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Modeling non-uniform airflow distribution in large grain silos using Fluent

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Abstract

Computational fluid dynamics software (Fluent) was used to successfully model non-uniform airflow through large grain storage silos using Ergun's equation, which can account for material properties of a grain mass such as porosity and fines concentration. Three example applications were investigated: a peaked grain mass, a grain mass with a high fines concentration core, and a grain mass aerated from a ring duct around the bottom of the silo wall. The velocity magnitude through a peaked grain mass decreased from 0.0163 m/s at the air inlet to less than 0.008 m/s at 1.0 m below the peak of the grain mass. The velocity magnitude in a core of high fine material concentration decreased from 0.0142 m/s at the air inlet to 0.008 m/s, which resulted in a 40 % lower effective airflow rate through the grain core versus the rest of the grain mass. This non-uniform airflow behavior confirmed the observation by practitioners that moving a cooling front through peaked grain or a core with high fines concentration takes substantially longer than through a leveled and/or cored grain mass. Aerating grain from a ring along the bottom of the silo wall in order to target, for example, chilled air through warmer grain near the silo wall resulted in the spreading of the airflow throughout the grain mass. The airflow became more and more uniform as it moved upwards and no targeted cooling effect would be expected beyond about 1/10 of the grain depth.

Key words: Aeration, Non-uniform Airflow, Fluent, Ergun's Equation, Peaked Grain, Grain Coring.

Introduction

The distribution of air in a grain storage structure has a significant effect on the ecosystem of the stored grain mass. Most grain storage structures have a non-uniform airflow distribution due to the variations in material properties of the grain mass, the geometry of the storage structure, and/or the design of the aeration system. Airflow is generally assumed to be uniform in silos with fully perforated floors and non-uniform in silos with aeration ducts, pads or partially perforated floors. The airflow distribution can also be non-uniform in a silo with a hopper bottom, peaked grain from overfilling, inverted grain from partial unloading, and high fine material concentration in the core of the grain mass (Bartosik and Maier, 2006). Airflow is also non-uniform in outdoor piles and horizontal storage buildings.

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Knowledge of the flow field of air in the grain mass and the pressure drop is essential to designing grain aeration systems. Additionally, most of the ecosystem models developed to predict heat and mass transfer in grain storage structures during aeration (Maier, 1992; Chang et al., 1993; Montross, 1999) assume airflow rate to be uniform through the grain mass. Solving and integrating the non-uniform airflow distribution into existing ecosystem models will result in a more accurate estimate of the heat and mass transfer during storage. The purpose of this study was to model non-uniform airflow distribution using FLUENT, a computational fluid dynamics software, and apply it to three example scenarios: a peaked grain mass, a grain mass with a high fines concentration core, and a grain mass aerated from a ring duct around the bottom of the silo wall.

Porous media properties

One of the primary causes of non-uniform airflow distribution is variation in the material properties of the grain mass. Airflow resistance is a function of particle size and porosity of the grain. Therefore, a number of material properties like distribution of fine material, loading method, moisture content, and compaction cause non-uniform airflow distribution. Airflow resistance increases when silos are filled using spreaders as the amount of fines in the grain increases. When silos are filled using a central fill conveyor or gravity spout, fines tend to concentrate towards the center of the silo and chaff moves towards the silo walls. This creates a region of lower resistance near the walls and higher resistance in the center of the silo. Orientation of the grain kernels can also cause a non-uniform airflow distribution as the grain kernels are not exactly spherical in shape. The non-spherical shape and random orientation of the grain kernels result in airflow resistance that is different in every direction. Grain also undergoes compaction during storage due to vertical pressure exerted by the grain mass in the silo, which is influenced by the grain type, bulk density, coefficient of friction between the grain and the wall, moisture content, angle of internal friction and filling method (Thompson et al., 1987). Giner and Denisienia (1996) showed that the experimentally determined pressure drop decreased by up to 30 % as moisture content increased from 12.8 % to 22.3 % in clean wheat beds. Molenda et al. (2005) concluded that the effect of grain orientation on airflow resistance was negligible, but the fill method significantly affected the airflow resistance.

