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RESEARCH ARTICLE

Numerical Simulation of Gas Flow through a Cylindrical Grain Storage

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Abstract This study is concerned with a process known as fumigation in the grain industry. During this process, fumigant is injected at the inlet of storage and is expected to distribute throughout the stored grain to kill the insects in it. The present research focuses on the study of the fumigant (phosphine) flow distribution based on mathematical modelling and numerical simulation through available Computational Fluid Dynamic (CFD) software. In particular, the mathematical modelling is translated into the CFD and simulation is ran to determine areas where insects might find refuge. Hence provide information for conducting more effective fumigation. Numerical simulation using CFD software, for example, FLUENT, is widely known as cost and time effective. However, the numerical simulation needs to be verified before conducting such studies. For a simple case, the analytical solution exists. Therefore, the analytic solution for a simple case, can be used for verification and serve as a basis for adopting a CFD software, FLUENT for an extended geometry and boundary conditions. The numerical results are found to agree well with the analytical results. Overall, the fumigant gas flows towards the outlet regardless of the position of the outlet.

Keywords: Porous medium, FLUENT, Laplace equation, Darcy's law, fumigation.

Introduction

Fumigation is the process of spreading a gas chemical called fumigant to the stored grain for the purpose of killing the grain insects during storage. For over 30 years, phosphine has been used for bulk grain fumigation as it is known as residue-free, cheap, and easier to be used [1-4]. However, the fumigation process sometimes is reported to fail [5,6]. Efforts to identify the causes of fumigation failure and the development of strategies for effective phosphine use amid the threat of insect resistance have started to take place [7-11]. Central to these efforts is the need for a good understanding of how the phosphine gas behaves in grain storage and the factors that influence the distribution of the gas. Surprisingly, this understanding is currently lacking [1,12,13]. Furthermore, experimentally study is very expensive to conduct.

A few studies have been conducted as to understand the behaviour of gas flow in stored grain. The literature can be highlighted into the mathematical model, the dimension and geometry involved, mathematical methods used, the imposed boundary conditions, and the type of gas used during the grain fumigation.

Hunter [14], studied the air flow field solution and pressure differences across seed storage for different duct and store cross-sections. This solution is derived for flow in two dimensions using conformal mapping techniques. The linear terms of Ergun's equation and the square-law term are considered. However, the pressure solution is not further used to obtain the velocity profiles.

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By using conformal mapping techniques, he then proceeded to study the traverse time of the air flow in [15]. This time, he omitted the square term of Ergun equation and neglect the changes in density of gas, so that the pressure satisfies the linear equation of the two-dimensional flow field. He considered various different geometries of air flow during his work. Some of them are two-dimensional fumigant flow geometry from a straight duct which is upwards and downwards flow. The approximate solutions of the upwards flow in the circular cylindrical store with a conical bottom and central supply duct have been found. These movements have also modelled as radial flow in two and three dimensions. For all, the inlet was treated as a point source with a constant volumetric flow rate.

Meanwhile, [16] have conducted a study of air flow by using a rectangular slab that depends on two variables (x and y). During their work, the air was blown at constant pressure to the grain bed by fans positioned below (z = 0) allowing the air to pass through the grain bed. The air flow is assumed to move in z-direction and will not escape the wall (x±1). However, the air is able to escape through the top bin (z = 1) as it is an open silo.

Previous work related to this problem was also conducted by Smith et al. [17, 18] who considered the flow of gas carbon dioxide in cylindrical storage. They assumed a uniform vertical flow and obtained an analytic solution using a perturbation approach based on the small curvature of streamlines. In [19], the same author used conformal mapping to obtain the gas pressure via the solution of Laplace Equation. They considered a rectangular symmetrical bin and instead of a point source at the inlet, the gas entered the bin as a finite curved shape at constant pressure.

Also, via the solution of Laplace Equation, [20] obtained a closed form series solution for the pressure, velocity, and streamlines in a cylindrically stored grain bed with either a circular or annular inlet. Velocity at the inlet is assumed constant and the top is open to the atmosphere. Furthermore, the walls are impermeable to the flow.

