Forced Air Ventilation through Bulk Grains for Cooling and Drying: An Overview

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SUMMARY

Considerable research related to cooling and/or drying of grains by forcing air thorough bulk grains has been reported and continues to be reported in published literature. Although the process is simple and works well when properly designed and implemented, this simplicity also leads to a lot of misunderstandings about the process. Therefore, many systems get designed to force less than optimum amounts of air to complete the task. This paper clarifies terms, raises the issues which must be considered while designing such systems for optimum performance and outlines the experimental and mathematical modeling tools for implementing and monitoring such systems.

INTRODUCTION

Stored-grain bulks are man-made ecosystems in which deterioration of grain occurs due to interactions among abiotic (e.g., temperature, moisture content, gaseous composition) and biotic (e.g., insects, fungi, mites) variables (Jayas, 1995). By manipulating abiotic variables such as lowering grain temperature and moisture content, an environment within the bulk grains can be created, which minimizes spoilage of stored grains (Figure 1). Forcing air at different conditions (temperatures and relative humidities) is a common unit operation for creating safe storage environments (Pabis et al., 1998). There are many terms which are used to categorize the forcing of air through bulk grains. The commonly used terms (defined below) are: aeration; chilled aeration; natural, near-ambient, low-temperature and high-temperature air drying; and dryeration.

Aeration is the forcing of small amounts of air (1 to 3 L/s per m^3 of grain) to typically cool grains after harvest using ambient air at temperatures below grain temperature during cooler hours of the day. The aeration can also be used to eliminate temperature gradients within bulk grains and thus to reduce moisture migration, remove spoilage odours from grains, remove fumigants from grains and remove small amounts of moisture from warm grains such as during dryeration (defined below). In colder climates such as in Canada, aeration could also be used to reduce grain temperature to below 10°C to reduce insect activity and population growth and to below -20°C to kill most life stages of insects. Careful warming of grain will have to be done during spring, if cooled to such low temperatures to avoid condensation problems in summer.

Chilled Aeration is the forcing of chilled air (1 to 5 L/s per m^3 of grain), conditioned using a chilling device, through bulk grains. The purpose of chilled aeration is to reduce the temperature of the grain below 10°C for slowing insect activity and population growth as well as to store wet grain without deterioration for 2-3 weeks during which it can be dried to safe moisture contents for storage.

Natural Air Drying is the forcing of ambient air (10 to 25 L/s per m^3 of grain) to decrease the moisture of grain to safe storage levels. The amount of air required increases if the initial moisture content or ambient relative humidity are high, or if ambient air temperature is low. The latter two are dependent on weather conditions following grain harvest.

Near-ambient Air Drying is similar to natural air drying but air temperature is a few degrees (up to 5°C) above ambient conditions which can be caused by frictional losses from the fan motor assembly when air is pulled over these.

Low-temperature Air Drying is similar to natural air drying but air temperature is 5 to 10°C above ambient conditions which can be caused by adding supplemental heat from any source such as electricity, propane, natural gas, wood, or solar panels.

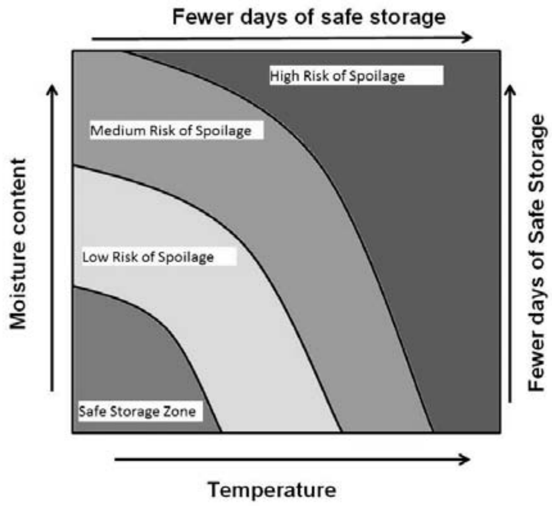

Figure 1. Typical relationship between safe storage time, temperature and moisture content of grain. The axes labels are different for different grain types.

High-temperature Air Drying is the forcing of air (15 to 30 L/s per m^3 of grain) at 50 to 250°C to remove moisture content from grain to safe storage levels. The air temperature and amount of airflow depend on mechanisms of dryers (e.g., concurrent, countercurrent, cross and mixed flow) as well as the initial moisture content of grain and grain type (Pabis et al., 1998).

