Chapter 11

PARTICLE SIZE SEGREGATION ON A BELT CONVEYOR

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ABSTRACT

Particle size segregation is a common phenomenon in many particulate processes and has many undesirable effects. The size segregation which occurs on a belt conveyor causes a serious problem for on-line particle size measurement using image-based techniques. Whether particle size distributions measured from the top layer of the belt are representative of the total particle population is largely dependent on the degree of size segregation. Therefore, it is important to understand the nature of such size segregation in order to make appropriate corrections for on-line particle size analysis. Monte Carlo simulation has been used to provide segregation information on particles with simple geometry and the results can help to determine important factors in experiments with irregularly shaped particles. It is expected that the relationship between the particle size distribution of the top layer and that of the entire particle population on a belt conveyor can be formulated as a model based function.

INTRODUCTION

On-line coarse particle size measurement has become increasingly attractive in many different industrial applications during the past decade. For example, in the mining and mineral processing industry on-line measurements of coarse particle size distributions have been used to monitor the size distributions of crushing/grinding product (Lange, 1988 and Lin et al., 1995), and in the rock blasting industry, blast control modeling requires information on the blasted particle size distributions (Hunter et al., 1990). In recent years, the gravel and quarry industry also has exhibited a strong interests in using on-line particle sizing instruments for product quality control (Miller et al., 1995). The basic requirement of on-line coarse particle size measurement is to match the speed of each specific process and provide real-time size information for subsequent process control. In this regard, all of the modern sizing instruments for coarse particle size analysis are built upon digital imaging systems. A typical, modern, image-based coarse particle size measurement system is depicted in Figure 1. A belt conveyor is frequently employed for transport of particles in the process. A video camera positioned above the belt captures the particle images and transfers these images to a computer by an image digitizer (the so called image frame grabber). It is then within the computer, these digitized particle images can be processed and measured in many different ways to produce the particle size distribution.

It should be obvious that any method using a video image-based sizing system may require correction of the raw data from the image of the top layer of the particle bed (Lin et al., 1995; Kemeny, 1994; Lange, 1988; Monoro and Gonzalez, 1993). Due to different loading mechanisms and material properties, different particle segregation mechanisms may occur and cause serious problems in on-line particle size measurements. Considering a segregated particle bed, if in case larger particles will have greater chance to be identified, the measured size distribution will be biased. This situation could be even worse if more than one segregation mechanism is involved. In this regard it is intended to investigate the segregation mechanisms which occur during the loading of particles on a conveyor belt

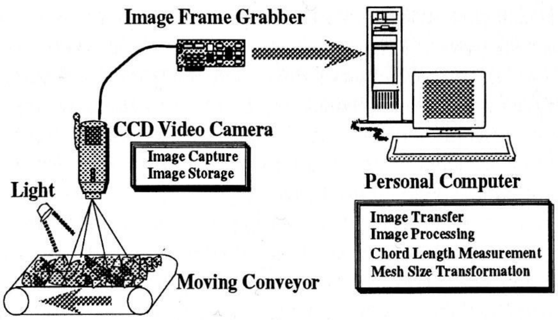


Figure 1. Schematic diagram for on-line coarse particle size measurements on a moving belt conveyor.

and to develop a correlation function between the measured particle size distribution and that of the entire particle population.

A Monte Carlo method has been used to simulate the phenomena of particle size segregation during free fall to form a packed bed, such as would occur on a conveyor belt during loading or at a transfer point. The basic idea behind using this simple method is its general utility. Of course sufficient modeling is needed to extract the most dominant parameters which influence particle size segregation under complicated conditions. Several of these "complicated" conditions that can be easily pointed out in an actual industrial operation are irregular particle shapes, dispersion of the size distribution and the absolute particle size. It is intended to determine whether the simulation results are sensitive to these complexities. It is clear that the simulation will not be acceptable if the simulation method itself is restricted by those complexities. In this regard, four assumptions have been made based on practical observations and the need for simplification: (1) Interparticle percolation is the dominant particle segregation mechanism, (2) uniform density of the particles, (3) well-mixed initial condition, and (4) the dominant mechanism of interparticle percolation is neither shape nor surface property dependent. With these assumptions, the study has considered the variations in particle size, the drop height, and the depth of the particle bed.

