Segregation Behavior for Fine Particles of Sintered Ores and Coke Supplied at the Top of a Two Dimensional Cold Model of Blast Furnace

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The segregation and accumulation behavior for the fines of sintered ore and coke was investigated experimentally with a two-dimensional cold model of blast furnace, charging the fines at the top of the equipment together with coarse particles. The fine particle was 0.5 mm in diameter and alumina sphere, 2.6 mm in diameter, was used as a coarse material. The following elemental motions govern the fines behavior. (1) The fines fall down through the space between the coarse particles. This permeation is due to the continuous change of the packing structure of the coarse particle bed during the descending motion and the fluidization of the fines. (2) The fines are blown up by the gas flow through the space between the coarse particles. In the peripheral charging method for the fines of sintered ore, there is little fines accumulation in the central part of the shaft and the permeation of fines going ahead of the coarse particles is very quick near the walls. This charging method is effective to secure the central stream of gas. In the horizontal uniform and center charges, the fines accumulation increases in the central part of the shaft and deadman surface. In the case of the fine coke of low density, a critical velocity over which the fines begin to move upward by elutriation is successfully estimated on the basis of the regular cubic arrangement of equal spheres. In the horizontal uniform charge, the bridging over between the walls appears when the accumulated fines layer grows to a certain critical thickness with repeating fines charge.

KEY WORDS: blast furnace; two-dimensional cold model; deadman; stability of gas stream; segregation of fine.

1. Introduction

Increase in the fines of sintered ore, coke and hence the fines of the reduced ore, which are originated from degradation of the quality of raw materials, is expected as one of the reasons why blast furnace performance becomes unstable as the high productivity is performed. The studies on the region where the fines are accumulated with high density have been investigated because the segregation and accumulation of the fines much affects the stability of gas stream and the behavior of coarse solid materials. However, most studies1–5) have been concentrated on the behavior of the fine coke or unburned char generated in the raceway or the lower part of blast furnace. Some conclusions obtained are that the fines are accumulated at the root area of cohesive zone where considerable change in gas flow direction takes place1,2) or at the surface layer of the deadman and near the furnace wall.3) On the other hand, the general knowledge is hardly found on the segregation behavior of the fine sintered ore or coke supplied at the top of the blast furnace.

In the present study, a fundamental segregation process for the fines of sintered ore and coke which are supplied with coarse solids at the top of the blast furnace, is investigated experimentally by using a two-dimensional cold model of blast furnace. In particular, the study is focused on how the fines permeate or diffuse through the bed of coarse particles under the drag by gas flow. The coarse particles are supplied continuously from the top of the equipment and discharged to the raceway, and the fines are intermittently charged at a certain intervals of time until the operation is finished to measure the deposition distribution of the fines in a whole region of the equipment. For the method of charging fine particles, two kinds of arrangement are adopted. One is uniform charge in the horizontal direction and the other is partial charge at some local area. The permeation and diffusion or bridging of the fines are discussed from viewpoint of the fluid drag and the fluidization of fines.

2. Experimental Equipment and the Method

2.1. Basic Operation

The two-dimensional cold model used in the present study is shown in Fig. 1. The equipment and the operation method described below are the same as the previous study.6) The model consists of transparent, acrylic region sheets. An alumina sphere was used as a coarse particle and
continuously fed from the top of the equipment. The height of the bed was kept constant at 5.4 cm below the top of the equipment. The consumption of coke in the raceway was simulated by such a way as to discharge the particles from a couple of pipes attached to the back surface with the angle 45°. The particles were also drawn out of a couple of pipes set up symmetrically at the bottom as shown in Fig. 1 to simulate the deadman renewal. The same solid renewal rate, \( W_{DN}/40 \), was adopted. The solid flow rate was regulated by electromagnetic feeder installed in a sealing box (i.e., closed box). Four tuyeres, 0.4 cm in inner diameter, are attached to each side. The air supplied at room temperature from the tuyeres was exhausted from the top of the bed to atmosphere. The air pressure was measured at the tuyere box. No air down-flow occurred because the solid was drawn out within the closed sealing box. After the solid flow attained steady state, the fines of sintered ore or coke were charged on the top of the bed at regular time intervals. Table 1 shows the experimental condition. The solid velocity and the superficial gas velocity at the top of the bed are shown in the table. The physical properties of the particles used are listed in Table 2. Assuming sintered ore has about 20 to 25 mm in representative diameter and regarding the solid under 5 mm in diameter as a fine, the ratio of the coarse particle to the fine is 4 to 5. The model fines diameter, 0.5–0.6 mm, was determined on the same ratio. The minimum fluidizing velocity \( u_{mf} \) and the terminal velocity \( u_t \) for a single particle were calculated for atmospheric pressure and room temperature, assuming the mean particle diameter 0.5 mm. The method to estimate \( u_{mf} \) will be described later.

