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EFFECT OF DEFLECTOR PLATE FOR PARTICLE SIZE SEGREGATION CONTROL

In general, uniform mixing of particles is desirable in the process of particle handling. However, during the charging of sinter feed and upper ore, size segregation must be induced to prevent heat imbalance, ensure bed permeability, and prevent the loss of fine ore. In this study, upper ore charging was simulated using a discrete element method (DEM) to find the optimal method for controlling particle size segregation, and the segregation characteristics in the upper ore bed were investigated when a deflector plate was applied to the charging machine. The degree of vertical segregation increased when a deflector plate was applied, and it was confirmed that the segregation direction in the upper ore bed can be controlled by adjusting the charging direction of the upper ore by using a deflector plate. In order to apply this method directly to the actual process, further study is needed to understand the influence of the characteristics of the deflector plate such as length and angle.

Keywords: Size segregation, Numerical analysis, Discrete element method

1. Introduction

Achieving good mixing of solid particles of different physical properties is very important in many industrial processes. However, when particles of different sizes or densities move, they become segregated. In the mixing process, it is generally desirable to suppress this segregation phenomenon to achieve a uniformly mixed state, but in some cases, it is desirable to induce size segregation in a specific direction.

For example, fine iron ores (8 mm) used in the ironmaking process must be agglomerated to maintain good gas permeability in the blast furnace. As shown in Figure 1, the sintering process, which is typically used to agglomerate fine iron ore particles, begins with the relatively large sintered ore, called the upper ore, at the bottom of the pallet to ensure gas permeability and to prevent loss of sinter feed [1]. Sinter feed consisting of fine ore, coke breeze, and limestone is then deposited on top of the upper ore bed through a charging chute. When sintering of sinter

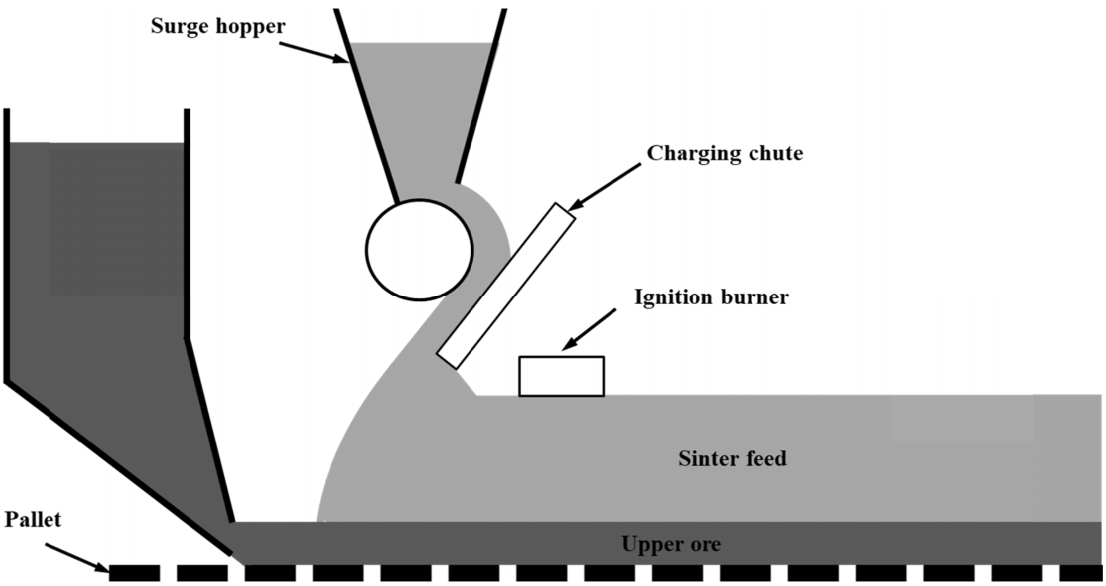

Fig. 1. Schematic diagram of sintering process of iron ore

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feeds is carried out of combustion of coke, a thermal imbalance occurs in the bed such as a lack of heat at the upper part and excessive heat at the lower part [2]. This can degrade the quality of the sintered ore. Therefore, to overcome this thermal imbalance, it is necessary to place cokes that is relatively small particles are located at the upper part of the bed when the sinter feed is charged [3]. Furthermore, since the grate bar installed at the bottom of the pallet has a pitch of 5 mm, larger ores should be placed above the grate bar to prevent the loss of fine ore particles smaller than 5 mm.