Ergun's equation for pressure drop through porous media

The relationship between the pressure gradient and velocity of the air through the grain mass must be known in order to estimate the airflow distribution. The air velocity used in equations describing this relationship is the superficial velocity, which is calculated as the volume flow rate divided by the cross-sectional area of the flow. Shedd (1953) plotted data for numerous grains with a wide range of airflow rates and proposed a relationship that has been widely used by engineers for the design of aeration systems and the sizing and selection of fans. Unfortunately, Shedd's expression is empirical in nature and contains no information about the properties of the product being aerated, or the fluid flowing through the product. Several researchers developed expressions for pressure drop through packed beds that have some physical basis. Darcy showed that the velocity of the fluid flowing through a porous medium is directly proportional to the pressure drop (Darcy's Law). According to Reynolds (1900), the total energy loss for a fluid flow is the sum of the viscous and kinetic energy losses. At low airflow rates (laminar flow), the resistance offered by friction to the motion of the fluid is directly proportional to the viscosity and velocity of the fluid. Darcy's law holds for low flow rates where viscous forces predominate and inertial forces can be neglected. At high airflow rates (turbulent flow), pressure loss is proportional to the product of the air density and the square of the fluid velocity as

viscous forces then become relatively negligible.

Ergun (1952) presented an equation for resistance to fluid flow based on the Reynolds Theory. According to this equation, the total energy loss in a packed bed should be treated as the sum of the viscous and kinetic energy losses. He examined the equation from the point of view of its dependence upon flow rate, properties of fluids (μ - viscosity and ρ – density), and porosity (å), orientation, particle diameter (dp), shape, and surface of the granular solids:

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

There is a sudden transition from laminar to turbulent flow in pipes and channels, and there is a critical value of the Reynolds number separating the two regions. It is unlikely that the air movement through the intergranular space is ever turbulent in nature (Navarro and Noyes, 2002). Airflow rates in fixed beds are mainly in the transition zone between laminar and turbulent flow (Fand et al., 1987), so both terms in Ergun's equation are important to calculate airflow resistance through a grain mass. A and B in Ergun's equation are dimensionless empirical constants and were calculated, by Ergun, to be equal to 150 and 1.75, respectively.

Ergun's equation is based on semi-theoretical relationships and the material properties of both the grain mass and the fluid flowing through that mass are part of the equation. A few researchers (Patterson et al., 1971; Giner and Denisienia, 1996) have used Ergun's equation to describe pressure drop through a granular material. But changes in the porosity and bulk density in a grain bed are difficult to measure, which reduces the applicability of Ergun's equation. Molenda et al. (2005) concluded that Ergun's equation could be utilized effectively for the design and analysis of grain aeration systems. Their experimental results showed that the filling method and moisture content have a significant effect on pressure drop.

Materials and methods

Modeling non-uniform airflow using fluent

Non-uniform airflow distribution was solved using a computational fluid dynamics (CFD) package called Fluent (Version 6.1). The storage silo was modeled as a 2D axisymmetric geometry and was meshed with a software package called Gambit. The 2D double precision model of Fluent was selected and the 2D grid from Gambit was imported into Fluent. The porous media model was used to solve the airflow distribution through the grain bed. The recommended maximum allowable perforated duct surface air velocity is 0.15 m/s for ducts with at least 10 % of the surface area open (MWPS-29, 1999). The Reynolds number for most of the grains at the maximum allowable duct surface air velocity lies in the region of laminar flow. Therefore, the 2D axisymmetric model was solved for laminar flow. A segregated solver was used to model airflow distribution in Fluent. Discretization schemes used in the model were Standard for Pressure, SIMPLE for Pressure-Velocity Coupling, and First Order Upwind for Momentum.

Coefficients of ergun's equation

The porous media model in Fluent incorporated an empirically specified flow resistance through the grain. In Fluent, flow resistance through the grain bed can be estimated using a power-law approximation, or Ergun's equation. Airflow resistance through the grain mass was modeled using the coefficients of the Ergun's equation to solve for non-uniform airflow. Shedd's equation (power-law approximation) was not used because of its limitations in modeling variation in the properties of the porous medium. The viscous loss coefficient (1/á) and the inertial loss coefficient (C2) values were calculated based on the material properties of the maize and the air as specified in Fluent:

$$\frac{1}{\alpha} = \frac{150(1-\varepsilon)^2}{d_p^2 \varepsilon^3} \quad [2]$$

$$C_2 = \frac{3.5(1-\varepsilon)}{d_p \varepsilon^3} \quad [3]$$

The value for porosity (ε) used in calculating the viscous and inertial loss coefficients was 0.38 (Brooker et al., 1992). The average (equivalent) particle diameter (d_p) used to model airflow resistance was based on the experimental results reported by Molenda et al. (2005). (Note: The methodology to calculate the average particle diameter for maize in this paper was based on the analysis reported by Molenda and co-workers in their research paper submitted for review. In the final paper submitted for publication by Molenda et al. (2005), the analysis was done differently, which can cause a change in the coefficients of Ergun's equation.)

