Review Report on Granular Segregation in the Blast Furnace

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Introduction:

In this note, we will be mainly discussing some of the phenomena involving solid or granular flow in the blast furnace, and therefore, our focus will be on the upper part of the blast furnace. Mainly, the principles, applicability and limitations of different mathematical modeling tools for granular flow will be reviewed with a special emphasis on the Discrete Element Method (DEM), which is considered to be the most powerful tool for dealing with complex granular flows. There are a few literature available and a very few corporate research laboratories (Baoshan Iron and Steel Corp[1]., BlueScope Steel[2], JFE[3]) have reported their results using DEM for understanding the burden distribution and related phenomena in spite of the fact that there is a vast body of knowledge already available in the literature on the fundamental aspects of granular flow. Since the flow of granular material is a very complex phenomenon, and it becomes more complex in blast furnace situation, this may be the reason behind these tools not getting widely used and successful in solving blast furnace solid flow problems. Many researchers have already shown the path by successfully solving simple engineering problems (sand pile formation, mixing in drums, chute flows) using the theory of granular flow. These techniques are still evolving, and though at present, there are a few researchers who have used these first principle techniques in blast furnace burden distribution, it can be well appreciated that if considerable research effort is put in by integrating blast furnace solid flow problem with these techniques, many un-answered questions will find their explanations in near future.

These modeling techniques of granular materials can be broadly divided into two categories – continuum and discrete. The understanding of surface flow and pile formation is poorly understood as of now. The knowledge base for mixing and segregation of granular materials is less developed than fluids (as in computational fluid dynamics or CFD). Small differences in either size or density leads to flow-induced segregation, a phenomenon without parallel in fluids. Most of the phenomena occurring in granular materials are imperfectly understood[4]. Continuum modeling thus far developed is regime dependent and has limited possibility of generalization[5]. BCRE[6] (named after the four proposers, see ref. 6) model along with a few reported techniques (see ref. 4 and references there in) can be used on ad-hoc basis to deal with the flow dynamics of granular materials. In continuum modeling, unlike fluid flow, there is no single differential equation available which is generic in nature and can describe the process of solid flow. In modeling fluid flow, we may use the Navier-Stokes equation, which describes the flow of a fluid in varied situations. But, continuum modeling for granular materials is at a nascent stage and a breakthrough is really needed to remove this knowledge barrier.

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The total process of burden distribution can grossly be sub-divided into following major modules:

- Material flow through the charging device (through conveyor, hopper, flow control gate, down comer and chute) and free stream of material trajectory
- Surface profile generation (surface flow)
- Size segregation
- Coke layer collapse
- Burden descent
- Gas distribution

All of these different modules are the inputs to the final burden distribution model in a blast furnace.

In the present review, we shall focus our discussion solely on the segregation phenomena occurring in the upper part of a blast furnace. The other modules would be dealt with in subsequent reports.

Segregation in the upper part of blast furnace:

The quantification of segregation is a pre-requisite for controlling burden distribution in the upper part of a blast furnace. The radial distribution of particle size leads to quantification of voidage or permeability distribution which, in turn, determines the gas distribution. Therefore, the knowledge of segregation is very important in controlling and obtaining a desired gas distribution through proper control of burden distribution.

Standish[7] outlined several mechanisms for segregation which are of particular relevance to the granular material flow in the blast furnace. The actual segregation patterns are numerous and depend on the prevailing segregation mechanism – the most prevalent being the percolation mechanism i.e., sifting of fines through the voids of larger particles. The following summarises different mechanisms as described by Standish:

- Percolation or consolidation trickling mechanism
- Angle of repose mechanism
- Inertia mechanism
- Trajectory mechanism (fluid resistance mechanism)

The angle of repose mechanism leads to an enhancement of central segregation of the material having the steepest angle. The inertia mechanism generally enhances the segregation of coarse particles to the periphery. Particles which roll rather than slide down sloping surfaces also enhance peripheral segregation and the more so the larger the particle size. Segregation may occur due to fluid resistance or drag on a particle which is of interest in blast furnace condition since the particles land on the stockline against hot ascending top gas. Particles are segregated due to fluid resistance and this force resisting the motion of particles is a strong function of the particle shape. Therefore, ore, sinter, coke and pellets can be expected under otherwise similar conditions, to have different fall parameters when charged onto the stockline.