### 2.2 Charging Method for the Fine Particles

Figure 2 shows the fines charging position. The horizontal uniform charge and the following three kinds of partial charge into a limited span were examined in the experiment. In the partial charge for fine sintered ore, the unit span is set about 4.4 cm, the length dividing the whole horizontal span at the bed surface into six equal parts.

The three kinds of partial charge are:

1. **Peripheral charge in the unit span at each side near the walls,**
2. **Middle charge in each unit span apart from the center with \( \pm 6.6 \) cm,**
3. **Center charge in twice the unit span at the center.**

The input amount of the fine ores for one charge is 135.6 g for all the charging method. When the input amount is divided into two spans, it becomes 67.8 g for each span. The fines charge was carried out 20 times every 6 min. When the fines were supplied, the discharge of the coarse particles was stopped but keeping gas flow. Moreover, the box type partition device as shown in Fig. 3 was used in order to keep a fixed charging condition avoiding a penetration of fines into wall side region caused by a slightly higher void fraction near the walls.

The order of setting up the fines is as follows.

1. Placing the box on the packed bed of coarse particles.

### Table 1. Experimental conditions.

| Solid mass rate \( W_0 \) (kg/s) | Solid velocity \( u_s \) (cm/min) | Superficial velocity \( u_{sf} \) (m/s) | Blast velocity \( u_b \) (m/s) | Solid renewal rate \( W_{DN}/40 \) |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| \( 2.72 \times 10^{-3} \)       | 1.23                            | 0.57                            | 74.6                            | \( W_{DN}/40 \)                  |

### Table 2. Physical properties of particles.

| Material         | \( d_p \) (mm) | \( \rho_s \) (kg/m³) | \( \rho_v \) (kg/m³) | \( \varepsilon \) | \( u_{mf} \) (m/s) | \( u_t \) (m/s) |
|------------------|---------------|------------------|------------------|---------------|----------------|----------------|
| Alumina sphere   | 2.6           | 1760             | 921              | 0.48          |                |                |
| Fine sintered ore| 0.5–0.6       | 4190             | 2170             | 0.48          | 0.41           | 5.57           |
| Fine coke        | 0.5–0.6       | 1369 **1**       | 671              | 0.51 **7**    | 0.19           | 2.64           |

* *) estimated from literature (7)
* *) calculated
2) Filling the gap between the box and the walls with coarse particles.
3) Supplying fine particles on the side lids of the box.
4) Filling the box with the fines lifting up the lids.
5) Pulling out the box and filling the space over the fines with coarse particles.

2.3. The Sampling of the Fine Particles

After all the charges of fines were finished, thin partition boards were carefully inserted in the particle bed according to the grid scale sheet attached on the front panel. The mixture of the coarse alumina particles and the fines in the cubic space divided by the two thin boards were sucked up using a thin nozzle by vacuum pump and caught in a container. The mixture was sieved to each component, the mass of the component was measured and finally the volume percentage of the fines was calculated. This operation was performed over the whole region of the equipment, starting from the top to the bottom.