Although it is necessary to study how particle size segregation phenomena can be controlled to solve these types of engineering problems, it is very difficult to understand the particle flow characteristics of large-scale processes. Therefore, we considered numerical method using the discrete element method (DEM) as one way to solve this problem. DEM is the most widely used numerical method for simulating solid particle behavior, and many studies using DEM in the ironmaking process have been published recently [3-7].

In this study, the charging of the upper ore was simulated using EDEM, which is a commercialized DEM-based particle behavior analysis software, and changes in the size segregation state of the upper ore bed deposited on the pallet were measured and compared.

2. Method for DEM analysis

2.1. Discrete element method

The discrete element method is the most widely used numerical method for simulation the solid particle behavior. The motion of each particle is calculated by the following governing equations [3].

$$m_p \frac{dv_p}{dt} = \sum_{j \neq i}^{N_c} F_c + F_f + F_g \tag{1}$$

$$I_p \frac{d\omega_p}{dt} = R_p \sum_{j \neq i}^{N_c} \left(F_{cs} - F_r \right) \tag{2}$$

In this equation, m_p, v_p, t, F_c, N_c, F_f, F_g, I_p, ω_p, R_p, F_{cs} and F_r indicate the particle mass, particle velocity, time, inter-particle contact force, number of particles contacted, force on the particle from the fluid, gravity, moment of inertia, angular velocity, particle radius, tangential force in the shear direction, and rolling resistance, respectively.

2.2. Condition of upper ore charging simulation

Particle properties such as size distribution and density, static friction coefficient and restitution coefficient of real upper ore were measured to model the particles for DEM simulation. The chemical composition of the upper ore used in the measurement is shown in Table 1. The particle size distribution was obtained as shown in Table 2 as a result of size separation of 10 kg upper ore. The sizes of the modeled particles were set to 2.5 mm, 4 mm, 8mm in diameter, respectively. The density of the upper ore which is the porous body, was calculated through measurement of weight and volume change when the upper ore was put into the measuring cylinder containing water. The coefficient of static friction used in particle modeling was calculated using Equation (3) after measuring the angle of slope at which particles begin to slide, as shown in Figure 2, and the coefficient of restitution was calculated using Equation (4) after measuring the height at which the particles bounced after falling, as shown in Figure 3.

Coefficient of Static friction, $\mu_s = mg\sin\theta / mg\cos\theta$ (3)

Coefficient of restitution, $C_r = \sqrt{h/H}$ (4)

The geometry and specifications of the upper ore charging machine for the DEM simulations were modeled on the basis of the actual equipment and operating conditions. A schematic diagram of the charging machine and charging conditions are

