A Review of Distribution and Segregation Mechanisms of Dockage and Foreign Materials in On-Farm Grain Silos for Central Spout Loading

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Abstract
Dockage and foreign material (DFM) distribution in grain silos is an important factor in managing stored grain. The DFM distribution in grain silos is dictated by the segregation mechanisms of DFM during grain loading. Loading grain into silos from a central spout is a special case of heap flows of granular materials. However, our understanding of heap flows is still evolving, and no models are currently available to predict the dockage and foreign material distribution in grain silos. Based on an extensive literature review, this paper identified the dominant mechanisms of DFM segregations during central spout filling in grain silos and main factors influencing DFM distribution. The DFM distribution patterns were characterized. The experimental methods for analyzing DFM segregations and distribution were also reviewed. The gaps of our knowledge on segregation mechanisms and factors influencing segregation were summarised and future research directions and challenges were discussed.

Keywords: dockage and fine material distribution, segregation mechanism, farm silo, stored grain

1. Introduction

Flat and hopper bottom cylindrical silos (bins) are commonly used in North America for on-farm storage of crop grains (cereal grains, oil seeds, and pulses). In Canada and USA, almost all of the harvested crop grains are stored in this type of silos. Typically, grain is lifted to the roof height of silo with a grain auger (or a bucket elevator) and discharged into the silo through a central spout. Grain contains dockage and foreign materials (DFM), which are different from grain kernels in terms of physical properties, such as density, size, and shape. The differences between grain kernels and DFM result in segregation during silo loading, causing ununiform distribution of DFM in the grain bulk. Ununiform distribution of DFM leads to uneven airflow through the grain bulk, which adversely affects grain storage management operations, such as aeration, drying, and fumigation for insect control. For example, if airflow is uneven, grain at the low airflow locations might not be cooled or dried, which may lead to grain spoilage during storage. There are very limited studies on the DFM distribution in on-farm grain silos, although segregation in granular materials during handling has been extensively studied (Fan et al., 2017; Gray, 2018; Mosby et al., 1996). Applying the knowledge of particle segregation to analyzing the DFM distribution may help to better understand the distribution of DFM in grain silos, thus improving management of stored grain to reduce grain spoilage.

Loading grain into silos through a central spout from the roof top is a special case of surface flows of granular materials, that is, a thin layer of grain continuously flows on the top of a nearly quiescent granular bed. Even though granular surface flows are important in many industrial practices and natural systems, and have been extensively studied, our understanding of surface flows is still incomplete at present, and in particular no constitutive laws are currently able to predict and explain all the range of segregation behaviours of DFM in grain silos. The relevant segregation mechanisms involved in DFM distribution have yet to be identified, although there were several studies on DFM distribution inside grain silos (Bartosik and Maier, 2006; Chang et al., 1981; 1983; Jayas, 1987; Narendran et al., 2019; Salarikia, et al., 2021).

Fan et al. (2017) extensively reviewed physical mechanisms of heap segregation and developed predictive models. Similar reviews were conducted by Gray (2018), and Mosby et al. (1996). However, these reviews did not provide any specific information of heap segregation for farm grain silos filled by a central spout. The review in this article focused exclusively on the segregation of DFM inside on-farm grain silos. The main objectives of this review...
were to identify the main mechanism(s) of DFM segregation and main factors influencing these mechanisms. Commonly used experimental methods and mathematical models to analyze segregations and DFM distribution were also reviewed.

2. Segregation mechanisms in grain silos filled by central spouting

Researchers have reported different mechanisms of particle segregation, including agglomeration, air current, avalanche, bouncing, displacement, embedding, fluidization, impact, percolation, push-away, rolling, sifting, sliding, and trajectory (Fan et al., 2017; Jian et al., 2019; Mosby et al., 1996; Tang and Puri, 2004). During grain loading and unloading, more than one of these mechanisms occur simultaneously, and some of these mechanisms overlap with each other or act as a special case of another mechanism. Jian et al. (2019) attributed the primary patterns of segregation to four main mechanisms in bulk grain handling: trajectory, fluidization, sifting, and impact segregation. Another phenomenon, avalanche, could result in sifting and fluidization segregation and induce variations of DFM distribution at the silo center and walls.

