CAF2020 Paper No. P-2-8-21

Jian F, Jayas DS (2021) Implications of dockage and foreign material distribution for fumigation and controlled atmosphere storage of grain in bins. Pp. 73-79. In: Jayas DS, Jian F (eds) Proceedings of the 11th International Conference on Controlled Atmosphere and Fumigation in Stored Products (CAF2020), CAF Permanent Committee Secretariat, Winnipeg, Canada.

Implications of dockage and foreign material distribution for fumigation and controlled atmosphere storage of grain in bins

Fuji Jian*, Digvir S Jayas

Biosystems Engineering, University of Manitoba, Winnipeg, MB R3T 2N2, Canada
*Corresponding author's email: fuji.jian@umanitoba.ca

Abstract

In addition to sound grain kernels, stored grain contains many other materials such as chaff, straw, fine materials, dust, sand, animal droppings, dead insects, or insect fragments. Segregation of these materials is an unavoidable phenomenon during grain transportation, loading, and unloading. Center filling of grain into silos usually results in a concentrated accumulation of small and high-density particles (smaller than the sound grain kernels) at the center of the bin and particles with large sizes (larger than the sound grain kernels) and low densities (lower than the sound grain kernels) at the periphery. The accumulation of the dockage and foreign materials at the center of the silo attracts insects and favors insect and fungi growth and multiplication. Uneven distribution of these materials could result in slower movement of fumigants and applied gas in the center and faster movement at the periphery, possibly resulting in non-uniform distribution of fumigants and applied gas. This non-uniform distribution might result in low insect mortality in the stagnant and low concentration zones. Implications of this characterized distribution were discussed in the context of fumigation and controlled atmosphere. The dominant mechanisms resulting in this non-uniform distribution were discussed.

Keywords: Dockage, Foreign materials, Segregation, Fumigation, Controlled atmosphere

Introduction

Commercially stored bulk grain encompasses desired sound grain kernels and undesired materials including (but not limited to) straw, rachis, internode, chaff, awn, un-threshed spikelet, shrunken and broken kernels, stone pieces, other grains, weed seeds, ergot, insect excreta, dead insects, bird droppings, and animal filth. These undesired materials are usually referred to as dockage and foreign materials, which have different physical and chemical properties than sound grain kernels especially in size, shape, density, color and textural properties, and nutritional value. Dockage is usually referred to as any material that can be removed from the grain by using approved cleaning equipment such as mechanical dockage testers or sieves (Canadian Grain Commission, 2019), while "material other than grain of the same class that remains in the sample after the removal of dockage" is defined as foreign materials. Therefore, foreign materials are other grains or materials which have the same shape and size as the grain kernels. Grain may be handled and stored at different stages, from harvesting to consumption. Segregation of these components during loading and unloading occurs, and dockage and foreign materials (DFM) in stored grain bulks do not have a uniform distribution due to their segregation. Uneven distribution of DFM, as well as grain kernels with different sizes, can cause many problems during storage, insect control (fumigation and controlled atmosphere storage), drying, and aeration because segregation of DFM in a grain bin can change the uniformity of small intergranular pores (Olatunde et al., 2016).

Fumigation is the process of using a gaseous fumigant or an aerosol in sufficient lethal concentration to control insect pests and/or microorganisms at the desired temperature, pressure, and relative humidity. In controlled atmospheres storage, intergranular gaseous composition is altered by modifying concentrations of carbon dioxide (CO_2), nitrogen (N_2), and oxygen (O_2) to create lethal concentrations of high CO_2 or low oxygen (O_2). Fumigation or controlled atmosphere treatment of stored products is carried out in airtight enclosures and structures such as warehouses and silos. To successfully control insect pests, the processes of fumigation and controlled atmosphere ideally require uniform distribution of the applied gases inside the entire storage structure. This uniform distribution requires that the applied gas be uniformly forced through the pores among the grain kernels in the grain bulk. The uneven distribution of DFM will result in non-uniform distribution of the applied gases. In this study, we will analyze the implications of DFM material distribution for fumigation and controlled atmosphere in storage grain bins.

Segregation mechanisms

Segregation

Segregation is the tendency of particles with similar physical properties to collect in one zone during handling of free-flowing bulk materials (de Silva et al., 2000). In the grain industry, this segregation phenomenon usually occurs during heap formation when free-flowing bulk materials are filled into bags, silos, and hoppers (Fan et al., 2017; Jian et al., 2019). On the contrary, the behavior of cohesive or poorly flowing bulk materials (such as high moisture grain) is controlled by interparticle adhesion forces, which reduce the mobility of individual particles and therefore their tendency to segregate. The segregation process of different particles in bulk materials, particularly bulk grain mixtures, is very complicated because many factors and mechanisms are involved.