Amongst the early literature, Drahun *et al*[8] seem to be the first workers who have done extensive experimentation on this particular topic by analyzing the effects of various variables on segregation. They have reported comprehensive findings on the mechanism of free surface segregation along a slope which can be helpful in understanding exactly the same phenomena occurring in the throat of the blast furnace. Their report also contained an assessment of previous work (15 references) done on the mechanism of segregation. They observed that although the existence of free surface segregation has long been recognised, there have been few attempts to produce theories that would predict quantitatively the amount of segregation. Most investigators were primarily interested in the prevention of segregation rather than the factors that caused it. Therefore, attempts were made to solve a particular problem on ad-hoc basis without fundamental understanding of its occurrence. Moreover, the results of some of the works are not generic and are not applicable universally. They have felt that, in general, analytical attempts have found it difficult to model the key features of free surface segregation (e.g., the predictive models by Matthee[9] and Tanaka[10]). The present work by Drahun *et al.* was conducted with binary systems with one component being present in small quantities. The experimental setup permitted the slope length, solid flow rate and solids fall height to be varied independently in order to assess the effect of independent variables (e.g., size, density, shape, free fall height etc.) on the rate and extent of segregation. Their results have been presented in dimensionless form. The major findings from their work are summarised below:

(a) Free surface segregation occurs by avalanching, inter-particle percolation and particle migration.
(b) Both diameter and density have a significant effect on segregation. The particle diameter as well as density ratio effect the segregation. Smaller particles sink by percolation and are found closer to the pouring point, whereas large particles rise to the surface by particle migration and are found at the extreme end of the surface. On the other hand, the denser particles being found near the pouring point and less dense particles at the far end.
(c) An increase in particle velocity onto the inclined surface influences the material distribution controlled by diameter but not that controlled by density. In particular, if the free fall height is increased, the smaller particles bounce down the free surface to the far end.
(d) A slight segregation in a feeding device like conveyor or hopper can markedly influence the free surface segregation.
(e) Free surface segregation can be minimised by appropriate balance of size ratio and density ratio.
(f) Particle shape, unless extreme such as needles or platelets, does not have much effect on segregation.

(g) Surface roughness or the surface friction arising out of this has no effect on segregation. Rolling and sliding do not contribute greatly to segregation.

Haru *et al.*[11] of Kawasaki Steel (JFE) have compared the segregation phenomena in bell-less and bell-armour charging devices. They have observed that the discharge behaviour of particles changes significantly owing to the difference in the charging method. An appropriate gas distribution can only be obtained if the radial size distribution or the segregation of charge material can be controlled. In general, the bell-less type blast furnace experiences more segregation than their bell-type counterparts and because of that the central gas flow becomes stronger. On the other hand, the gas distribution for bell-armour charging tends to flatten and this poses a problem in micro-control of the burden distribution. Therefore, there is a need to control the segregation (rather, promote radial segregation) in case of bell armour charging in order to get a desired strong central gas flow and controlled peripheral gas flow to decrease Si content and suppress scaffold generation. The work by Haru *et al* has suggested some measures to control radial segregation and stabilise the furnace operation. Separate material charging and size segregated sinter charging are well known methods for obtaining desired burden distribution in bell armour charging. The former is aimed at controlling layer thickness and radial particle size distribution in the furnace by reducing the charge quantity per dump, and the latter is used for charging coarse particle to the central part of the furnace to increase permeability in the centre. The present workers have studied the effect of charging rate and bell stroke and bell stroke speed on the particle size segregation. The findings are summarised below:

(a) The segregation is promoted if a slower discharge rate is chosen in bell armour charging. This is in line with the observation that in bell less furnaces the segregation is higher since the discharge rate is slow due to its large charging angle which causes the reduction in speed.

(b) Raw materials are charged closer to the furnace centre if the bell stroke is 2/3rd and MA notch position is 0. For higher notches, with the same bell stroke, the materials are directed towards furnace periphery. With reduced stroke speed, the coarser particles are accumulated in the central region thus improving the permeability at furnace centre.