Moreover, there are some studies that have attempted to predict the hydrodynamics of fumigation and related characteristics of porous medium and other types of flow systems numerically using CFD. For example, [21] used CFD (FLUENT) to conduct a 3D simulation on a facility with fumigant sulfuryl fluoride. The model used is unsteady with incompressible ideal gas properties. While [22] also study 3D simulation of the phosphine flow during fumigation of wheat, but in a horizontal warehouse and by adopting a turbulence model. Also, a CFD (FLUENT) simulation to predict fumigant distribution and leakage in a flour mill during a 24-hour, fan circulation assisted, sulfuryl fluoride fumigation was conducted in [23] and [24].

Meanwhile, [25] ran a numerical study using the FLUENT and COMSOL solvers to predict phosphine gas flow in cylindrical grain storage. Overall, FLUENT and COMSOL predict similar flow behavior with good agreement. Furthermore, [26] showed that CFD-based modelling was accurate to predict the distribution of phosphine in a cylindrical storage. They investigated the distribution for a flat base storage with a circulation system.

Based on the above literatures, several analytical solutions have been obtained for air or fumigant flow in grain beds where the pressure, velocity, streamline, and traverse time have been calculated. The grain storage is assumed whether as a two dimensional planar [14,15,16,19], 2D axisymmetric (cylindrical storage) [15,17,18,20,25] or a three-dimensional domain [21,22,23,24,26]. However, none investigated the geometrical configurations considered in this present study which are physically reliable finite size inlet on the base of a cylindrical storage.

The present work aims to investigate the behavior of the gas flow numerically using CFD (FLUENT) for three geometrical configurations which are cylindrical storage with an outlet at the top of the silo, outlet above the grain surface, and outlet below the grain surface. For verification purposes, the numerical solution is first verified with an analytical solution for a simple case.

Model Equations

The fluid flow during fumigation is a low speed gas flow, and since this is a flow in porous medium, the equation of motion satisfies Darcy's law [27]

$$\boldsymbol{V} = -\frac{k}{\mu}\boldsymbol{\nabla} p,$$

which relates the pressure p and velocity of the gas $\boldsymbol{V}$, defined as the volume of gas crossing a unit area of porous medium per unit time. Here, k is the permeability and μ is the dynamic viscosity. The specific gravity of phosphine is similar to air [28]. Therefore, the effect of gravity is neglected here. Also, temperature variation in the grain bed during fumigation [29] is negligible and pore distribution is assumed uniform with height. The flow is treated incompressible [17,18], so together with the continuity equation, $\boldsymbol{\nabla} \cdot \boldsymbol{V} = 0$, the pressure satisfies Laplace's equation $\nabla^2 p = 0$. In cylindrical coordinates (r, z), the Laplace's equation becomes

$$\nabla^2 p = \frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} + \frac{\partial^2 p}{\partial z^2} \tag{1}$$

For a simple case, the flow is calculated for a prototype geometry as illustrated in Figure 1. The geometry is a vertical cylinder with a circular inlet at the centre of the silo base. This allows an axisymmetric analysis. The gas is pumped continuously at velocity v_0, into the grain bed through an inlet of radius b. The stored grain is assumed to open to the atmosphere, and hence at the surface $z = h$ the condition $p = p_a$ is used, where p_a is the atmospheric pressure. The base and the vertical wall of the grain storage are assumed impermeable except at the inlet. Therefore, on the base of the cylinder ($z = 0$)

$$\nabla p \cdot n = \begin{cases} -\frac{\mu v_0}{k} & 0 < r < b \\ 0 & b < r < a \end{cases} \tag{2}$$

where a is the radius of the storage. Whereas, on the vertical wall, (1) is solved subject to the zero normal velocity boundary condition

$$\nabla p \cdot n = 0 \qquad \text{for} \quad r = a \tag{3}$$

where $\boldsymbol{n}$ is the unit normal vector to the boundary.

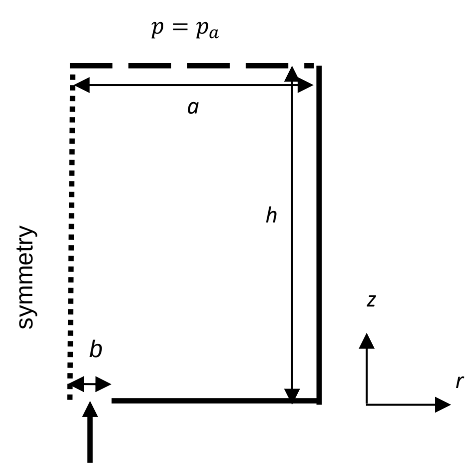


Figure 1. Schematic diagram (not to scale) for the model of flow gas in cylindrical 2D axisymmetric flow.

