Dynamics and stability of particle flow with lateral gas blasting

Kaoru Nakano, SUMITOMO METAL INDUSTRIES, LTD., Kamisu, Ibaraki, Japan

Introduction

Lateral gas blasting into packed bed makes cavity with circulating particles called raceway in blast furnace. The raceway plays an important role in distributing reducing gas and heat upward in blast furnace while regularity of particle descent and gas distribution relies on stability of raceway. Therefore, stability of raceway is important for operation of blast furnace. Many works (Wagstaff et al. [1], Hatano et al. [2]) have been reported about size of raceway. And recently Umekage et al. [3] numerically simulated raceway unsteadiness using Discrete Element Method (DEM). However, raceway and fluidization phenomena have not been sufficiently understood. In this study, the influence of tuyere diameter and blast volume, which are main factors on formation of raceway in front of tuyere, on stability of raceway is discussed in terms of energy balance between gas and particle bed by DEM simulations.

Simulation model

Continuum model

The fluid field is calculated from the continuity and Navier-Stokes equations based on the local mean variables by use of SOLA method [4]. The fluid is assumed to be incompressible and inviscid. The equations are written as follows:

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\varepsilon \mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\varepsilon \mathbf{u}) + \nabla \cdot (\varepsilon \mathbf{u}\mathbf{u}) = -\frac{\varepsilon}{\rho_g}\nabla p + \mathbf{f}_d \tag{2}$$

where ε, $\mathbf{u}$, ρ_g, p are void fraction, gas velocity, gas density and pressure, respectively, and $\mathbf{f}_d$, volumetric fluid-particle interaction force, is given by

$$\mathbf{f}_d = \mathrm{F_p} \cdot \varepsilon(\mathbf{v} - \mathbf{u}) \tag{3}$$

where $\mathrm{F_p}$ is evaluated by Ergun's equation for void fraction less than 0.8 or Wen and Yu's equation for void fraction greater than 0.8 as shown in following expression.

$$\mathrm{F_p} = \begin{cases} \dfrac{\mu_g(1-\varepsilon)}{\rho_g \varepsilon^2 \mathrm{D_p}^2}[150(1-\varepsilon) + 1.75\,\mathrm{Re}] & (\varepsilon \le 0.8) \\ \dfrac{3}{4}\mathrm{C_D}\,\dfrac{\mu_g(1-\varepsilon)}{\rho_g \varepsilon^{3.7} \mathrm{D_p}^2} \cdot \mathrm{Re} & (\varepsilon > 0.8) \end{cases} \tag{4}$$

where $\mathrm{D_p}$ and μ_g are particle diameter and gas viscosity, respectively, and $\mathrm{C_D}$, the fluid drag coefficient, Re, the Reynolds number, can be expressed respectively as

$$\mathrm{C_D} = \begin{cases} 24(1+0.15\,\mathrm{Re}^{0.687})/\mathrm{Re} & (\mathrm{Re} \le 1000) \\ 0.43 & (\mathrm{Re} > 1000) \end{cases} \tag{5}$$

$$\mathrm{Re} = \frac{|\mathbf{v}_i - \mathbf{u}|\rho_g \varepsilon \mathrm{D_p}}{\mu_g} \tag{6}$$

Discrete model

DEM was originally developed in the field of soil mechanics by Cundall and Strack [5]. And Tsuji et al. [6,7] applied it to particle-fluid systems. The translational and rotational motion of a particle can be described by the following equations:

$$m_i \frac{d\mathbf{v}_i}{dt} = m_i \mathbf{g} + \sum_{j=1}^{k_i} (\mathbf{F}_{cn,ij} + \mathbf{F}_{ct,ij}) + \mathbf{F}_{Di} \tag{7}$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{i=1}^{k_i} \mathbf{T}_{ij} \tag{8}$$

where m_i, I_i, $\mathbf{v}_i$, $\boldsymbol{\omega}_i$ and $\mathbf{T}_{ij}$ are, respectively, the mass, moment of inertia, translational and rotational velocities and torque. The forces involved are the gravitational force, and the inter-particle forces between particles i and j, which include the normal and tangential contact forces, and the fluid drag force. The inter-particle forces are summed over the k_i particles in contact with particle i. The contact force model used is linear model, which is given by

