Analysis of Effect of Packed Bed Structure on Liquid Flow in Packed Bed Using Moving Particle Semi-implicit Method

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Liquid flow in blast furnaces has a significant influence on gas flow and pressure drop. Therefore, the stability of blast furnace operations and productivity are affected by liquid flow. In a furnace, liquid flows in a packed bed consisting of coke. Holdup is an important phenomenon in packed bed flow. It changes with the variation of the packed bed structure and the physical properties of the liquid. In this study, a numerical simulation for packed bed flow is carried out. The effects of a packed bed structure on holdup phenomena were analyzed by the moving particle semi-implicit (MPS) method.

KEY WORDS: ironmaking; blast furnace; liquid dripping; packed bed; MPS method.

1. Introduction

Flows of molten slag and molten iron in the lower part of a blast furnace have a significant influence on the productivity and stability of ironmaking processes. In the past, some studies have focused on liquid flow in a coke bed in the lower part of the blast furnace—for example, cold model observation,1–5) prediction of holdup,1–3,6,7) formulation of flooding phenomena, and modeling of the flow pattern.7–10) There are major models for the liquid flow in the lower part of the furnace: the continuum model7,8) and the stochastic model.9,10) However these models simplified actual liquid flow in blast furnace. In the lower part of a furnace, the space among the coke particles is not filled with liquid. The liquids disperse and coalesce as they flow in a coke bed. Wettability between the coke and liquid and surface tension have a significant influence on liquid flow. Although the relationship between these factors and liquid flow has also been researched,1–3,6,7) the relationship has yet to be clarified systematically. Moreover, physical properties about wettability between coke and molten slag or iron are insufficient to analyze effects on liquid flow numerically. Previous numerical simulations2–10) were unable to analyze the influences of packed bed structure and physical properties such as surface tension on liquid flow with high accuracy. The moving particle semi-implicit (MPS) method11,12) is one of useful method to analyze the effects of wettability, surface tension, and packed bed structure on liquid flow. The MPS method can calculate flow of incompressible fluid and the influence of wettability on liquid motion.13) It can also be used for ironmaking process analysis. Nishioka et al.14) analyzed liquid motion in a blast furnace hearth using the MPS method. The authors calculated liquid motion in a packed bed using the MPS method and analyzed the influences of viscosity and wettability on liquid flow in previous studies.15,16) These researches made no discussion about the effects of packed bed structure because they used respective one packed bed structure.

This study focuses on a packed bed structure, as it influences liquid flow. Liquid flow in packed beds that have different structures is analyzed by the MPS method.

2. Dripping Model

In this study, liquid motion in cohesive zone in BF is calculated by the MPS method. In the cohesive zone, ore begins to melt and drip. In this area, the space among the coke particles is not filled by liquid. Liquid flows in the coke bed and changes shape. The MPS method is a particle method and Lagrange method. Liquid is represented as an aggregate of liquid particles. The MPS method simultaneously tracks all liquid particles that have certain mass and volume. MPS method has no numerical diffusion by discretization of the convective term and can calculate liquid flow with a free surface easier than the Euler method.12) As mentioned previously, the MPS method is suitable for liquid flow analysis in the lower part of the cohesive zone, which has surface deformation. The governing equations for liquid flow are the continuity equation (Eq. (1)) and the Navier–Stokes equation for incompressible flow (Eq. (2))

\[
\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{v} \hspace{1cm} \text{(1)}
\]

\[
\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \mathbf{v} + \frac{1}{\rho} \mathbf{F} \hspace{1cm} \text{(2)}
\]

where \( \mathbf{v} \), \( t \), \( \rho \), \( P \), \( \nu \), \( g \), and \( \mathbf{F} \) are the velocity vector [m/s], time [s], density [kg/m³], pressure [Pa], kinematic viscosity...
acceleration of gravity \([\text{m/s}^2]\), and force by surface tension and wettability \([\text{N/m}^3]\), respectively. The governing equations were converted to a set of simultaneous equations describing particle motion by replacing differential operators with a discretization model (the interparticle interaction model). Discretization of the gradient and Laplacian of velocity \(v\) are performed as follows using the respective differential operators. The interparticle interaction model used a weighted average based on the weight function (Eq. (6)).

