Flow of Non-Homogeneous Particulates in Rotating Drums

Abdel-Zaher M. Abouzeid
Dept. Mining, Faculty of Engineering, Cairo University
Douglas W. Fuerstenau
Dept. Materials Science and Engineering, University of California

Abstract
Numerous industries deal with particulate systems such as the cement, ceramics, chemical, metallurgical and pharmaceutical industries. Usually the particulate systems handled in these industries are non-homogeneous, that is, their constituents are heterogeneous in their physical properties such as particle size, density, particle shape, and surface roughness. Handling of these systems during transport and/or manufacturing is usually associated with movements of these particulates at transfer points, being shaken, moving through drums, or sliding over inclined planes, which leads to the particulate mass being energized or disturbed. Disturbing such non-homogeneous systems results in mutual separation of the particulate constituents as a result of differences in their physical properties. The mutual separation is a natural phenomenon called segregation. In some instances, segregation is desired, while in most cases it is detrimental. Segregation in particulate systems takes place as a result of several forces, mainly frictional and gravitational forces, acting on the individual particles inside the system while it is energized. It is well known that the contribution of these forces in controlling the movement of particles are functions of the physical properties of the constituting components of the system. This paper concerns investigation and discussion of the mechanisms of particulate motion and the role of the forces acting during energizing a particulate system, particularly while moving through rotating drums, and their effects on the quality of the final products of non-homogeneous particulate systems.

Keywords: segregation, particulate systems, flow of non-homogeneous particulates, rotating drums, mixing-demixing of particulates, continuous flow of powders

1. Introduction
Particulate systems in most processes consist of various constituents. These constituents may differ in their physical properties such as size, shape, density, surface roughness, etc. Differences in the properties of the constituents are reflected in the behavior of each species when the system is set in motion. In industrial processes, differences in behavior of the various species can affect the quality of the final product. Handling and processing of particulate systems are essential sub-processes in all industries dealing with powders such as cement, chemical, fertilizer, metallurgical and pharmaceutical production. Examples of these operations in mineral processing are size reduction, size enlargement, drying, cooling, induration, calcination, roasting, and clinkering. Processing of these powders is usually accompanied by physical and/or chemical changes. The extent of these changes and the efficiency of these processes are strongly related to the homogeneity (degree of mixedness) of the flowing material. These changes occur whether the process is carried out in batch, continuous, or semi-continuous operations.

It is becoming evident that the role of material flow and transport in product quality and process efficiency is a major one. Several phenomena in the mineral processing and powder technology could not be explained without the consideration of the

\[ \text{Accepted: July 27th, 2010} \]
\[ ^{1} \text{Giza 12613, Egypt} \]
\[ ^{2} \text{Berkeley, California 94720, USA} \]
\[ ^{*} \text{Corresponding Author} \]
\[ \text{abdel.abouzeid@gmail.com} \]
\[ \text{TEL: +20 2 3586 4665} \]
\[ \text{FAX: +20 2 3572 3486} \]
material behavior while being transported, energized (disturbed), or rolled down an inclined plane. Quality control of the product is also manipulated through controlling the powder flow regime.

This paper presents the main mechanisms of particle motion, while moving within a particulate system, while being energized. It also deals with how mixing (homogenizing) and demixing (segregation) actions take place during the relative motion of the powder constituents. Flow of powders in rotating drums will be stressed as an obvious example of powder flow in several industrial processes which deal with powder technology, handling and processing.

1. Mechanisms of Particle Motion within a Particulate System

For simplicity we will limit ourselves to the flow behavior of cohesionless powders, homogeneous and non-homogeneous, in continuous systems, particularly in rotating drums.

1.1 Homogeneous systems: Homogeneous particulate systems are those whose constituents are identical in all their physical properties such as size, density, shape, etc. These are known as ideal systems, but they do not exist in real life\(^7\). However, for practical purposes, we may obtain systems close enough to ideal systems. Early in the sixties, efforts were made towards isolating the basic mechanisms occurring in particulate mixing operations\(^6\). To produce a satisfactory mixture the spatial arrangement of particle must be changed, that is, particles must be moved from one place to another within the system. There are four basic mechanisms by which this can be accomplished: a) diffusion which is the random motion of individual particles or small aggregates in the space occupied by the mixture under consideration, b) convection, where the particles move collectively in groups or clusters, c) shear, where clusters of particles are sheared on several planes, and d) directional flow, where particles move under a driving force, e.g., head gradient, concentration, etc. Shearing action changes the relative position of the constituent particles and is considered to be a representation of a specific combination of diffusion and convection\(^6, 10\).

Pure diffusion, when it is feasible, is highly effective leading to very intimate mixtures at the individual particle level. However, it is generally an exceedingly slow process\(^11, 12\). On the other hand, pure convection is much faster but tends to be somewhat less effective in mixing, leading to a final mixture which may still exhibit poor mixedness on a finite scale. This fact suggests that an effective particulate mixing operation can be achieved by an optimum combination of both mechanisms which incorporates both the speed of convection and the effectiveness of diffusion. The directional mixing mechanism leads to the movement of all the species in the system towards a lower potential energy or concentration level\(^13\).