Mechanisms of particle segregation in bulk materials have been reviewed by several researchers and many different segregation mechanisms including rolling, sliding, embedding, sifting, avalanche, trajectory, fluidization, impact, displacement, percolation, air current, agglomeration, push-away, and bouncing have been identified (de Silva et al., 2000; Fan et al., 2017; Jian et al., 2019; Tang and Puri, 2004). Typically, more than one of these mechanisms occur simultaneously, and some of these mechanisms overlap each other or may be considered a special case for another mechanism (Jian et al., 2019; Tang and Puri, 2004). Furthermore, some mechanisms do not apply to bulk grain. For instance, agglomeration segregation can occur only during the mixing fine particles with a diameter smaller than 50 µm, or in cohesive fine particles like powders, due to interparticle forces (Tang and Puri, 2004). Narendran et al. (2019) observed the segregation effects of rolling, sliding, impact segregation, fluidization, trajectory, and avalanches during the loading of wheat mixtures with 3 or 6% in total of canola, kidney bean, and soybean into a bin. Jian et al. (2019) categorized the primary patterns of segregation into four main mechanisms occurring in bulk grain handling as: trajectory, fluidization, sifting, and impact segregation.

Trajectory segregation
Trajectory segregation is the combined effect of particle momentum and air drag, which changes the trajectory of moving particles. At the initial velocity of grain kernels being loaded into a bin, large particles have a higher momentum than small particles. In addition, different shapes of particles will have different air resistances (drag force) during moving or falling. This combined effect causes the larger particles to travel farther than the smaller particles (Fig. 1). Trajectory segregation is significant when bulk materials are being loaded in a horizontal or an inclined direction (such as loading into a bin using an inclined auger or pneumatic conveyor). It can also occur when the dropping height is high, or during relatively high rolling or sliding velocity scenarios. Hence, the rolling or sliding segregation effect on a heap is considered to be a special case of trajectory segregation (Tang and Puri, 2004). The result of trajectory segregation during central loading is that fines, dusts, broken grain kernels, and small stones are concentrated at the central dropping location, while larger particles such as chaff are deposited closer to the periphery of the bin (Jayas, 1987).

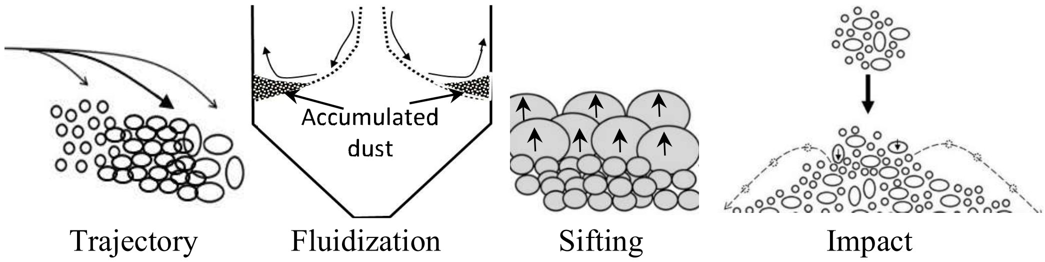

Fig. 1. Schematic of four primary segregation mechanisms in bulk materials suggested by Jian et al. (2019).

Fluidization segregation
Fluidization segregation can occur when a mixture containing fine particles and larger particles with low density (such as chaff) is loaded into a bin because the falling stream of mixture can induce air currents that carry the fine particles, or particles with low density to the periphery of the bin (Fig. 1). A greater drop height and loading rate can cause the air current effect to increase. If the grain bin is loaded several times periodically, the fine particles and less dense materials may be concentrated in layers near the bin walls. Fluidization segregation can also occur during grain loading and unloading when the mixture is moving.

Sifting segregation
Sifting segregation can occur when particles in the grain mixture roll or slide down on the surface of a grain pile (Fig. 1). The heap surface acts like a sieve because smaller particles are more likely to be embedded in the surface pores and gradually sink down to the bottom of the moving layer. Larger particles have a higher probability of sliding or rolling down further from the top of the heap and stay at the surface level of the heap (Tang and Puri, 2004). This embedding effect is a special case of the sifting phenomenon in grain segregation.

