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Note

Holdup Characteristics of Melt in Coke Beds of Different Shapes

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Numerical analysis was carried out on the dripping and holdup behaviors in the lower part of a blast furnace for coke bed structures having different shapes; a discrete element method smoothed particle hydrodynamics scheme was used considering the size distribution immediately above the raceway. Even for coke beds with similar void fractions, the averaged-coke-shape factors such as ϕ and $(\phi D)^2$ give little clear correlation for holdup sites. Instead of averaged-coke-shape information, only the direct evaluation of the void shape of the packed bed can explicitly trace the holdup site.

KEY WORDS: ironmaking; blast furnace; dripping zone; holdup; DEM-SPH; coke shape.

1. Introduction

For an ironmaking blast furnace, because low-coke-ratio operation causes lower permeability due to an increase in the reaction load of the coke, there is concern that the gas flow resistance of the furnace increases, making it possible that the gas permeability may remarkably deteriorate because of the melt occupying the free space (static holdup) in the zone below the cohesive zone.^{1,2)} To ensure gas permeability in the furnace, flow passes ought to be maintained by inserting coke whose strength is controlled. Nevertheless, the holdup behavior of the melt in the lower part of the blast furnace is difficult to control; this remains one of the most important issues from the viewpoint of operational stability, because it decreases the permeability of the packed bed. The deformation mechanism of coke is complicated, because it takes into consideration the reaction and surface degradation effects in high temperature fields.

The recently developed Lagrangian numerical simulation technique is a promising method for directly analyzing the individual coke's behavior^{3–7)} or dynamically tracking melt dripping.^{8–13)} Recently, the authors obtained coke surface shape information by using 3D-scanning technology, which can output space coordinates with submillimeter resolution for direct dynamic numerical analysis in the coke bed.

Based on this approach, a method was suggested to track numerically the coke bed structure, local void shape, and molten slag flow.^{14–17)} In this research, we aim to determine for the first time a direct relationship between coke shape information and holdup sites exerted by the shape of the coke by using the above-mentioned approach.

2. Method

The motion of rigid-body was assumed for the coke, and a compressible viscous flow was used for the melt based on following governing equations.¹⁶⁾

I. Coke's translational motion equation: $m_s d\mathbf{v}_s/dt = \Sigma(\mathbf{F}_{c,i} + m_i \mathbf{g})$

II. Coke's rotational motion equation: $\mathbf{I}_s d\boldsymbol{\omega}_s/dt = \Sigma \mathbf{T}_{c,i}$

III. Melt's motion (Navier–Stokes) equation: $\rho_l D\mathbf{v}_l/Dt = -\nabla p_l + \mu_l \nabla^2 \mathbf{v}_l + \rho_l \mathbf{g} + \mathbf{F}_{l,st}$

IV. Melt's equation of state for pressure estimation: $(Dp_l/D\rho_l)_s = c_l^2$

where m is mass, $\mathbf{v}$ is velocity, t is time, $\mathbf{F}_c$ is contact force, $\mathbf{g}$ is gravity, $\mathbf{I}$ is moment of inertia, $\boldsymbol{\omega}$ is angular velocity, $\mathbf{T}$ is torque, ρ is density, p is pressure, μ is viscosity, $\mathbf{F}_{st}$ is surface tension, c is sound speed, and subscripts s , l , and S denote solid, liquid, and isentropic, respectively. Although the discrete element method (DEM) is a popular scheme for predicting the movement of spherical particles, if a granular material consists of particles with complex shapes, such as a coke sample, a number of spherical bodies can be used as an approximation. For this purpose, spherical bodies are inscribed into the complex particles such that, at each contact point of the sphere and complex body, a tangential plane can be constructed. However, the smoothed particle hydrodynamics (SPH) method, which discretizes a continuous fluid phase by moving particles, is suitable for the analysis of interfacial flow, even for the large numbers of the dispersed liquid phase.