The effect of charging rate on particle size segregation has been modelled based on single particle approach where both sliding and rolling has been considered. The coefficient of restitution e has been related with the harmonic mean diameter of particles D_p by the following equation:

$$e = 1 - exp[\, -(0.2D_p - 0.1)]$$

Moreover, the coefficient of friction has been assumed to follow a Weibull like distribution which is given by the following equation:

$$F(\mu_\alpha) = 1 - exp[\, -\frac{(\mu_\alpha - 0.4)^{0.75}}{1.3}\,]$$

The choice of distribution or the justification for such a correlation has not been explained by the authors.

There has been a number of published reports on the time series particle size distribution and discharge behaviour of particles from top bunkers installed above the bell-less apparatus. The work by Aminaga *et al.*[12] of Sumitomo Metal (1987), Standish[13] (1988), Yamaguchi *et al.*[14] of Nippon Steel (1991) and Jung *et al.*[15] of POSCO (2001) deserve special mention in this regard. Their works are summarised below.

The segregation history of the charge material before passing through the rotating chute influences further segregation in subsequent processes. Therefore, the segregation of the charging material in the bunkers is to be known a priori in order to predict the radial distribution of the burden material in the throat of the blast furnace. The discharge behaviour of particles also change depending upon the devices in use, say, centre-feed type (CF) or parallel-type bunkers (PB). Aminaga *et al.* has reported, for the first time, the influence of the charging rate on the segregation of sinter particles from a CF type bunker. They have also cited several references (first six references there in) where similar type of investigations have been carried out which are insufficient and partly complete. The investigation was carried out using a full scale model and a 1/10 scale model. The burden used for experiments was exclusively sinter, since the segregation phenomena is more predominant for sinter than coke[16]. The particle size distribution for sinter used in the 1/10 model is 1-2 mm (10%), 3-5 mm (45%) and 7-10 mm (45%). The main observations are noted below:

(a) The size segregation is reduced if the charging rate is increased which results in a more uniform size distribution during discharge from the bunkers.
(b) It is difficult to obtain a plug flow by the installation of an insert in the bunkers.
(c) A stone box with suitable size and position would control the size segregation during charging into the bunkers. For CF type bunkers, a stone box in the lower bunker is necessary to control the segregation from the lower bunker. The suitable position of the stone box is close to the upper burden surface.

Similar type of work (CF type bunkers) has also been performed by Standish. The hopper used for the experiment was smaller in diameter than was previously used by Aminaga *et al*. Standish used five sinter size fractions from 0.5-3 mm. Some of the observations made by Aminaga *et al.* do not match with the results obtained by Standish. According to Standish, a conical insert with proper design and position in the hopper can change the funnel flow into a plug flow. Moreover, Standish's experiments show that a stone box near the upper burden surface does not significantly change the size variation in the lower hopper which is in contrast to Aminaga *et al.*. Several promising alternatives were tried to reduce the size variation from both the hoppers. Installation of a stone box ahead of the conveyor belt discharge could reduce size variation from both the hoppers remarkably.

Yamaguchi *et al.* of Nippon Steel have developed an online system in Kimitsu No. 4 blast furnace which is capable of measuring time series particle size by image analysis and by using microwaves. These data are then composed in a process computer by using Rosin-Rammler's technique and this composite data is fed to the RABIT model to obtain the trend of the gas flow distribution. The time series particle size is controlled for a desired gas distribution by the use of certain segregation controlling devices. The storage bins are equipped with upper and lower dampers which may be operated to change the particle size in the main belt conveyor and a rotating chute is installed in the upper hopper of the CF type bunker to control the segregation behaviour of particles charged in the furnace. With the installation of this system, only the tilting angle of the upper hopper rotating chute needs to be changed in place of the bell-less notch adjustment for taking any control action with regards to changing the gas distribution. Therefore, unlike other furnaces, different gas distributions can be obtained with a single fixed charging sequence with this system.