3. Permeability of Fine Particles in the Coarse Particle Bed

3.1. Gravitational Permeation

As a most simple model of the local packing structure of the coarse particle bed, a regular cubic arrangement of equal spheres was adopted to discuss the permeability of fines through the particle bed. The assumption is based on that the void fraction of the regular cubic arrangement ($\varepsilon=0.48$) is close to that of the coarse particle bed. This simple model is sufficiently helpful for analyzing the segregation behavior of fine particles as described later. The size of the minimum constriction part of such a packing structure is 1.08 mm for the diameter of circle as shown in Fig. 4, that is, nearly equivalent to the length for two fine particles. Since critical opening size of the orifice for particulate material which does not cause a blockage is about 4 to 5 times as large as a particle diameter in general,9) it will be difficult for the cluster of fine particles to fall down freely under gravity through the space between the coarse particles. In the blast furnace, however, the packing structure of moving solids is always changing due to the shear deformation so that the blockage or bridging may be easily collapsed. Therefore, even if the fines are in a cluster to some extent, they will be able to permeate the space between the coarse particles.

3.2. The Fluid Drag on Fine Particle and the Elutriation

A fine particle receives the drag force ($F_D$) by the ascending gas flow. Defining $F_D$ as the external force (or body force) exerted by a single fine particle (=self-weight−buoyancy= self-weight), if $F_D$ is greater than $F_E$, then the fine can fall down overcoming the drag force. Let us consider the interaction between fine particle and gas flow in the narrowest channel (i.e., minimum constriction part of the model packing structure) as follows. The interstitial gas velocity ascending through the narrowest channel depends on the number of fine particle occupying the channel. The fluid drag on a single fine particle was calculated based on the interstitial velocity $u$ for the case that $n$ fine particles exist in the narrowest section of Fig. 4 with cross sectional voidage ($\varepsilon$), and the result is shown in Table 3. The superficial gas velocity $u_s$ is 0.57 m/s at the top of the shaft and 0.38 m/s at the bottom of the shaft.

In the calculation, the following relationship to express the variation of drag coefficient $C_D$ with Reynolds number Re was adopted here.

$$C_D=10Re^{-0.5} \quad \text{for} \quad 0.4<Re<500 .................(1)$$

Then drag force $F_D$ for a single static particle is given as follows.

$$F_D=(5/4)\pi(p_du)^{1.5} \quad \text{for} \quad \text{sintered ore}$$

From Table 3, when the number of fines, n, in the channel is 1 to 3, the relation $F_D<F_E$ holds for sintered fine ore in the top area of the shaft, which makes possible the fines move downward through the narrowest channel. On the other hand, when a larger number of fines such as $n=4$ is intended to fall down through the channel simultaneously, the fluid drag $F_D$ will exceed the $F_E$ and the fines may be blown up (elutriation) and dispersed. However, since the average voidage of the coarse particles is large as $\varepsilon=0.48$, the $F_D$ will decrease rapidly in a larger voidage region just above the narrowest part and the elutriated fines will begin to fall down again.

For the fine coke, the fluid drag is always larger than the external force in the whole region of the shaft except for the case $n=1$ at the shaft bottom. Accordingly, the transportation of fines by the airflow toward the upper part may occur.

3.3. Fluidization of Fines

Superficial minimum fluidization velocity $u_{mf}$ for the...
packed bed of fine particles was evaluated from the solution of the following equations derived on the basis of the Ergun pressure-drop equation.9)

\[
\text{Ar} = 150 \left(1 - \varepsilon_m^e \right) / \left( \varepsilon_m^e \right) \text{Re}_m + \left(1.75 / \left( \varepsilon_m^e \right) \right) \text{Re}_m^2 \quad \cdots (3)
\]

\[
\text{Ar} (\text{Archimedes Number}) = \left( \rho (\rho_p - \rho) g d_p^3 \right) / \mu^2 \quad \cdots (4)
\]

\[
\text{Re}_m = \mu u_{mf} d_p / \mu \quad \cdots (5)
\]

Here, \( \varepsilon_m \) is the voidage just when the fines begin to fluidize. \( \phi \) is the sphericity defined as ‘surface area of a sphere of the same volume as the particle divided by surface area of the particle’ and the value was approximated 0.8 referring to the literature.9) The calculated value of \( u_{mf} \) is shown in Table 2 as \( u_{mf} = 0.41 \) m/s. Even the fine sintered ores of high density, therefore, can be fluidized in such an upper region of the shaft as superficial gas velocity exceeds \( u_{mf} \). In addition to the shear motion between coarse particles stated before, the fluidization encourages the diffusion or distribution of fines. Consequently, the fluidization is to be a factor that makes possible the sintered fine ores descend through the bed of the coarse particles easy.