In contrast to liquids and gases, in which diffusion can be regarded as “spontaneous”, particulate systems, will only be mixed as a result of mechanical agitation, or some sort of relative motion, which provides circumstances for the particles to change their relative positions collectively of individually. Agitation is provided to the system by shaking, vibration, tumbling, handling, etc.

1.2 Non-homogeneous systems: These are the real particulate systems whose components have different physical properties. When these systems are set in motion, their components tend to sort themselves out into regions rich in one or the other of the system constituents\(^7, 11\). These systems are said to be “segregated” or “demixed”. Segregation seems to occur whenever there are differences in any of the particle physical properties between the system components\(^15\), such as differences in particle size, shape, density, electrical, magnetic, and surface properties. Size, shape, density and surface roughness are generally recognized to be the most prevalent\(^16\). In the case of moistened systems, they are strongly affected by the degree of hydrophobicity of the constituents\(^7\).

When particles having different densities are shaken in a container, it is found that the denser particles tend to settle to the bottom of the container\(^17\). Presumably, because in this way, the total potential energy of the system is lowered. When coarse and fine particles are set in motion, the fine particles tend to segregate to the bottom. In part, this can be explained by a “percolation-biased” diffusion mechanism, whereby the fines can pass through the interstices between large particles with minimum friction. Williams\(^17, 18\) also showed that large particles placed in a bed of smaller particles will, upon vibrating the bed, tend to rise towards the top of the bed, even when their density is greater than that of the finer particles. The explanation offered for this trend is that the large solid particles, which will generally be denser than the loosely packed bed of fine particles, causes a compaction of the bed immediately beneath the coarse particle, consequently, its freedom to
move in response to the vibration is restricted to the lateral and upward directions, and the net result is a tendency to rise. These explanations of segregation phenomena are only applicable for certain situations. A generalized theory, regardless of the particular circumstances in which the operation takes place, has not yet been offered to explain the segregation action in particulate systems. Although efforts have been made towards numerical parametric studies, quantitative predictions, rate and extent, of the final picture of a segregating system do not exist. Modeling attempts of particulate transverse segregation and scaling up of rotating drums have been exercised but for limited conditions.

In the authors’ opinion, a generalized theory that can explain the segregation action in moving particulate systems governed by any type of motion (such as tumbling, vibration, shaking, rolling on inclined surfaces, etc.) may be possible by considering the forces acting on the individual particles in a surrounding medium of other particles. The vertical as well as the lateral pressures on the specific particle, calculated from the soil mechanics relationships, and the friction opposing its motion should be considered. A small particle, in a mixture of small and large particles, is affected by its weight and the frictional forces opposing its motion laterally and vertically. For this particle to move in the interstices of the particulate system, it will encounter less friction than a large particle, and hence moves to a deeper location. A heavy particle will be under the influence of its weight and the frictional forces restricting its motion. It is obvious that a heavy particle will experience friction proportional to its weight and size, but the gravitational force pulling it down is relatively larger than that for a light particle. A smooth-surfaced particle in a system where all of its components have the same size and density will experience less frictional forces than any particle of the other constituents. These principal aspects of force analysis on individual particles in a moving particulate system are applicable to any type of particle motion such as handling, heap- ing, tumbling, shaking, and vibration.

2-Mixing-Demixing Equilibrium

In any blending operation, the mixing and demixing mechanisms will be operational. The participation of each of these two operations will be dictated by the environment and the tendency of each component to segregate out of the system as a result of the differences in their physical properties and the extent of these differences. Since the two operations, mixing and demixing, are acting against each other, an equilibrium level of mixedness will be attained as the final state of the mixture.

If we take a mixture of particles of two different sizes in a container and energize it by shaking or vibrating, mixing and demixing will be going on simultaneously. An equilibrium state between these two processes will be achieved, with a final state where the large particles will be dominating near the top regardless of the start state. The extent of mixedness as a function of time will depend on the way the components are loaded in the container at the beginning. Loading of the two components in the container before energizing it can be: 1) layer loading with fine particles in the bottom and coarse particles on the top, 2) layer loading with coarse particles in the bottom and fine particles on the top, or 3) with the two components being thoroughly mixed. Fig. 1 shows the schematic progress of mixing and demixing for the three loading conditions. If we think of the variance of the mixture as a function of mixing time to be an indication of the state of mixedness, line A represents the extent of mixing as a function of mixing time when the initial conditions start with the coarse particles on the top. The degree of mixedness continues increasing (the variance decreasing) smoothly and gradually until it reaches a steady state (equilibrium). This equilibrium state will be such that there is a top region of coarse particles, a bottom region of fine particles, and a middle region of coarse and fine particles with the ratio of coarse to fine particles decreasing downward and a ratio of fine to coarse
decreasing upward. When the initial conditions are such that the coarse component is in the bottom, the degree of mixedness follows line B. In this latter case, a state of “overmixing” is observed. The physical meaning of this state is that the two components are crossing each other towards their natural stability at equilibrium, i.e., coarse on the top, fine in the bottom, and a mixed layer in the middle. In these two cases, the mixing mechanism dominates the system in its initial stage, with a decreasing rate as time passes until the rate of mixing is counter balanced by the rate of demixing at the equilibrium level. Line C represents the mixing course of an initially well-mixed system. Under these conditions, the demixing (segregation) mechanism dominates the system in its initial stage. As time passes, the demixing rate decreases as it is counter balanced by the mixing mechanism until the system reaches its equilibrium level. The equilibrium state, obtained after a long time of setting the system in motion, for the three cases, is the same.