Impact segregation
Impact segregation is caused by the collision of moving particles during grain loading. When particles on surface of the heap are hit by the particles being loaded, the small particles due to their lower mass and lower momentum gain a higher velocity, and consequently tend to bounce farther

down the grain pile (Fig. 1). Impact segregation may result in a wider distribution of some small particles.

Distribution of DFM

Dominant mechanism during center loading
Grain silos are usually filled continually from the top center of the bins. Trajectory and fluidization segregations occur before particles are loaded on the grain heap, while impact segregation occurs when particles hit the heap, and sifting segregation occurs when particles are moving on the surface of the heap. The impact segregation acts in contrary to the sifting segregation (Jian et al., 2019). If the concentration of fine particles is low, the sifting segregation becomes more significant, while fluidization is the dominant mechanism of segregation at a high dropping height of the grain mixture with a high concentration of fine and less dense particles (Tang and Puri, 2004). Dusts and chaff might concentrate at the peripheries by the fluidization segregation but will not generate layers of dust if the grain is continually loaded. Avalanching might occur on the surface of a heap during bulk material loading when stationary layers are formed near the center of the heap. These layers gradually become unstable with increasing thickness of the layer and suddenly slide down the heap. Avalanching can intensify sifting segregation.

Distribution of DFM
When grain mixtures are center-loaded, the dominant segregations usually result in a concentrated distribution of small and high-density particles (smaller than the sound grain kernels) at the center of the bin, and particles with large sizes (larger than the sound grain kernels) and low densities (lower than the sound grain kernels) at the periphery. Even though different researchers had different conclusions on the effect of a single factor influencing segregation, researchers usually reported this similar distribution pattern (Bartosik and Maier, 2006; Jian et al., 2019; Narendran et al., 2019; Salarikia, 2020). In a 10-meter diameter bin, Salarikia (2020) found fine particles, dust, fragments, and foreign materials (corn and soybean kernels) mainly accumulated in the center, while shrunken and broken kernels accumulated mostly near the wall of the bin. Loading height did not influence true density and test weight of clean and unclean wheat. Thousand kernel weight, dimensions, and sphericity of wheat kernels were similar at different radial locations of the bin at different loading heights.

Detrimental effect of segregation on stored grain

Change in airflow resistance
The increase of fine particles (particles smaller than sound grains) increases the airflow resistance of bulk grains, while the increase of chaff (particles larger than sound grain kernels) has an inverse effect and decreases the airflow resistance. The accumulation of fine particles is of greater concern because it can create regions of high resistance, and fumigants or controlled atmosphere gases may not reach these areas at the same level as the rest of the bulk. Therefore, most of the papers demonstrating increase in airflow resistance due to fines are summarized in the following sentences. One of the most detrimental effects of segregation is the decreased pore size and porosity because fine particles fill the voids among grain kernels. After pores are filled by fine particles, the shape of the pores might also change. Decreasing pore size and porosity, along with any change of shape, result in an increase of airflow resistance (Górnicki and Kaleta, 2015 – Part I; Górnicki and Kaleta, 2015 – Part II). The airflow resistance of bulk corn increases with an

increase of fine particles smaller than 4.76 mm (Haque et al., 1978). Similarly, Grama et al. (1984) reported that with an increase in fine particles in shelled corn and with a decrease in size of these fine particles, airflow resistance increased. When these fine particles are removed from bulk corn either by screening or aspiration, airflow resistance is reduced significantly. Pressure drop in clean bulk wheat is lower than that of unclean wheat (Kumar and Muir, 1986). In oat seeds, the presence of fine materials has the same expected effect and increases the airflow resistance (Pagano et al., 2000). The increase of fine particles increases the airflow resistance of bulk flax seeds, while the increase of chaff has an inverse effect and decreases the airflow resistance (Pagano et al., 2000).

When grain is center-loaded into a bin with a partially perforated floor, a peak at the center of the bin rises at the repose angle of the grain, and this will further increase the airflow resistance which could then decrease the effectiveness of fumigation and controlled atmosphere. Aeration studies can further explain the effect of differential airflow resistances on fumigant distribution because such studies have not been done with fumigants. During aeration, Panigrahi et al. (2020) reported negligible airflow coming out from the grain peak with a quadratic increase in velocity from the peak to the walls. They found about 14.3% of the total grain volume, including a significant proportion of the top grain volume, exhibited a lower airflow rate than the recommended. Because 85% of the silo floor was non-perforated, 12.6% of the lower grain volume (up to a maximum height of 4.4 m above the floor) exhibited lower airflow than the recommended. Olatunde et al. (2016) reported the porosity at the core was lower than that near the walls. The solution for this uneven airflow resistance is to core the grain in order to reduce the height of the center grain. Bartosik and Maier (2006) found that the fines were 2.27% (from 0.77 to 3.55%) at the center, and 0.54% (from 0.11 to 0.93%) at the periphery in 14 farm bins. When the grain peak was not leveled in these 14 farm bins, the airflow distribution resulted in a non-uniformity factor of 89% versus 36% after coring.