2.1 Trajectory segregation

When a mixture of particles with different sizes, shapes and densities leaves a loading equipment, such as a spout, auger, and conveyor, at an initial velocity, dense and larger particles have higher momentums than light and small particles. In addition, particle shape and size differences also result in different air drag forces while the particles are moving in the air. Due to this combined effect of momentum and drag force small and light particles do not travel as far as large and dense particles, and thus accumulate under the spout at the center of silos (Fig. 1). After the particles have landed on the heap, the momentum in the horizontal direction causes them to roll or slide along the heaped surface and small particles percolate through the pores among larger particles during rolling or sliding, resulting in sifting segregation. The momentum in the vertical direction pushes particles far away from the drop location, resulting in impact segregation.

If the initial velocity of particles leaving the loading equipment is zero in the horizontal direction, rolling and sliding occur on the surface of heap due to the difference in repose angle between different materials, resulting in sifting segregation.

The consequence of trajectory segregation during central spout loading is that fines, small stones, other particles larger and denser than grain kernels, such as internode and wild oat kernels, and other larger grain kernels with similar density are concentrated at the central of the silo (Fig. 1). This result was consistent with the observations reported in the literature. Salarikia et al. (2021) found that broken and shrunk kernels even distributed from the center to the walls in a grain silo. This could be explained by their similar shapes and densities as the small grain kernels, which were not segregated from the sound grain kernels. Other particles which are larger and less dense than grain kernels, such as chaff, straw, knuckle, rachis, and spikelet, could be more influenced by sifting segregation on the heap surface.

2.2 Impact segregation

When particles hit the heap surface, larger particle can push small particles further down the heap surface towards the silo periphery (Fig. 1) due to lower mass of the small particles (Carson et al., 1986). This impact segregation may result in a wider distribution of some small particles, while the larger particles mostly stay at the heap center. Narendran et al. (2019) found that small canola kernels were concentrated at the periphery of the bin filled with clean wheat mixed with soybean, red kidney bean, and canola. The authors suggested the impact segregation was responsible for the canola distribution, while some of red kidney bean and soybean kernels were embedded in the wheat mixture after pushing away the canola kernels. Furthermore, impact and trajectory segregation also result in the same distribution for large and heavy particles (like stones). For small particles, even though impact segregation can result in a different segregation pattern from trajectory and sifting segregation, its effect in farm silos might be minimum because of the low percentage of the large and...
heavy particles in grains (Jian et al., 2019). In other words, impact segregation might not be a main mechanism for the DFM distribution pattern in farm silos.

2.3 Fluidization segregation

Fluidization segregation can occur when a grain bulk containing light materials such as dusts and small chaff is loaded into a silo and the drop height is high enough to induce air currents by the moving streams of grain (Carson et al., 1986; Mosby et al., 1996). The effect of the air currents increases with the increase of drop height and loading rate. This type of fluidization segregation results in settling of dust and chaff on the surface of the grain pile (Fig. 1), which might not influence the DFM distribution because dust and chaff on the heap surface would be further segregated on the heap surface due to the surface flows. Fluidization segregation can also occur when the grain mixture fluidizes on the surface of the heap and pushes lighter and larger particles away from the heap center (Zigan et al., 2008). This type of fluidization segregation might be more influenced by the avalanche segregation (Fig. 2). The dust content is usually much lower than other impurities in stored grain (Jian et al., 2019). Therefore, fluidization segregation in farm silos might not be a main mechanism influencing the DFM distribution.