Experimental work is being carried out to confirm the simulated results predicted by the Monte Carlo method. A simple experimental setup has been designed and relevant comparisons made between computer simulations and experimental results.

PARTICLE SIZE SEGREGATION

Literature Survey

Particle segregation has been extensively studied in areas where particle mixing is important. It is by nature a particle separation phenomenon which occurs when a polydispersed particulate system is subjected to external forces. To be more specific, the different properties relevant to particle segregation are particle size, density, shape, and particle resilience. Williams (1976) has summarized the research works made during early years and concluded that difference in particle size is the most important factor which accounts for particle segregation. The three different segregation mechanisms given by Williams are (1) Trajectory Segregation, (2) Percolation of Fine Particles (interparticle percolation), and (3) The Rise of Coarse Particles on Vibration (coarse particle migration). The first one is largely caused by the high viscosity of the fluid which carries the particles. The second type of particle segregation occurs whenever rearrangement of a particle bed takes place. Gaps or voids formed between particles formed during bed expansion and for rearrangement create passages for small particles moving down. Although Williams has mentioned a very important segregation phenomenon during bed formation, he didn't distinguish it as a different segregation type from that of Percolation. Later, Drahun and Bridgwater (1983) named this type of segregation as Free Surface segregation. The third type of segregation is formed because of external vibration or shaking forces (Harwood, 1977). Particles being periodically lifted and dropped during vibration could form a stratified particle packing structure with large particles sitting on top of the bed and small particles at the bottom. Of course this action is well studied from the jigging of particle beds.

Most of the early research works on particle segregation were performed by experiment alone. Lawrence and Beddow (1968) designed an experiment for die filling on metallic powders with sizes ranging from 40 to 2000 µm. From their results it was concluded that the difference in particle size is much more dominant than the shape and density factors; a conclusion which is in consistent with Williams' summary. The surprising discovery from their experimental results was that the drop height of the powders influences the degree of particle segregation when the range in particle sizes is large. The degree of segregation is inversely proportional to the drop height and the feed rate. For different applications, many segregation models have been proposed. Shinohara et al. (1972) proposed a screening model for the investigation of particle size segregation during the filling of a hopper. A mixing ratio, M, was defined to help determine the degree of segregation. Again, they concluded that the degree of segregation can be reduced by increasing the feed rate. Bridgwater and co-workers (1969), (1971), (1978) have focused on the study of Interparticle percolation. The rate of interparticle percolation for a binary particulate system was found to be determined by the statistical diameters of the bulk and percolating particles, the particle shape factors, the density of bulk and percolating particles, acceleration of gravity, and the strain rate. The difference in density was shown to play a particularly important role in percolation.

In recent years, computer simulation has been used more extensively for research on particle segregation as a result of the availability of computers with increased computing power. A number of researchers have employed different physical models for the simulation of particle segregation. Visscher and Bolsterli (1972) first used skillful simulation techniques to simulate particle migration under vibration, Jullien and Meakin (1988) used a Ballistic projection model for the study of percolation, Rosato and co-workers (1986), (1991) proposed that particle migration is a simple geometric process in which the only factor of significance is particle size and they used the Monte Carlo method to successfully demonstrate that the rate of migration depends largely upon particle size. Baxter and Behringer (1990), Fitt and Wilmott (1992), Deserable et al. (1994) employed the Cellular Automata model to study segregation in granular flow.

There are cautions to be taken for each model mentioned above. The ballistic projection model is sequential in nature. Without a relaxation process following the projection, this method is of little use in the study of real segregation problems. The cellular automata model requires given rules for filling or voiding the lattice sites; it could be difficult to set those rules appropriately for complicated systems. When using the Monte Carlo method to simulate particle segregation, the particulate system has to be carefully examined to determine if such an approach is applicable.