$$\mathbf{F}_{cn,ij} = -\kappa_{n,i} \boldsymbol{\delta}_{n,ij} - \eta_{n,ij} \mathbf{v}_{n,ij} \tag{9}$$

$$\mathbf{F}_{ct,ij} = -\kappa_{t,i} \boldsymbol{\delta}_{t,ij} - \eta_{t,ij} \mathbf{v}_{t,ij} \tag{10}$$

where the subscripts n and t denote the normal and tangential direction, respectively; κ_i and η_i are the spring constant and viscous contact damping coefficient of particle i, respectively; $\boldsymbol{\delta}_{ij}$ is the displacement vector between particle i and j, $\mathbf{v}_{ij}$ is the velocity vector of particle i relative to j at the contact point. The spring constant and the viscous contact damping coefficient in the tangential direction are evaluated based on Thornton and Yin's work [8]. $\eta_{n,ij}$ is determined by restitution coefficient of particle as follows:

$$\eta_{n,ij} = 2\gamma\sqrt{m_i \kappa_i} \tag{11}$$

where γ is given by $\gamma = \frac{\alpha}{\sqrt{1+\alpha^2}}$, where α is given by

$$\alpha = -\frac{1}{\pi} \ln e \tag{12}$$

where e is the restitution coefficient. The magnitude of the tangential component of the contact force is subjected to the Coulomb's law of friction. When $|\mathbf{F}_{ct,ij}| > \mu_{ij} |\mathbf{F}_{cn,ij}|$ is satisfied, sliding occurs with the tangential force as described as follows:

$$\left|\mathbf{F}_{ct,ij}\right| = \mu_{ij}\left|\mathbf{F}_{cn,ij}\right| \tag{13}$$

The fluid drag force can be written as follows:

$$\mathbf{F}_{Di} = \frac{\pi \mathrm{D}_{pi}{}^{3} \rho_g \mathrm{F}_{\mathrm{p}}}{6\varepsilon(1-\varepsilon)} \cdot \varepsilon(\mathbf{u} - \mathbf{v}_i) \tag{14}$$

In this simulation model, the fluid drag force is calculated to balance its summation in calculation cell with the fluid-particle interaction term in eq. (2).

Experiment

Physical experiments to form raceway with lateral gas blasting were carried out to examine the validity of the simulation model.

Conditions for experiments and simulations

As shown in Fig. 1, the rectangular container was filled with many particles to form packed bed. The packed bed was laterally blasted by cold air through tuyere, which is attached to the side wall, to form raceway. The burden descent was induced by discharge of particles from the bottom of the container. The discharging area was located from 0.05 to 0.15 m in horizontal distance from the side wall to which tuyere was attached. And particles were provided from the hopper which placed on the top of the container to keep the stock level of the bed, while particles were discharged. The pressure at the point where was 0.1 m apart from the side wall, to which tuyere was attached, on tuyere axis was measured in the experiments. The conditions for the experiments are listed in Table 1. And conditions for DEM simulations are listed in Table 2. In this simulation, particle diameter was set to be greater than real one to reduce time for calculation. In this operation, the fluid drag force was calculated to the real particle diameter.

Table 1 Conditions for experiments

Particle diameter (mm)	3
Particle density (kg/m^3)	1000
Blast volume (Nm^3/s)	1.33×10^{-2}
Tuyere diameter (mm)	8, 12
Length of tuyere (mm)	0
Rate of burden discharge (kg/s)	8.0×10^{-3}
Raceway factor[2] (-)	560 - 1800

Table 2 Conditions for calculations

Particle diameter for calculation (mm)	6
Particle density (kg/m^3)	1000
Blast volume (Nm^3/s)	1.33×10^{-2}
Rate of burden discharge (kg/s)	8.0×10^{-3}
Length of tuyere (mm)	0
Stiffness constant (N/m)	1.6×10^{4}
Restitution coefficient (-)	0.9
Friction coefficient particle-wall /particle-particle (-)	0.3 / 0.3