The pressure drop was regressed against the air velocity and the permeability (k) was calculated by dividing the air viscosity (μ) by the slope of the line in the linear range, which was represented by data having air velocity less than 0.10 m/s. The specific surface area (S) was determined from the calculated permeability after rearranging the following equation:

$$k = \frac{\varepsilon^3}{5S^2(1-\varepsilon)^2} \quad [4]$$

Then, the equivalent particle diameter was determined to be 3.6 mm (for 14 % moisture content value) from the specific surface area as follows:

$$d_p = \frac{6}{S} \quad [5]$$

The values of the viscous loss coefficient (1/ α) and the inertial loss coefficient (C2) values for the Fluent model were calculated to be 8.10810E7 and 10985.2, respectively, using Equations [2] and [3]. The effect of grain orientation on airflow resistance in typical storage silos was predicted to be negligible by Molenda et al. (2005). Therefore, the airflow resistance through a stored maize mass was assumed to be the same in all directions. The superficial velocity was used to solve and present results for airflow distribution in all Fluent simulations.

Results and discussion

An understanding of airflow distribution is important to designing aeration systems for grain storage structures with confidence. The Fluent software is a useful package to study airflow in grain storage structures. Fluent can solve airflow distribution for different geometries and can also incorporate the variation in porous media parameters like porosity, moisture content, distribution of fine material, packing, and orientation of kernels within the grain mass. In the result graphs presented in this paper, the left-hand side represents the centerline of the silo and the right-hand side represents the steel wall.

Silo with peaked grain

Fluent was used to show the effect of a peaked grain surface on the airflow distribution in a large silo. A silo of diameter 21.9 m and eave height of 10.6 m was modeled as a 2D axisymmetric model. The slope of the roof was 30 °, the eaves were assumed to be sealed, and the vent for the air outlet was at the roof peak. The location of the vent was investigated (data not shown) but did not have much effect on the airflow distribution in the grain mass. Therefore, the vent was placed at the top to keep the model 2D axisymmetric. The peaked grain mass was modeled with an angle of repose of 23 ° resulting in a peaked grain depth of 15.3 m. The total volume of maize in the silo was 3350 t. The total airflow of 6.1 m^3/s was used to aerate the silo based on a design flow rate of 0.11 m^3/min/t. The air inlet velocity through the fully perforated floor was 0.0163 m/s.

Although peaking of the grain mass added 425 t to the storage capacity of the silo, the peaked volume also increased the airflow resistance. Contours of static pressure and velocity

magnitude are shown in Figures 1 and 2, respectively. The static pressure at the air inlet was 325 Pa and decreased at a slower rate through the grain under the peak than the grain near the wall. Air followed the path of least resistance and the grain mass in the peaked volume received less airflow than the grain in the rest of the silo. The velocity of the air increased to more than 0.018 m/s near the corner of the headspace and silo wall, while it decreased to less than 0.008 m/s in the top 1.0 m below the grain peak. In the center, air velocity decreased to 75 % at about two-thirds of the peaked grain depth, 50 % at about ninety percent of the peaked grain depth, and 25 % near the air outlet. This confirms what practitioners have always known, i.e., that it will take much more time to cool the peaked grain volume than the rest of the grain mass in the silo. And if leveling of the peak or cooling of the peak is neglected, grain spoilage can result due to self-heating.

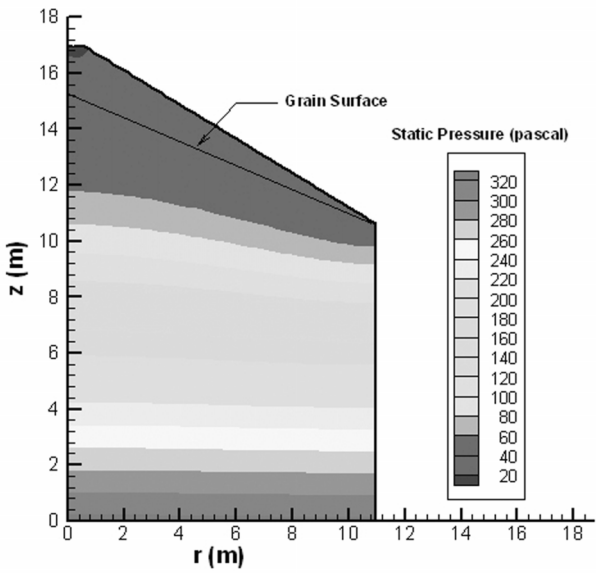

Figure 1. Contours of static pressure due to an airflow rate of 0.11 m^3/min/t in a silo with a fully perforated floor holding 3,350 t of peaked maize.