2.4 Sifting (sieving) segregation

Sifting segregation occurs when particles are moving over each other (Fig. 1), e.g., particles in the grain bulk roll or slide down on the surface of a grain pile when the angle of the heap is larger than the repose angle of the grain bulk. The heap surface acts like a sieve and smaller particles are more likely to be embedded in the surface pores and gradually percolate down to the bottom of the moving layer, while larger particles have a higher probability of sliding or rolling down further from the top of the heap and stay on the surface (Ketterhagen et al., 2007; Nourmohamadi-Moghadami et al., 2020; Tang and Puri, 2004). Johanson et al. (2005) identified three requirements for sifting: 1) the fines must be small enough to fit through the pores in the coarse matrix; 2) inter-particle motion must exist to allow the fine particle to be exposed to multiple voids, and 3) the fines need to be significantly free flowing to pass through the pores and result in percolation. Carson et al. (1986) concluded that sifting (sieving) was the most important mechanism in heap segregation when the content of fines was low because when there were enough large particles to form a moving layer, the fines could pass through this layer and percolate downwards. The effect of sifting segregation is that small particles end up at the locations close to the heap center, which is similar to the pattern of trajectory segregation. Grain bulks usually have low concentrations of fines and the size ratio of grain kernels to the fines is usually larger than 1.5 (Makse et al., 1998), which explains why stratification rarely occurs and the sifting segregation for fines in grain silos might be one of the main mechanisms.

2.5 Avalanche segregation

Avalanche segregation on heaped surfaces has been extensively studied (Dahmen et al., 2011; Fan et al., 2017; Gray, 2018; Lemieux and Durian, 2000; Pouliquen et al., 1997; Woodhouse et al., 2012), but not specific to loading of crop grain into storage silos. Narendran et al. (2019) were the first to report the occurrence of avalanche during grain loading. At low loading rates, the particles can build up at the apex of the pile and the dynamic angle of repose gradually increases. After the dynamic angle of repose becomes larger than the static repose angle of the heap, the dynamic angle collapses, which results in an intermittent and periodical avalanche. Sifting segregation occurs during avalanching because small particles percolate to the bottom of the flowing layer and large particles move upwards as the grain and DFM mixture moves along the heaped surface. This results in a stratification pattern which has interleaved layers of large and small particles. The stratification layers are then buried by subsequent avalanches, which ultimately may result in a Christmas tree distribution pattern. At high loading rates, the grain continuously moves down the heap, resulting in fines close to the drop point and the large particle close to the base of the heap or the silo walls (Fig. 2). Surface avalanches, during which the grain bulk can shear and dilate freely on the heap surface, provide the

![Fig. 2 Schematic of avalanche segregation and kink.](image-url)
ideal conditions for segregation because: 1) shear force on the surface of the heap could slow down the moving of the particles and different velocities of different particles will enlarge spaces between them; 2) more large spaces make more particles sifting down possible; and 3) low velocities give particles more time to sift down. In certain situations (e.g., condensed chaff at the moving front of avalanches), the large particles are stopped before the flowing particles reach the base of the pile, which leads to the formation of a kink. This kink moves in the direction opposite to the flow of grain, conserving its profile until it reaches the top of the pile. When a grain bulk contains a small number of larger particles (than the grain kernels), a kink might not occur, but the silo walls might produce the same effect as the kink movement when grain kernels have a small repose angle (Fig. 2). A kink will not occur when grain particles in different avalanches move together. The phenomena of kink and Christmas tree have not been reported during grain loading.

A structure of “Christmas tree” had been observed in discrete avalanching flow (Gray, 2018; Khakhar et al., 2001; Lemieux and Durian, 2000). The “Christmas tree” distribution of DFM would not be observable during grain loading if frequency of avalanche is high so that grain mixtures in different avalanches move together at the same time. This high frequency can occur at high loading rate which was observed in most published studies (Bartosik and Maier, 2006; Chang et al., 1981; 1983; Jayas, 1987; Narendran et al., 2019; Salarikia et al., 2021) and during grain loading into farm silos (Fig. 2). If the total percentage of DFM is low, the “Christmas tree” distribution will not occur neither (Narendran et al., 2019).