Modeling of Particle Size Segregation on a Moving Conveyor Belt

It will be very difficult to analyze particle size segregation phenomena in a conveying system without any assumption to simplify the problem. The first step toward discovering the most significant segregation mechanism(s) is to specifically define the system under study. The reason for this argument is that different loading methods at particle transfer points will induce different segregation mechanisms. In other words, it will not be possible to make a simulation without knowing what to simulate for.

In Figure 2 the particle conveying system is defined by loading of polydispersed particles through a feeder onto a moving conveyor belt. The mass flow rate and the conveyor speed are set such that a particle bed is developed on the belt. Particles released from the feeder are assumed to be well mixed. There are two zones on the belt conveyor that need to be defined - the Transfer Zone and the Imaging Zone. The Transfer Zone is right at the transfer point where particle rearrangement takes place whereas the Imaging Zone is set at as close as possible to the Transfer Zone and yet most of the particles are moving with the speed of the conveyor. This definition makes it possible to determine which segregation mechanism is operative.

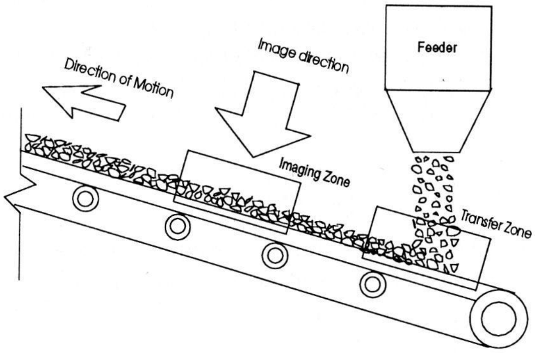


Figure 2. Illustration for the modeling of particle size segregation at the transfer point of a moving belt conveyor.

There are four segregation mechanisms to be considered:

(1) Interparticle Percolation (size dominated),
(2) Particle Migration,
(3) Trajectory Segregation, and
(4) Free Surface Segregation.

In the first case, Interparticle Percolation, according to Williams (1976) and practical observations, segregation will occur in the Transfer Zone since particle rearrangement is taking place. Small particles can easily penetrate the gaps formed by larger particles and reach lower equilibrium or pseudo equilibrium positions. Particle migration, the rise of larger particles, does not occur here due to the lack of significant vibration or shaking forces in the system. Although the motion of the conveyor does produce a small periodic displacement in the vertical direction, the vibrating force induced from this displacement is negligible. As for Trajectory Segregation, it is usually significant when particles are moving in liquid media which again is not the case here. The last mechanism, Free Surface Segregation, will occur during bed formation in the Transfer Zone. Large particles on the surface will have larger momentum and roll over to the sides of the particle bed. Fortunately, Free Surface Segregation is not important if the entire top surface is measured. Although it is believed that the small displacement caused by the motion of conveyor is not a source for migration, it is a possible source for continued percolation of fine particles during transport. In this regard, the Imaging Zone has to be set as close as possible to the Transfer Zone to avoid continued percolation of fine particles taking place.

The Monte Carlo method has been chosen to simulate interparticle percolation. It should be noted that there is no direct calculation of any forces between particles. It is thus intended to simulate this segregation phenomenon without regard to shapes, surface properties, and interaction forces, but rather simply to simulate the segregation phenomenon on the probability of particles of different sizes to penetrate down to lower layers during the transfer process. In this regard, the segregation can also be viewed as a process controlled by minimizing its potential energy subjected to geometric constrains. It is a much simpler approach compared to other simulation models, and should be useful if those assumptions given in the introduction are valid. It is expected that important factors which influence the particle size segregation can be easily examined.

COMPUTER SIMULATION

Monte Carlo Method

A 3-dimensional Monte Carlo Simulation has been done to simulate particle segregation during particle bed formation onto a belt conveyor. The main procedure of the simulation follows the procedure developed by Rosato et al. (1986). The procedure can easily be done in either 2 or 3 dimensions. First a random number generator is used to generate the center coordinates of each hard spherical particle within a rectangle container. The term "hard spherical particle" is defined by a pair interaction energy. For a 3 dimensional simulation, N particle system, the pair interaction energy U(s) is defined as:

$$U(s)=\begin{cases}0, & if\ s\geq d_s\\ \infty, & if\ s<d_s\end{cases} \tag{1}$$

where d_s is the sum of the radius of two spherical particles and s is the distance between the centers of two particles. The interaction energy becomes infinite for any two particles overlapped in space because no deformation is allowed for "hard" spherical particles.