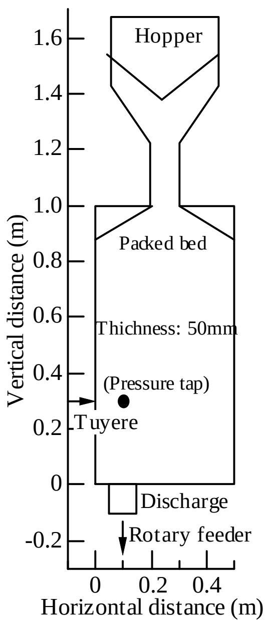


Fig. 1 Experimental apparatus

results

The particle bed was laterally blasted through the tuyere with different diameter on condition that gas volume is fixed. Figure 2 and 3 show the results of particle configuration obtained in the experiments and simulations, respectively. Stable raceway formed in front of gas inlet in case that the tuyere diameter is 8 mm, whereas the raceway became unstable and showed slugging from raceway roof near the side wall, to which tuyere was attached, in case that the tuyere diameter is 12 mm. The simulation results show good correspondence with experimental results.

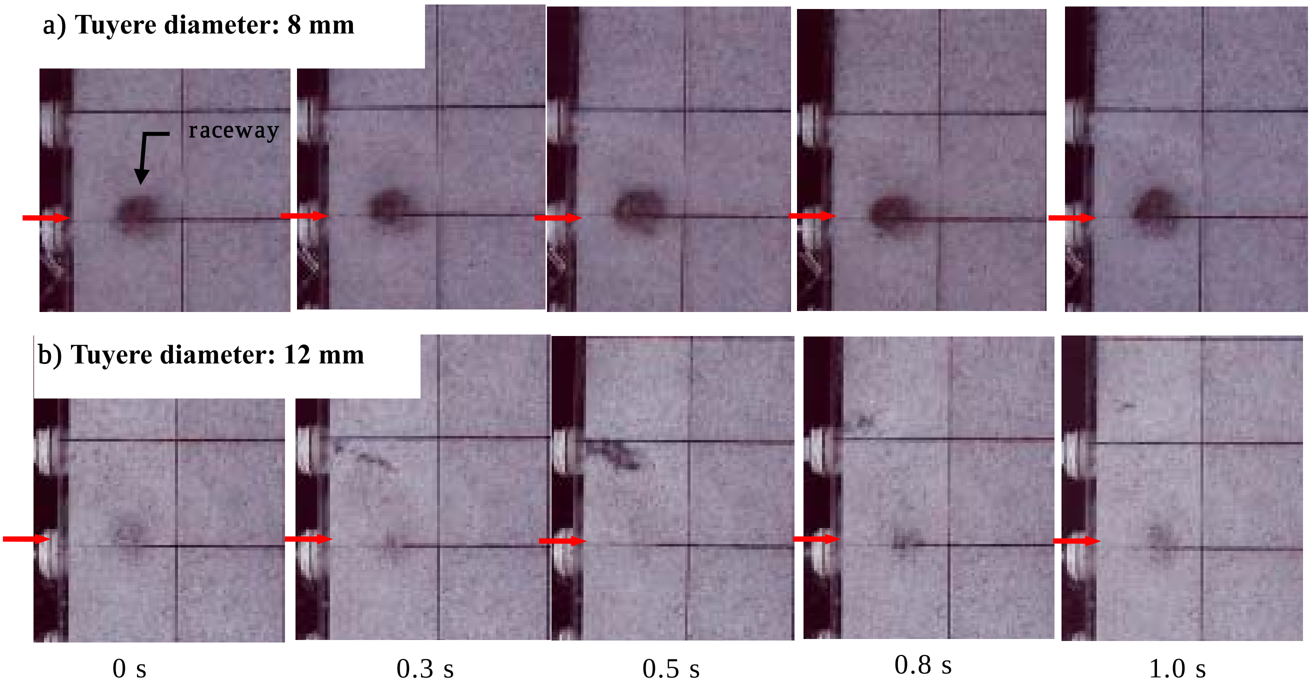


Fig. 2 The instantaneous particle positions (Experiment)