Dryeration, also known as combination drying, is the cooling of hot grain after high-temperature air drying by aeration and the removal of 1 to 2 percentage points of moisture. Thus, grain is dried to about 2 percentage points above desired safe moisture content using high-temperature drying, tempered for 8 to 10 h for redistribution of moisture within grain kernels and then cooled by aeration using ambient air. The main advantages of dryeration over high-temperature drying are increased drying capacity, use of higher air temperatures, energy savings, elimination of cooling section in high-temperature dryers and reduced stress cracks in grains (Pabis et al., 1998).

Components of Forced Air Systems

Except in some high-temperature air drying systems and the high-temperature air drying component of dryeration, the main components of the forced air systems are: a flat-bottom storage bin containing a deep layer (more than 1 m deep) of grain, a plenum to introduce air into the grain bulk, a fan and duct arrangement to force air through the bulk grain, and vents to exhaust the air once it has passed through the grain (Figure 2). A plenum with a fully perforated floor over concrete (or solid) foundation and levelled grain surface provides most uniform airflow distribution in the grain mass. Thus, fully perforated floors are commonly used but several partially perforated floors are also used in flat-bottom bins. The examples of partially perforated floors are one or more straight circular or semi-circular ducts on the floor; square, rectangular, circular, Y, + or × shaped pad centered at the bin floor. These partially perforated floors could either be flushed with floor or raised few centimeters (> 15 cm) above the bin floor.

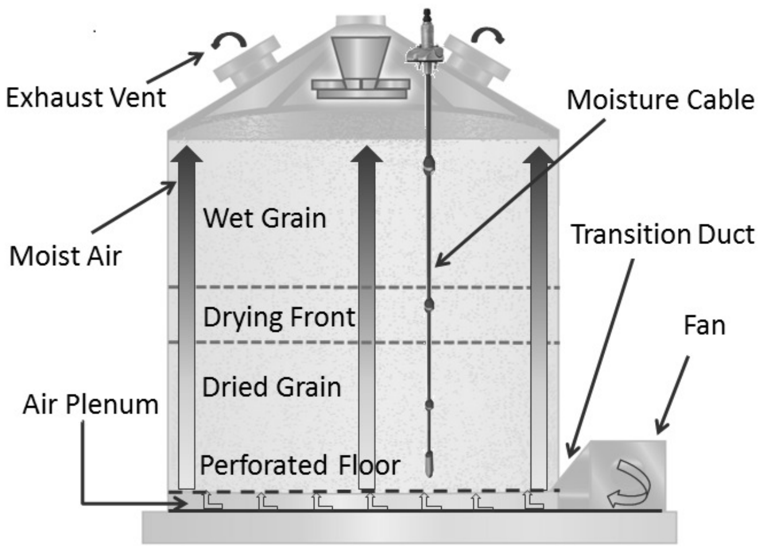

Figure 2. Components of the flat-bottom bin based system used to force air though bulk grain for cooling and/or drying grain (Source: Singh at al. 2014a).

Many farms also have hopper-bottom bins, which are equipped with different configurations of perforated plenums to introduce air into the grain (Pabis et al., 1998). The area of partially perforated flooring through which air can be introduced into the bulk grain should be sufficient to avoid formation of stagnant zones in the bulk grain. The size of perforations in the floors should be small enough to support the smallest-seeded grains to be stored in the bin and the number of perforations should be enough (equivalent to >10% of the perforated floor area) to cause minimum pressure drop across the floor.

The fan should be sized properly to ensure sufficient airflow through grain at its maximum depth and for a grain which offers maximum static pressure at that airflow rate while taking into consideration a thorough understanding of type of fan and its characteristics, i.e., relationship between the airflow rate (L/s) supplied by the fan against different static pressures (Figure 3).