Segregation patterns due to avalanches are dependent on several factors, including how the heap forms, the heap geometry, the loading rate, and the size ratios of the particles on the heap (Mosby et al., 1996). Even though avalanche is a simple phenomenon, its occurrence is difficult to predict, and it is not known how and when it occurs under what grain loading conditions. Therefore, DFM segregation due to avalanche is also not fully known. Avalanches might frequently and irregularly develop at the free surface of heaps. Therefore, segregation due to avalanche is complex because the heap geometry changes continuously during grain loading, and so do the static and dynamic angles of repose on the heap. The angle of repose is mostly influenced by irregularity of the particles (e.g., larger sphericity has a smaller repose angle) and the composition of the particle assembly at the apex, both might change continuously during grain loading. At the same time, high moving speed of avalanche can cause fines and larger particles to move far away from the central drop point, resulting in sifting segregation and wide distribution of fines. Grain mixtures can either segregate into layers or remain mixed, dependent on the balance between particle-size and particle-density segregation. Therefore, segregation due to avalanche could result in variations of DFM distribution even at the same grain loading conditions and might be the main reason causing the DFM variations at the center and walls. This speculation should be further verified.

### 3. Segregation mechanisms responsible for DFM distribution during grain loading

Grain loading consists of several consecutive steps: heap formation at the drop point, particles moving along the heap surface and stopping at the walls, and avalanches occurring at the apex of the heap. Therefore, multiple segregation processes (mechanisms) occur simultaneously when grain is loaded into the silo. Most experiments reported in the literature only presented the final conditions after the grain had been loaded into the silos. It is difficult to systematically assess each segregation mechanism at each step of grain loading.

In on-farm grain silos in Canada and USA, the DFM is usually lower than 1% and occasionally could reach to the maximum 15% (Jian et al., 2019). When the DFM concentration is low, the trajectory and sifting segregation might become more significant. Avalanching can intensify sifting segregation and fluidization segregation of chaff. Therefore, these main segregation processes (trajectory, sifting, and avalanche segregation) result in a concentrated distribution of smaller and denser particles (smaller than the sound grain kernels) at the center and larger and lighter (than the sound grain kernels) particles at the walls. The cleanest location (minimum amount of fines and chaff) is the annular area about the midway between the silo center and walls (Jayas, 1987; Salarikia et al., 2021). Even though different researchers had different conclusions on the dominant mechanisms of segregation and the factors influencing segregation, they usually reported this similar distribution pattern (Bartosik and Maier, 2006; Chang et al., 1981; 1983; Salarikia et al., 2021), and the only exception is the fine distribution in canola silos (Jayas, 1987) (Table 1). Chang et al. (1981) reported that more than 10% fines were found at center of a corn silo, while less than 4% fines were found at other locations. In a wheat silo, Chang et al. (1983) found more than 4% of fines were at the silo center, while less than 4% fines at other locations. In a 10-meter diameter silo, fine particles, dust, fragments, and foreign materials (corn and soybean kernels) mainly accumulated in the center, while chaff accumulated mostly near the walls (Salarikia et al., 2021). Jayas (1987) found chaff was concentrated near the walls of a canola silo.
4. Factors influencing segregation

Many factors influence DFM distribution, including the bin size and shape; physical properties of particles (grain kernels and other materials), such as the size and size distribution and size ratio, percentage of dockage and foreign materials, density, moisture content, shape and shape factor, modulus of elasticity, friction coefficient, surface texture, cohesion, and adhesion; and process variables (loading method, loading direction and rate, drop height, size of the loading outlet, heap size, and mixing ratio). The factors that are mostly studied include the drop height, grain type, silo size, and composition of grain bulks. Less studied factors are the loading method, loading direction and speed (loading rate), and the size of loading outlet. There are several reports on DFM distribution by using spreaders. However, spreader is rarely used now due to the increased airflow resistance.