From this simple case, the numerical simulation is extended to the three-dimensional storage shown in Figure 2. In this investigation, the geometry is divided into three cases. The first case involves an outlet at the highest height of the silo. In second case, the outlet will be on the side but above the grain surface. Lastly, for the third case of this simulation the outlet will be at the side, but down below the grain surface.

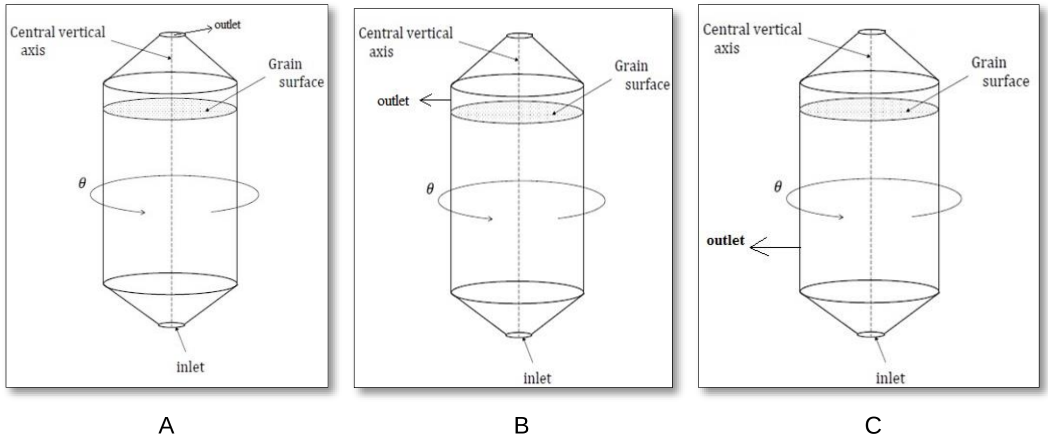


Figure 2. Three schematic cylindrical silos (not to scale) considered in this work with height, *h* of 8m, radius, *r* of 2m and inlet/outlet size radius of 0.1m. (A) Outlet at the top of the silo. (B) Outlet at the above of the grain surface. (C) Outlet at the below of the grain surface.

Methodology

For a simple case, the numerical simulation model is an exact replica of the geometry in Figure 1 with boundary and initial conditions given in equations (1) to (3). The silo is a cylindrical in shape with one inlet position and is solved as a 2D-axisymmetry problem. The height, *h* and radius, *r* are 6m and 2m respectively with inlet size *b* of 0.1m, relevant to on-farm size.

Meanwhile, the extended geometries are given in Figure 2 with the same radius and inlet/outlet size. As a conical shape is implemented here at the bottom and top of the silo, the silo's height is extended for 1m each to a total of 8m height all together. For this research purpose, the storage is assumed to be filled with wheat. The value of permeability k of wheat is given by 5.78×10^{-9} m^2 [30] and the dynamic viscosity μ is 1.1×10^{-5} $kgm^{-1}s^{-1}$.

In the numerical simulation, the material properties are incompressible, homogeneous, and Newtonian fluid with a density of 1.379 kg/m^3, and the flow is assumed to be laminar. The operating temperature, and pressure are 298K and 101,325 Pa respectively [31]. Continuity and Navier–Stokes equations are solved for the fluid. No-slip boundary conditions are imposed at the wall. A uniform velocity profile at the inlet boundary is applied with the mean velocity of an inlet boundary is fixed at 0.2 m/s under steady state conditions. At the outlet boundary, the pressure is assigned as atmospheric pressure. The governing equations are discretized using the first order upwinding scheme.

Results and Discussion

This section will first present the verification between the numerical simulation with the analytical solution for a simple case. Then, the numerical solution for the extended geometry will be provided.

Numerical simulation verification

For a simple case, the analytical solution to equation (1) together with boundary conditions (2) and (3) for the geometry as in Figure 1 was obtained by [20]. For the purpose of verification, two variables which are the pressure and velocity are plotted. It can be seen that from Figure 3 and Figure 4, the analytical and numerical solution provide similar flow behaviour with satisfactory agreement.