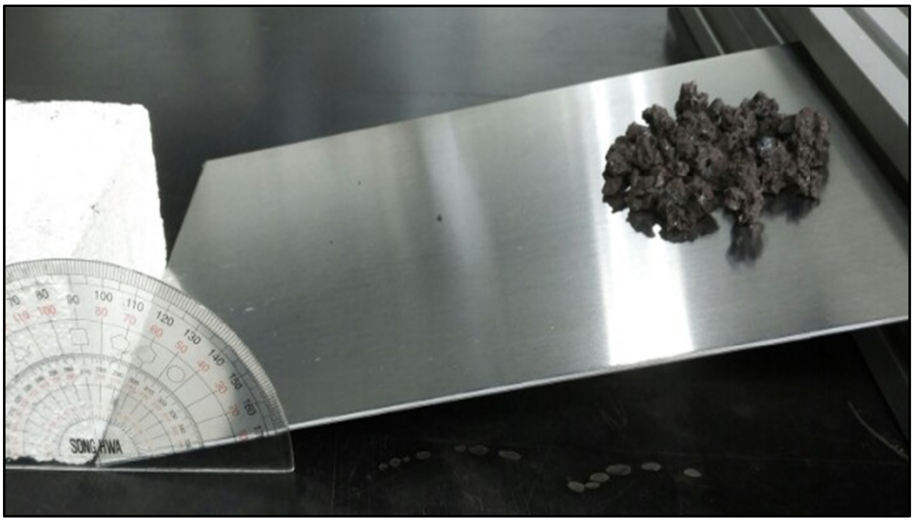

Fig. 2. Measuring method of coefficient of static friction

TABLE 1

Chemical composition of upper ore

Fe_2O_3	83.15	[wt.%]
SiO_2	9.14	
Al_2O_3	5.87	
CaO	0.19	
MnO	1.30	
MgO	0.35	

TABLE 2

Size distribution of upper ore

2 ~ 2.8 mm	8.38	[wt.%]
2.8 ~ 5 mm	49.74	
5 ~ 9.5 mm	41.88	

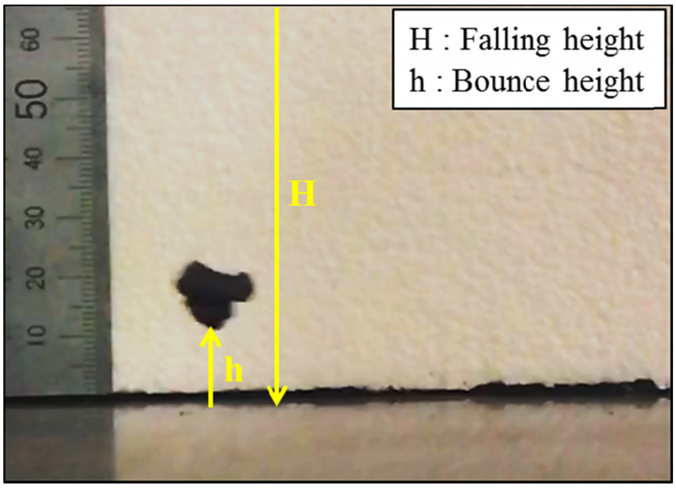

Fig. 3. Measuring method of coefficient of restitution

shown in Figure 4 and Table 3. In order to investigate the effect of a deflector plate on the charging behavior and size segregation of upper ore, guide plates and deflector plates were installed in combinations of three types. The bed height was set to be 60 mm by controlling the charging speed and the width of the pallet was reduced to reduce calculation time assuming that the particle size distribution is uniform in the width direction. Furthermore, to avoid the influence of the wall, the width was set to 80 mm which is ten times the largest particle diameter [7].

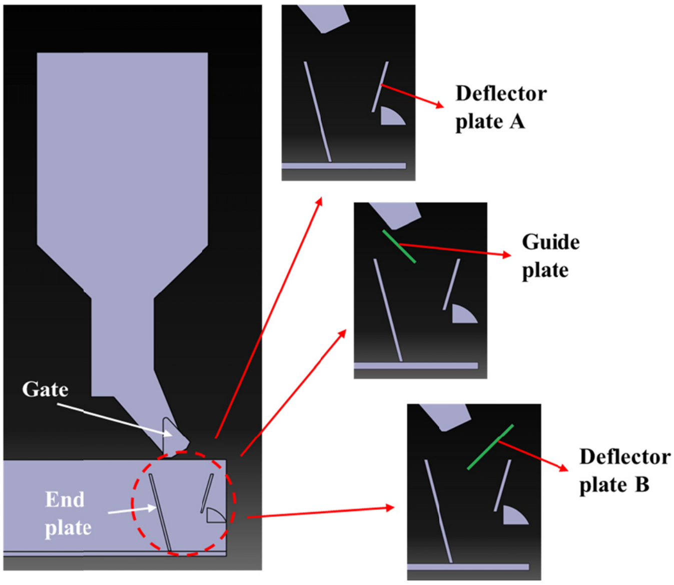

Fig. 4. Upper ore charging machine with (a) deflector plate *A*, (b) guide plate and deflector plate *A*, (c) deflector plate *B* installed

2.3. Measurement and definition of size segregation

The following method was used to compare the degree of size segregation in the upper ore bed. First, we calculated a dimensionless mean particle size at the top, middle, and bottom layers in the bed. The result of this calculation was plotted against the total bed height, and then a linear equation of the form of $Y = AX + B$ was derived by linear regression. The slope, A, of this linear equation was defined as the size segregation index [8].