\[
\langle \nabla v \rangle_i = \frac{n_i}{n^2} \sum_{j \neq i} \left[ \frac{w_{ij}}{r_{ij}^2} \mathbf{r}_{ij} \mathbf{w}_{ij} \right] \quad \text{(3)}
\]

\[
\langle \nabla^2 v \rangle_i = \frac{2d}{n^2} \lambda \sum_{j \neq i} \left[ (\mathbf{v}_j - \mathbf{v}_i) \mathbf{w}_{ij} \right] \quad \text{(4)}
\]

\[
\lambda = \sum_{j \neq i} \left( \frac{w_{ij}}{r_{ij}^2} \right) \quad \text{(7)}
\]

Weighting of interaction strength is given by defining the weight function. The subscripts \(i\) and \(j\) represent the calculation object particle and existing particles within an influence radius from particle \(i\), respectively, where \(d\), \(r_c\), and \(r_j\) are the number of dimensions \([-\text{]}\), the influence radius \([\text{m}]\), and the distance between the particles \([\text{m}]\), respectively. In this research, the influence radius \(r_c\) was set as 2.1\(l_0\), where \(l_0\) was the particle diameter.\(^{11)}\) For normalization of weighted average in the interparticle interaction model, the sum of the number of neighboring particles \(n_i\) was defined as the average in the incompressible state.\(^{12)}\) In this study, \(n^2\) was set as \(N_i\) of the particle surrounded in cubic lattice by other particles in the range of \(r_c\), and \(\beta\) was set as 0.85.\(^{11)}\)

The surface tension model proposed by Natsui et al.\(^{13)}\) was used in this study. It based on the interparticle potential model proposed by Kondou et al.\(^{19)}\) and has been improved to calculate a three-phase energy relationship. Details of this model are provided in somewhere.\(^{13)}\)

### 3. Analysis of Liquid Flow in Packed Bed

#### 3.1. Calculation Conditions

Tables 1 and 2 provide the calculation conditions for liquid flow in a packed bed. To analyze the relationship between liquid flow and a packed bed structure, three patterns of a packed bed structure were used for calculation. First one consists of sphere of 20 mm in diameter, Second is of spheres of 14 mm. Third consists of mixed spheres of 14 and 20 mm. In all packed bed, the spheres are packed randomly.

The liquid and packed materials are represented by the aggregate of the tiny particles. Spheres of 14 and 20 mm consist of 2 440 and 7 568 particles, respectively. The liquid initially has a spherical shape with a diameter of 32 mm and

\[
N_i = \sum_j w_{ij} \quad \text{(11)}
\]

\[
w_{ij} = \begin{cases} 1 & (r_j \leq r_c) \\ 0 & (r_j > r_c) \end{cases} \quad \text{(12)}
\]

Where \(N^0\) and \(\beta\) are the standard neighboring particle number in the incompressible state \([-\text{]}\) and a coefficient for surface judgment \([-\text{]}\), respectively. In this study, \(N^0\) was set as \(N_i\) of the particle surrounded by cubic lattice by other particles in the range of \(r_c\), and \(\beta\) was set as 0.85.\(^{11)}\)

### Table 1. Calculation conditions.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle number</td>
<td>33 398</td>
</tr>
<tr>
<td>Particle diameter</td>
<td>0.8</td>
</tr>
<tr>
<td>Droplet diameter</td>
<td>32</td>
</tr>
<tr>
<td>Surface tension</td>
<td>7.28(\times)10(^{-2})</td>
</tr>
<tr>
<td>Kinematic viscosity</td>
<td>1.39(\times)10(^{-6})</td>
</tr>
<tr>
<td>Density</td>
<td>1 000</td>
</tr>
<tr>
<td>Wetting angle</td>
<td>30(^\circ), 60(^\circ), 120(^\circ), 150(^\circ), 180(^\circ)</td>
</tr>
</tbody>
</table>