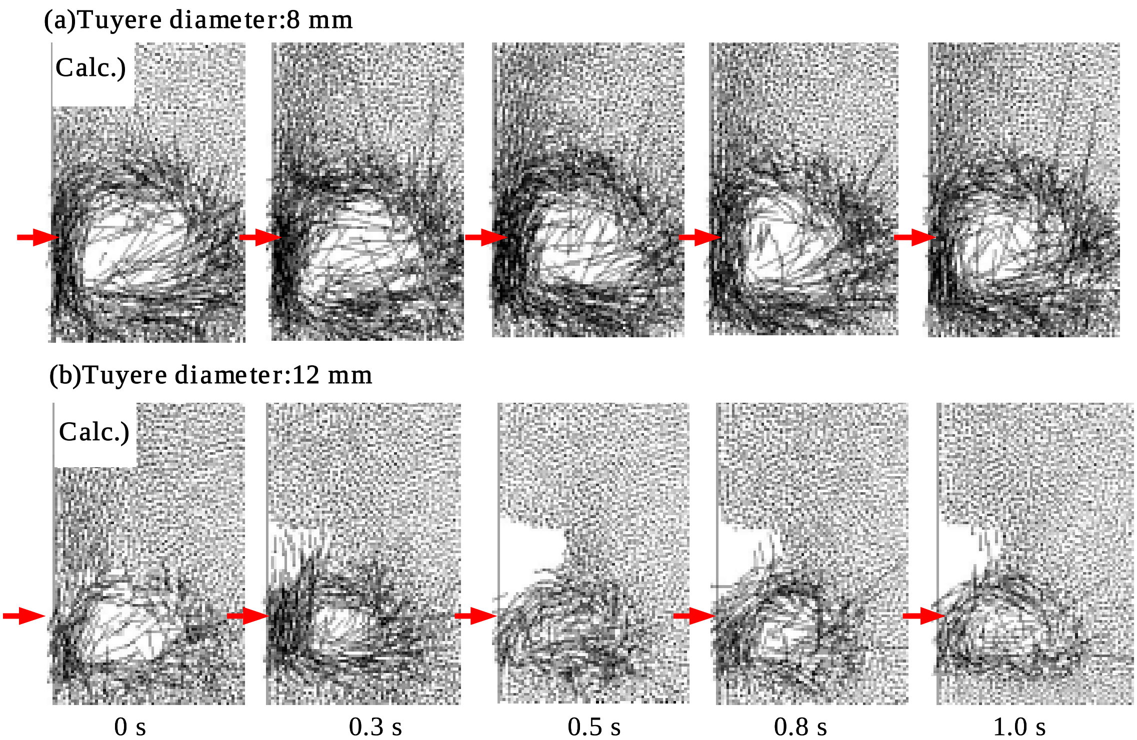
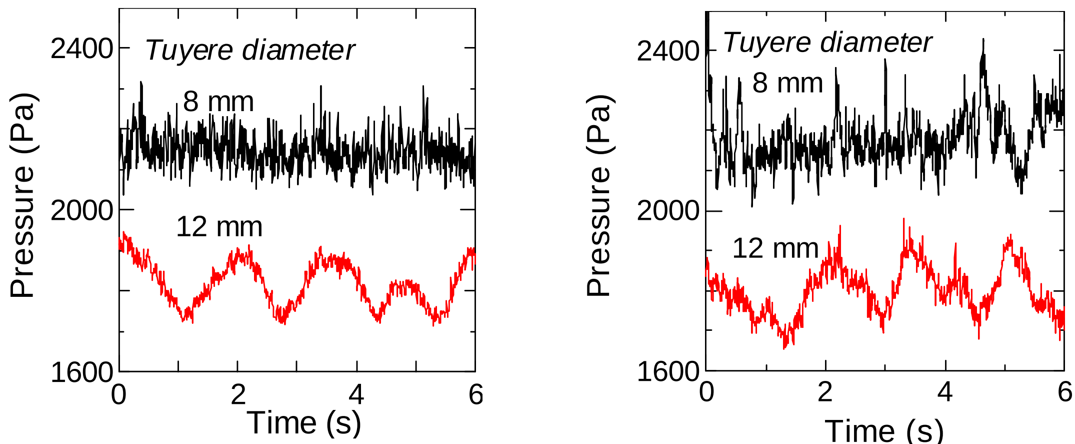


Fig. 3 The instantaneous velocity vectors of particles (Simulation)

Figure 4(a) and (b) show the pressure variations obtained in the experiments and the simulations, respectively, at the pressure tap of the experimental apparatus. The pressure variations have long-term and short-term fluctuations in case of 12 mm diameter of the tuyere. The long-term fluctuation corresponds to the state of unstableness of raceway. The pressure behavior obtained by the simulation shows the same features observed in experiment. Therefore, it is confirmed that the simulation model is valid for calculation of such raceway behavior.



a) Experiment b) Simulation

Fig. 4 Pressure fluctuations in the raceway

Raceway dynamics and stability

In this section, raceway dynamics of real blast furnace scale is discussed from the viewpoint of raceway stability by use of the simulation model.