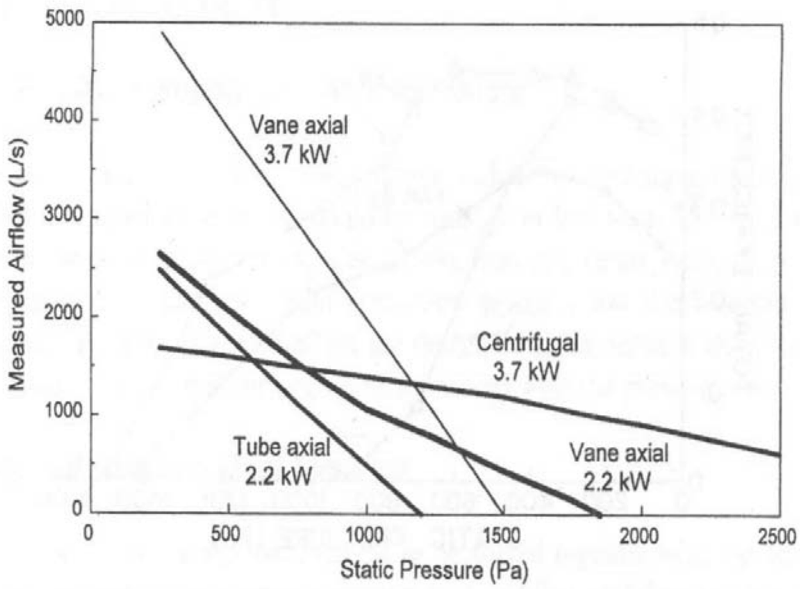

Figure 3. Comparison of the measured performances of different types of fans from one manufacturer (Source: Metzger et al., 1981).

The amount of airflow from the fan decreases as the static pressure increases. Thus, a fan sized for shorter depth may not dry grain in the expected time if grain depth is increased. Similarly, a fan sized to provide a certain airflow rate, say for wheat, will not provide the same airflow rate for canola because pressure drop per unit length of canola is 2 to 2.5 times more than for wheat and fan output would be lowered considerably at the increased pressure offered by grain for all fan types (Figure 3).

Transition between fan and plenum should be smooth to reduce static pressure. The vents should be enough in number and size to avoid stagnation of air in the bin and thus cause minimal back- pressure to be overcome by fan. The appropriate amount of airflow through grain ensures proper drying in the specified period. The excess amount of airflow will dry grain sooner but may also result in more non-uniformity in grain moisture content with continuous airflow. Grain mixed with fines (particles smaller in size than grains) offers more pressure drop per unit length than clean grain, and the moisture content of grain also affects pressure drop (Moses et al., 2013). Therefore, a good estimate of static pressure in order to properly size the fan should consider all of the factors which affect pressure drop across grain (Alagusundaram and Jayas, 1990; Moses et al., 2013). Also, measured fan characteristics, if available, should be used in sizing the fans because at times the values reported by the manufacturers give higher air flow rates than the measured on-site values for the same static pressure. If the difference between measured and reported values is large, then a fan sized using manufacturer's data will be undersized for actual drying conditions. In most systems, air is forced vertically upwards but some systems also pull air downwards. Systems which force air horizontally through grains will be more energy efficient and will dry grain more uniformly than systems forcing air vertically because pressure drop per unit length in the horizontal direction is 1/2 to 2/3 of the pressure drop in the vertical direction (Kumar and Muir, 1986; Jayas et al., 1987, 1991; Jayas and Muir, 1991; Alagusundaram et al., 1992). However, not too many systems use horizontal airflow.

Role of Mathematical Models

For efficient cooling or drying of grain, the introduced air must be uniformly distributed in the grain mass. The best method to understand airflow distribution in bulk grain would be to measure airflow amount and direction within the grain mass at multiple points, but there are no airflow measurement devices to measure airflow in-situ in bulk grain. The next best approach is to measure static pressure at multiple points within the grain mass and then draw iso-pressure lines and streamlines, which are perpendicular to iso-pressure lines, to visualize airflow paths (Alagusundaram et al., 1994). The number of experiments required to consider all grain types with different amounts of foreign materials and moisture conditions in different flat-bottom and hopper-bottom bins equipped with different air introduction systems will be cost prohibitive and time consuming. Also, when new grains and systems are introduced in the market more experiments will be needed. Mathematical models based on fluid flow through porous media (bulk grains) and incorporating airflow-pressure drop relationships of grains can predict pressure patterns and airflow distributions in bulk grains (Jayas et al. 1990; Moses et al. 2014a, 2014b). Figure 4 shows pressure patterns in a flat-bottom bin having a fully perforated floor and filled with canola having a peaked surface, and in a hopper-bottom bin having a vertical rocket-type perforated tube and filled with wheat having a peaked surface).