Most recently, Jung *et al.* (2001) have performed similar type of work like Aminaga *et al*. and Standish on a centre feed-type bunker. They have primarily used a 1/12 scale model and also an actual blast furnace (Pohang No. 1) to observe the effect of discharge rate and interior structure of bunker (lower bunker with stone box, without stone box, stone box with central chute) on the time serial particle size change during discharging from the lower bunker and the radial particle size distribution in the blast furnace. The size ranges used in this study for ore and coke were 0.5-4.75 mm and 2-6.35 mm respectively. A suitable particle size distribution was also considered for both ore and coke. The following observations are to be noted:

(a) The particles size distribution of ore during discharging from the surge hopper to the upper hopper was not changed with discharge rate varying from 54-130% of the standard value (1.27 Kg/s).
(b) In the upper bunker, the particle size at the lower part of the hopper was smaller than the upper part of burden layer. Also, the particle size at the wall region was larger than the central part regardless of the vertical location of the sampling points.
(c) In the lower bunker of the scale model, the particle size distribution was greatly different from the upper bunker. The particle size distribution changed inconsistently in the vertical and radial direction as compared with the consistent change in the upper bunker. This big difference and abnormal distribution has been attributed to the central location of the stone box in the lower bunker and it was concluded that the particle size distribution in a bunker with a stone box depends on the dimension of the bunker. Therefore, as opposed to the results of Aminaga *et al.* and Standish, the stone box may produce peculiar size distribution depending on the size of the bunker and it is expected that small sized blast furnace with CF-type bunkers equipped with stone box might have an extraordinary time serial particle size change during discharging from the lower bunker.
(d) In order to overcome the problem with a stone box, the present workers installed a central chute around the stone box to change the shape of the burden layer from M to inverted-V. Through adjusting the shape of burden layer by reconstruction of the lower bunker, it was possible to obtain the normal particle size distribution

in which large particles were deposited on the wall part and small particles on the centre part.

Tanaka *et al.*[17] have developed a first principle 2D mathematical model which is capable of describing the macroscopic movement of an assembly of particles. It was originally used to simulate the granular flow and related segregation phenomena in hoppers and later modified by Kajiwara *et al.*[18] and Tanaka *et al.*[19] to analyze the formation process of burden distribution at blast furnace top and the flow dynamics of granular materials in the upper part of blast furnace. The mathematical model uses discrete approach to analyze the granular flow problem. The distinct element method or DEM technique has been employed to write down the equation of motion (Newton's 2nd Law) of each single particles and the constitutive equation for interaction between two particles is described by a Voigt-Kelvin rheological model with a slider and dashpot. Originally, Cundall *et al.*[20] (1979) described such type of discrete modeling to model the behavior of a group of particles, but they did not consider the viscous effect to estimate the sliding condition. But, Kajiwara *et al*. used a slider and dashpot which represented the kinetic energy dissipation of particles and the accuracy of the model was enhanced. In the present study, the dashpot factor was experimentally determined. The authors have cited a few references (first seven references) where different techniques were reviewed and their drawbacks in effectively modeling the flow dynamics of granular material were mentioned. There is extensive literature on the flow of granular materials under the assumption of continuum, but they lack generality and cannot capture the segregation phenomena with higher analytical accuracy. The present authors claim that their work has led to a better understanding of the solid flow in the process and can remove the inherent difficulties in continuum approach.

In the above analysis, an infinitesimal displacement of particle in a very small time step generates the force among particles through the constitutive equations. This force, in return, produces infinitesimal displacements among particles again through the equations of motion. Thus, alternative solving of constitutive equations and equation of motion on each particle with respect to variables, such as velocity, force and coordinate under the appropriate boundary condition with time marching provides the macroscopic dynamic behavior of an assembly of granular materials. This model has been applied to understand the segregation behavior during discharge from a hopper. It has been used to analyze the particle size distribution when a stone box was used in the hopper. The results are similar to as obtained by Aminaga *et al.* and it has been found that the installation of a stone box suppresses the variation of particle size distribution during discharge in the radial direction. The present model also precisely describes the frictional wall effect in solid flow and bridge formation. The size segregation phenomena in bell charging has been quantitatively evaluated with the application of this model. The effect of charging rate on particle size distribution has also been analyzed with this model. The quantitative results are in agreement with the experimental findings of Haru *et al.* An increase in charging time increases the small particle content in the wall region and decreases the same in the central part.