3-Analysis of the Continuous Flow in Rotating Drums

Rotary drums are used extensively for particulate processes in several industrial operations\(^{29}\). In mineral processing, they are used in comminution, pelletizing, mixing, drying, calcination, and roasting\(^{29}\). They are also used in food, chemical, cement, and pharmaceutical industries. The flowing materials in most of these operations are non-homogeneous, i.e., the constituents differ from each other in one or more of their physical properties such as size, density, shape, etc\(^{29}\). The Impulse-Response technique is used to follow the behavior of the flowing material inside the rotating drum through monitoring and analyzing the Residence Time Distribution, RTD, of tracers that simulate each of the flowing components\(^{29}\). This technique is the most common one used for studying the behavior of particulate flow in such systems\(^{29}\). In this technique, a tracer (trace amount) which represents one of the components, and does not disturb the flow, is injected at the entrance of the feed and followed at the exit discharge of the drum. The exit age distribution function, \(E(t)\), is analyzed, using the \(E\)-curve, in the form of the residence time distribution, RTD, through the \(C\)-curve. The \(E\)-curve is the number fraction of particulates in the effluent stream with ages between \(t\) and \(t+dt\). The \(C\)-curve is the concentration of tracer particles in the effluent at dimensionless time, \(\theta\). The residence time distribution is used to characterize the flow by calculating the mean residence time, MRT, \(\tau\), where \(T\) stands for Tracer), of the component as well as the variance of this distribution \(\sigma^2\) and the standard deviation \(\sigma\) and the time taken by the tracer to first show up at the exit end of the drum, \(t_0\). Through these parameters, the behavior of the component within the bulk, and the type of flow inside the drum can be characterized\(^{29}\). The RTD can be presented as time-dependent, relative concentration of the tracer, \(C_t / C_0\), designated as \(C(t)\), versus \(t\) in seconds, or as dimensionless distribution, \([C_t / C_0]\) versus \(t / \tau\), where \(C_0\) is the initial concentration of the tracer, \(C_t\) is the instantaneous tracer concentration in the RTD at time \(t\), \(\tau\) is the mean residence time, and \(t\) is the time at which the sample just came out from the drum discharge end, calculated from the time the tracer was injected into the drum at the inlet end\(^{31, 32}\).

The foregoing parameters are estimated as follows:

\[
\int E(t) \, dt = \int C(t) \, dt = 1 \tag{1}
\]
\[
\tau = \frac{\int t \, C(t) \, dt}{\int C(t) \, dt} = \int t \, C(t) \, dt \tag{2}
\]
\[
\sigma^2 = \int (t - \tau)^2 \, C(t) \, dt \tag{3}
\]

The dimensionless variance, \(\sigma^2 = \sigma^2 / \tau^2\)

and the dimensionless time, \(\theta = t / \tau\)

The mean residence time can also be estimated from the values of the hold up material in the drum, \(H\), and the material feed rate, \(F\), as follows:

\[
\tau_H = \frac{H}{F} \tag{6}
\]

This paper presents, discusses, and analyses the results of an extensive research work, which deals with the flow of non-homogeneous particulate systems flowing in a rotating drum. The systems studied here consist of particulate species different in their size, density, shape and surface roughness. It includes tracers flowing in bulk of different properties, and two major components different in their physical properties flowing simultaneously in the rotating drum. Flow of powders in rotating drums is stressed as an important unit operation step commonly involved in powder technology.