In consideration of the particle size distribution immediately above the blast furnace raceway,¹⁸⁾ sieving was performed using mesh sizes of 15 mm and 35 mm to obtain 15 representative coke samples (indexed from No. 1 to No. 15, see Fig. 1). By using a 3D laser scanner (Matter and Form), surface points of each coke sample were obtained. The

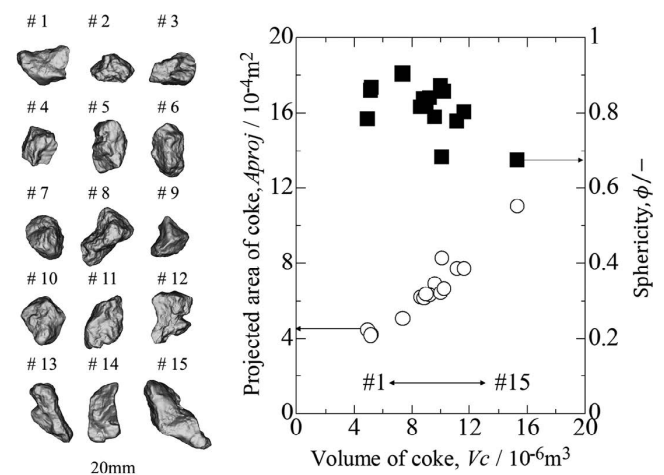


Fig. 1. Various coke shapes used: (a) the STL data obtained from the shape of each coke sample surface and (b) shape factor characterized by coke size.

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obtained coordinates were converted to standard triangulated language (STL), and the surface shape was polygonate with a triangular mesh. Forty pieces of 15 representative coke samples were numerically generated; thus, 600 pieces were prepared. Coke samples with density $\rho = 1\,050\text{ kg/m}^3$, dynamic friction coefficient = 0.43, Young's modulus = 2.4 GPa, and Poisson ratio = 0.35 were employed.¹⁵⁾ The position and rotation angles of each coke sample were determined by using a pseudorandom number, and the packing simulation into a box-type container with 0.20-m sides was performed. Next, we simulated the slag trickle flow in the coke-packed bed. The packed bed obtained was used as the boundary condition with a no-slip condition. Molten slag with a width of 0.20 m and height of 0.01 m was placed immediately above the packed bed. The slag composition was assumed to be typical $45\text{SiO}_2\text{--}45\text{CaO--}10\text{Al}_2\text{O}_3$ at 1 873 K: density $\rho = 2\,600\text{ kg/m}^3$, surface tension $\sigma = 0.5\text{ N}\cdot\text{m}^{-1}$, and viscosity coefficient $\mu = 0.1\text{ Pa}\cdot\text{s}$.^{19,20)} Coke was assumed to be completely nonreactive and with slag (static contact angle, 180°).²¹⁾ Calculations were performed until all particles reached a sufficiently low velocity ($v < 0.01\text{ m}\cdot\text{s}^{-1}$). The tests were repeated three times.

3. Results and Discussion

Figure 2 shows one of the calculation results. The natural packing behavior of the coke was simulated as shown in Fig. 2(a). When the same calculation was repeated three times, the packed-bed height did not change significantly; thus, the difference in the void fraction caused by the random arrangement was small. The average void fraction was $\varepsilon = 0.4384$, with a minimum value of 0.4172 and a maximum value of 0.4539. The time change in molten slag-free surfaces in the packed bed is shown in Fig. 2(b). The molten slag passed through a certain void in the packed bed, and the holdup sites were dispersed in the coke packed bed, as shown at $t = 4.0\text{ s}$. Many researchers have reported that holdup h_s should be related to modified capillary number Cp_m ,^{22–28)} and both Cp_m and modified Galilei number Ga_m ,^{29,30)} as follows:

$$h_s = k(Ga_m)^n(Cp_m)^m;$$

$$Cp_m = \frac{\rho g(\phi D)^2}{\sigma(1 + \cos\theta)(1 - \varepsilon)^2} \text{ or } \frac{\rho g\left(\frac{\varepsilon}{1 - \varepsilon}\right)^2(\phi D)^2}{|\sigma \cos\theta|}; \dots (1)$$

$$Ga_m = \frac{\rho^2 g(\phi D)^3}{\mu^2(1 - \varepsilon)^2} \text{ or } 1$$

Here, k , n , m are the experimental fitting parameters, θ is the contact angle, ϕ is sphericity, and D is the coke diameter. The parameters for the coke shape in the packed bed are concentrated in only ϕ and D . Because h_s is determined by the integration of droplet volume in local holdup sites, it can be broken down into contributions for each coke shape. Thus, we calculated the average projected area A_{proj} of the coke and the equivalent volume equivalent diameter D_v .¹⁶⁾ Carman's shape factor $\phi(= \pi D_v^2/4A_{proj})$, which is one of the indices representing sphericity,^{31,32)} was obtained from the 3D surface data of all cokes, and the relationship with holdup was analyzed as described in the following. **Figure 3** shows the number of droplets and the volume sum distribution classified by the various coke shape parameters. Here, the number of droplets n_d and the volume of droplets V_d are classified by the cokes in contact with all holdup droplets. When n_d and V_d were arranged for Carman's shape factor ϕ , as in Fig. 3(a), and the variable in capillary number $(\phi D_v)^2$, as in Fig. 3(b), a clear correlation was not obtained. It may be impossible to represent explicitly a holdup site with only averaged shape information of the coke. We can consider that local melt flow (flow direction and momentum in 3D coordinates) determines the holdup site. However, A_{proj} in the direction of gravity of the coke — see Fig. 3(c) — shows