Inada *et al.*[21] had developed another model for bell type charging which could be used for multiple size systems since their DEM based previous model would take large computation time for simulation of multiple size system with more number of particles. The present model uses the theory of percolation to model the sieving behavior of smaller particles on the slope (Figure 1). The deposit behavior on the slope is modeled considering whether the flow down the slope is a thick or thin flow (Figure 2). The percolation frequency of the small particle is dominated by particle size ratio (d_b/d_p) and the velocity gradient *dv/dh*. Therefore, for particles of the same physical properties, the percolation frequency λ of small particle is expressed by the following equation:

$$\lambda=\lambda(d_b/d_p, dv/dh)$$

Where λ ( ) is a function to be determined experimentally. Experiments by Bridgewater *et al.*[22] have shown that the functional behavior of λ is as follows:

$$\lambda = \begin{cases} \alpha(dv/dh)(d_b/d_p)^3 : & d_b > d_p \\ 0 \qquad : & d_b \leqq d_p \end{cases}$$

Where α is a constant dependent on particle surface properties. The probability of small particle to be found at a distance l and at a time t is given by a Poisson distribution function. The calculation flow of the present model is shown in Figure 3. The layer thickness of particle flow at the falling point of burden (h_0) is calculated by the following equation:

$$h_0 \simeq \dot{W}/(2\pi R V_0 \cos\theta \cdot \rho_b)$$

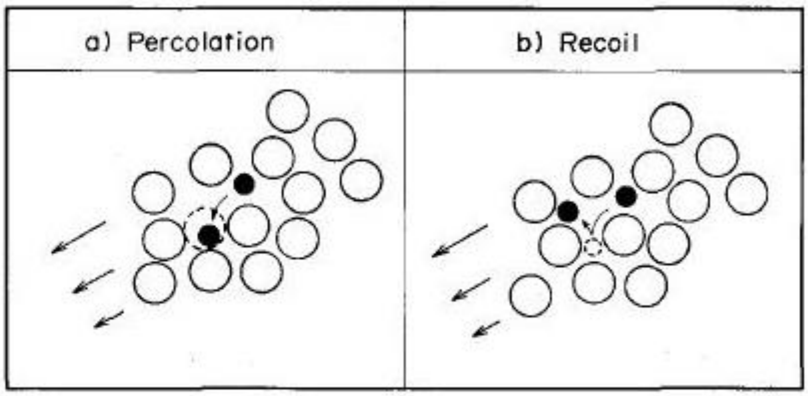
The nomenclature for the above calculation is shown in Figure 4. The vertical division number of the flowing layer at the falling point (N) is calculated by the following equation (Figure 2):

$$\mathcal{N} = \frac{h_0}{d_b}$$

Δt is the traveling time of particles from one deposit region to the next.

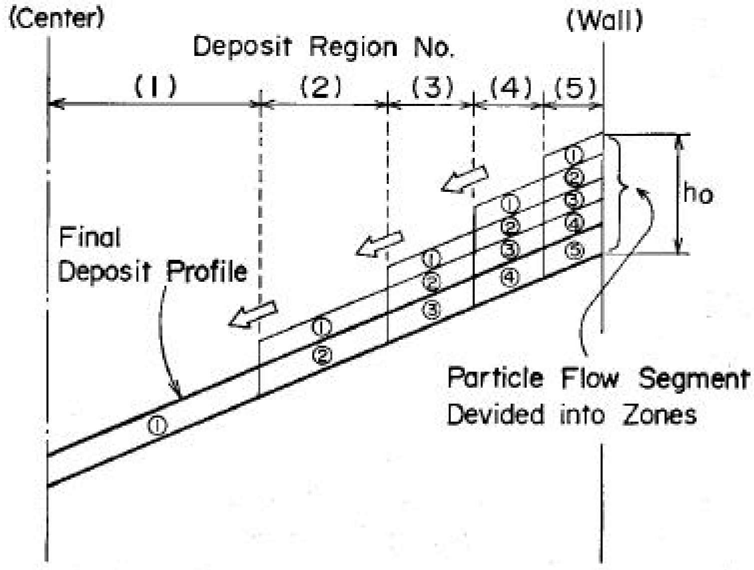
The above model was successfully applied to the prediction of the increase in permeability in the centre and suppression of peripheral gas flow of Wakayama #4 blast furnace caused by the enhancement of size segregation through the decrease of large bell stroke.