4.1 Drop height

Researchers have drawn different conclusions on the effect of drop height. Narendran et al. (2019) investigated the effect of three different drop heights of 0.8, 1.6 and 2.4 m on segregation of canola, kidney beans, and soybeans mixed with wheat in a 2 m diameter steel ring. All grains were cleaned before test and at ≤ 11% moisture content (wet basis). They concluded that loading height significantly influenced the distribution for canola but not for soybeans and kidney beans and the DFM distribution in canola was mainly dictated by the impact segregation. Nourmohamadi-Moghadami et al. (2020) found that as the drop height decreased in a 1-m diameter bin filled with shelled corn, broken kernels and foreign materials found in the periphery of the bin decreased. They explained that the velocity of the particles in the flowing layer of the grain on the heap surface decreased as the drop height decreased, which gave more time to the small particles to be embedded among large particles. Wheat in a 10 m diameter silo...
was studied for five loading heights (1.6, 2.5, 3.4, 4.3 and 5.2 m) by Salarikia et al. (2021). They observed that the drop height significantly influenced the radial distribution of fine particles, dust, and fragments, but not the distribution of other grain kernels (corn, soybean, white bean) and other particles (straw, internode, knuckle, rachis, spikelet, large chaff, wild oat kernels and stem) mixed in the wheat. Even though the drop height influenced the fines and dusts, no particular distribution pattern was found. Chang et al. (1986) observed that the drop height up to 7.4 m had no significant effect on the distribution of fines in bulk corn. Jayas (1987) reported that the effect of drop height up to 7 m on the distribution of fines and chaff in canola was insignificant. These different observations could be explained by the low drop height in the reported studies (≤ 7 m) and different definitions of fines. A greater drop height mostly results in more impact segregation which embeds more larger particles and bounces more small particles away from the silo center. The amounts of larger particles and small particles are usually lower than the fines and chaff in grain silos, and therefore the drop height effect on DFM distribution might not be observable.

### 4.2 Silo diameter

Heap formation during grain loading is one of the main reasons that trigger particle segregation because sifting segregation occurs as the particles move down on the heap surface. Increase of the silo diameter leads to greater moving distances, hence large silos would intensify segregation (Mosby et al., 1996). However, Prasad (1974) reported that the distribution of dockage (smaller and larger than wheat kernels in bulk wheat) followed the same trend in 4.2 m and 5.4 m diameter bins. But it was not known whether this no-difference was caused specifically by the small silo diameters or not.

### 4.3 Size ratio

The difference in particle sizes (or the size ratio) is the most important reason for segregation in bulk materials. The degree of segregation increases with the increase of the size ratio. Unfortunately, size ratio was not reported in the literature related to the segregation of crop grain mixtures because it was difficult to quantify the size ratio in a crop grain mixture with different particle sizes. Therefore, size ratio can be estimated by using the average size of sound kernels and the average size of the segregated particles. Stephens and Foster (1978) pointed out that the segregation of fines (smaller than 1.2 mm) in wheat and sorghum (larger than 2.0 mm) was lower than the segregation in corn (larger than 4.8 mm). However, Chang et al. (1983) showed no difference in the trend of fine distribution between corn, wheat, and sorghum in 6.4 m diameter silos.

### 4.4 Percentage of DFM and moisture content

The percentage of DFM and moisture content of grain might also influence the particle segregation because: 1) grain kernel with a higher moisture content is usually larger than the same kernel with a lower moisture content; 2) grain kernels with different moisture contents might have different shapes and different friction forces between kernels; 3) different amounts of DFM could influence the occurrence (frequency and size) of avalanches and associated segregation; and 4) more DFM with a larger size ratio could result in more impact and kink segregations. In a silo, different parts might be subjected to different segregation mechanisms if the percentage of dockage and foreign materials, moisture content of the grain mixture change. However, Narendran et al. (2019) found that the percentage of other grains (kidney bean, soybean, and canola) in the wheat bulk did not have any significant effect on the distribution and segregation of the other grains.