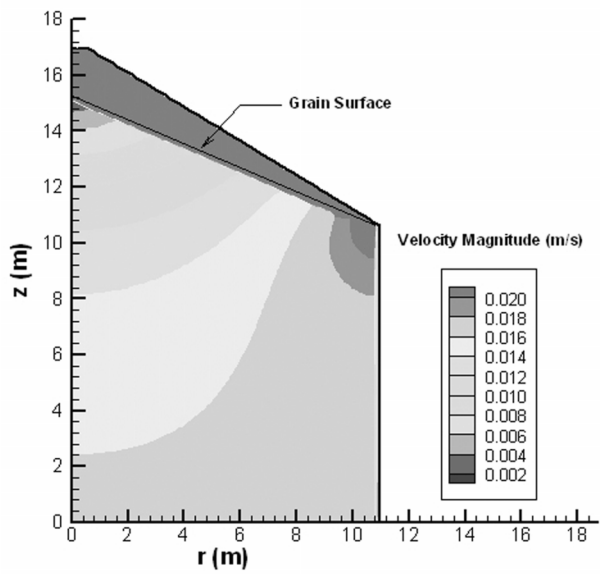

Figure 2. Contours of velocity magnitude due to an airflow rate of 0.11 m^3/min/t in a silo with a fully perforated floor holding 3,350 t of peaked maize.

Silo with core of fines

The effect of the distribution of fine material on airflow distribution was also modeled using Fluent. A silo with diameter 21.9 m and eave height of 10.6 was modeled using a 2D axisymmetric geometry. The silo was level filled up to the eave height with a total maize volume of 2,900 t. The air was introduced using a fully perforated floor with 0.0142 m/s velocity corresponding to a total airflow of 5.3 m^3/s at a rate of 0.11 m^3/min/t. The central portion of the silo with a 2.0 m radius and cylinder height equal to the grain depth was modeled as the region with a high fines concentration. The high concentration of fine material in the center of the silo decreased the porosity and the average particle size of the grain. There is a lack of available experimental data on the effect of the fines concentration on the porosity and equivalent particle diameter of the maize mass. Therefore, these values in the center core were assumed in order to illustrate the effect of concentrated fines on airflow distribution. The assumed porosity and equivalent particle diameter values were 0.34 and 3.2 mm, respectively, or about 10 % less compared to 0.38 and 3.6 mm in the rest of the maize.

Figures 3 and 4 show the pressure and velocity magnitude contours in the silo. The high concentration of fine material increased the airflow resistance in the center of the silo. The static pressure required to push air through the grain mass with uniform conditions was 252 Pa.

It increased to 284 Pa in the core with the high fines concentration. The higher airflow resistance in the core forced the air to move out of the core into the rest of the grain mass as it moved upwards. This resulted in a small increase in the air velocity in the rest of the grain mass. The velocity magnitude was between 0.014 and 0.015 m/s in most of the grain mass except the core. The velocity magnitude in the core decreased rapidly from 0.0142 m/s to 0.008 m/s within about the first one-third of the grain depth. It then remained in the range of 0.007 to 0.008 m/s (about 50 % of the inlet velocity) in most of the core as the air moved upwards. The airflow rate in terms of m^3/min/t for the core was calculated based on the average velocity value of 0.008 m/s. The grain capacity of the core was 97 t and the airflow rate was 0.1 m^3/s based on the average velocity magnitude of 0.008 m/s. This resulted in an effective airflow rate of 0.066 m^3/min/t through the grain in the core versus 0.11 m^3/min/t through the rest of the grain mass, which was a 40 % reduction even though the porosity and average particle size only changed by about 10 %. Cooling time, in hours, is generally estimated by dividing the number 15 by the airflow rate in m^3/min/t. Thus, cooling of the core would have taken at least 227 h compared to at least 150 h in the rest of the grain mass.