Conditions for simulation

The simulations are carried out in a rectangular bed as shown in Fig. 5. The bed is laterally blasted through the tuyere to form raceway. The burden descent is induced by disappearance that corresponds to coke combustion in front of the tuyere. And particles are provided from the top of the bed with the equivalent rate to particle disappearance in front of the tuyere to keep the stock level of the bed. To reduce time for calculation, the opposite side of the gas inlet is assumed to be fixed bed, of which void fraction is set to be average of the particle region at initial state and only gas flow was calculated. Table 3 lists the parameters used in the present simulations.

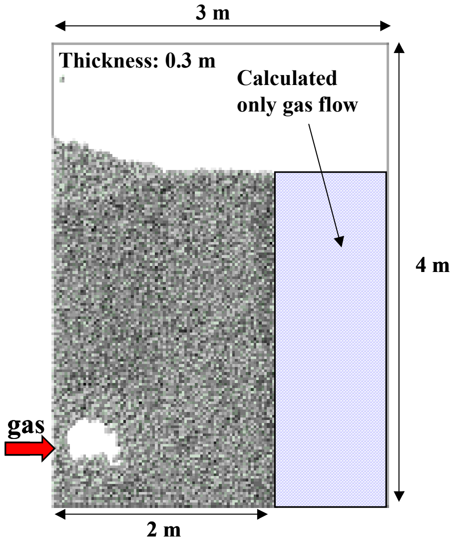


Fig. 5 Geometries used in Simulation

Table 3 Conditions for calculations

Particle diameter (mm)	40
Particle density (kg/m^3)	1000
Blast volume (Nm^3/s)	2.2
Rate of burden discharge (kg/s)	1.68
Length of tuyere (mm)	0
Stiffness constant (N/m)	5×10^5
Restitution Coefficient (-)	0.5
Friction coefficient particle-wall /particle-particle (-)	0.3 / 0.3

Effect of tuyere diameter on raceway stability

Figure 6 shows raceway behavior with the different the tuyere diameter on condition that blast volume is fixed. Raceway becomes unstable with the larger tuyere diameter. In the unstable raceway, stoppage of burden descent and expansion of the cavity followed by burden slip near the side wall above the gas inlet occur repeatedly, whereas, in the stable raceway, particles are almost steadily supplied into the raceway from the region between the side wall and raceway roof. The fluctuations of the pressure in front of gas inlet and total kinetic energy of particles in the system concerning the unstable raceway are shown in Fig. 7. In this figure, two different modes can be found in behaviors of both variables, that is long-term and short-term fluctuations. The long-term fluctuation of the pressure corresponds to that of the total kinetic energy, that is, the pressure increases, the total kinetic energy decreases, and vice versa. The state of particle motion in the raceway, such as stoppage of burden descent, expansion of the cavity and burden slip above the gas inlet, corresponds to the fluctuation of the pressure. When the expansion of the cavity occurs, the pressure and the total kinetic energy become lower and higher, respectively. Therefore, the tuyere diameter affects the gas inlet velocity, fluctuations of pressure and particle motion, and raceway stability.