Insect and fungi multiplication

Stored grain insects usually prefer grain with a high percentage of dockage, broken kernels, and foreign materials. Locations with a high percentage of dockage and broken grain kernels often have a higher moisture content. Because of this, grains stored at such locations are more likely to become highly infested by insects, and thus deteriorate more quickly than clean grain (Hagstrum and Flinn, 2012; Jian et al., 2005; McGregor, 1964). It has been reported that the moisture content of dockage is higher than that of the grain kernels (Hagstrum et al., 2012). Prasad et al. (1978) found the average moisture content of rapeseed dockage was significantly higher than the rapeseed kernel itself. Insects were found to be more active in the center of bin where the concentration of fine materials was higher (Athanassiou and Buchelos, 2020). McGregor (1964) reported that the adult red flour beetle, *Tribolium castaneum* (Herbst), preferred wheat with a high dockage content. Cracked and broken wheat kernels are more favorable than whole wheat kernels for the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens). Sinha (1975) showed that the proportion of eggs that developed into adults in external infesters of grain like the rusty grain beetle, increased in the presence of dockage. Jian et al. (2005) found that rusty grain beetles preferred locations with higher than 10% dockage in wheat. Fine and broken kernels with a higher moisture content also provide suitable conditions for some stored grain fungi multiplication (Prasad et al., 1978). Fungi respiration produces heat and water which can encourage insect multiplication. Dust and moisture produced by insects provide even more suitable conditions for fungi growth. As a result, hotspots may develop at these locations. Thus, to effectively control insects and fungi, these locations should have enough concentration of fumigant. However, it might be difficult to achieve this goal if the segregation of DFM and insect and fungi multiplication are not considered when fumigant and modified gas are applied.

Implications for fumigation and controlled atmosphere

To increase the effectiveness of fumigation and controlled atmosphere, fumigant or modified gas are usually applied by using an aeration system such as an aeration duct or a partially perforated floor at an aeration airflow rate. This system may result in uneven distribution of the applied fumigant or modified gas due to the uneven airflow resistance. Fumigation in grain bins with uneven distribution of dockage and foreign materials has an uneven distribution of fumigant which influences the fumigation result (Harein, 1961). The presence of dockage significantly reduces the effectiveness of fumigation in grain bins by increasing airflow resistance in some parts of the grain bin (Harein, 1961), and also reduces the mortality of insects when using diatomaceous earth (Kavallieratos et al., 2007). Navarro and Navarro (2020) reported the CO_2 treatment of a welded-steel silo filled with 6,881 t of winter wheat. After 39 h purging of CO_2 through the aeration duct at the bottom center of the silo, the moving-up speed of the CO_2 front at the center of the bin was slower than that at the periphery. The CO_2 concentration at the center peak was lower than 40%, while the other locations below the CO_2 front had higher than 80% CO_2. Therefore, CO_2 was added from the top of the grain bulk for an additional 106 h. After this adding, CO_2 was higher than 60% in the entire bin. During the maintenance period, CO_2 in the center bottom of the grain bulk was higher than the periphery because airflow resistance impeded the CO_2 diffusion in the area. Therefore, to overcome this uneven airflow resistance, the application system of fumigants or modified gas should be optimized for minimizing dead airflow zones.

Conclusions

Center-loading of grain into silos usually results in a concentrated distribution of both small and high-density particles at the center of the bin, and particles with large sizes and low densities at the periphery due to the dominant segregation mechanisms under this grain loading condition. This uneven distribution of dockage results in uneven distribution of airflow rate during aeration, natural air drying, and the application of fumigants and modified gas. The segregation of fines and broken kernels at the center of the silo also attracts insects and favors insect and fungi growth and multiplication. When fumigant or modified gas are applied, this uneven distribution of airflow rate also results in uneven distribution of the applied gas, and as a result, insects have a low mortality in these dead airflow zones.

References

Athanassiou CG, Buchelos TC (2020) Grain properties and insect distribution trends in silos of wheat. J Stored Prod Res **88**: 101632.