From the view point above mentioned, it is expected that the mechanism of the segregation behavior of the sintered fine ores consists of the following elemental motions.

1. The fines descend with the coarse massive particles.
2. The fines permeate the coarse particle bed due to the fluidization and the continuous change of the packing structure. The loci of fines motion gradually deviate from the stream of coarse particles, having a tendency to move down vertically.
3. The more the fines are dispersed, the easier the permeation takes place.
4. The elutriation of fines due to gas flow takes place in the space between the coarse particles if the fluid drag exceeds the external force. The direction for the elutriation depends on the gas flow direction.

Thus, the degree of segregation varies depending on the intensity of the coarse particles shearing motion and gas flow.

4. Result and Discussion

A fundamental flow pattern of coarse particles in the two-dimensional model is shown in Fig. 5 with the time line at intervals of 6 min and the stream line. Deadman is renewed by means of extracting particles from the bottom. The quasi-stagnant region called the dynamic deadman exists, and the deadman is refilled by only the particles supplied within a central limited area at the top of the bed. The experimental findings and analyses of the same quasi-stagnant region are also carried out in references (10) and (11).

4.1. Segregation Behavior for Fine Particles of Sintered Ore

4.1.1. Horizontal Uniform Charge

Figure 6 shows the distribution of the fines fraction at the time 36 min after 6 times charge of fines and at the 126 min after 20 times charge of fines, respectively. The 2nd step layer from the top level in Fig. 6(a) corresponds to the position that the finally charged fines layer reaches. The fines are distributed almost all over the bed except deadman, and moreover interesting is that the segregated fine is found in the central part of the first step layer where the fine must not exist originally. On the other hand, in Fig. 6(b), the finally charged fines arrive at the third step layer from the top, showing some difference from the case in Fig. 6(a). This difference is attributed to that the solid flow channel is
reduced according to the increase of the fines deposition amount, as described later. This figure shows that the fines segregation proceeds both on the deadman surface (A) and in the central area of the first or second layers from the top (B). The behavior of the case (A) can be explained by the elemental motions (1)-(4) stated in the section 3.3 and the motionless structure of deadman with no particle-to-particle shear. The case (B) is mainly caused by the elutriation due to the elemental motion (4). The fines segregation pattern described in Fig. 6(b) suggests that ascending gas seems to be forced to pass through the periphery region of the model furnace. Furthermore, a high concentration accumulation is found in front of the raceway and near the bosh walls. The more detailed data will be shown in the Sec. 4.1.5.

The amount of the fines discharged out of the equipment and the fines total holdup in the equipment every 30 min of time interval and the air pressure change in time are shown in Fig. 7, respectively. The pressure is made dimensionless form by the atmospheric pressure, $p_0$. The fines are not discharged from the equipment until the time 30 min after the first input of fines, and this fines holdup contributes to the deposition distribution shown in Fig. 6(a). As the fines discharge becomes remarkable after the 30 min, the holdup also continues to increase, to which the pressure change corresponds. The time lines and the stream lines of the coarse particles with the fines are shown in Fig. 8-① to 8-④. The time 0 min in each figure indicates when colored tracer particles of coarse material were placed horizontally on the top of the bed to determine the flow pattern. The tracer charge was carried out every 30 min. The numbers with the time lines indicate the residence time of the tracer particles. It should be noticed that at each time 0 min, there are not fines charged on the bed surface but tracer particles only and the fines were charged every 6 min after the tracer descended downwards. In Fig. 8-①, the tracer coarse particles reach near the raceway after about the 30 min. This means that it passed 24 min since the first fines were supplied. If the fines keep on descending together with the coarse particles, the fines must not reach the raceway at that time yet. However, as shown in Fig. 7, discharge of the fines to the sealing box has already started after the 30 min. Accordingly, it seems that the fines do not descend with the same velocity as of the coarse particles, but going ahead of the coarse particles. Roughly speaking, the fines fall down to permeate going ahead of the coarse particles by about 6 min or more, judging from the flow pattern shown in Fig. 8-①.