**Experimental Technique and Materials**

**Experimental Set up:** The experimental set up
The feeding system consists of three main parts; feeding system, rotating drum, and sampling system (Fig. 2). The feeding system consists of two parallel lines each of which consists of a bulk material storage bin, a constant head funnel, and a vibratory feeder of the ERIEZ MAGNETICS type model 10 A which is connected to a voltage stabilizer. The particulate material flows from the bottom of the storage bin to the constant head funnel directly underneath. The arrangement of the bin and the funnel is such that regardless of the material level in the bin the material level in the funnel will be constant, and hence the rate of particulate flow from the funnel will be fairly constant (coefficient of variation 0.031 for 30-second samples). The material flowing from the bottom of the funnel falls directly onto the vibratory feeder, which delivers the material to a feed chute that passes directly to the feed end of the rotating drum. The feed rate is controlled by gates on the vibratory feeder (coarse adjustment) and controlling the amplitude of the vibrator (fine adjustment). The rotating drum, made from a transparent Lucite tube, was 8 cm in diameter and 25 cm in length fitted with two flanges at its two ends, each 20-cm in diameter. The flange at the feed end of the drum has an opening 1.8 cm in diameter, and that at the discharge end has an opening 4.5 cm in diameter. Along the interior surface of the drum (parallel to the longitudinal axis), eight equally-spaced lifter bars of 0.3 cm diameter were mounted. The lifters are needed to insure proper flow of the particulate material in the drum without slipping or surging. The drum is divided longitudinally into two halves such that one half can be replaced by a sampler to split the drum contents into 20 equal samples at the end of the experiment. The drum assembly is rotated by friction on two neoprene rollers (7.5 cm diameter) driven by a Graham variable speed motor. The discharge material from the drum flows into a circular riffler type sampler through an exit chute and a rectangular funnel. The bottom of the rectangular funnel is shaped in the form of an elongated chute and a rectangular funnel. The sampler has 40 equal size buckets under which sample collection bottles are placed. The sampler is rotated by means of a variable speed motor for adjusting the sampler speed, and hence, controlling the sample size (coefficient of variation of sample weight 0.048 for 30-second samples).

**Procedure:** The Tracer Impulse-Response technique was used to characterize the material flow inside the drum. Tracers were prepared by taking a fraction of the bulk material, dying it with a food-stuff dye, drying, and screening to obtain the precise size fraction. The tracers are distinguished from the bulk by a different color. A tracer, about one gram, is injected into the feed chute, and the response is obtained by collecting the samples at the discharge end. Samples are collected continuously by the sample riffler until all the tracer, visually, comes out of the drum. The discharged samples are timed, designating the tracer injection time as zero time, t₀. Each sample is spread over a white sheet, and the colored tracer particles counted. The tracer concentration, Cᵣ/C₀, is plotted as a function of the exit time. From this plot, all the required parameters can be calculated. By the end of each experiment, the hold up material inside the drum is sampled and weighed.

**Material:** The particulate materials used in this investigation, either as bulk or tracer, are:

- Dolomite of size fractions 12 × 14, 14 × 20, 20 × 28, 28 × 35, 35 × 48, and 48 × 65 mesh.
- Hematite of size fractions 12 × 14, 14 × 20, and 20 × 28 mesh.
Magnetite of size fraction 35×48 mesh.
Galena of size fractions 20×28 and 35×48 mesh.
Glass beads of size fractions 20×28 and 35×48 mesh.
Copper shot of size fractions 20×28 and 35×48 mesh.

These species represent differences in particulate properties such as: size, density, shape, and surface roughness.

Results and Discussion

To get a clear picture about the flow of non-homogeneous particulate systems in rotating drums, it may be necessary to start with an example of some homogeneous systems flowing in rotating drums\(^a\). This way, the contrast in the flow behavior between the two systems, homogeneous and non-homogeneous, becomes obvious. When the flowing material is homogeneous, i.e., very narrow size range with all particles having the same density, shape, and surface roughness, the residence time distribution of the tracer represents perfectly the flow of the bulk inside the rotating drum. Moreover, it seems that the flow characteristics are not affected by the properties of the flowing material whether it is heavy, coarse, fine, regular or irregular shaped as long as it is homogeneous and the drum parameters (speed, diameter, and length) as well as the feed rate are fixed. Fig. 3 presents the RTD curves for three different materials, of different size fractions, flowing in a rotating drum. There is no noticeable difference in the three RTDs. As a matter of fact, the mean residence times of the three materials range between 165 and 167 seconds with no trend. Fig. 3 represents the RTD for homogeneous particulate systems where the bulk and tracer in each experiment were the same, both of them were dolomite of the same size fraction, only the tracer was colored with food color, dried, and screened. The RTDs and the mean residence times, MRTs, are almost the same.

Another feature of the flow of the homogeneous materials in the rotating drum is that there is no difference in the value of the bulk mean residence time, \( \tau_B \), and the tracer mean residence time, \( \tau_T \). Fig. 4 presents a correlation between \( \tau_B \) and \( \tau_T \), which shows perfect matching between the two parameters even though the values were obtained under a wide range of operating conditions, drum speed, drum size, discharge opening diameter, feed rate, particle size fraction, etc.

Fig. 3 Residence time distributions for homogeneous particulate systems of different particle sizes.

Fig. 4 Comparison between the mean residence times of homogeneous particulate systems flowing in a rotating drum as calculated from the RTD and the H/F relationship.

\( a \) A tracer flowing in a bulk: As we have seen in Fig. 3, as long as the tracer and the bulk have the same physical properties, their RTDs under specific operating conditions are almost the same regardless of the size of the flowing particles. In Fig. 3, it can be seen that the mean residence time of the tracer and bulk is the same at any operating conditions provided that both of them have the same physical properties and the operating conditions are the same. This means that, under these conditions, particle flow is absolutely random and all the particles are affected equally by the prevailing forces.