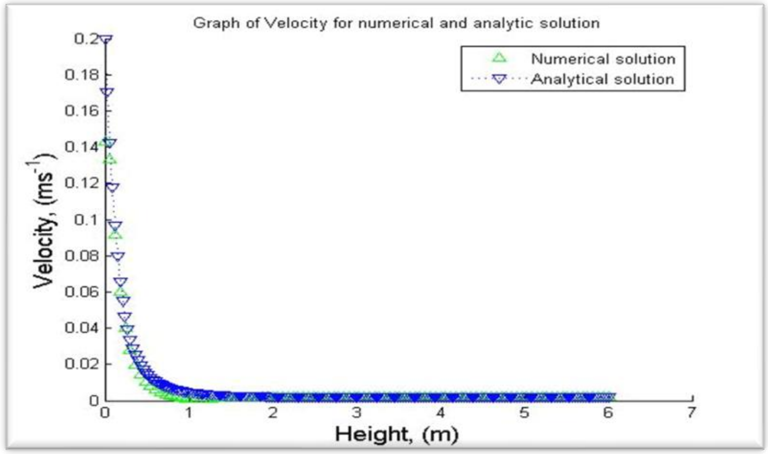


Figure 3. Gas velocity comparison between analytical [20] and numerical simulation.

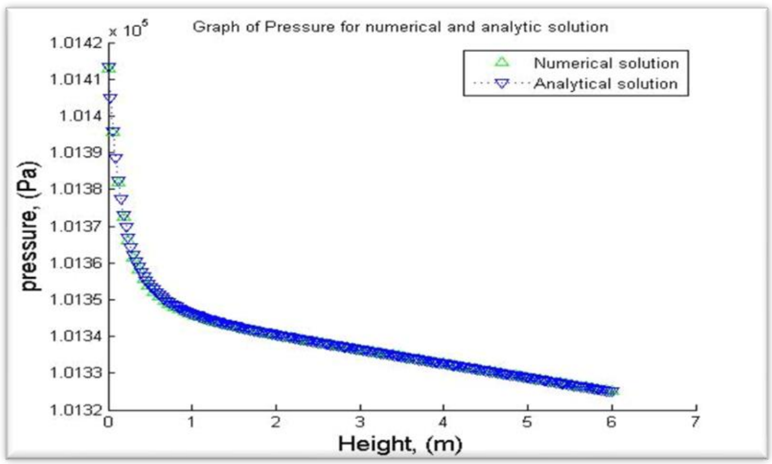
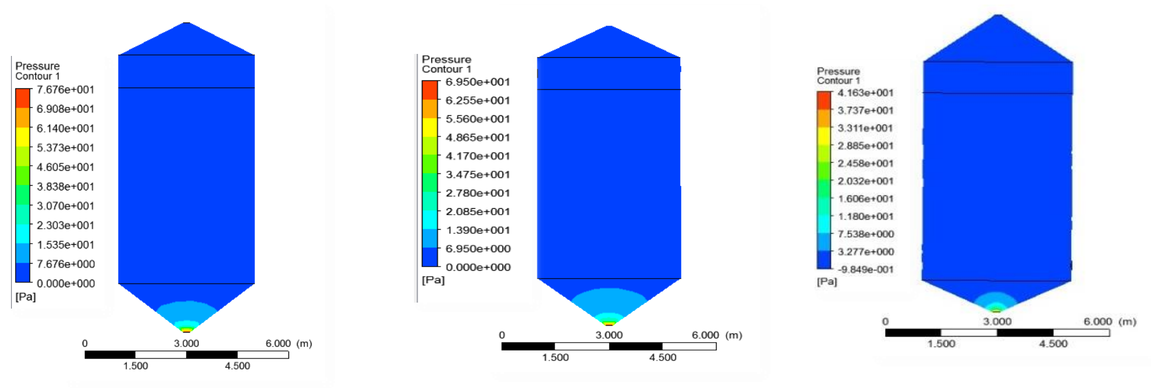


Figure 4. Gas pressure comparison between analytical [20] and numerical simulation.