At the start of the simulation, a configuration of N particles can be created and denoted by

$$\tilde{r}:=(r_1,r_2,\ldots,r_N) \tag{2}$$

where $r_j=(x_j,y_j,z_j)$ be the location in the x-, y-, z-planes and j denotes the j-th particle. The total energy of this system $E(\tilde{r})$ which is the sum of the pair interaction terms and the gravitational potential energy,

$$E(\tilde{r})=E_g(\tilde{r})+U(s) \tag{3}$$

$$E_g(\tilde{r})=\sum_{j=1}^{N}m_j g z_j \tag{4}$$

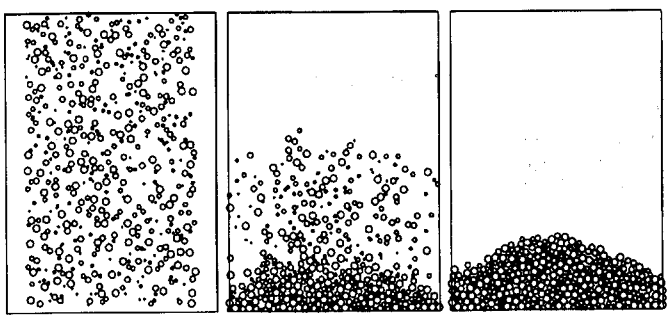
where m_j is the mass of the jth particle and g is the gravitational acceleration. In every cycle of the simulation, a triplet of random numbers is generated for each particle in the system. These random numbers then multiplied by a small positive number, α , to produce a new location for the particle j,

$$\begin{aligned}x_j^{'}&=x_j+\eta_x\delta\\ y_j^{'}&=y_j+\eta_y\delta, \quad -1\leq\eta_x,\eta_y,\eta_z\leq 1\\ z_j^{'}&=z_j+\eta_z\delta\end{aligned} \tag{5}$$

A periodic boundary condition is applied to particle motion in the x and y directions. A trial configuration $\tilde{r}'$ is created and compared with the current configuration. If the total energy decreased after each trial,

$$\Delta E=E(\tilde{r}^{'})-E(\tilde{r})\leq 0 \tag{6}$$

the trial configuration is accepted to replace the current configuration. When the criteria for decreasing energy is no longer met, the trial configuration is discarded and the current configuration is kept. Particles which reach the bottom of the container are fixed and longer move. A check on the total energy change between two consecutive cycles is performed at the end of each cycle. The simula-



(a) (b) (c)

Figure 3. Illustrations of 2-D Monte Carlo simulation of free falling spheres, (a) initial configuration, (b) configuration after 200 simulation cycles, and (c) final configuration. (100 spheres for each size with diameters 2, 4, 6, 8, and 10; the width of the rectangle region is 300 and the drop height is 400)

tion stops when the total energy change is smaller than a predefined positive number. A 2-dimensional simulation result is shown in Figure 3 to illustrate the initial, intermediate, and final stages of the particle bed formation.

Simulation Parameters

In order to correlate the particle size distributions between the top layer and the entire particle population, it is useful to establish a functional form to represent the size distribution itself. Many researchers report that the particle size distribution from crushing will usually follow a Rosin-Rammler distribution (Konya and Walter, 1990; Csoke et al., 1996):

$$F(d) = 1 - \exp\left[-\left(\frac{d}{d_c}\right)^{\alpha}\right] \tag{7}$$

where $F(d)$ is the distribution probability function, d is particle size, d_c is the 36.8% over size, and α is a measure of the variation of the size distribution. Simulations can be evaluated by generating different particle size distributions with different values of d_c and α. When the actual particle size distribution does not follow the Rosin-Rammler distribution, there is a general transformation model that can represent Normal, Log-Normal, Rosin-Rammler, and modified Beta distributions (Yu and Standish, 1990).