Now let us see what happens if the tracer and the bulk have different physical properties. Fig. 5 presents the RTDs for two dolomite systems; one of them represents the tracer and the bulk of the same size, 35×48 mesh, and in the other system the size of the bulk was 35×48 mesh with the tracer being 48×65 mesh. The mean residence time (MRT) in the first case, homogeneous system, is 162 seconds, where as the MRT in the non-homogeneous system is 177
Fig. 5 Residence time distributions for two dolomite particulate systems. In one of them, the tracer and bulk are of the same size, and in the other, the tracer particle size is smaller than that of the bulk.

Fig. 6 Residence time distributions for tracers of different densities flowing in dolomite bulk of the same particle size as the tracers.

Fig. 7 Residence time distributions of tracers of different physical properties flowing in a dolomite bulk of the same particle size as the tracers.

This means that the smaller tracer particles were delayed in comparison with flow of the somewhat larger bulk particles. In this latter case, the tracer was radially segregated to the core of the flowing bulk which moves towards the discharge end more slowly than the surface layer (shear zone). Since the discharge of the flowing material from the exit end of the rotating drum is from the shear zone, top layer, the particles in the core, which includes most of the tracer material, take longer time than the average particle in the bulk.

Fig. 6 presents the RTDs for three tracers that differ in their specific gravities, dolomite (sp.gr. = 2.9), magnetite (sp.gr. = 5.2), and galena (sp.gr. = 7.5), flowing in dolomite bulk of the same size as the tracers, namely 35 × 48 mesh. In these systems, the dolomite tracer represents the flow of the bulk. Transport of the denser tracers, magnetite and galena, is retarded because they are segregated radially to the core of the flowing bulk, and hence exited later from the drum than the dolomite tracer. The heavier tracer, galena, is delayed more than the lighter one, magnetite, because it has a greater tendency than magnetite to segregate into the core of the flowing bulk. The MRTs of the three tracers, as calculated from their RTDs, are 156, 185, and 198 seconds for dolomite, magnetite, and galena, respectively. The shape difference between magnetite (irregular) and galena (cubical) may have affected the mean residence time to some extent.

The combined effect of tracer shape, density, and surface roughness is shown in Fig. 7. The bulk and tracers have the same particle size, 35 × 48 mesh. The MRT of dolomite, which represents the bulk material, is 158 seconds, whereas it is 181 and 182 seconds for glass beads and copper shot. Although the specific gravity of the glass beads (sp.gr. = 2.7) is very close to that of dolomite, they differ in the particle shape and surface roughness, so the RTDs and the MRTs are quite different. Because of the spherical shape of the glass beads, they penetrate radially to a lower plane from the surface and probably do not disperse much due to not being totally in the shear zone. They are mainly driven by the driving head of the flowing material towards the discharge end. Since they are slower in motion and not well dispersed, they reach the exit end somewhat late, and a large number of the tracer particles are poured out in a short span of time. This makes the mode of its RTD higher than that of dolomite, with less dispersion and longer MRT compared with the average bulk particles. The copper shot being spherical in shape, having smooth surface, and high density (sp.gr. = 8.9) behave differently. They percolate fast from the top of the moving charge, shear zone, down to the toe, raised up by friction with the rising charge to the
top, percolate down to the toe, raised up to the top, and so on facing less friction, having higher momentum, and cutting longer distances radially and axially, i.e., dispersing faster than the average bulk particles. This repeated sequence of motion makes the copper shot in the rotating drum behave as if it were moving in a stirred tank reactor, although it is not thoroughly mixed with the dolomite bulk. Hence, they report earlier than the bulk at the exit and disperse over longer time as shown in Fig. 7.

A series of experiments was carried out under fixed operating conditions, using bulk and tracers of the same size, $20 \times 28$ mesh, but differ from the bulk in their specific gravity. The bulk was dolomite and the tracers were glass beads, dolomite, hematite, galena, and copper shot. The mean residence time for each tracer was calculated and plotted against the relative density, $[\text{tracer density}] / [\text{bulk density}]$. Fig. 8 shows the relation between the MRT of the tracers as a function of the relative density between the tracer and the bulk. The MRT increases as the ratio of the tracer density to bulk density increases as long as both tracer and bulk are natural particles different only in density. Of course this is an indication of segregation. However, when particle shape and surface roughness of the tracer enter into the picture, irregular behavior is observed as can be seen in the case of glass beads and copper shot flowing in dolomite bulk of the same particle size. Interestingly, the MRTs of the two spherical tracers, even though their densities differ widely, tend towards similar values, see Fig. 7.

