison between airflow distributions with varying ratios of mass inflow rates between the central tower, flexible perforated air ducts under the tarp and the perforated side wall was made. The velocity profile of the air movement and absolute pressure exerted by the airflow inside the grain pile and between the tarp and grain surface interface were also studied. For each mass flow case, the velocity magnitude and the absolute pressure exerted by the airflow increased near each of the three air inlets. The mass flow ratio of 1:1:1 had the highest percentage (77 %) of flow velocity above the critical velocity of 0.03 m/s needed for ozonation. Additionally, using a 3D CFD approach to evaluate aeration system design for large storage structures such as outdoor grain piles proved useful.

Key words: Computational Fluid Dynamics, airflow, ground pile, storage, aeration system design.

Introduction

Deterioration in the quality of stored grain by insects, molds and mycotoxins causes economic losses to farmers, elevators managers and processors throughout the world. The current trend is toward a reduction in the dependence on chemicals. Aeration is one of the most feasible non-chemical alternatives to control insects without the use of chemicals. Insect development in stored grains is a function of time, grain moisture content and grain temperature. The use of aeration contributes towards a safer environment by reducing the chemical residues in the food and feed supply chains.

Storage of grain in outdoor ground piles is a common practice in the U.S. to complement a lack of permanent storage structure capacity during the harvest rush. Usually outdoor piles store grain for periods not exceeding 6 months before grain is moved or marketed. In order to maintain grain quality, it should be placed in the pile with a temperature below 15.5 °C and safe storage moisture content of 15 % or less (Foster

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et al., 1979; Maier and Wilcke, 1998).

Aeration requires a mechanical ventilation system that can be used to manage grain temperatures by moving air with the desired properties through the grain mass preventing moisture movement and accumulation therefore maximizing grain storage life (Foster and McKenzie, 1979). In North America, numerous aeration system designs exit to aerate large outdoor grain piles (up to 50,000 tonnes). The main purpose of aeration is to cool grain by moving air through the grain mass by suction (negative pressure) or by pushing (positive pressure). In order to achieve cooling as uniformly and quickly as possible, an aeration system design must provide as uniform of an air distribution through the grain mass as possible. The most common aeration method in outdoor grain piles is by suction airflow in order to hold in place the tarps covering the piles.

Airflow distribution throughout the grain mass of an outdoor grain pile is presumed to be non-uniform and is affected by different factors: pile geometry, equipment used in the aeration system, variation in cleanliness of grain, and distribution of broken grain and foreign material. In order to optimize the designs of aeration systems in any grain mass, the concept of non-uniform airflow needs to be fully understood. According to Garg (2005), most computer models developed for predicting heat, mass and momentum transfer in grain storage structures assume airflow rate to be uniform through the grain mass. In reality, there are many storage structures such as outdoor piles, storage sheds, large diameter silos, and hopper bottom bins in which airflow is not uniform. Therefore, there is a need to model aeration systems for grain storage structures using a non-uniform airflow distribution. One of the primary causes of non-uniform airflow distribution is variation in the material properties of the grain mass. These variations in material properties of the grain bulk affect the resistance offered by the grain to airflow. Airflow resistance is a function of particle size and porosity of the grain. Any material property that affects the particle size or porosity of the grain will also affect the resistance of the grain to airflow. Therefore, a number of material properties like distribution of fine material, loading method, moisture content, and compaction cause non-uniform airflow distribution.