Also simulations have been completed in which the effect of drop height and the mass flow rate (weight) have been evaluated.

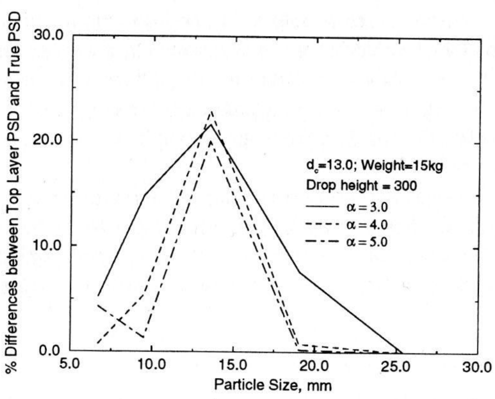


Figure 4. Comparison of the effect of variation in the particle size distribution (α).

Results and Discussion

Figure 4 shows the effect of varying the distribution modulus, α , on the degree of segregation. The data are plotted by comparing the difference between the size distributions of the top layer and that of the entire particle population. It is obvious that the larger the variation in size of the original size distribution the larger the difference between the particle size distribution of the top layer and the original particle size distribution. Figure 5 shows the effect of particle size, d_c , on segregation. It can be observed that it only affects the size ranges around the d_c greatly. The results indicate that particle size segregation is mostly controlled by the distribution modulus, α, rather than the size d_c .

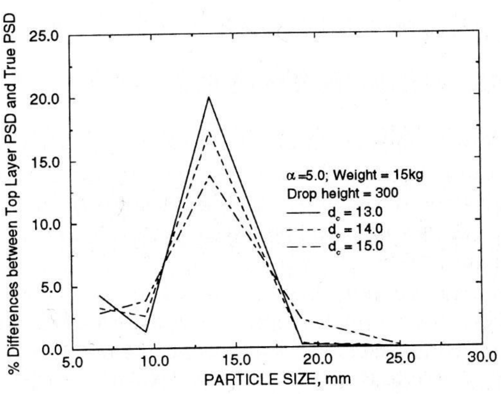


Figure 5. Comparison of the effect of relative top size (d_c) on particle size segregation.

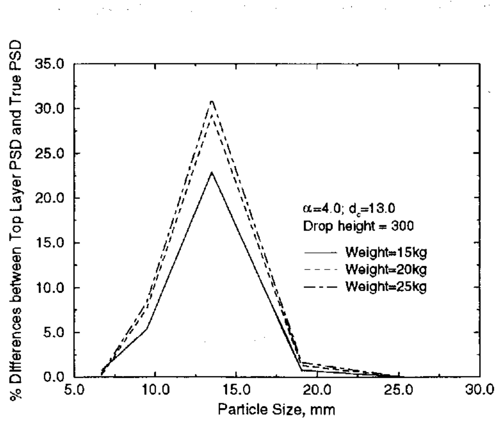


Figure 6. Comparison of the effect of mass flow rate on particle size segregation.

In Figure 6, the effect of mass flow rate is shown to be consistent with the nature of particle segregation. Less correction should be required if the mass flow rate is smaller. In other words, there should be no segregation occurred when only one layer of particles is formed on the moving belt conveyor. Also it can be observed that a saturation of the mass flow rate will be reached beyond which correction for size segregation will not change. The results suggest that on-line particle size measurement and correction can only be made when information on the mass flow rate is available. This conclusion should not be confused with situations where the Free Surface Segregation is considered. Reduced degree of Free Surface Segregation by increasing the mass flow rate of particles, as has been observed by other researchers, is not important here.

Figure 7 gives the comparison for the effect of drop height on segregation. It is not clear at the present time exactly how to correlate the drop height in Monte Carlo simulations to the actual drop height in laboratory experiments or plant operations. In Lawrance and Beddow's (1968) experiments, it was found that drop height will influence the degree of segregation if the particle size ratio is large, *i.e.* if the range of particle sizes is larger. The higher the drop height the less the degree of segregation.

