Simulation of Airflow Distribution in Stored Bulk Grain – A Review

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ABSTRACT: Drying (to remove moisture) and aeration (to remove heat) are important unit operations during grain storage. In most practical cases; however, substantial amount of losses in terms of energy, product quality and consumer value occur. The foundation of an efficient aeration/ drying system depends on the proper understanding of the resistance to airflow through bulk grain or the pressure drop characteristics of grain beds. The airflow distribution through stored grain may be determined using physical experiments or predicted using mathematical models. Full-scale experimental studies are expensive and time consuming. On the other hand, validated mathematical models are more versatile and may be used for different storage structures and in different geographical locations. Several mathematical models are available to predict the airflow distribution patterns in grain bins. This review highlights the governing equations for these models and their applications. Research work in this field would facilitate design of efficient drying/ aeration systems with appropriate configurations, prediction of equipment performance, process optimization and overall process control.

Keywords: airflow, pressure drop, stored grain, simulation, mathematical model.
INTRODUCTION

Stored grain bulks are man-made ecosystems. They are subject to several deteriorative reactions that are dependent on various biotic and abiotic factors; mainly grain and storage conditions. Among these, temperature and moisture are critical storage parameters (White, 1995). This justifies the need for efficient grain drying and aeration systems. From a practical point of view, with respect to the air condition and flow rate used; grain drying may be further categorized as: hot air drying, near ambient drying and natural air drying (Jayas et al., 1988). These unit operations are energy intensive and directly or indirectly affect grain quality and allied market value. The efficacy of these processes depends primarily on the pressure drop characteristics and airflow distribution within grain bulks. If airflow distribution across an entire grain bed is not uniform, there is a risk to the formation of non-aerated/stagnant zones (Miketinac et al., 1986) and hence result in huge losses. A proper understanding of the airflow profiles would hence be of importance to design engineers (Smith and Jayas, 2004) and subsequently to grain handlers.

The most suitable method to determine the pressure patterns in grain bulks is to conduct physical experiments. Air velocities are not measured directly as it is a tedious process, especially at low airflow velocities. The static pressure at various points may be determined more accurately using a manometer (Alagusundaram and Jayas, 1990). However, this approach is time consuming and expensive. Further, the conclusions from the results obtained have a narrow range of applicability. Nevertheless, it is the only accepted method to validate mathematical models (Alagusundaram et al., 1994). Mathematical models on the contrary, can answer several ‘what if’ questions (Jayas, 1995). Unlike physical experiments, they may also be used in other geographical locations. The purpose of this article is to review the various modeling approaches used to predict airflow distribution in grain bins. The most recent research developments in this context have also been highlighted.

1. THEORETICAL CONSIDERATIONS

Grain bulks may be regarded as porous medium (Sutherland et al., 1971). Air is the permeating fluid and its properties are governed by the laws of fluid dynamics. The essential theoretical aspects to be considered in developing mathematical models that predict airflow patterns in beds of cereal grains are given below:

1.1. Factors affecting resistance to airflow

Stored grain bulks are essentially anisotropic (Jayas et al., 1987b, 1991). The resistance to airflow is different in every direction. When air is passed through the bin, the major factor that affects the resistance to airflow is the non-homogeneous grain itself (Khatkatourian and Savicki, 2004; Jayas et al., 1987a). The resistance to airflow varies with product type, foreign material content, filling method, moisture content, airflow direction, bed depth, duct configuration and the airflow rate (Jayas et al., 1990). But, the degree to which each of these factors affect air movement varies. A sound knowledge of the resistance to airflow of different products is essential to mathematically model the airflow profiles in grain bulks.

1.2. Airflow velocity and pressure drop relationships

Even for the same Reynolds’s number, the pressure - velocity relationships vary for each grain type. This is because of the aforementioned concept - the resistance to airflow. A modified form
of the Darcy’s equation can be used to model the pressure drop - velocity relationships in grain bulks (Ville and Smith, 1996); for sufficiently low airflow rates. The generalized Schwarz-Christoffel transformation has also been applied to bins with different bottom geometries (Peng et al., 1999). The basic equations used to model airflow though grain beds are given as Eq. 1 and Eq. 2.

\[ \nabla p = -R \times u \quad [1] \]

and

\[ \nabla \times u = 0 \quad [2] \]

where: Equation 1 is the momentum equation with ‘\( \nabla p \)’ as the pressure gradient, ‘\( u \)’ as the fluid velocity and ‘\( R \)’ as the resistance to airflow (Smith, 1995). Generally, the resistance to airflow data of grains and oilseeds are represented in either of the following ways (Alagusundaram and Jayas, 1990):

a) a plot of the pressure drop per unit bed depth versus airflow rate on logarithmic scale or
b) by means of empirical/ semi-empirical equations.

Once the governing relationships are established, they are solved by considering the law of conservation of mass (explained by continuity equation). Some of the essential assumptions made are:

a) the fluid is incompressible (Pierce and Thompson, 1975)
b) the system is in steady-state (Jindal and Thompson, 1972)
c) bin walls are impermeable to airflow (Jayas et al., 1987a)
d) stored grain is anisotropic (Jayas et al., 1987b, 1990) and
e) the problem is axisymmetric (Stephens and Foster, 1976; Jayas et al., 1990).