Computational fluid dynamics (CFD) is an engineering tool to model and design efficient aeration systems by considering factors like airflow requirement, geometry and storage capacity, crop type and aeration duct configuration in ground pile storage. CFD analysis has the potential benefit of modeling different design configurations before practical implementation using non-uniform airflow distribution. CFD analysis can also predict the air velocities and pressures inside the grain mass using a three dimensional flow profile. The modeling of non-uniform airflow distribution using CFD also helps in the design of ozonation systems because it predicts the air velocities throughout the grain mass. Ozone is a powerful oxidant that has several applications like elimination of odors, removal of organic and inorganic compounds, preservation of vegetables and fruits and more recently sterilization of grain. Ozonation treatment could potentially play an important role in preventing spoilage and deterioration of grain in ground piles. Mendez et al. (2003) stated that a minimum air velocity of 0.03 m/s is optimal to move ozone through a grain mass. Therefore, a CFD simulation of non-uniform airflow through the grain mass of an outdoor grain pile can predict what percentage of the aerated grain mass will have a minimum air velocity of 0.03 m/s. Also, modeling of airflow allows for the study of which part of the grain pile will be more susceptible to mold growth because the simulation model will reveal which portions of the grain pile will have too little airflow to achieve timely cooling.

The goal of this research was to predict airflow distribution in outdoor grain piles numerically using Computational Fluid Dynamics (CFD) and to improve aeration system design in outdoor grain piles to make airflow more uniform.

Materials and methods

Non-uniform airflow distribution was solved using the CFD package Fluent (Version 6.1) based on a proposed aeration system design for an outdoor grain storage pile located in the Midwest with a capacity of 32,000 tonnes. This outdoor storage pile was modeled as a 3D geometry and airflow was assumed to be laminar. The 3D model (Figure 1) was generated and meshed using Gambit (Version 2.1). To reduce the amount of time for simulation and to make the number of elements smaller, the storage pile was subdivided into an axisymmetric pile slice $1/5^{th}$ of its total volume with a total capacity of 6,400 tonnes. The volume flow rate used was $0.085 m^3$/min/tonne (1/13 cubic feet per minute per bushel), which was slightly below the commonly recommended airflow rate of $0.1 m^3$ /min/tonne for aeration. The total volume of air flow into the grain pile slice was $8.1 m^3/s$. The mass flow entering the axisymmetric pile was 9.93 kg/s.

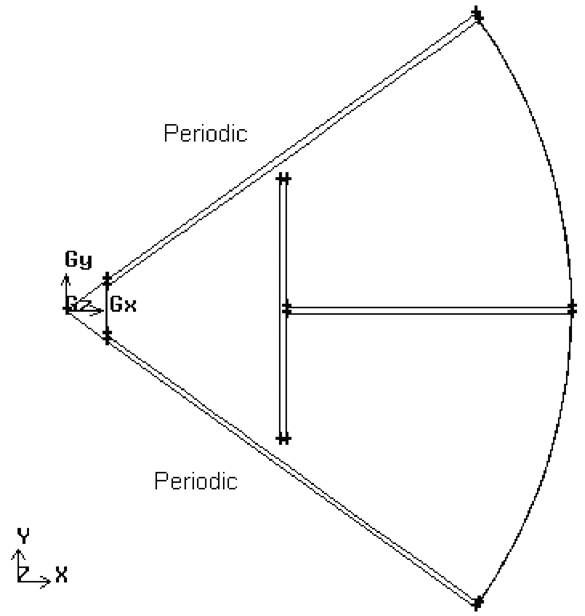

Figure 1. View of the outdoor grain pile $1/5^{th}$ axisymmetric slice as implemented in Fluent

The model of the airflow distribution was based on Ergun's equation (1), which is an equation that relates the resistance offered to fluid flow based on Reynolds theory. According to this equation, the total energy loss in a packed bed should be treated as the sum of viscous and kinetic energy losses:

$$\frac{\Delta P}{L} = \frac{A\mu(1-\varepsilon)^2}{d_p^2\varepsilon^3}V + \frac{B\rho(1-\varepsilon)}{d_p^2\varepsilon^3}V^2 \qquad (1)$$