TABLE 3

Conditions of upper ore charging simulation

Modeling of particle	Diameter of particle	small	2.5	[mm]
		medium	4.0	
		large	8.0	
	Density of particle		3650	[kg/m^3]
	Charging ratio	small	8.38	[%]
		medium	49.74	
		large	41.88	
	Shear modulus		0.85	[MPa]
	Poisson's ratio		0.3	[-]
	Coefficient of static friction	particle-particle	0.5	[-]
		particle-wall	0.5	
	Coefficient of restitution	particle-particle	0.3	[-]
		particle-wall	0.2	
Charging condition	Charging speed		2.0	[kg/s]
	Pallet speed		0.46	[m/s]
	Bed height		60	[mm]

3. Results and discussions

Figure 5 shows a cross section of the upper ore bed. When only the conventional deflector, plate *A*, was installed, the particle size distribution was uniform. The addition of the guide plate increased the segregation effect, resulting in large particles being located at the bottom of the bed and small particles being located at the top. On the other hand, in the case of deflector plate B, not only was the height of the bed lower, but reverse segregation also occurred, in contrast to the case of deflector plate *A*. As described above, the mean particle size at the top, middle, and bottom layers of the bed was measured and the size segregation index was calculated. The results are shown in Figures 6 and 7. When the guide plate and deflector plate *A* were installed together, the mean particle size decreased toward the bed surface, and thus the segregation index was negative and increased. On the other hand, since deflector plate *B* resulted in a positive segregation index, it can be confirmed that reverse segregation definitely occurs.

Williams [9] classifies particle size segregation mechanisms as shown in Figure 8. Among the particles moving on the deflector plate, the larger ones rise by the principle of 'rising of coarse particles by vibration', while the smaller ones adjacent to the slope of the deflector plate decrease in speed due to friction.