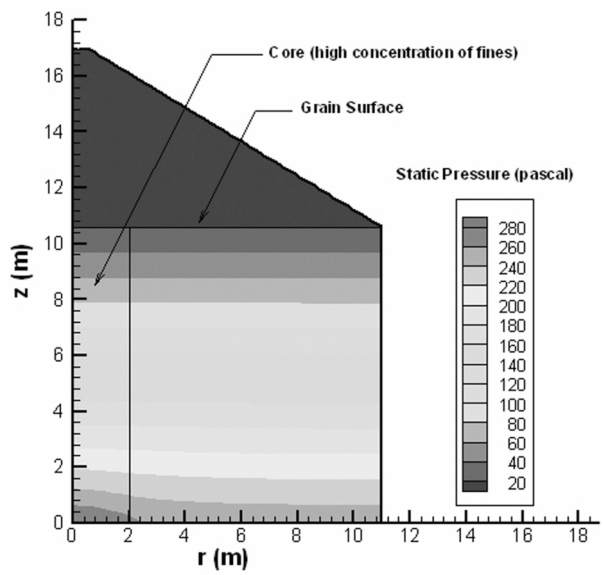

Figure 3. Contours of static pressure due to an airflow rate of 0.11 m^3/min/t in a silo with a fully perforated floor holding 2,900 t of level filled maize with a core of 2.0 m radius having high fine concentration.

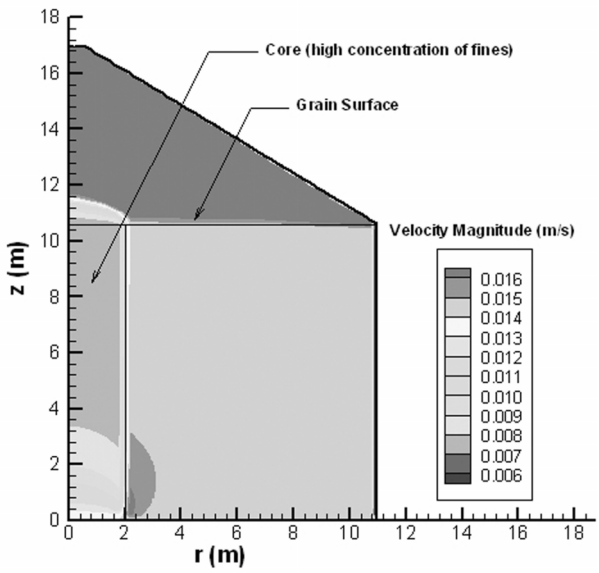

Figure 4. Contours of velocity magnitude due to an airflow rate of 0.11 m^3/min/t in a silo with a fully perforated floor holding 2,900 t of level filled maize with a core of 2.0 m radius having high fine concentration.

This confirms what practitioners have always known, i.e., that it will take much more time to cool the core than the rest of the grain mass in the silo. And if coring of the grain mass or cooling of the core is neglected, grain spoilage can result due to self-heating. Fine material including broken kernels tends to remain in the center and whole kernels tend to move outward as a silo is loaded from a central fill hole in the roof top. Concentration of the fine material in the core results in increased airflow resistance and thus, a lower airflow rate in the center of the silo. Removal of fines or uniform distribution of this material would result in more uniform airflow through the grain mass.

Silo with targeted aeration

Simulation results from a stored grain ecosystem model (PHAST-FEM) developed by Montross (1999) indicated that aeration from a ring duct along the bottom of the silo to target the airflow up along the wall had the potential to

make chilled aeration a more economical and effective insect control strategy. Partial chilled aeration to target the airflow along the silo wall results in non-uniform airflow distribution, which was solved using Fluent (Garg, 2005).

Air was introduced near the wall only through an in-floor ring duct covered with perforated metal to model the partial chilled aeration effect. The air inlet area comprised the outer 19 % of the total floor area, which corresponded to the outer 10 % of the radius along the silo wall in the 2D axisymmetric model. A single vent for the air outlet was placed at the peak of the silo roof and eaves were assumed to be sealed. The diameter and eave height of the silo was 32.0 m and 15.5 m, respectively. The total grain volume in the silo with level filled grain up to the eave height was 9068 t (353,652 bu). The air inlet velocity was 0.1092 m/s, which corresponded to an airflow rate of 0.11 m^3/min/t. The airflow rate was within the recommended maximum allowable perforated duct surface air velocity of 0.15 m^3/s (MWPS-29, 1999).