Recently, Sunahara *et al.*[23] of Sumitomo Metal (1999) have also studied the mechanism of size and density segregations of particles deposited on the slope at blast furnace top by experiments and numerical analysis. They have felt that though the basic particle segregation mechanisms has been studied by many researchers (first six references there in), there are very few reports which have actually applied these fundamentals in an actual blast furnace operation, especially on mixed charging. An inevitable problem of mixed charging is the particle segregation by which the deposited position of the coke and ore cannot be controlled. The present work was specially aimed at understanding the segregation when mixed charging is used which, if used favorably, may increase the central gas flow. In the present work, experiments were carried out with a 1/7 scale rectangular model to investigate the fundamental phenomenon of particle size segregation. Steel, alumina, glass, nylon, sintered ore, coke with different densities and diameters were used. In the formulation of the mathematical model for size segregation,



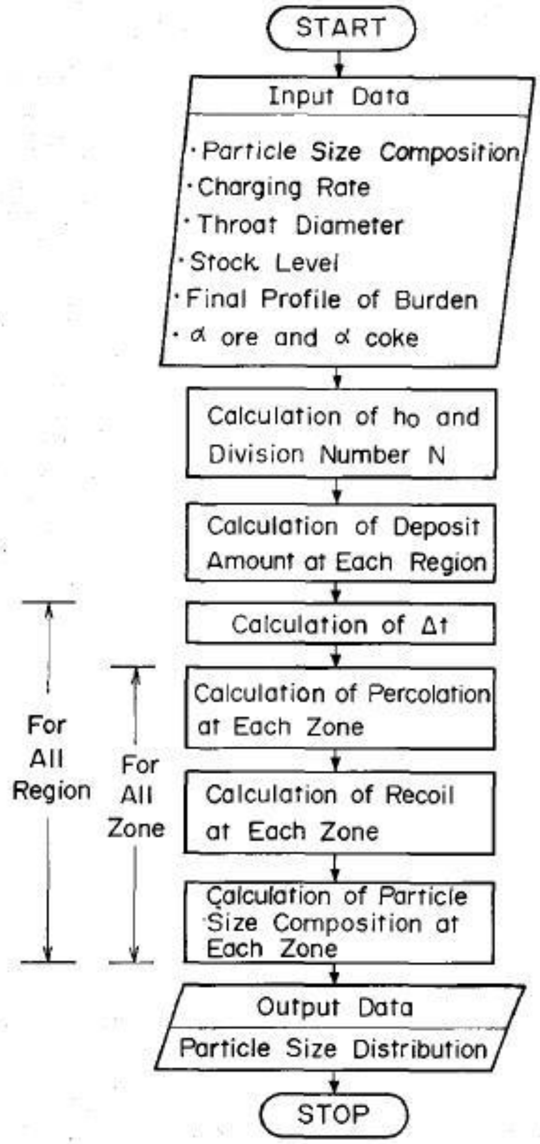
Scheme of percolation and recoil of a small particle on the slope.

Figure 1



Deposit behavior of flowing particle on the slope.

Figure 2



Calculation flow chart of the mathematical model for particle size distribution.