**b) Major components flowing simultaneously:**

When a particulate system is comprised of more than one major component that differ in their physical properties flows continuously through a rotating drum, the same phenomenon, segregation, takes place. Segregation may be observed inside the drum by the naked eye in some cases, and in other cases, although it is happening, additional measurements are needed for confirmation, e.g., sampling of the hold up material inside the drum in the axial direction \(^{31, 32}\). To study this, a series of experiments was carried out using hematite and dolomite, $14 \times 20$ mesh, flowing through the drum at a ratio of 1:1 by volume. Fig. 9 shows the RTDs of the two components as measured by Impulse-Response technique (following the tracer at the exit end). The main observation that one sees inside the drum is a mixed feed (black hematite particles and white dolomite particles) entering the drum for a short distance beyond the drum inlet, after which only white dolomite is observed on the surface of the flowing charge. Of course what has happened in this case is that, in the first few seconds after entering the drum, the heavy component, hematite, percolates through the flowing bulk to the core of the charge leaving the light component, dolomite, on the surface. Because the particles in the core of the flowing stream progress more slowly towards the exit end than do the surface layers, the heavy component accumulates inside the drum until a steady state is reached at which the feed composition becomes the same as the discharge composition. However, at steady state, the ratio of the hold up of the two components inside the drum becomes different than their ratio in the feed, with the heavy component having higher volume ratio than the light component. This is why in Fig. 9 the MRT of hematite is longer than that of dolomite, with more dispersion.

In Fig. 10, more interesting results are reported. In this series of experiments, the hematite-dolomite
mixture was flowing in the rotating drum at a volume ratio of 1:1. Keeping the particle size of the hematite constant, 14×20 mesh, the particle size of the dolomite was varied, 14×20, 28×35, and 48×65 mesh. The differences in physical properties between the mixture constituents in this series were density and particle size. At steady state, when the two components were of the same particle size, the hematite component accumulated inside the drum, occupying a larger volume than its ratio in the feed and in the discharge product, as mentioned earlier. The accumulation of the heavy component was not regular along the drum axis but it was increasing towards the exit end as a result of the convection movement from the inlet to the outlet of the drum. This explains the results presented in Fig. 9. When the size of dolomite particles, the lighter component, was smaller than that of the hematite, the heavier component, their volume ratio and their distribution along the drum axis became close to their ratio in the feed and in the discharge. The explanation of this behavior is that each of the two components has a property that favors radial percolation towards the core of the flowing charge: hematite particles are heavy and dolomite particles are small. When the size of the dolomite particles gets smaller than that of the hematite particles, successive and alternating bands of the coarse hematite and the fine dolomite start to form. These bands, which are less intensive at the inlet end and more intensive at the exit end, cause the discharge to fluctuate, i.e., the volume ratio of the components in the discharge fluctuates with time. This means that the rate of percolation and mobility of the fine dolomite particles are faster than that of the large hematite particles, and when this is combined with the natural perturbation of each species, the bands form.

These interesting results show that there is a delicate balance among the forces acting on the individual particles within the flowing charge. For example, the forces created as a result of the difference in size and those created as a result of the difference in specific gravity are balanced, in our case, only when dolomite (sp.gr. 2.9 and size 28×35 mesh) was flowing in equal volumes with hematite (sp.gr. 5.2 and size 14×20 mesh), but not otherwise.

The same banding effect is observed when two dolomite components of different particle sizes, 10×14 mesh and 28×35 mesh, are flowing through the rotating drum at a volume ratio of 1:1. A series of photographs was taken for this last case, the banded flow, and the bands are numbered and followed. In about 2.7 minutes, four pairs of bands were discharged. Fig. 11 shows this sequence of bands and how they progress towards the exit end.

Minimizing the Segregation Tendency

Segregation in some non-homogeneous systems
is desirable such as in balling drums, screening, particulate separation and cement kilns. Because the exit ends of these units are fully opened and the drums are inclined towards the exit end, the hold up material is small (5-10% of the drum volume) and the mean residence time is short. In such cases, segregation takes place radially, and there is no chance for axial segregation. In fact segregation in such systems is essential and should be enhanced for size enlargement of the flowing charge, which is one of the required functions of these systems.

On the other hand, particulate segregation in most operations, carried out in rotating drums, is detrimental to the final product, and hence, should be eliminated or at least minimized. If a material is being roasted in a rotating drum and if there is radial segregation, particles in the segregated core may not have undergone reaction. Among the more common operations are pharmaceutical preparations, food for human and livestock, and all other processes that require homogenization of their constituents. In such cases, mixing aids are used to enhance the convective mechanism, shuffling the particulates back and forth, radially and axially within the drum to produce a homogeneous product. Similar effects, if the conditions prevail, may be obtained by moistening the particulate material before being introduced to the mixer. The moisture content will increase the formation of particulate clusters which can be shuffled and sheared with minimum diffusion and maximum dispersion. The preceding paragraph shows clearly that minimizing diffusion in particulate systems flowing in rotating drums is the key for minimizing segregation. The diffusion mechanism can be eliminated or minimized, as we have seen, by introducing a means of stirring agent, which enhances shuffling the particulates back and forth, radially and axially within the drum to produce a homogeneous product. Similar effects, if the conditions prevail, may be obtained by moistening the particulate material before being introduced to the mixer.