### Table 2. Packed bed structures used in calculations.

<table>
<thead>
<tr>
<th>Packed bed structure</th>
<th>Φ20 mm</th>
<th>Φ14 mm</th>
<th>Φ20, 14 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of Packed bed</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Height of packed bed</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Diameter of packed materials</td>
<td>20</td>
<td>14</td>
<td>20, 14</td>
</tr>
<tr>
<td>Number of packed materials</td>
<td>40</td>
<td>112</td>
<td>29 (Φ20)</td>
</tr>
<tr>
<td>Harmonic mean diameter</td>
<td>20</td>
<td>14</td>
<td>16.2</td>
</tr>
<tr>
<td>Specific surface area</td>
<td>181.4</td>
<td>248.8</td>
<td>207.0</td>
</tr>
<tr>
<td>Viod fraction</td>
<td>0.395</td>
<td>0.409</td>
<td>0.375</td>
</tr>
</tbody>
</table>
consists of 33,398 particles. **Figure 1** shows the packed bed structures and the initial position of the liquid droplet. The packed bed shape is a cylinder with a diameter of 80 mm and a height of 60 mm. The droplet’s initial position is on the center axis of the packed bed and a height of 82 mm from the bottom of the packed bed; the droplet is dropped by gravity from the initial position at the beginning of the calculation. To prevent the liquid particles from leaking from the calculation domain, saucers were set underneath the packed beds.

In blast furnace, physical properties of molten iron and slag change greatly with temperature, composition, and the other factors. Previous researches reported that the kinematic viscosity of molten iron was in the range from $10^{-6}$ to $10^{-5}$ m$^2$/s and that of slag was in the range from $10^{-5}$ to $10^{-4}$ m$^2$/s. The wettability varies greatly depending on the interfacial reactions and composition of the melt. For conditions in the blast furnace, Fukutake et al. estimated that wetting angle of slag on the surface of the coke was in the range of $105^\circ - 160^\circ$ and molten metal wetting angle was $125^\circ$. Based on these estimations, the kinematic viscosity was set at $1.39 \times 10^{-6}$, $1.39 \times 10^{-5}$ and $1.39 \times 10^{-4}$ m$^2$/s in this study. The wetting angle was set from $30^\circ$ to $180^\circ$ in steps of $30^\circ$. For surface tension, $7.28 \times 10^{-2}$ N/m, which was of water, was used in this analysis. The motion of the liquid was calculated for 3.0 s, after the droplet stated to drop.

### 3.2. Simulation of Liquid Flow in Packed Bed

**Figure 2** shows the simulation results of the liquid flow in three types of the packed bed with the wetting angle of $90^\circ$ and the kinematic viscosity of $1.39 \times 10^{-6}$ m$^2$/s. The figure shows a perspective view from the side and liquid flow from 0 to 1.0 s with increment of 0.1 s. At 0.1 s, the liquid flow in packed bed of 14 mm spheres (b) was faster than the others. At 0.2 s, liquid was dripping out from the bottom of the packed beds in all calculation conditions, but less liquid dripped from packed bed (b). Liquid dripped from all packed beds from 0.4 to 0.8 s. At 0.9 s, liquid was dripping only from packed bed of mixed spheres (c). The liquid finished dripping from all packed beds before 1.0 s. The liquid that was trapped at 1.0 s stayed still in the packed bed at 3.0 s. In all cases, the shapes of the trapped liquid were small droplets and no film shapes of the trapped liquid were observed.