### 4.5 Missing link

It is generally agreed that segregation can be influenced by many factors, but these factors are not all considered in most studies. Specifically, 1) most studies only separated the larger and smaller particles from the grain kernels (Table 1); 2) some factors were not controlled or difficult to control (Table 1), so the multifactor effects or interaction of multifactors might be missed if only examining the final DFM distribution; and 3) the segregation mechanisms might be induced from the DFM distribution, and these mechanisms are usually specified in a qualitative mode, which further contributes to the mystery of the effect of these factors on segregation.

### 5. Experimental studies

#### 5.1 Focus of measurements

One of the main reasons why particle segregation is remained somewhat mysterious is that it is difficult to collect the evolving particle size distribution data to verify the segregation mechanisms. In grain storage management, the most concerned detrimental effects of DFM distribution are: airflow resistance during drying and aeration; insect multiplication and fungi infestation in concentrated DFM regions; uneven distribution of fumigants during fumigation; and uneven distribution of gases (CO2, N2, and O2) during controlled atmosphere storage. Therefore, most methods used to measure the DFM segregation are designed to determine the airflow resistance and sample the loaded grain to determine the DFM distribution after the loading is completed. Compared to sampling grain
5.2 Field studies

There are a few studies on the mechanisms of segregation of DFM in grain silos filled by center spouts (Table 1). Typical size on-farm grain silos with 4 to 10 m diameter and up to 7.5 m drop heights have been tested (Table 1). The tested crops included corn, wheat, sorghum, and canola. Most of these studies were aimed to compare the DFM distributions between spreader loading and spout loading. It was found that spreader loading increased the airflow resistance even though the DFM distribution was more even than spout loading. In these studies, grain at different locations was sampled after loading, and larger impurities (chaff), small impurities, and grain kernels were separated from the grain samples by using sieves. All these studies did not further separate the larger and smaller impurities except one study conducted by Salarikia et al. (2021). Salarikia et al. (2021) further separated the small impurities into shrunken and broken kernels, fine particles, and dusts and fragments. The larger impurities were further separated into stones, other grains, and other particles by using sieves. This further separation provided more details of the DFM distribution in silos.

5.3 Laboratory studies

Under lab conditions, the following factors influencing DFM distribution have been studied: drop height, components of the grain bulk (mixture), filling method, loading rate, and fill pipe diameter (Narendran et al., 2019). The lab studies have improved our understanding of DFM segregation mechanisms, but they are usually conducted by using smaller than 2 m diameter silos or rings, which limits the heap size (please refer 4.2).

5.4 Limitations of current studies

One of the common limitations in most studies is the focus on the DFM distribution without exploring the segregation mechanisms. Few studies have isolated the main segregation mechanisms from other mechanisms. If only measuring the final distribution, experiments are simple because just loading the grain mixture into a grain silo can achieve this goal. However, identifying particle movement and segregation mechanisms during their movement requires different approaches and complex techniques, such as high quality imaging and laser tracing (Lemieux and Durian, 2000; Pouliquen et al., 1997). Due to the lack of information associated with the segregation of moving grain kernels, segregation mechanisms and their impact on DFM distribution can only be inferred from the final observed DFM distribution, which might generate uncertainties. Currently, segregation mechanisms of grain kernels are also inferred from studies using non-grain kernels such as sand and lead particles. Some early studies on the segregation mechanisms of these non-grain particles used the mechanical approaches such as mass and momentum balances of the purely frictional fluid (Savage and Hutter, 1989), slow heap formation of cellular automata (Frette et al., 1996), conservation of particles being absorbed into the stationary heap or eroded from the heap into the flowing layer (Bouchaud et al., 1994), and quasi-two-dimensional heap formation of open and closed systems (Khakhar et al., 2001). These approaches and models are capable of describing the qualitative behavior of the system, but they cannot predict the quantitative distribution of DFM in grain silos because these predictions require the estimation of several phenomenological parameters associated with grain kernels and identification of the dominant segregation mechanisms, which have not been fully understood.