Where ε is porosity, μ is viscosity, ρ is density, d_p is particle diameter, A and B are dimensionless empirical constants with a value of 150 and 1.75, respectively obtained from Molenda et al. (2005). The variables are DP for pressure gradient and *V* for air velocity which is a superficial velocity (Ergun, 1952). The material properties of both the grain mass and the fluid flowing through that mass are part of the equation. Fluent has the capability of modeling airflow distribution when the resistance coefficients of Ergun's equation vary in the grain mass. The effect of various parameters like distribution of fine material, porosity, moisture content, particle size distribution, bulk density, and air properties can be evaluated using this equation. This is a major advantage of being able to use Ergun's equation compared to Shedd's equation (ASAE Standard, 2001) and has only recently been made possible through the work by Molenda et al. (2005). Air velocity was calculated as the volume flow rate divided by the cross-sectional area of the flow. The superficial velocity was lower than the actual velocity of the air flowing through the porous media (i.e., the grain mass). The velocity of the air flowing through the inter-granular spaces is known as the physical velocity.

The viscous loss coefficient $1/\alpha$ and the inertial loss coefficient C_2 values were calculated based on the material properties of maize and air (Garg, 2005), and were specified in Fluent as follows:

$$1/\alpha = 8.10810E7 \qquad (2)$$

$$C_2 = 10985.2 \qquad (3)$$

The value of the porosity, ε, was:

$$\varepsilon = 0.38 \tag{4}$$

The airflow resistance through the stored maize mass was assumed to be the same in all directions (Molenda et al. 2005). The viscous and inertial loss coefficients of Ergun's equation were assumed to be constant when calculating airflow distribution. The velocity and pressure magnitude distribution of non-uniform air flow was calculated by solving Ergun's equation numerically using the finite volume method.

The analysis of non-uniform air flow distribution was simulated for mass flow ratios through three different air inlets to the outdoor grain pile.

1. Mass flow inlet only through the central tower opening at the top and from there directed vertically downward and then horizontally through presumed perforations in the tower into the grain mass.
2. Mass flow inlet through the central tower and side wall perforation, which is the supporting fence surrounding the pile.
3. Mass flow inlet through the central tower, side wall perforation and two perforated ducts placed under the tarp and along the upper edges of the pile slice. In this case, the air inlet for perforated ducts laid on the grain surface but under the tarp was simulated in the model with small perforations placed on both sides of the tarp on the pile slice edges symmetrically.

Each case is defined by the mass flow ratio described as 0:0:0, where the first number stands for mass flow through the central tower, the second for mass flow through the side wall and the third for mass flow through the perforated ducts under the tarp. The mass flow ratios are summarized in Table 1. For each case, the results for static pressure and velocity contours for the whole domain and the central symmetric plane were analyzed. Also, the percentage of grid points with velocities above the critical value of 0.03 m/s needed for effective ozonation was also quantified for each case.

An actual outdoor grain pile located in the Midwest was used as a basis for the simulation model. This pile had a diameter of 84 m and a center pile depth of 19.2 m resulting in a storage capacity of 32,000 tonnes of maize at 15 % moisture content. The aeration system of the pile consisted if five aeration ducts extending in from the side wall fence towards the center placed equally around the perimeter. Each duct ended in a T-section cross duct near the center to increase airflow through the peak of the pile. Each fan connected to the air ducts provided enough power to move 0.085 m^3/min/tonne. Each duct consisted of a solid section of 24.4 m length and 0.61 m diameter lying in the middle of each grain pile slice and connected to a perforated cross duct of 22 m length and 0.61 m diameter. Both solid and perforated ducts formed a T shape, to move air uniformly as possible through the grain mass of the entire pile. Modeling the details of these aeration ducts was neglected because it produced several computational challenges. Therefore, a flow outlet function in Fluent was used to model the air movement from grain mass into a trend-like floor. Air was exhausted from the pile through the floor section without producing any extra pressure to the profile of the grain pile slice, (as an aeration duct would normally add), which was considered a reasonable assumption.