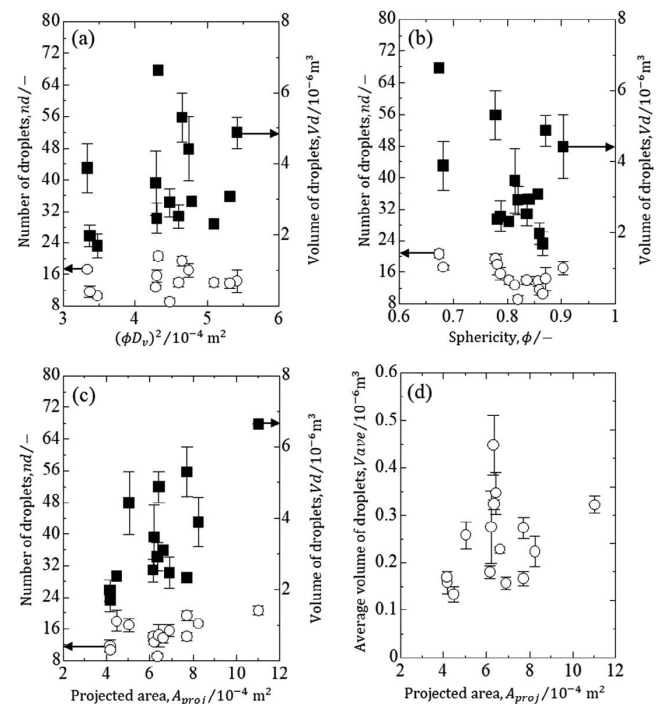


Fig. 3. Number of droplets and the volume sum distribution classified by the various coke shape parameters.

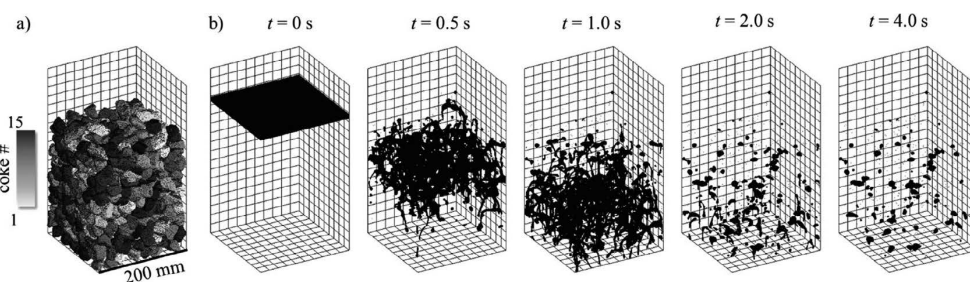


Fig. 2. (a) Changes in packed structure of 600 cokes in 15 different shapes (*i.e.*, 40 cokes of the same shape were charged) and (b) calculated shape change in molten slag interface progressing through a packed structure.

a relatively good correlation with V_d . As A_{proj} increased, the n_d and V_d tended to increase. In other words, coke having a large A_{proj} contributes to the formation of a holdup site, regardless of D_v . However, the deviation was still large. As is clear from the relationship between $V_{ave} = V_d/n_d$ and A_{proj} (Fig. 3(d)), we could not obtain the simple correlation with the holdup site. This indicates that the 3D shape of the void in the packed bed is difficult to characterize using 2D information. The 3D evaluation of the void shape was left for future work, but topological data analysis³³⁾ to evaluate the correlation between random dispersed points has yielded useful results, and it will be applied to this problem.

4. Conclusion

DEM-SPH simulations were performed for the analysis of the nonspherical packed-bed structure of metallurgical cokes of different shapes; molten slag trickle flow and holdup characteristics were also evaluated. As the projected area of the nonspherical solid shape increased, the liquid holdup tended to increase. Variations in the holdup sites and number were caused by the coke shape. However, even if coke beds with similar void fractions were used, the averaged coke effective diameter $(\phi D)^2$ or ϕ provided only few clear relationships for the holdup site's tendency. For the explicit specification of holdup sites, it is necessary to evaluate the 3D void shape made by various coke networks.

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