Mathematical models based on heat and mass transfer along airflow paths can predict drying and cooling patterns in grain mass (Thompson 1972; Metzger and Muir, 1983; Smith et al. 1992a, 1992b; Smith and Jayas, 2004a, 2004b). Typical shape of drying curves when forcing air through deep bed is shown in Figure 5. Such curves can be drawn using measured or predicted moisture contents. In a system with air moving vertically upwards the bottom layer dries first while the top layer stays close to initial moisture content. As drying progresses, more layers from bottom to top dry, but sometimes rewet if air relative humidity of incoming air is greater than the equilibrium relative humidity of grain moisture in the layer. Drying could be stopped based on many criteria such as: (i) top layer is at the target moisture content but this may cause severe over drying in the bottom layers, (ii) average grain moisture content is at the target moisture content but this may require grain mixing after drying is stopped, or (iii) moisture in all layers is within certain percentage point of the target - producing the most uniform drying. These criteria could be applied using measured data or using mathematical models.

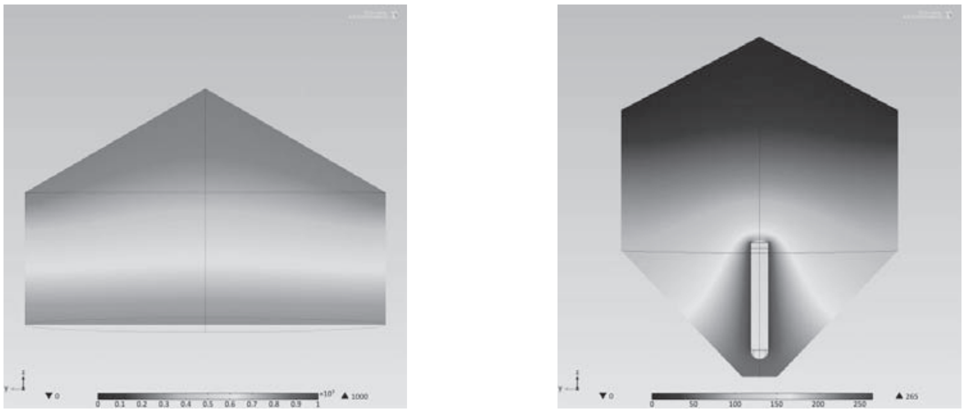

Figure 4. Predicted pressure patterns in a flat-bottom bin (left) and a hopper-bottom bin (right) (Source: Moses et al. 2014a, 2014b).

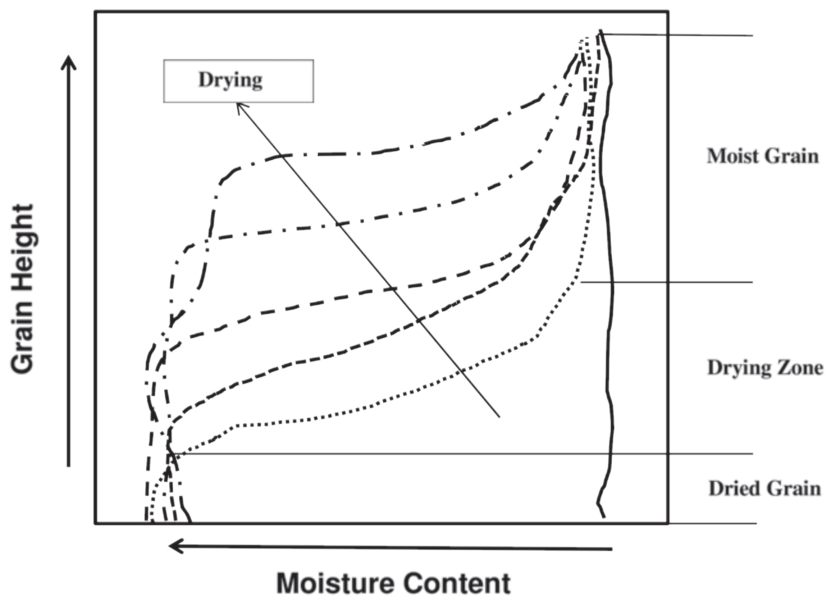

Figure 5. Progression of grain drying during forced air ventilation.

Monitoring Progress of Cooling or Drying

Monitoring of cooling due to forced ventilation in grain can be done using temperature sensors distributed along expected airflow paths, but commonly, temperature sensors are installed in vertical fashion (Figure 2). Using these measured temperatures, the cooling front can be detected and isotherms can be drawn which also represent iso-moisture lines (Smith and Jayas, 2004a, 2004b). Another option is to install relative humidity sensors along with temperature sensors and convert measured relative humidity to moisture contents using equilibrium moisture content and equilibrium relative humidity equations (ASABE, 2013). Using the calculated moisture contents, iso-moisture lines can be drawn to locate the drying front and to visualize the progression of drying. The progression of drying can also be predicted using mathematical models.