As seen from Figs. 8-① and 8-②, there is no remarkable difference in solid flow pattern until the 60 min after the run started. However, after the 60 min, the descending velocity of the coarse particles increases gradually as indicated by the time lines of Figs. 8-③ and 8-④. This is considered because the solids flow channel becomes narrow owing to the fines accumulation around the deadman as if it were growth of deadman size.
In Fig. 6(b), the fines charged at the 12 min before the completion of run can be recognized in the 7th layer from the top (i.e., at the top of the belly). On the other hand, referring to the flow pattern of Fig. 8-➃, the fines charged at 12 min before the completion of operation will reach near the position shown by the coarse particles time line of 18 min still assuming the fines go ahead of the coarse particles about 6 min. This agrees with the fines position at the 7th layer shown in Fig. 6(b).

4.1.2. Peripheral Charge

The fines deposition distribution, the amount discharged from the equipment, the holdup in the equipment and the air pressure change are shown in Fig. 9. Further, the flow pattern of coarse particles with fines is shown in Fig. 10. No elutriation and accumulation of the fines in the upper or central part of the shaft is shown in Fig. 9. Since the gas may flow up mainly through the central region according to a chimney effect, the fines keep on the concentrated state near the both sidewalls without diffusion even when they are descending through the 3rd layer region from the top. Moreover, there is less accumulation on the deadman surface compared with the horizontal uniform charging method, and remarkable accumulation can be found only in the lower part of the bosh and near the raceway. Judging from both (1) the discharge of fines to the sealing box has been already started before 30 min from the input and (2) the coarse particles take about 40 min to move from the top to the raceway as suggested in Fig. 10-➀, the fines permeation during descending motion is very quick. For the peripheral charge, it is also the feature that there is less amount of the inner holdup of fines and much amount of discharge from the equipment as obvious on comparing Fig. 9 with Fig. 7.

On the time line of the 6 min in the upper part of the shaft in Fig. 10-➁, a hollow is seen near the wall side. This may be attributed to that the coarse particles fill up such a void space as formed after the rapid permeation of fines. In other words, this is a sort of replacement of the voids with coarse particles. The replacement, which makes the descending velocity of the coarse particle increase, must be remarkable in the upper part of the shaft where the fines concentration is high. The influence of it reaches to the lower part of the blast furnace, namely the coarse particles reach the raceway only by the 24 min after they were supplied at the top. Thus, the replacement phenomenon influences the flow of the massive coarse particles.

The pressure of air rises up about 30 min after the start of run, corresponding to the time for the fines to reach the raceway region judging from the time when the fines appear in the sealing box. The pressure after a long time run is in a trend to have a little smaller value compared with the uni-

Fig. 9. Same as Fig. 6, but peripheral charge (126 min after the run).

Fig. 10. Same as Fig. 8, but peripheral charge.
form charging method.

4.1.3. Middle Charge

The result for the middle charging method of the fines is shown in Fig. 11. Although the fines are accumulated on deadman surface larger than in the peripheral charge, the accumulation in the central part of the shaft is not found.

4.1.4. Center Charge

The experimental results are shown in Figs. 12 and 13. According to the vertical descent of the fines, the peripheral gas flow with high velocity is due to develop, which prevents the fines to diffuse broadly and helps the fines elutriation and condensation in the central and upper parts of the shaft. As understood from the fines discharging time to the sealing box being 60 min, the velocity of the fines movement along deadman surface is very slow. In other words, it means the hold up of the fines becomes larger compared with that in the other charging method and this corresponds with large amount of the fines accumulation shown in Fig. 12. From the time line in Fig. 13-① to Fig. 13-③, there is no remarkable difference among the flow patterns. This suggests that the motion of the coarse particles in the circumferential part is not almost influenced by the fines. However, as the accumulated fines amount becomes large, the descending velocity of the coarse particles increases as seen in Fig. 13-④ because the solid flow-channel is reduced.