2. SIMULATION AND MATHEMATICAL MODELING APPROACHES

Physical experiments cannot take into account, the combined effects of several factors that affect airflow distribution. However, mathematical models can consider all major parameters. Sensitivity analysis can be used to check the relative importance of each variable (Sinicio et al., 1997). Once validated, simulation studies that help in process control and optimization of the drying/ aeration processes may be well utilized. Mathematical modeling techniques used by researchers in this context are the analytical and numerical methods. The latter is used to obtain an approximate solution when an analytical solution could not be obtained; as in most practical cases. There is no generalized theory available to model the permeability through grain bulks. Gayathri and Jayas (2007) have presented a concise review of various mathematical models developed from the basic principles of fluid flow and experimental values. The governing relation for these models is the Navier- Stokes equation. Several researchers have used its modified forms to suit specific applications (Ergun, 1952; Shedd, 1953; Hukill and Ives, 1955).

2.1. Analytical solutions

Analytical solutions such as the ones used by Spencer (1969), Hunter (1983) and Goudie et al. (1993) involve Laplace’s equation. Once formulated in terms of partial differential equations, the exact solutions of the air traverse time, pressure distribution and velocity profiles may be obtained. Studies have also been conducted to obtain analytical solutions using perturbation expansions to model the flow of CO\(_2\) through grain bulks (Smith et al., 2001). Further, the analytical solution approach has been used to test the accuracy of numerical solutions (Miketinac and Sokhansanj, 1985). Nonetheless, they are not much preferred due to the
tediousness in solving and other end-use oriented limitations. Hence, there is a need for validated numerical models.

### 2.2. Numerical solutions

Numerical models are powerful techniques used to predict and explain the behavior of several physical systems. Quite a few models have been developed to predict the temperature distribution in stored grain bulks (Alagusundaram et al., 1988, 1990; Jayas et al., 1994 and Jian et al., 2005). Numerical modeling approach has also been used to predict CO₂ diffusion in grain bins (Alagusundaram et al., 1991 and 1996). A modified approach may be incorporated to study the airflow distribution patterns within grain storage systems too. The two basic approaches employed in attaining approximate numerical solutions are: finite difference models, and finite element models.

#### 2.2.1. Finite difference models

In the method of finite differences, Taylor’s series expansion is used to approximate the derivatives of pressure values at any specified point in the bin by considering the pressure at adjacent mesh points. A system of algebraic equations obtained from partial differential equations are solved for nodal values. Using this method, Brooker (1961) found minimal variations between the measured and predicted values while studying the pressure patterns in bulk grain. This was not so in the case of shelled corn (Brooker, 1969). Both these experiments were conducted in rectangular bins and were based on Shedd’s resistance data. Modified approaches were used to predict pressure values in grain stored in other configurations (Jindal and Thompson, 1972; Pierce and Thompson, 1975).

#### 2.2.2. Finite element models

Another method of obtaining approximate solutions to airflow distribution problems is the finite element analysis. Finite element models better suit non-linear problems (Miketinac et al., 1986). The first noted works in this context were by Marchant (1976) and then by Khompis (1983) in circular grain bins. A two-dimensional non-linear airflow problem was solved using finite element method (Miketinac and Sokhansanj, 1985). Smith (1982) used a modified method of Marchant (1976) for prediction of airflow patterns in three-dimensional rectangular grain geometry. Other researchers have also studied the effect of foreign matter, moisture content, airflow direction and method of filling on the airflow patterns (Haque et al., 1981; Jayas et al., 1990, 1991). The major advantages of the finite element method are that it can easily handle geometries with mixed boundary conditions, irregular boundaries, varying material properties and the fact that there are several software packages available for computational purposes. Some of these are mentioned in subsequent sections of this article, because of their wide range of application and notable advantages. Further, proper validation of finite element models can overcome the inadequacy of determining only an approximate solution.

### 3. OTHER APPROACHES TO PREDICT AIRFLOW PATTERNS

Apart from these methods, airflow patterns have been studied using gas tracer techniques (Lamond and Smith, 1982) and surface escape velocity measurements (Burrell, 1974). A modified methodology was also used to analyze the chilling patterns in grain bulks owing to the fact that temperature may be more conveniently measured than velocity. However, these
approaches have their own limitations and may not be practicable in several cases (Comarty, 1968).

Miketinac et al. (1986) in their study used TWODEPEP, an IMSL package to develop a finite element solution to predict airflow at different points in a bed of cereal grains. Khatchatourian and Savicki (2004) developed a mathematical model and simulation software for airflow predictions in bulk soybean storage. The software employs an iterative process to obtain a finite element solution. A similar approach was used by Khatchatourian and de Oliveira (2006), who also considered the thermal state of the storage system. Lopes et al. (2006) implemented a simulation software AERO based on the model proposed by Thorpe (1997). The advantage of this aeration model is that it considered grain hot spots and may be applicable for different geographic locations too.

Powerful Computational Fluid Dynamics (CFD) packages can be a suitable option to conveniently simulate airflow profiles under varying grain, structure and flow conditions. The CFD software packages have advanced features such as: automatic mesh generators and user-friendly graphical user interfaces (GUI’s) that make the modeling process more convenient to a research engineer.

CONCLUSION

In spite of the numerous works done in this field, the grain handling industry faces copious issues during operation and scale-up in terms of grain drying and aeration systems. Further, limited work is available for hopper bottom bin configurations; the ones that farmers mostly prefer and the same are more affected with issues related to non-aerated zones. Future research needs to be directed to experimentally validate available mathematical models. Emphasis is also required to develop cost–effective techniques that can be used at farm level to ensure that there is no loss in terms of quantity/quality in grain aeration/drying processes.

REFERENCES


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