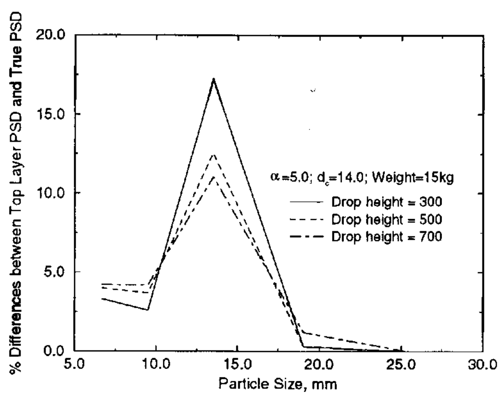
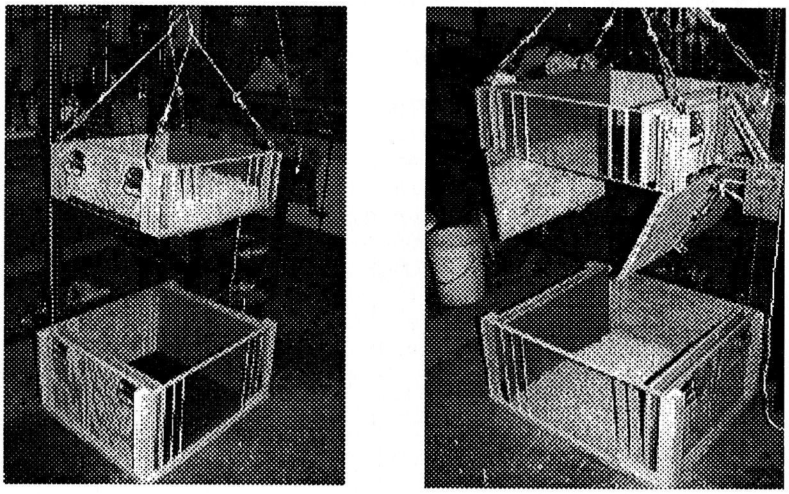


Figure 7. Comparison of the effect of drop height on particle size segregation.

DESIGN OF EXPERIMENTS

The setup for laboratory experiments is revealed by the photographs presented in Figure 8. The upper box of the apparatus can be moved vertically by a pulley and has trap doors for center discharge and release of the particle population. Particles of the desired size distribution are mixed and then loaded into the upper box with a flat shovel. The lower box is fixed in position with dimensions larger than that of the upper box to collect the falling particles. At the present time drop heights, 3 loading rates (particle weights or concentrations), and 9 particle size distributions are being considered.

After particles have been released into the lower box, 4 images for every experiment are taken to cover the entire surface of the particle bed. In order to verify the reproducibility of the experimental results, each condition is repeated 3 times in random order. Captured particle images are then passed to the computer for subsequent image processing and particle size measurement. A model based correction function for transforming the top layer size distribution into the true particle size distribution can be formulated by a set of the following form:



(a) (b)

Figure 8. Experimental setup for the measure of particle size segregation such as might occur at a transfer point on a moving belt conveyor, (a) before release, and (b) after release.

$$d_c = f(d_c', \alpha', h, w) \quad (7)$$

$$\alpha = g(d_c', \alpha', h, w)$$

where d_c is 36.8% size over of the original particle size distribution and d_c' is 36.8% size over of the top layer size distribution, α is the true variation of the original particle size distribution and α' is that of the top layer particle size distribution, h is the drop height and w is the particle mass flow rate. Experimental results will be published in a subsequent contribution.

CONCLUSION

The Monte Carlo method has been used to simulate the particle size segregation which might occur on a moving belt conveyor where only interparticle percolation is the dominant mechanism of segregation. Simulation results suggest that the size range is the most controlling factor of segregation. The mass flow rate and drop height also contribute but less significantly to the extent of segregation. Experimental verification of these results is in progress at the present time and it is expected that a model based transformation function can be established in order to predict the size distribution of the entire particle population from image analysis of the top layer of a particle bed on a moving belt conveyor.

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