Fig. 12 presents the RTDs of various tracers different in their densities, shape, and surface roughness, flowing in a dolomite bulk of the same size as the tracers in presence of mixing aids. Fig. 13 shows the RTDs of hematite and dolomite flowing at the ratio of 1:1 by volume. Thirty percent of the drum was filled with Lucite balls of diameter 2.54 cm, density 1.2 g/cm$^3$ and each weighing 10.3 grams, as mixing aids. If we compare the RTDs in Fig. 12 with those reported in Fig. 7, we realize that the presence of the mixing aids have almost eliminated the segregation tendency of the tracers flowing within the dolomite bulk regardless of their differences in the physical properties. This is an important finding in particulate mixing in vital processes where the degree of mixedness is critical, such as in mixing drug tracers in a bulk of the carrying material. Comparing the RTDs in Fig. 9 and the drastic complications inside the drum, Fig. 10, with the RTDs in Fig. 13, one can appreciate that the complex particulate system of hematite and dolomite flowing in the rotating drum at a volume ratio of 1:1 has been thoroughly mixed by the presence of the mixing aids.
similar to that of added mixing aids in producing non-segregated product, which confirms the fact that the key to obtaining a homogeneous product is to eliminate or minimize diffusion of the individual particles within the flowing bulk.

Summary

All non-homogeneous particulate systems suffer mutual separation, segregation, among their constituents whenever these systems are energized, i.e., there is a relative motion among the moving particles. In the case of transporting such systems in rotary drums, the particulates are energized as a result of the drum rotation and the driving material head due to continuous feeding and discharging. This energizing causes relative motion among the particles axially and radially. Because the physical properties (size, density, shape, and/or surface roughness) of particles differ from one component to another, the resultant forces acting on the individual particles (frictional and gravitational forces) will be different from one component to the other. The pass through which particles move within the bulk will differ from one component to the other. The difference in acting forces, coupled with the phenomenon of natural perturbation, lead to regional concentration of one of the components pulling out from the flowing bulk. This is what is called segregation.

Segregation can be axial in nature, forming alternative bands of the flowing components, or radial, forming a core of one component and a shield from the other component.

Segregation may be eliminated or minimized by reducing the motion of single particles within the surrounding bulk, and enhancing the motion of particles in groups, i.e., reducing the diffusion mechanism and encouraging the convective motion (shuffling) associated with shear mechanism. These restrictions can be done by adding mixing aids to the flowing powders in the rotating drums or moistening the flowing material to produce homogeneous products.