Table 1. Mass flow ratios (tower:wall:ducts) used to analyze airflow distribution through the 1/5th slice of the outdoor grain pile

1:0:0	0:1:0
2:1:0	1:1:1
1:1:0	1:2:1
1:2:0	1:4:1
1:4:0	1:6:1
1:6:0	1:8:1
1:9:0	0:0:1

Results and discussion

Effect of mass flow ratio on velocity profiles and pressure contours

In the first case, the complete mass flow rate was assumed to enter through the central tower inlet with a ratio of 1:0:0 (Figure 2). The velocity contour on a 2D graph for the symmetric plane confirmed that the velocity magnitude as expected was higher at the entrance of the air inlet and lower near the side wall perforation and tarp ducts where no air was allowed to enter for this case. This higher velocity magnitude was due to the high airflow volume of 8.1 m^3/s moving through the 1.22 m diameter air inlet of the central tower. The airflow was drawn through the central tower and flowed through the grain pile decreasing the magnitude of its velocity from 0.9 m/s at the top of the central tower to 0.0001 m/s at the sealed side wall perforation. The velocity magnitude decreased due to the airflow resistance caused by factors such as porosity, fines, compaction, etc. as well as due to the aeration duct design. The grain mass under the tarp and near the sealed sidewall and above the solid aeration duct formed a no airflow dead zone, which would raise the spoilage potential of this non-aerated grain.

The absolute pressure magnitude profile in the 3D graph (Figure 3) showed that the airflow entering the grain pile exerted more pressure on the grain due to its higher velocity, but decreased as the velocity magnitude decreased.

In the second case, mass flow entered through the central tower and side wall perforation. Several mass flow ratios were studied (Table 2). In the case of the 1:1:0 ratio, the total air flow of 8.1 m^3/s was divided into equal 4.05 m^3/s flows through the central tower and side wall perforation, respectively. The 3D contour (Figure 4) shows a more uniform velocity magnitude of around 0.06 m/s throughout much of the grain pile with a higher velocity magnitude of 0.3 m/s at the top of the central tower. The previously observed dead zone around the periphery of the pile was eliminated as air was allowed to be drawn in through the perforated side wall and flow through the grain under the tarp and above the solid aeration duct towards the perforated duct sections.

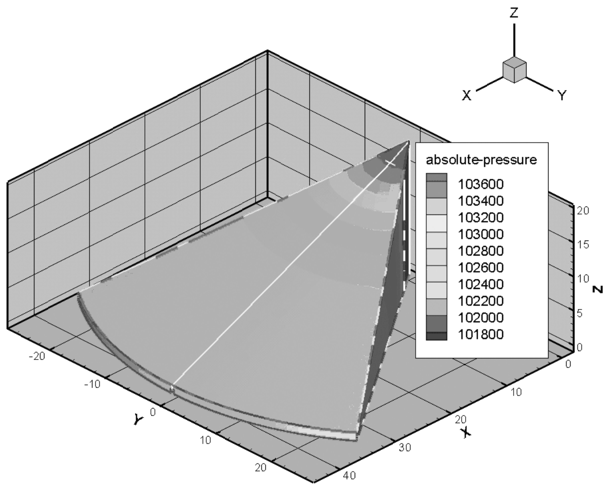

Figure 3. Absolute pressure magnitude contour 3D graph for case 1:0:0 (pressure in Pascals)

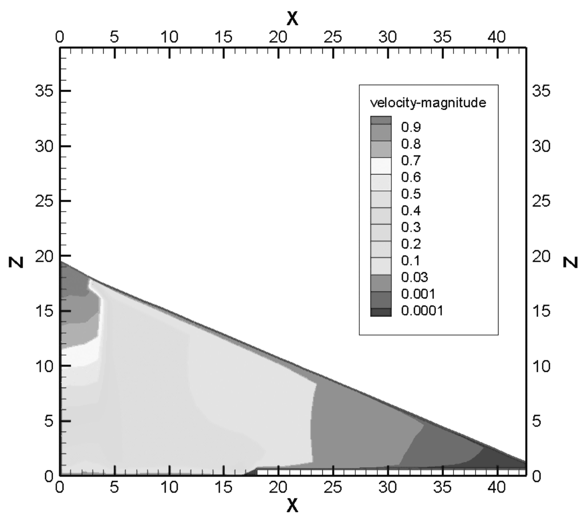

Figure 2. Velocity magnitude contour in a 2D graph for case 1:0:0 (velocity in m/s).