4.1.5. Fines Accumulation Near the Raceway and Bosh

In the bosh, the fines deposition distribution was measured more precisely with large number of sampling points. The result is shown in Fig. 14. Under the condition with gas flow [Figs. 14-(2), 14-(3)], a high concentration of fines more than 10 to 15% is found in a limited region from the front of the raceway to the top of the bosh. This phenomenon is to be caused by the elutriation of fines at the high gas velocity. The fines are elutriated not only toward the deadman surface but also toward the bosh wall, and this deposition distribution is similar to the pattern that the fine coke generated in the raceway is accumulated. On the other hand, in Fig. 14-(1) for the case with no gas flow, there is little amount of the fines accumulation (less than 5%) at the top of bosh.

4.2. Segregation Behavior for Fine Coke

The fine coke of which physical properties are listed in Table 2 was charged horizontally with a uniform thickness at the level 11.4 cm below the top of the shaft (say, fines input level). The input amount is 45 g and the thickness is about 5 mm. Coarse particles (alumina spheres) were packed over the fine cokes layer with the thickness 5 to 6 cm, and in this situation the height of solid-free zone to the top of the shaft is about 5.4 cm. The fines were supplied every 6 min.

According to visual observation with various gas velocities, the input fines began to fluidize when the superficial velocity $u_f$ attains 0.17 m/s at the input level and began to move up through the void of the coarse particles bed when
attains 0.38 m/s at the same level. Superficial minimum fluidization velocity calculated, $u_{mf}/H = 0.19$ m/s shown in Table 2, agrees with the observation. As shown in Table 3, when $u_f = 0.57$ m/s at the top of the shaft, that is, $u_f = 0.54$ m/s at the fines input level, the relation $F_D > F_E$ holds always regardless of the number of fines in the narrowest part of the model packing structure. At the bottom of the shaft with the velocity $u_f = 0.38$ m/s, the fluid drag takes over the external force, $F_D > F_E$ when $n > 2$ as shown in the lower columns in Table 3, hence, this velocity gives a critical state for the fines capable of moving up through the space between the coarse, corresponding to the visual observation.

Considering the situation mentioned above, the following two cases were adopted for the experimental condition.

(A) $u_f = 0.36$ m/s at the fines input level ($u_f = 0.4$ m/s at the top of the shaft): A slightly smaller velocity than the critical velocity for the fine coke to be able to move up.

(B) $u_f = 0.54$ m/s at the fines input level ($u_f$ is 0.57 m/s at the top and 0.38 m/s at the bottom of the shaft): A velocity for the fines elutriation to take place certainly everywhere in the shaft.

Those velocities are larger than the $u_{mf}$ of fines bed, so charging the fines was carried out in the state of no gas supply and no solid discharge.

Figure 15 shows the fines deposition distribution in the case (A). The 4th layer from the top is such a level as the fines supplied 6 min before the end of operation (i.e., finally supplied fines) may reach. The segregated fines can be found in the central part at the 3rd layer and also near the wall sides at the 4th layer. However, according to the visual observation, most of fines descended with the coarse particles in a fluidized state going ahead of the coarse particles, and discharged to the sealing box 30 min after the start of operation. During this process, fines are accumulated with high concentration on the deadman surface as shown in Fig. 15. Furthermore, the fine coke has a trend to permeate deadman inside in spite of its low density. This may be due
to the fluidizing effect helping the diffusion of fines.

In the case (B), a bridging was formed in the upper part of the shaft. Figure 16 shows the situation for the bridging to grow. The charged new fines and the fines segregated during previous period, (1), moves upwards to the top surface of coarse particles and are segregated/accumulated again at the region near the both walls (2), and then fines descend with coarse particles in fluidizing state (3). Supplying again coarse particles and fines as shown in (1), the fines move upwards again incorporating with the formerly segregated fines layer to develop a new accumulated layer expanded between walls (4) and the layer descends again with the coarse particles (5). When the thickness of the accumulated fines layer increases and the fluid drag on the fines layer increases so as to be capable of sustaining the weight of coarse particles, the bridging comes into existence (6).