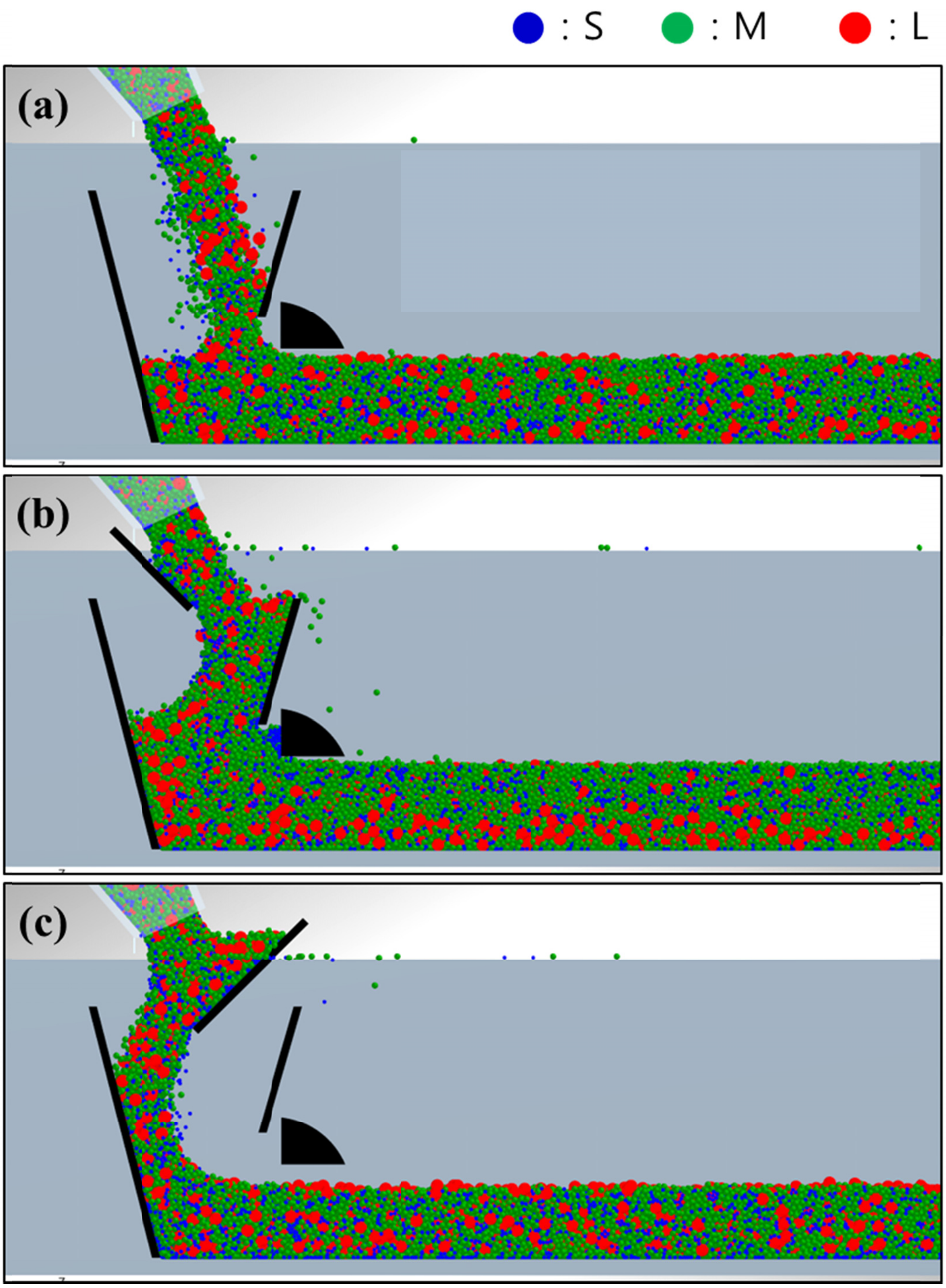

Fig. 5. Charging behavior of upper ore: (a) deflector plate *A*, (b) guide plate and deflector plate *A*, (c) deflector plate *B*