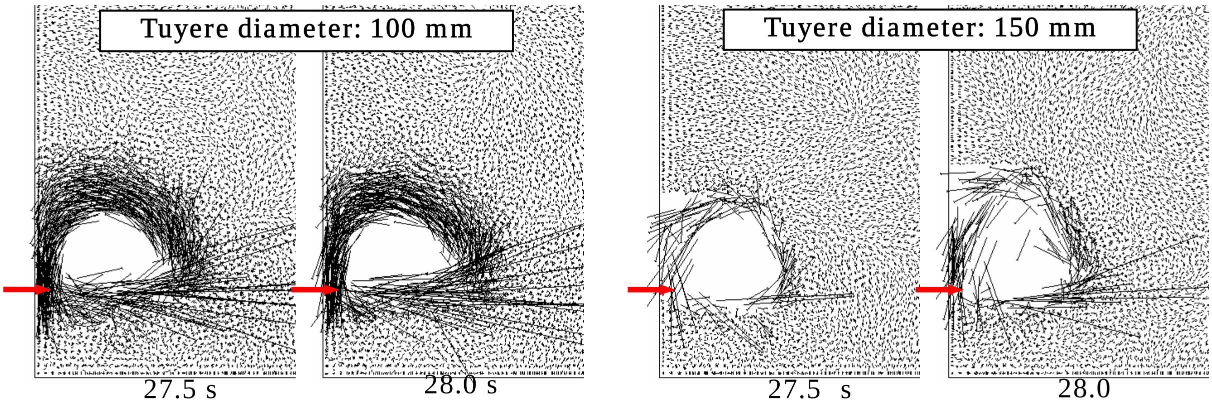


Fig. 6 Effect of tuyere diameter on raceway stability (Velocity vectors of particles, V_b=2.2 m^3/s)

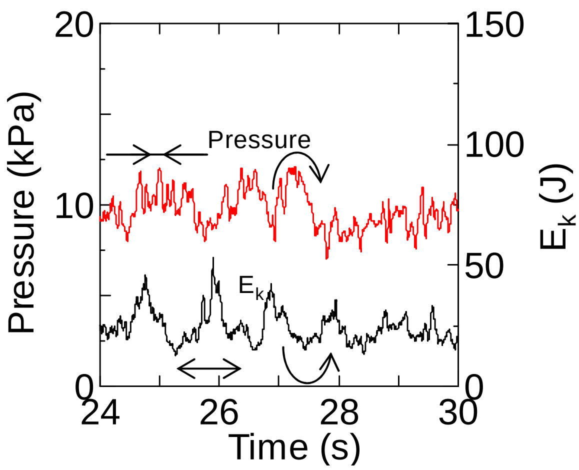


Fig. 7 Fluctuations of the pressure and kinetic energy with unstable raceway (V_b=2.2 Nm^3/s, D_{ty}=150 mm)

Effect of blast volume on raceway stability

Figure 8 shows the change in raceway behavior with the increase of blast volume on condition that the tuyere diameter is unchanged. Raceway becomes unstable over a certain blast volume with the tuyere diameter. The unstable raceway fluctuates in the direction between tuyere axis and upward along the side wall above the gas inlet. And when the raceway expands upward along the side wall, the particles are discontinuously supplied into the raceway along the wall. Figure 9 shows the fluctuations of the pressure in front of gas inlet and the total kinetic energy in the system with the unstable raceway. There are also long- and short-term fluctuations. However, in contrast with the case of enlargement of the tuyere diameter, which is described in the previous section, as for long-term fluctuation, the variation of pressure and the total kinetic energy shows the same behavior. The raceway expansion in the direction of the tuyere axis induces the increase of the pressure and the total kinetic energy, whereas the raceway expansion along the side wall above the gas inlet induces the decrease of these. Therefore, the blast volume also affects the gas inlet velocity, fluctuations of pressure and particle motion, and raceway stability, which are different behavior from the case that tuyere diameter is changed.