5.5 Inconsistencies

5.5.1 Confusion of definitions

Different studies use different definitions of DFM which might lead to different conclusions. For example, fines are usually defined in the literature as the particles smaller than grain kernels (Table 1). However, different grain kernels have different sizes, and the fines have different sizes in different reports. For example, Jayas (1987) defined the fines as the particles passing through a Tyler woven wire mesh with 1.18 mm opening and canola kernels were the underflow of a 1.70 mm opening and overflow of the 1.8 mm opening (Table 1). Chang et al. (1983) defined the particle passing 1.6 × 9.5 mm² oblong-hole for wheat, 4.8 mm diameter round-hole for corn, 2.0 mm circle triangular-hole for sorghum. Salarikia et al. (2021) defined the fines as the particles smaller than 2.0 mm. Therefore, fine distribution inside canola bulks should have different patterns from larger grain kernels if we define the fine as the particles less than the grain kernels. Salarikia et al. (2021) found dusts were concentrated in the bin center, while Jayas (1987) found fines were not concentrated at the center of the bin, and the concentration of fines near the bin center was almost equal to that near the sides of the bin. These results are not comparable due to the inconsistency in definitions.

5.5.2 Different sampling methods

Another reason generating different conclusions of DFM distribution might be the method of sampling. Different researchers used different sample sizes and units. Most
Researchers took less than 1 kg samples at few locations and only separated chaff and fines from the samples (Bartosik and Maier, 2006; Chang et al., 1981; 1983; Jayas, 1987). Considering the uneven distribution and low concentration of DFM, a few samples of 1 kg grain taken from a silo holding more than 100 tonnes of grain might not represent the DFM distribution (Jian et al., 2014). Salarikia et al. (2021) took about 22 kg at each sample location and different categories of DFM were further separated: stones, other grains, other particles, shrunken and broken kernels, fine particles, dusts, and fragments. Based on the larger samples, this study had different conclusions from other published studies on the distribution of shrinkage and broken grain kernels, other particles, dust and fragments, and small and larger grain kernels.

6. Mathematical and numerical modeling

6.1 Mathematical modeling

Even though there is no theoretical model developed to directly describe the DFM segregation in grain silos with spout filling, models related to heap segregation have been in existence. Some models are developed based on continuum of mass and advection diffusion combined with flux function. Some examples are the one-dimensional models developed by Bridgwater et al. (1985) and Savage and Lun (1988), and two-dimensional models developed by Dolgunin and Ukolov (1995). Many models are developed based on mixture theory (Gray and Ancey, 2015; Tunuguntla et al., 2014), and Gray et al. (2015) provided an extensive review on these models. Non-diffuse theory is also used by researchers to develop models describing particles sheared over large heap surface (Pouliquen et al., 1997; Pouliquen and Vallance, 1999; Woodhouse et al., 2012). Depth-averaged models have been developed to describe avalanches and finger instability (Woodhouse et al., 2012). Other approaches such as segregation induced by shear force (Fan and Hill, 2011), pure density (Tripathi and Khakhar, 2013), and size (Marks et al., 2012) have been tested. Gray et al. (2015) provided a review on the modeling of a single avalanche (without mass exchange). Even though these models mentioned above can help us to understand the segregation mechanisms, these models are not capable of predicting DFM segregation in silos because they only consider the binary mixture or three components. Gray (2018) reviewed these equations and solution techniques. Even though polydisperse mixture might be able to be modeled, some additive decomposition mechanisms must be introduced, hence the complexity. Marks et al. (2012) developed an alternative theory for polydisperse segregation with a continuous grain-size distribution that is closer to the reality of both industrial and geophysical materials. This model must be solved simultaneously in five dimensions: space, time, and the three dimensions of grain-size coordinates.