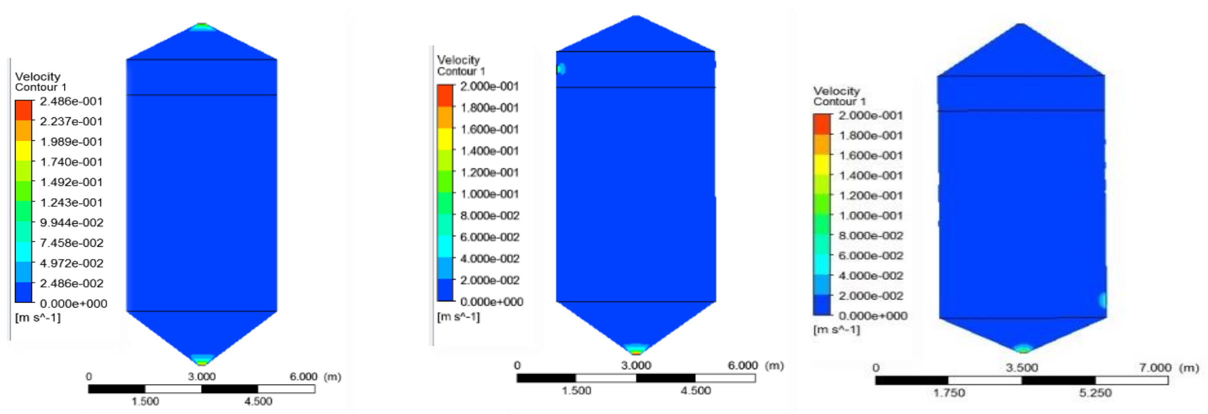
Numerical simulation for extended geometry

The numerical simulation is extended to three-dimensional storage shown in Figure 2 where the geometry is divided into three cases. Overall, for the three cases investigated here, we can see that the highest pressure and velocity occur only at a small region close to the inlet (Figure 5 and 6). Also, as can be seen in Figure 7, the gas flows from the inlet and moves towards the outlet regardless of the outlet location. In the reality, the outlet can be considered as a leaky hole. If the leaky hole is at the lower part, the phosphine might possibly not reach the top part of the silo.



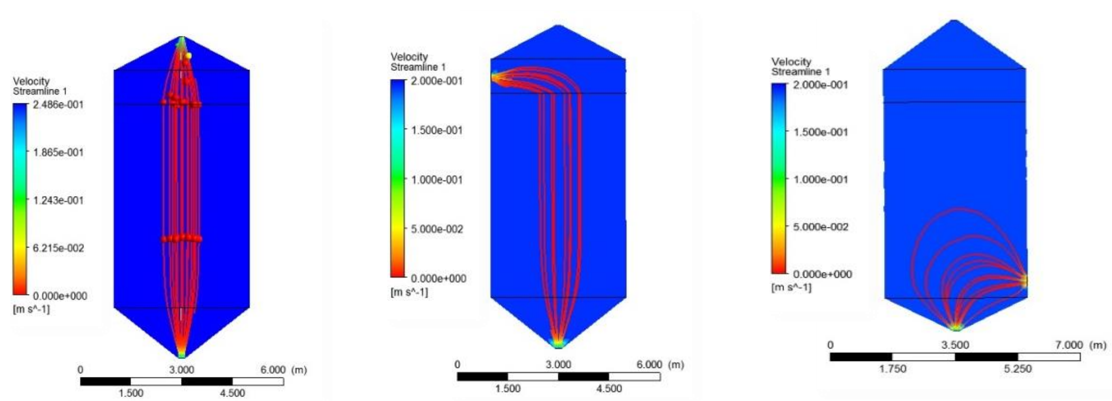
A B C

Figure 5. Gas pressure contour plot for (A) Outlet at the top of the silo. (B) Outlet at the above of the grain surface. (C) Outlet at the below of the grain surface.



A B C

Figure 6. Gas velocity contour plot for (A) Outlet at the top of the silo. (B) Outlet at the above of the grain surface. (C) Outlet at the below of the grain surface.



A B C

Figure 7. Streamlines for (A) Outlet at the top of the silo. (B) Outlet at the above of the grain surface. (C) Outlet at the below of the grain surface.

Conclusions

In this study, results are interpreted for phosphine fumigation of wheat in a silo. The CFD has been verified with the analytical solutions. Then, three different outlet positions corresponding to the inlet at top of silo, upper part of the grain, and below part of the grain are investigated. The streamlines show that the gas flow towards the outlet regardless of the position of the outlet. In the reality, the outlet can be considered as leaky hole. Therefore, the position of the leak is significantly affects the fumigant distribution. There is a possibility of an insufficient dosage area at the top part of the silo if leaks are predominantly located at the lower part of the silo. These results are significantly important to the people in the industry so that a better decision could be made regarding the fumigation practice.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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