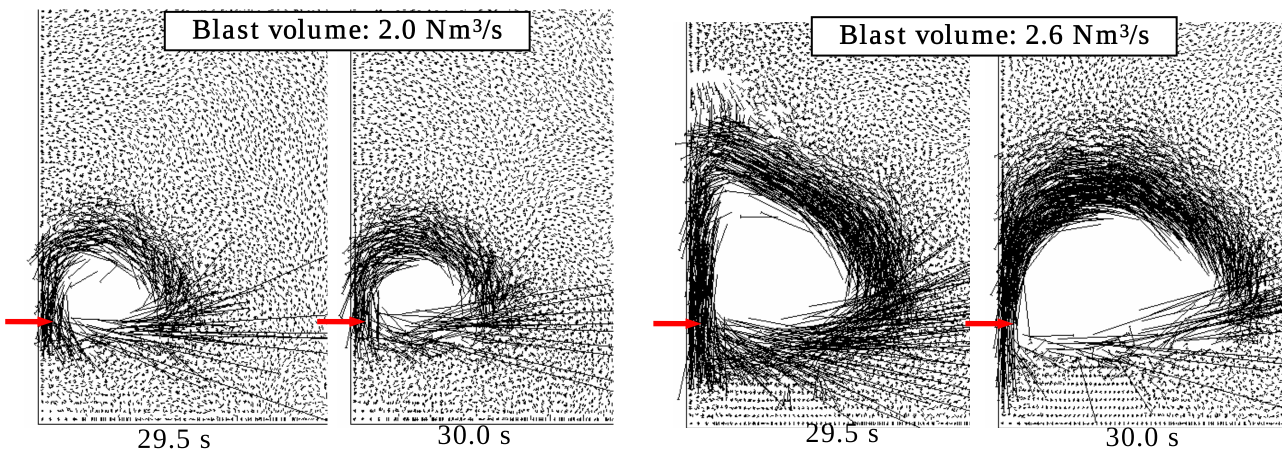


Fig. 8 Effect of blast volume on raceway stability (Velocity vectors of particles, D_t=100 mm)

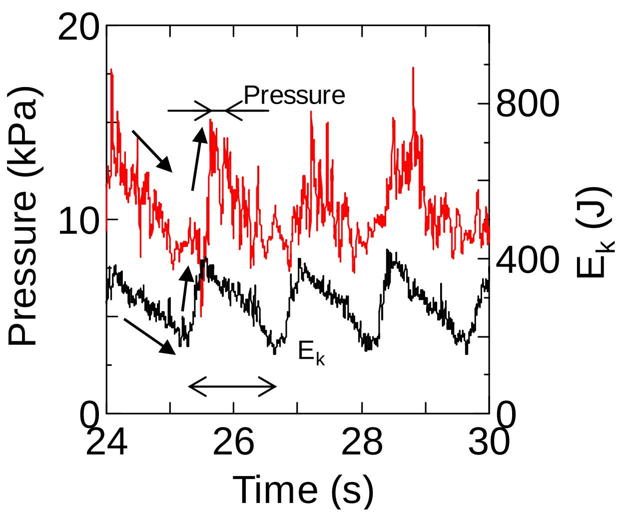


Fig. 9 Fluctuations of pressure and kinetic energy with unstable raceway (V_b=2.6 Nm^3/s, D_{ty}=100 mm)

Energy balance of raceway and stability

Raceway stability is discussed in terms of energy balance in this section. When blast volume is increased from zero to a certain value and reaches an apparent steady state of raceway, the energy transferred from gas to particles in the system, $\Delta E_{g\to s}$, can be written as follows:

$$\Delta E_{g\to s} = \eta(E_b^{in} - E_b^{out}) = \Delta E_p + \Delta E_k + E_{loss} \tag{15}$$

where E_b^{in}, E_b^{out} and η are input energy to the system, output energy of the system and the efficiency of energy transfer from gas to particles in the system, respectively; $\Delta E_p, \Delta E_k$ and E_{loss} are the changes of the total amount of the potential and elastic energy, the total kinetic energy and the total dissipative(frictional, viscous) energy of all particles in the system. The energy transferred from gas to particles is changed into kinetic energy, dissipative energy of particles in the system as well as the potential and elastic energy. When eq. (15) is applied to the changes between two different apparent steady state, the energy transferred from gas to particles balances with the dissipative energy because $\Delta E_p \cong 0$, $\Delta E_k \cong 0$ on the time average. Therefore, eq. (15) can be written as follows:

$$\Delta E_{g\to s} \cong E_{loss} \tag{16}$$

And due to $E_b^{in} >> E_b^{out}$, that is because outlet gas velocity is negligible to that of inlet, the efficiency of energy transfer from gas to particles in the system can be written as follows:

$$\eta \cong \frac{E_{loss}}{E_b^{in}} \tag{17}$$

where all the variables in this equation are in long-enough-time-range to the fluctuation of raceway after the apparent steady state. Equation (17) can be also applied to unstable raceway if the changes are in long-enough-term to the fluctuation, because the fluctuation of unstable raceway almost periodically occurs as described above.