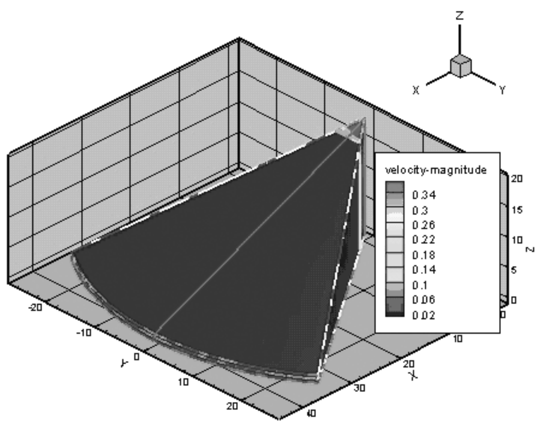

Figure 4. Velocity magnitude contour 3D graph for case 1:1:0 (velocity in m/s)

Table 2. Percentage ratio of the pile slice grain volume above the critical air velocity of 0.03 m/s needed for ozonation

Case	Percentage
1:0:0	26.18
2:1:0	70.61
1:1:0	73.76
1:2:0	72.72
1:4:0	67.75
1:6:0	65.53
1:9:0	64.75
0:1:0	63.17
1:1:1	77.13
1:2:1	74.93
1:4:1	68.15
1:6:1	65.58
1:8:1	64.17
0:0:1	54.25

Given that the central tower air duct has a relatively small cross-sectional air inlet into the air duct, the velocity magnitude will be higher compared to the side wall perforation, which has a much larger cross sectional air inlet area. The absolute pressure magnitude 3D profile (Figure 5) shows a slightly higher magnitude near the two air inlets and decreasing towards the middle of the pile slice.

In the third case, mass flow entered through the central tower, side wall perforation and perforated ducts under the tarp along the upper pile slice edges. Several mass flow ratios were modeled (see Table 2). In the case of the 1:1:1 ratio the total airflow of 8.1 m^3/s was divided into equal 2.7 m^3/s flows through the three air inlets of the grain pile. The 3D contour graph (Figure 6) shows that the velocity magnitude for the grain pile was almost uniform throughout the entire domain. Velocity ranged between 0.06 m/s and 0.1 m/s.

The velocity magnitude was slightly higher near each of the three air inlets and lower throughout the rest of the grain pile slice. The absolute pressure magnitude 3D profile (Figure 7) showed a higher absolute pressure at the lower corners of the grain pile slice where both ends of the air inlets of the side wall perforation and perforated ducts under the tarp came together.

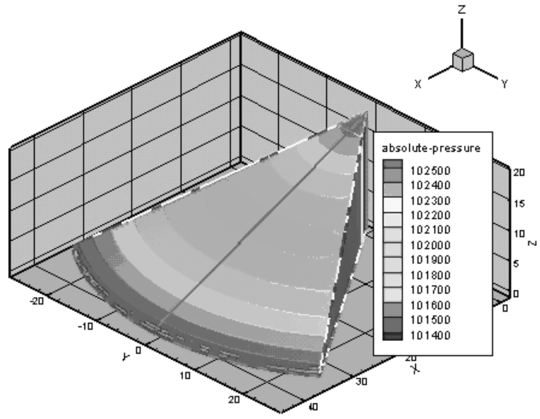

Figure 5. Absolute pressure magnitude contour 3D graph for case 1:1:0 (pressure in Pascals).

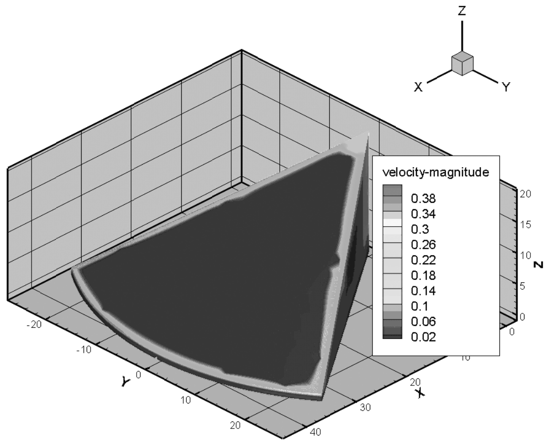

Figure 6. Velocity magnitude contour 3D graph for case 1:1:1 (velocity in m/s).