REFERENCES

1) Hog, R., Shoji, K., and Austin, L.G., (1974): Powder Technology, vol. 9, pp. 99-106.
2) Austin, L.G., Luckie, P.T. and Ateya, B.G., (1971): Cement and Concrete Research, vol. 1, pp. 241-248.
3) Karra, V.K. and Fuerstenau, D.W., (1977): International Journal of Mineral Processing, vol. 4, pp. 1-9.
4) Boating, A.A., (2008): Rotary kilns, Butterworth Heinemann, Pub., 368 p.
5) Sheehan, M.E.; Britton, P.F.; Schneider, P.A., (2005): Chemical Engineering Science, Vol. 60, No. 15, pp. 4171-4182.
6) Li, S.Q.; Chi, Y.; Li, I.-D.; Yan, J. -H; Cen, K.-F., (2002): Powder Technology, Vol. 126, No. 3, pp. 228-240.
7) Li, H., (2005): Impact of cohesion forces on particle mixing and segregation Ph.D. dissertation, University of Pittsburgh.
8) Hogg, R. and Fuerstenau, D.W., (1972): Powder Technology, vol. 6, No. 3, pp. 139-148.
9) Santomaso, A.; Olivi, M.; Canu, P., (2004): Chemical Engineering Science, Vol. 59, No. 16, pp. 3269-3280.
10) Hogg, R., (2009): KONA Powder and Particle Journal No. 27, pp3-17.
11) Hogg, R., Cahn, D.S. Healy, T.W. and Fuerstenau, D.W., (1966), Chemical Engineering Science, vol. 21, pp. 1025-1037.
12) Hog, R., (1971): Bulletin of College of Earth Sciences, Penn State University, vol. 40, No. 6, pp. 41-44.
13) Santomaso, A.; Olivi, M.; Canu, P., (2005): Powder Technology, Vol. 152, No. 1-3, pp. 41-51.
14) Shinbrot, T; Zeggio, M.; Muzzio, F.J., (2001): Powder Technology, Vol. 116, No. 2, pp. 224-231.
15) Wegryn, M., (2004): Electronic Journal of Polish Agricultural Universities, vol. 7, No.2, 10 p.
16) Ingram, A., Seville, J.P.K., Parker, D.J., Fan, X. and Forster, R.G., (2005), Powder Technology, vol. 158, No. 1-3, pp. 76-91.
17) Williams, J. C., (1968/1969): Powder Technology, vol. 2, pp. 13-20.
18) Williams J. C., (1963): Fuel Society Journal, vol. 14, pp. 29-34.
19) Esken, D. and Kalman, H., (2000): Chemical Engineering and Processing, vol. 39, No. 6, pp. 539-545.
20) van Puyveld, D.R.; Young, B. R.; Wilson, M.A.; Shmidt, S.J., (2000): Chemical Engineering Research and Design, Vol. 78, No. 4, pp. 634-650.
21) Ding, Y.L.; Forster, R.N. Seville, J.P.K.; Parker, D.J., (2001): Chemical Engineering Science, Vol. 56, No. 12, pp. 3737-3750.
22) Himmellblau, D.M., and Bischoff, K.B., (1968): Process Analysis and Simulation, Willey, New York.
23) Abouzeid, A.-Z. M. and D.W. Fuerstenau, D.W., (1982): J. Egyptian Society of Engineers, vol. 21, No. 3, pp. 52-60.
24) Abouzeid, A.-Z. M., (1989): Powder Handling and Processing, vol. 1, No. 2, pp. 173-177.
25) Swaroop, S.H.R.; Abouzeid, A.-Z.M., Fuerstenau, D. W., (1981): Powder Technology, Vol. 5, No. 5, pp. 253-260.
26) Boaling, A.A., (2008): Rotary Kilns, Elsevier publisher, pp. 15-31.
27) Felix, G., Falk, V., and D`Ortona, U., (2002): Powder Technology, vol. 128, pp. 314-319.
28) Wes, G.W.J., Drinkenburg, A.A.H., and Steemerding, S., (1976): Powder Technology, vol. 13, No. 2, pp. 177-184.
29) Abouzeid, A.-Z. M., Mika, T.S., Sastry, K.V.S., Fuerstenau, D.W., (1974): Powder Technology, vol. 10, pp. 273-285.
30) Abouzeid, A.-Z. M., (1973): Transport and mixing behavior of particulate solids through rotary drums, Ph.D. dissertation, University of California, Berkeley, California.
31) Abouzeid, A.-Z. M. and Fuerstenau, D.W., (1985): Powder and Bulk Solids Handling and Processing: Proceedings, Powder Advisory Center, London, pp. 711-721.
32) Venkataraman, K.S. and Fuerstenau, D.W., (1985): Powder and Bulk Solids Handling and Processing: Proceedings, Powder Advisory Center, London, pp. 704-710.
33) Abouzeid, A.-Z. M. and Fuerstenau, D.W., (1979): Powder Technology, vol. 23, pp. 261-269.
34) Sugimoto, M., (1981): Proceedings, International Symposium on Powder Technology, Japan, pp. 726-735.
35) Nakagawa, M., Furuuchi, M., Yamahata, M., and Gotoh, K., (1985): Powder Technology, vol. 44, pp. 195-203.
36) Shinohara, K., (1986), Powder Technology, vol. 48, pp. 151-160.
37) Furuuchi, M., and Nagakawa, M., Suzuki, M. Tsyumine, H., and Gotoh, K., (1978): Powder Technology, vol. 50, pp. 137-146.
38) Furuuchi, M., and Gotoh, K., (1988): Powder Technology, vol. 54, pp. 31-40.
39) Abouzeid, A.-Z. M. and Fuerstenau, D.W., (1972): I & EC Process Design & Development, vol.11, pp.296-301.

Author’s short biography

Abdel-Zaher M. Abouzeid
Professor Abdel-Zaher M. Abouzeid received his Ph D in Mineral Processing and Extractive Metallurgy from the Department of Materials Science and Mineral Engineering, University of California, Berkeley, California, USA (UCB) in 1973. He also got an M. S. in Mineral Technology from UCB, M. Sc. and B. Sc. in Mining Engineering from Cairo University, Egypt. Now, he is an Emeritus Professor of Mineral Processing in the Department of Mining, Faculty of Engineering, Cairo University, Egypt. His main fields of interest are Mineral Processing, Powder Technology, Comminution, Transport of materials in mineral processing units, Agglomeration of fine powders, and Environmental protection and preservation. His publications and presentations in the above fields exceed 100 articles. Dr. Abouzeid is a member of several professional organizations in Egypt and abroad.

Douglas W. Fuerstenau
Douglas W. Fuerstenau received his Sc.D. degree in metallurgy (mineral engineering) from MIT. After a period in industry working for Union Carbide Metals Co. and Kaiser Aluminum and Chemical Co., he joined the faculty of the Department of Materials Science and Engineering in the University of California at Berkeley in 1959, where he continues as a Professor in the Graduate School. He has been actively involved over the years in fundamental and applied research on processing minerals and particulate materials, including extensive research on interfacial phenomena in these systems. A member of the National Academy of Engineering since 1976, he was recently recognized as the 2006 recipient of the Particle Technology Forum Lifetime Achievement Award from AIChE.