Bartosik RE, Maier DE (2006) Effect of airflow distribution on the performance of NA/LT in-bin drying of corn. Trans ASABE **49**(4): 1095-1104

Canadian Grain Commission (2019) Official grain grading guide. (CGC Industry Services - ISO 9001:2008 - Service & Industries CCG). Canada Grain Commission.

de Silva S, Dyroy A, Enstad GG (2000) Segregation mechanisms and their quantification using segregation testers. Pp. 11-29. In: Rosato AD, Blackmore DL (eds) IUTAM Symposium on Segregation in Granular Flows. Kluwer Academic Publishers, Boston.

Fan Y, Jacoba KV, Reireich B, Lueptow RM (2017) Segregation of granular materials in bounded heap flow: A review. Powder Tech **312**: 67-88.
Górnicki K, Kaleta A (2015) Resistance of bulk grain to airflow – a review. Part I: equations for airflow resistance. Ann Warsaw Univ Life Sci **65**: 31-41.
Górnicki K, Kaleta A (2015) Resistance of bulk grain to airflow – a review. Part II: effect of process parameters. Ann Warsaw Univ Life Sci **65**: 43-51.
Grama SN, Bern CJ, Hurburgh JCR (1984) Airflow resistance of mixtures of shelled corn and fines. Trans ASAE **27**(1): 268-272.
Hagstrum D, Flinn P (2012) Insect pest management decisions for raw comoodities during storage. Pp.213-218. In: Hagstrum DW, Phillips TW, Cuperus G (eds) Stored Product Protection. Kansas State Research and Extension, Kansas, USA.
Hagstrum DW, Phillips TW, Cuperus G (2012) Stored Product Protection. Kansas State Research and Extension, Kansas, USA. 51 p.
Haque E, Foster GH, Chung DS, Lai FS (1978) Static pressure across a corn bed mixed with fines. Trans ASAE **21**(5): 997-1000.
Jayas DS (1987) Resistance of canola (rapeseed) to airflow. PhD Dissertation. University of Saskatchewan, Saskatoon, Canada.
Jian F, Narendran RB, Jayas DS (2019) Segregation in stored grain bulks: kinematics, dynamics, mechanisms, and minimization - a review. J Stored Prod Res **81**: 11-21.
Jian F, Jayas DS, White NDG (2005) Movement and distribution of adult *Cryptolestes ferrugineus* (Coleoptera: Laemophloeidae) in stored wheat in response to temperature gradients, dockage, and moisture differences. J Stored Prod Res **41**(4): 401-422.
Kumar A, Muir WE (1986) Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage. Trans ASAE **29**(5): 1423-1426.
McGregor HE (1964). Preference of *Tribolium castaneum* for wheat containing various percentages of dockage. J Econ Entomol **57**(4): 511-513.
Narendran RB, Jian F, Jayas DS, Fields PG, White NDG (2019) Segregation of canola, kidney bean, and soybean in wheat bulks during bin loading. Powder Tech **344**: 307-313.
Navarro S, Navarro H (2020) Advances in insect pest management in postharvest storage of cereals: use of controlled atmosphere and temperature control. Pp. 231-266. In: Maier DE (ed) Advances in Postharvest Management of Cereals and Grains. Burleigh Dodds Science Publishing, Cambridge, UK.
Olatunde G, Atungulu GG, Sadaka S (2016) CFD modeling of air flow distribution in rice bin storage system with different grain mass configurations. Biosys Eng **151**: 286–297.
Pagano AM, Crozza DE, Nolasco SM (2000) Airflow resistance of oat seeds: effect of airflow direction, moisture content and foreign material. Drying Tech **18**(1-2): 457-468.
Panigrahi SS, Singh CB, Fielke J (2020) CFD modelling of physical velocity and anisotropic resistance components in a peaked stored grain with aeration ducting systems. Comput Electron Agric **179**: 1-10.
Prasad DC, Muir WE, Wallace HAH (1978) Characteristics of freshly harvested wheat and rapeseed. Trans ASAE **21**(4): 782-784.
Salarikia A (2020) Segregation of dockage and foreign materials in wheat during loading into a 10-meter diameter bin. MSc Thesis. University of Manitoba, Winnipeg, Canada.
Sinha RN (1975) Effect of dockage in the infestation of wheat by some stored product insects. J Econ Entomol **68**(5): 699-703.
Tang P, Puri V (2004) Methods for minimizing segregation: a review. Particulate Sci Tech **22**(4): 321-337.
.