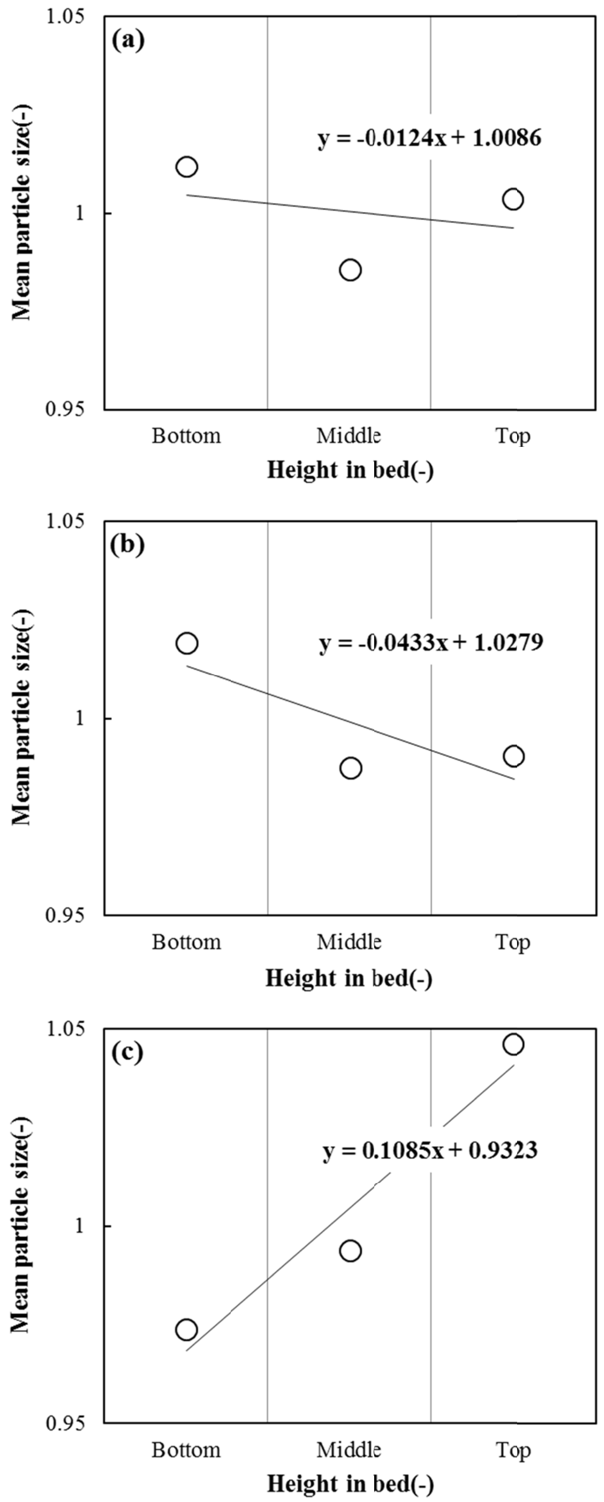

Fig. 6. Mean particle size distribution with different deflector plate types: (a) deflector plate *A*, (b) guide plate and deflector plate *A*, (c) deflector plate *B*