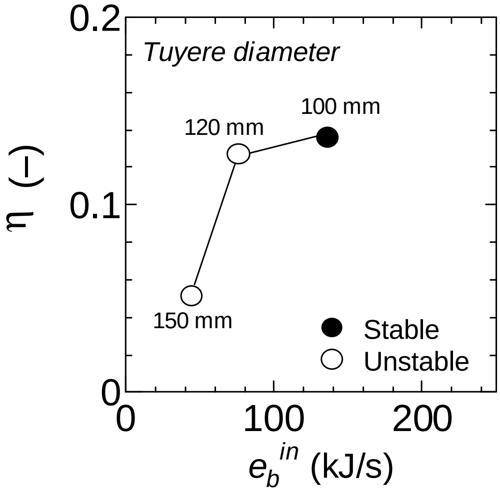
Now, efficiency of energy transfer from gas to particles in the system is calculated by eq. (17). The rate of the blast energy per unit time is given as follows:

$$e_b^{in} = \left(\frac{1}{2}\rho_g {u_g}^2 + p\right)\cdot V_b \tag{18}$$

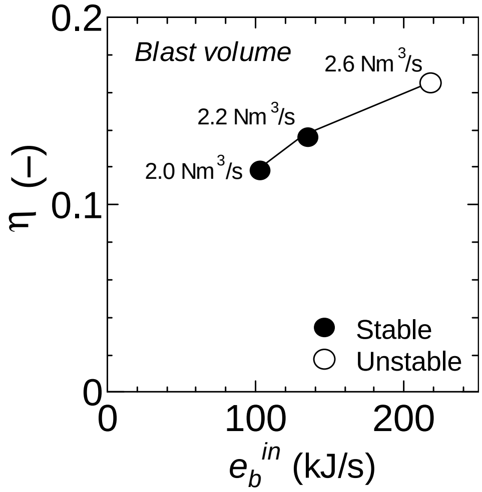
where u_g, p and V_b is the gas velocity at the gas inlet, the gas pressure at the gas inlet and blast volume, respectively. The dissipative energy per unit time due to friction and collision of inter-particles in the linear model can be written as follows:

$$e_{loss} = \sum_{j=1}^{k_i} (\eta_{n,ij} {\mathbf{v}_{n,ij}}^2 + \eta_{t,ij} {\mathbf{v}_{t,ij}}^2 + \mu_{ij} \cdot |\mathbf{F}_{cn,ij}||\mathbf{v}_{t,ij}|) \tag{19}$$

The integration of e_b^{in} and e_{loss} over the long-enough-term to the fluctuation of the state of raceway gives E_b^{in}, E_{loss}, respectively, in eq. (17). The effect of the input energy of gas blasting on the efficiency of the energy transfer from gas to particles is shown in Fig. 10. While enlargement of the tuyere diameter, on condition that blast volume is unchanged, makes raceway unstable, the efficiency of the energy transfer from gas to particles decreases. On the other hand, the efficiency of the energy transfer increases with increasing blast volume on condition that the tuyere diameter is unchanged, regardless of stability of raceway. It is because the size of the raceway, in which gas velocity locally overcomes the minimum fluidization velocity, increases with increasing the blast volume even if the raceway becomes unstable. Therefore, the stability of raceway is independent of the efficiency of the energy transfer from gas to particles.



a) With the same blast volume



b) With the same tuyere diameter

Fig. 10 Effect of blast energy on the efficiency of the energy transfer from gas to particles

The efficiency of the energy transfer from gas to particles corresponds to the efficiency of the coke degradation in raceway in blast furnace according to eq. (16). The input energy of gas blasting is desirable to be small to restrain from generating coke fines which close the void of the bed and make the permeability of the blast furnace worse, while raceway could become unstable when the input energy of gas blasting is too large or too small as described above. Therefore, the input energy of gas blasting should be controlled within appropriate range as to the blast volume to form stable raceway.

Conclusions

The following conclusions are obtained by simulation of raceway with lateral gas blasting into bed.

(1) Stable raceway shows that particles are almost steadily supplied into the raceway from the region between the side wall and raceway roof. On the other hand, unstable raceway repeatedly shows stoppage of burden descent and expansion of the cavity followed by burden slip near the side wall above the gas inlet.

(2) Unstable raceway shows long-term fluctuation in the variations of the pressure and total kinetic energy in addition to short-term fluctuation, which is also showed by stable raceway.

(3) Raceway becomes unstable when the tuyere diameter and/or blast volume exceeds a certain value.

(4) The efficiency of the energy transfer from gas to particles increases with increasing the input energy of gas blasting. However, the stability of raceway is independent on the efficiency of the energy transfer.

(5) The input energy of gas blasting should be controlled within appropriate range as to the blast volume to form stable raceway.

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