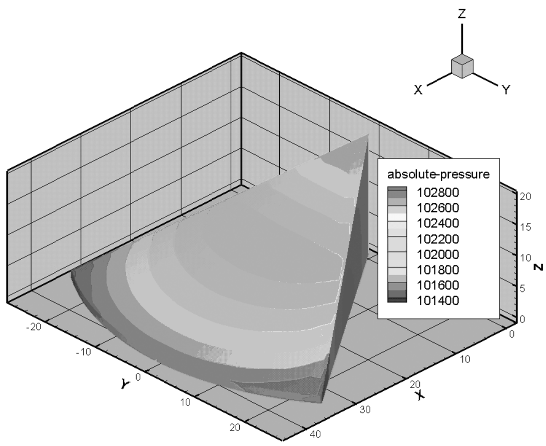

Figure 7. Absolute pressure magnitude contour 3D graph for case 1:1:1 (pressure in Pascals).

Effect of mass flow ratio on uniformity of air velocity

The percentage ratios of the number of grid points above the critical value of 0.03 m/s for ozonation for all cases tested are given in Table 2. The ratios with the highest percentage of velocities above the minimum 0.03 m/s critical for ozonation were the ones utilizing all three air inlets, i.e., the mass flow ratio of 1:1:1 yielded 77.1 % and 1:2:1 yielded 74.9 %.

When the mass flow ratio increased through the side wall perforation (1:4:1, 1:6:1 and 1:8:1), the percentage ratio decreased to 68.1 %, 65.5 % and 64.2 %, respectively. Thus, increasing the mass flow ratio through the side wall by more than a factor of two compared to airflow through the central tower and perforated ducts under the tarp increased non-uniformity of the velocity profile. Most of the air volume moved from the inlet of the side wall perforation inlet toward the center of the grain pile and out through the exhaust duct rather than distributing towards the center of the pile and the pile surface under the tarp. However, allowing air to flow in through a perforated side wall fence is critically important to avoid dead zones in the pile peripheries grain volume. For the cases of only one air inlet (1:0:0, 0:1:0 and 0:0:1), the percentage ratios were the lowest compared to the other cases. In order to achieve a higher percentage than 77.1 % of grid points above 0.03 m/s, the airflow through the grain pile would have to be increased. However, in order to increase uniformity of airflow, the aeration system design would have to be improved by adding an additional outlet ducts on the floor of the pile. Additionally, the air inlet through the ducts placed on the grain surface under the tarp is not a practical situation. Although some operations place such ducts on the grain surface before tarping, it is a labor intensive and dangerous task to accomplish. Additionally, many outdoor piles have tarp-on fan systems that are raised via the central tower similar to a circus tent and grain is allowed to fill in under the tarp while it is slowly raised. Adding grain surface ducts under the tarp is impossible in those systems. However, this option was considered in the model to determine whether there would be a possibility of adding ozone through these openings to the grain pile.

Conclusions

The CFD tool can be utilized to predict airflow distribution in outdoor grain. The airflow distribution was more uniform for equal mass inflow from two inlets (central tower and side wall perforation) or all the three inlets (central tower, side wall perforation and perforated ducts under the tarp) 1:1:0, 1:1:1 compared to one inlet (1:0:0, 0:0:1 and 0:0:1). The mass flow ratio of 1:1:1 resulted in the most uniform airflow distribution of up to 77 % of the grain volume exposed to the minimum air velocity of 0.03 m/s or higher, which would be needed to ozonate the grain pile effectively with the design airflow rate of 8.10 m^3/s.

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