Figure 3

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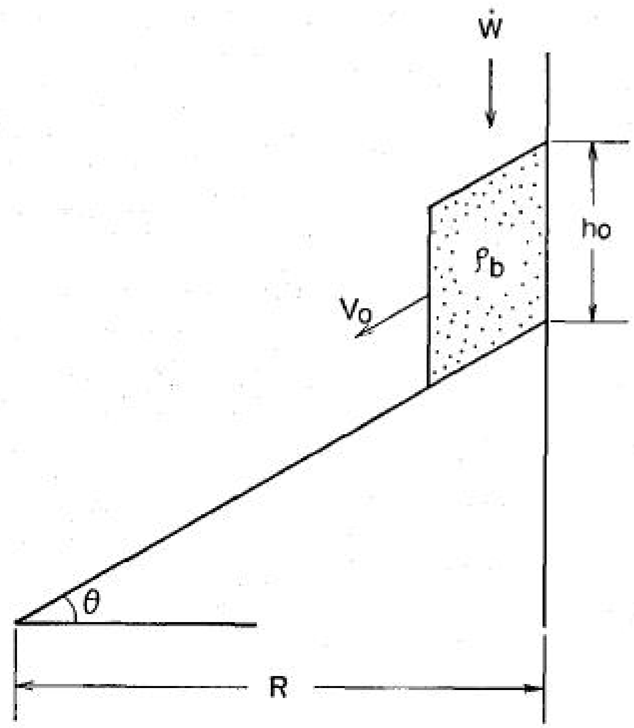

Notation used for calculation of h_0.

Figure 4

the same percolation theory as reported by Inada *et al*. was used. The density segregation was modeled using a simple two particle colliding system where the momentum was conserved in the collision. A density segregation parameter β was introduced which depends on particle surface properties and is to be determined experimentally. The percolation frequency was related with particle density and an inequality was obtained which marked the limits for the size and density segregation.

Kondoh *et al.*[24] of Kawasaki Steel (JFE), Okuno *et al.*[25] of Nippon Steel and Hockings *et al.*[26] of BHP steel (BlueScope Steel) reported same size classification approach of powder technology to predict the radial size segregation in the blast furnace. The following equation developed by Miwa[27] was used by all of them:

$$log\left(\frac{x_n}{x_{n-1}}\right)=log\left(\frac{x_n^f}{x_{n-1}^f}\right)-(\alpha_n-\alpha_{n-1})l$$

Where:
l: distance in the flowing direction
x_n: weight fraction of nth size
α_n: size segregation constant
f: a suffix for the feed

By substituting x^0_n at l=0 for x_n^f and rewriting for only nth size the above equation can be expressed as:

$$\ln\left(\frac{x_n}{1-x_n}\right) = -\alpha l + \beta$$

where β is a constant.

Usually, α and β are determined experimentally as is done by Hockings for BHP Steel. A plot (Figure 5) for $ln(x_n/1-x_n)$ versus distance from wall for one size fraction of coke *(+50 mm*) and of sinter (*+13.2 mm*) indicates two typical regions. From this plot, two values of α, one for the centre and the other for the wall side can be obtained. β can be calculated from the boundary condition. Figure 6 shows the accuracy of this model to predict radial size segregation of coke and sinter.

Once the particle size distribution is known the void fraction distribution in the radial direction can be calculated. Kajiwara *et al.*[28] of Sumitomo Metal used the following equation for estimating radial void fraction for coke and ore:

$$\varepsilon_C\left(\frac{r}{R_O}\right) = 0.153\log\left\{d_p\left(\frac{r}{R_O}\right)\right\} + 0.418$$

$$\varepsilon_O\left(\frac{r}{R_O}\right) = 0.403\left\{d_p\left(\frac{r}{R_O}\right)\right\}^{0.14}$$

Where:

ε_c: void fraction of coke at dimensionless position r/R_o

ε_o: void fraction of ore at dimensionless position r/R_o

d_p: harmonic mean size of particle at r/R_o

The above equation was actually proposed by Yamada *et al.*[29] of Kawasaki Steel. Before using this equation, Kajiwara *et al* had actually measured the particle size distribution by burden sampling in the furnace filling tests. The particle size distribution in their case was approximated by a quadratic function of radial position which they have not reported.