5. Conclusions

Supplying fine sintered ore or fine coke at the top of a two-dimensional cold model of blast furnace, the fundamental behavior of the segregation and accumulation for the fines was studied experimentally. As the conclusions, the following elemental motions govern the behavior of the segregation or accumulation for sintered ore fines. (1) The fines descend together with the coarse particles. (2) The fines fall down in almost vertical direction through the space between the coarse particles. This permeation is due to the continuous change of the packing structure of the coarse particles during the descending motion and the fluidization of the fines. (3) The fines are elutriated by the gas flow through the space between the coarse particles.

In the peripheral charging method, there is little the deposition or accumulation of the fines in the central part of the shaft. The permeation of fines going ahead of the coarse particles is very quick. On the other hand, in the horizontal uniform and center charges, the deposition of the fines increases in the central part of the shaft and deadman surface. It is expected for the gas flow that the central stream, flowing through the central region of the furnace, is secured by the peripheral charge and the peripheral stream grows by the horizontal uniform and center charges. Accordingly, peripheral charging method is effective to secure the central stream of gas and to prevent the fines segregation and accumulation in the central part of the shaft.

In the case of the fine coke of low density, the behavior depends considerably on the gas velocity. There is a critical gas velocity over which the fines begin to move upward by elutriation through the space between coarse particles. The critical value is successfully estimated assuming the regular cubic arrangement of equal spheres for the packing structure of the coarse particle bed. The ascending motion of the fines causes the unstable behavior as bridging of the material. In the horizontal uniform charge, the bridging over between the walls appears when the accumulated fines layer grows to a certain critical thickness with repeating the input of the fines, therefore, the fluid drag acting on the accumulated layer increases so as to be capable of sustaining the weight of coarse particles.

It can be concluded that gravitational permeation, fluid drag and fluidization are to be the factors with particles shear deformation determining the segregation behavior of the fines.

Nomenclature

\[\text{Ar}: \text{Archimedes number, defined by Eq. (4)}\]
\[\text{C}_D:\text{ Drag coefficient} \]
\[\text{d}_p:\text{ Particle diameter (mm, m)}\]
\[\text{D}: \text{Drag coefficient (m/s)}\]
\[\text{F}_D: \text{Fluid drag on a single, static particle at the constriction part of the model packing (N)}\]
\[\text{F}_b: \text{Body force exerted by a single particle (N)}\]
\[\text{g}: \text{Gravitational acceleration (m/s^2)}\]
\[\text{p}: \text{Static pressure of air at tuyere (Pa)}\]
\[\text{P}_a: \text{Atmospheric pressure (Pa)}\]
\[\text{Re}: \text{Reynolds number, (d}_p\mu\rho)/\mu(-)\]
\[\text{Re}_m: \text{Reynolds number, (d}_p\mu m\rho)/\mu(-)\text{ at } u_{mf}\]
\[\text{u}_i: \text{Interstitial gas velocity at the constriction part of the model packing (m/s)}\]
\[\text{u}_{mf}: \text{Superficial minimum fluidizing velocity of packed bed (m/s)}\]
\[\text{u}_{s}: \text{Solid velocity (cm/s)}\]
\[\text{u}_{t}: \text{Terminal velocity of a single particle (m/s)}\]

Greek letters

\[\varepsilon: \text{Voidage of packed bed (}-\)\]
\[\varepsilon_n: \text{Voidage of the constriction part of the model packing with n fine particles (}-\)\]
\[\varepsilon_{mf}: \text{Voidage of packed bed at minimum fluidizing velocity (m/s)}\]
\[\rho: \text{Density of gas (kg/m^3)}\]
\[\rho_s: \text{Apparent density of solid (kg/m^3)}\]
\[\rho_b: \text{Bulk density of packed bed (kg/m^3)}\]
φ: Sphericity of particle
µ: Viscosity of gas (Pa·s)

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