The contours of the static pressure and velocity magnitude are shown in Figures 5 and 6. The air inlet velocity was 0.1092 m/s at the bottom along the silo wall and reduced to less than 0.030 m/s at one third of the grain depth. The air velocity was between 0.0208 and 0.0300 m/s along the silo wall in the rest of the silo. The air velocity for a fully perforated floor would be 0.0208 m/s throughout the entire depth of the grain mass. The air was introduced in the partial aeration system at a velocity of more than five times the air velocity in the uniform aeration system, but the air velocity achieved along the silo wall beyond a depth of 4 m was less than 1.5 times the velocity for uniform aeration. The advantage of partial aeration to target the air along the silo wall was significant only in the bottom 1/10 portion of the silo. As a result, Garg (2005) developed the idea of partial chilled aeration further by designing a special air outlet system near the top of the silo that channels more of the chilled air up along the silo wall to achieve the desired cooling effect (data not shown).

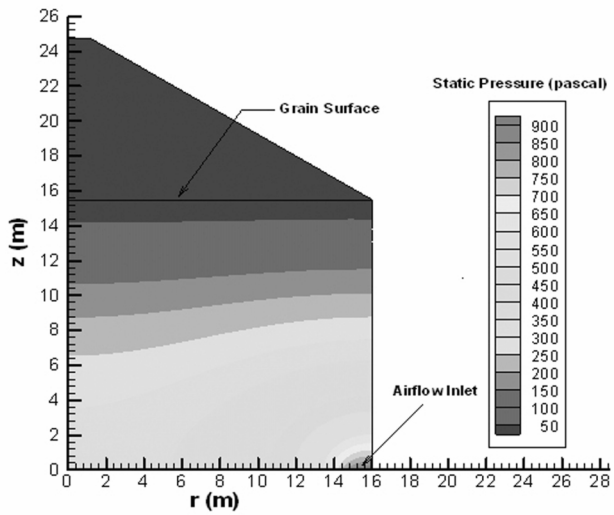

Figure 5. Contours of static pressure due to aeration from a ring duct along the bottom of the silo wall holding 9,068 t of maize.

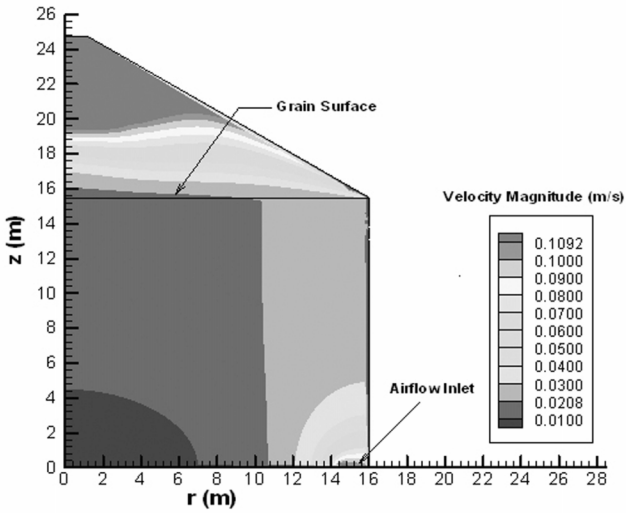

Figure 6. Contours of velocity magnitude due to aeration from a ring duct along the bottom of the silo wall holding 9,068 t of maize.

Conclusions

The main objective of this research was to model non-uniform airflow distribution in grain storage structures using Ergun's equation and the computational fluid dynamics package Fluent. The main conclusions were:

1. Non-uniform airflow distribution resulting from silo geometry or from variation in material

properties of the grain mass can be analyzed efficiently using Fluent. However, more experimental data on the changes in material properties of the grain mass is required to accurately predict airflow distribution.

2. In peaked grain, the velocity magnitude decreased from 0.0163 m/s at the air inlet to less than 0.008 m/s at 1.0 m below the peak of the grain mass. This confirms the observation by practitioners that moving a cooling front through a peaked grain mass takes substantially longer than a level grain mass.

3. In uncored grain, the velocity magnitude in the core of high fine material concentration decreased from 0.0142 m/s at the air inlet to 0.008 m/s. This resulted in an effective airflow rate of 0.066 m^3/min/t through the grain core versus 0.11 m^3/min/t through the rest of the grain, which would result in a cooling front taking at least 227 h compared to 150 h for the rest of the grain mass.

4. Non-uniform airflow distribution was solved for the placement of a ring duct along the bottom of the silo to target chilled air through the grain near the silo wall. The resistance offered by the maize resulted in the spreading of the airflow throughout the grain mass and the airflow became more and more uniform as it moved upwards in the grain silo.

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