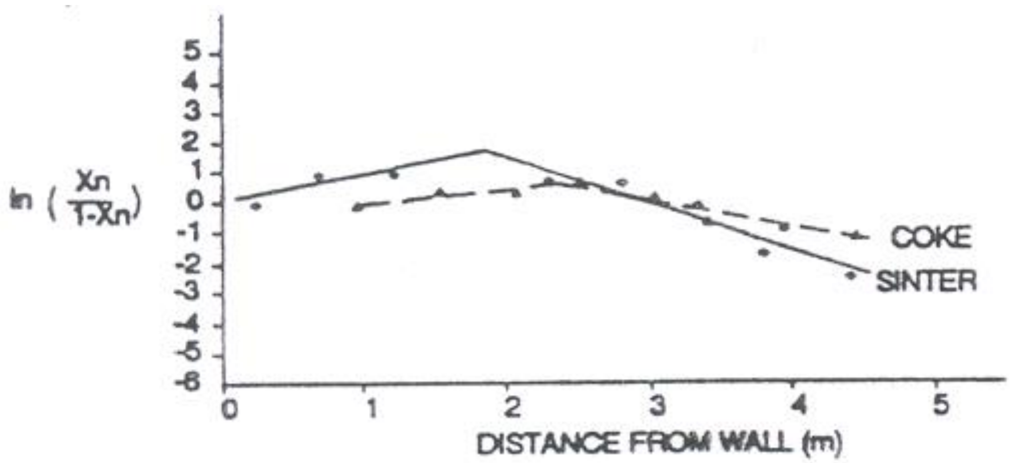

Figure 5

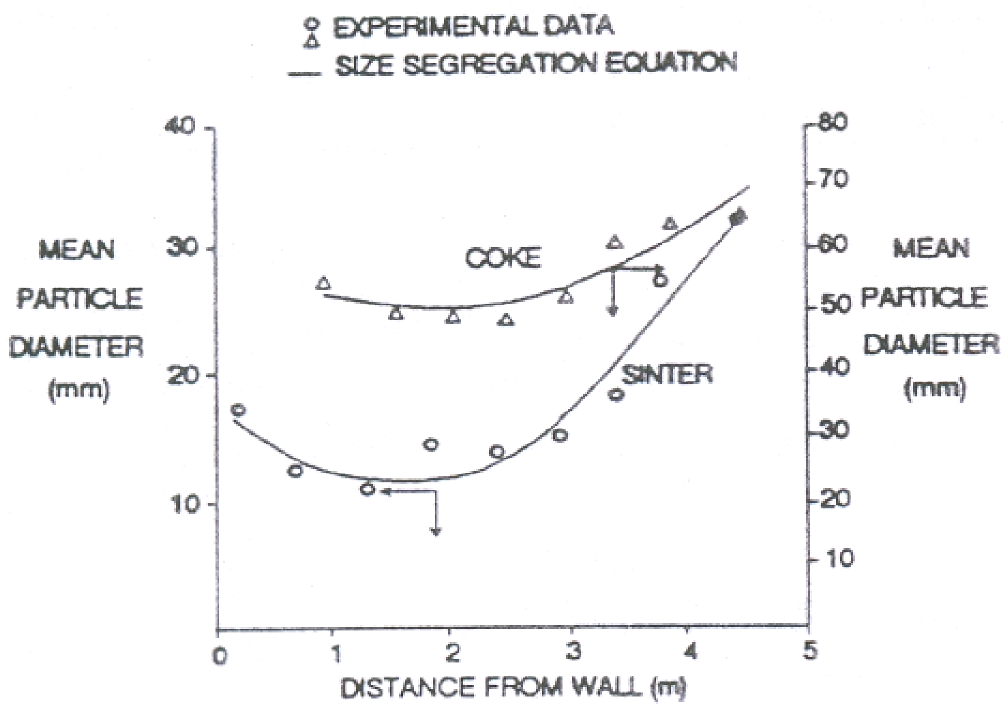

Figure 6

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Conclusions:

- Most of the reports contain experimental methods to understand the segregation phenomena. Effects of different variables on the segregation can be established from these experiments, but sometimes, the findings are not reproducible owing to the fact that experimental conditions were not same. Moreover, most of the reports contain information for certain conditions, which may not be generalised and thus lacks universal utility. Some reports lack technical detail and justification owing to the secretive nature of industrial models.
- Fundamental understanding of the segregation phenomena is not yet complete. Mathematical approaches are not generic in nature and may not be applicable for other systems. Most of the time, a solution to a problem has been sought rather than the understanding of a phenomenon. Therefore, a working model may be developed on ad-hoc basis which may not necessarily be universal.
- Both continuum and discrete approach of modeling should be employed and efforts should be made to gain the insight from a physics point of view.

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