It should be noted that the models discussed above only considered the open flow. Segregation in grain silos is the closed flow except at the beginning of loading before grain reaches the walls. The complexity of these models, as well as the difficulties to solve the equations in the models, limits the practical applicability of these models to predicting particle distributions.

6.2 DEM modeling

The discrete element method (DEM) has been used to simulate the segregation of particle mixtures, but these simulations are mostly used as a tool to understand the segregation principles by using the idealized materials and are not yet at the stage of simulating segregation in real grain silos. For example, by using DEM simulation, Pereira et al. (2011) verified a continuum theory based on a species balance equation in the flowing layer by balancing the convective flow with diffusion and segregation fluxes. Khakhar et al. (1999) used transport equations from the kinetic theory of mixtures for a mixture of nearly elastic smooth particles to analyze density segregation. Marks et al. (2012) used the approach based on partial stresses in their DEM simulation. Tripathi and Khakhar (2013) simulated the segregation of granular mixtures of equal-size particles with different densities. Using three-dimensional DEM model, Fan and Hill (2011) proved that a gradient of shear rate alone could drive segregation in dense sheared systems. The effect of shear caused small particles to move to the regions of low shear rate and large particles in the opposite direction. Currently, DEM simulations are typically limited to spherical particles, and it is difficult to treat particles having irregular shapes and a wide size distribution directly because of mathematical complexity and computational demand. The compromise is to treat the particles as “spherical particles with an equivalent rolling behavior to the particle with arbitrary shape” (Shimoska et al., 2013). This assumption increases the prediction error, and the error is usually unacceptable for the grain industry because grain kernels and DFM are usually not spherical particles.

7. Challenges and directions for future research

A challenge of studying segregation in grain silos is the difficulty in collecting the reliable detailed data which can be used to identify the effect of individual segregation mechanisms. High speed camera and laser used to capture the motion of individual kernels during grain loading might be the examples of collecting the reliable detailed
for the understanding of segregation mechanisms. Another challenge is to develop predictive models capable of handling multiple segregation factors and mechanisms. Currently, researchers mostly focus on the final distribution which can be directly used for grain storage management. There are rarely fundamental studies on segregation mechanisms and factors influencing these segregation mechanisms. Without studying segregation mechanisms and factors influencing segregation, focusing only on the DFM distribution might impede the understanding of the segregation mechanisms.

8. Conclusions

Loading grain into silos from a central spout is a most common method used by the grain industry in the world and a special case of heap flows of granular materials. This loading method results in a concentrated distribution of smaller and denser particles (smaller than the sound grain kernels) at the center and larger and lighter (than the sound grain kernels) particles at the walls of silos. The main mechanisms responsible for this distribution pattern are trajectory, sifting, and avalanche segregations. The main factors influence these main segregation mechanisms are size ratio and percentage of DFM and moisture content, while the contribution of drop height and silo diameter to this distribution pattern is not known due to limited studies and contradictory reports on these factors. The following facts also contribute to our incomplete understanding of this distribution pattern: 1) both lab and field studies focus on final distribution of DFM; 2) inconsistencies of term definition, sampling method, and sample analysis; and 3) no theoretical model is developed to directly explain the DFM segregation in grain silos. One of challenges of studying segregation in grain silos is the difficulty in collecting the reliable detailed data which can be used to identify the effect of individual segregation mechanisms. Fundamental studies on segregation mechanisms and factors influencing these segregation mechanisms in the future might help our understanding of this distribution pattern and develop a theoretical model to predict this distribution pattern.

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