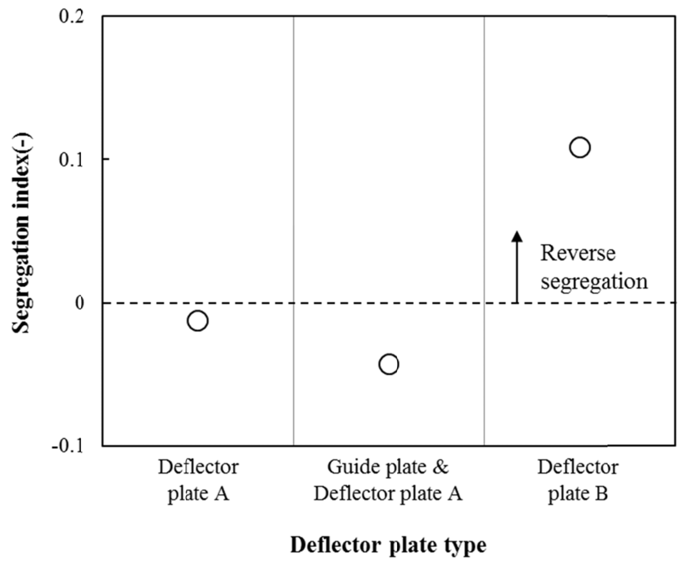

Fig. 7. Changes in segregation index with different deflector plate types

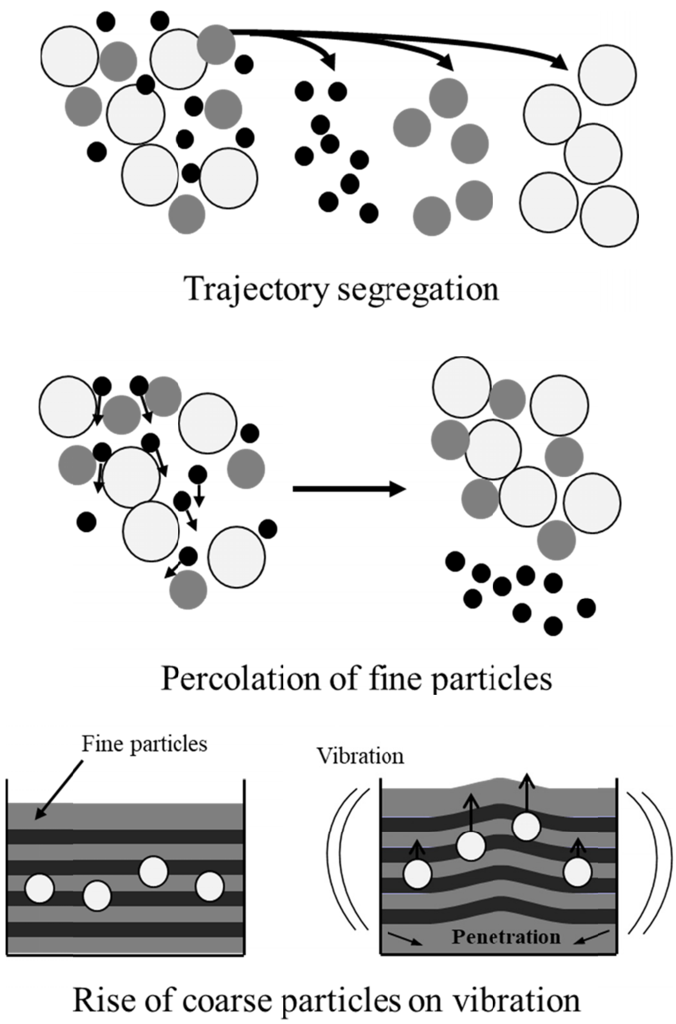

Fig. 8. Classification of size segregation mechanism

Then, the distances that the particles fall from the deflector plate are differentiated by the principle of 'trajectory segregation', and this difference causes horizontal segregation.

This horizontal segregation changes to vertical segregation when particles reach the moving pallet. Therefore, when particles are charged through deflector plate *A*, the charging direction is opposite to the moving direction of the pallet, so that the larger particles are positioned on the bottom and the smaller particles are stacked on top. On the other hand, when deflector plate *B* was installed, since deflector plate *B* substantially serves as a guide plate and the end plate serves as a deflector plate, particles were charged in the same direction as the motion of the pallet. This also means that the segregation direction was reversed and 'reverse segregation' occurred.

We have confirmed that it is possible to induce size segregation and control the direction of particle segregation during charging by simply adding a deflector plate to the existing process. Furthermore, it is confirmed that a sufficient degree of control can be obtained even though the moving distance on the deflector plate is short compared with the upper ore size, and the bed height is lower as 60 mm. However, variables such as the angle, length, and position of the deflector plate, and the interactions between particles and the plate should have a large effect on particle flow, so further studies of the basic properties of deflector plates are needed.

4. Conclusions

In this study, in order to find an effective method of controlling particle size segregation, the charging behavior of upper ore in the ironmaking process was analyzed using DEM simulations and the following conclusions were obtained.

1) Installing a deflector plate near the outlet of the hopper may cause directional size segregation when the upper ore is charged, and it was confirmed that the segregation direction can be changed by controlling the particle flow through the combination of guide plate and deflector plate.
2) Directional size segregation occurs through two steps. First, on the deflector plate, due to 'rising of coarse particles by vibration', large particles are positioned on the surface of the particle flow. Secondly, segregation occurs due to the difference in travel distance by the principle of 'trajectory segregation' when particles leave the deflector plate.
3) Segregation can be effectively controlled by using a guide plate and deflector plate because sufficient segregation occurs even if the upper ore bed height is low. However, in order to apply this method directly to the actual process, further study is needed to understand the influence of the characteristics of the deflector plate such as length, angle, and other properties.

Acknowledgments

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REFERENCES

[1] S.S. Yoon, D.S. Shin, J.N. Lee, J. of the Korean Inst. Of Met. & Mater. **34**, 1202 (1996).
[2] H.J. Kang, S.M. Choi, W. Yang, B.K. Cho, ISIJ Int. **51**, 1065 (2011).
[3] K.M. Kim, K.W. Lee, J.H. Kwon, H K. Jeong, J.W. Han, Korean J. Met. Mater. **55**, 896 (2017).
[4] R. Soda, A. Sato, J. Kano, E. Kasai, M. Hara, T. Kawaguchi, ISIJ Int. **49**, 645 (2009).
[5] J.I. Park, H.J. Jung, M.K. Jo, H.S., Oh, J.W. Han, Met. Mater. Int. **17**, 485 (2011).
[6] S. Ishihara, R. Soda, Q. Zhang, J. Kano, ISIJ Int. **53**, 1555 (2013).
[7] M. Nakano, T. Abe, J. Kano, K. Kunitomo, ISIJ Int. **52**, 1559 (2012).
[8] S. Mizukami, T. Maehana, H. Murata, J. Soc. Powder Technol. **23**, 871 (1986).
[9] J.C. Williams, Powder Technol. **15**, 245 (1976).