Control Strategies

There are many control strategies which can be used for turning the fan on or off during drying, but the best strategy should be the one which: requires the least energy for both the operation of fan and the supplemental energy if used, results in most uniform drying, minimizes over-drying and spoilage of grain, and completes drying within the specified period. The examples of different fan control strategies are: (i) fan running during certain number of hours (e.g., six hours on and six hours off cycle, fan running during daytime only or fan running during night time only, fan running continuously), (ii) fan on when temperature of ambient air is above certain set point (thermostat), (iii) fan on when humidity is below certain set point (humdistat), (iv) fan on when there is a set temperature difference between grain temperature and ambient temperature (ΔT), (v) fan on when there is a set relative humidity difference between grain equilibrium relative humidity and ambient relative humidity (ΔRH), (vi) fan on when there is a set difference between grain moisture content and equilibrium moisture content based on air conditions (ΔEMC), (vii) fan on when plenum EMC and temperature are within a set target range (NAD), or (viii) fan and/or heater on using self-adapting variable heat (SAVH) with NAD control. The best strategy can be selected by running simulations using historical weather data for multiple years (> 25 years) for several locations based on different climatic zones of a region, with different initial harvest moisture contents, different harvest dates, different amounts of airflow rates through different grains, and for different control strategies. An example of results from such simulations is given in Figure 6 (Singh et al. 2014b) which shows the grain moisture variation around target moisture content for four start dates and five fan control strategies. The figure also shows success rate defined as the percent number of years out of 30 simulation years during which drying will be completed at 13 locations, distributed across western Canada. These simulated results show that the SAVH is the best strategy for drying grain under western Canadian conditions.

Economic Considerations

The fixed costs for the aeration and drying systems are the costs for the purchase and installation of the components of the system and are usually not optimized when deciding on best operation strategy for cooling or drying of grain. The variable costs are energy to operate fan, energy for supplemental cooling (as in chilled aeration) or supplemental heat (as in low temperature drying). Other variable costs are over-drying (shrink) of grain below designated “dry” moisture content for grain trading, and maximum allowable loss of dry mass (typically less than 0.5%) due to spoilage before completion of drying. All of these variable costs should be minimized when designing a grain drying system. Mathematical models can be used for such optimizations.

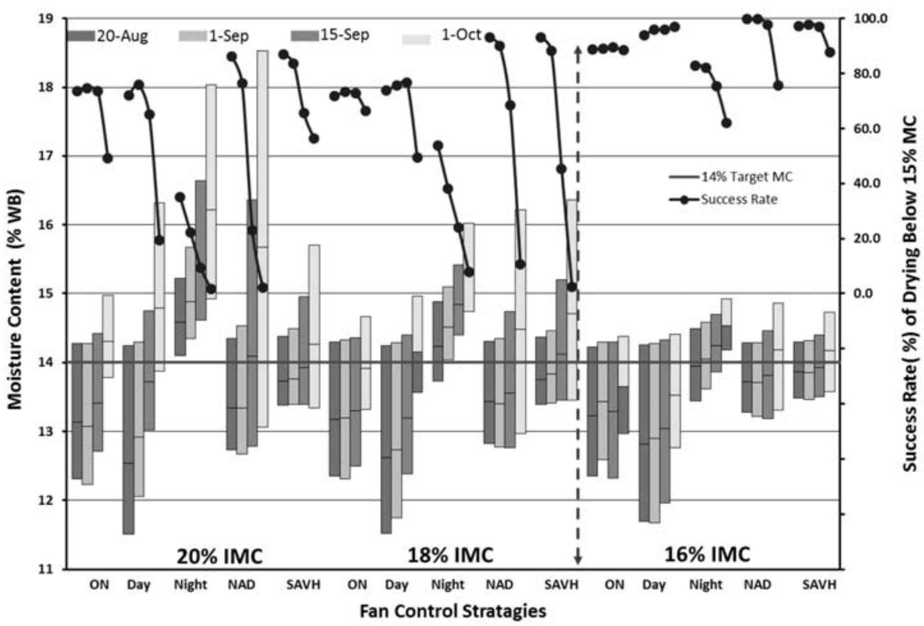

Figure 6. Wheat drying simulation results for several initial moisture contents and drying start dates with 1.00 cfm/bu (18.5 L/s per tonne) (Source: Singh et al., 2014b).

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