**Figures 3** through **5** show the changes in the number of particles in a packed bed for the wetting angles of 60, 90 and 120°, respectively, and the kinematic viscosity of $1.39 \times 10^{-6}$ m$^2$/s. In all conditions, the number of liquid particles reached maximum value and thereafter began to decrease. Under the condition of the wetting angle 60° and packed bed of 14 mm sphere, all liquids are held in the packed bed and no liquids drips out from the packed bed. Comparing the number of liquid particles in the packed beds at 1.0 s, the packed bed of 14 mm spheres holds most liquid particles, and the packed bed of 20 mm spheres holds the.
least. For the cases with the wetting angle $90^\circ$, the change of the number of liquid particles after 0.8 s is pretty small. The packed bed of 14 mm spheres holds most liquid particles, and packed bed of 20 mm spheres holds the least at 1.0 s. This tendency is the same as the cases with a wetting angle of $60^\circ$. With a wetting angle of $120^\circ$ (Fig. 5), the liquid finishes dripping before 0.5 s in all packed bed structures and small amount of liquid is trapped in the packed beds.

4. Analysis of Holdup and Average Dripping Rate

4.1. Calculation of Average Dripping Rate and Static Holdup

Holdup is the amount of liquid in a packed bed and has two definitions,

H. L. Shulman et al. defined holdups in a packed bed with continuous supply of the liquid as dynamic holdup and static holdup. The former is the amount of the liquid discharged from the packed bed after stopping of liquid supply and the latter is the liquid that remains in the packed bed. In this study, liquid supply is only once and dynamic holdup of this definition is unable to be applied. Therefore the average dripping rate is defined to discuss the behavior of the dynamic holdup and the volume fraction of the liquid in a packed bed at 3.0 s is set as static holdup. As shown in Figs. 3 through 5, the number of liquid particles reaches maximum and decreases thereafter. The schematic diagram in Fig. 6 shows a change in the number of liquid particles with time. The average dripping rate $v_{ad}$ [m/s] is defined as follows:

$$v_{ad} = \frac{n_{max} - n_{min}}{\Delta T} \cdot V_p \cdot \frac{1}{S} \quad (13)$$

Where $n_{max}$, $n_{min}$, $V_p$, $\Delta T$, and $S$ are the maximum number of liquid particles in the packed bed [-], the minimum number of liquid particles in the packed bed [-], liquid particle volume [m$^3$], the time from the beginning to end of dripping from the bottom or 3.0 s (the maximum time length of simulation in this study) [s], and the horizontal cross sectional area [m$^2$] of a packed bed, respectively. Average dripping rate is superficial velocity at the bottom height of a packed bed.
bed. Decrease in the average dripping rate is equivalent increase in the dynamic holdup.

### 4.2. Comparison of Average Dripping Rate

Figures 7 and 8 show the changes in the average dripping rate with kinematic viscosity and the packed bed structure. With the wetting angle of 30°, all the liquid was trapped in all packed bed structures. For the wetting angle of 60°, no liquid dropped from the packed bed of 14 mm spheres. These calculation results were excluded. The average dripping rate decreased with the increase in the kinematic viscosity. With the wetting angles of 60 and 90°, the average dripping rate of the packed bed of 20 mm spheres is the highest. With a wetting angle of 120, 150 and 180° (Fig. 8), the influence of the packed bed structure on average dripping rate is smaller compared to the conditions with a wetting angle of 60 and 90°. Figure 9 shows the variation of the average dripping rate with the wetting angle. Horizontal axis is \( \cos \theta \) and \( \theta \) is wetting angle [°]. The average dripping rate increases with increase in the wetting angle, except wetting angle of 180°.

### 4.3. Relationship between Static Holdup and Packed Bed Structure

Figure 10 shows the relationship between static holdup and the wetting angle. The static holdup is calculated only on the conditions that the number of the liquid particles reaches a constant value within 3.0 s. The dotted line in the figure shows the maximum static holdup at which all the liquid particles are trapped in the packed bed. The static holdup increases as the wetting angle decreases. With wetting angles of 60 and 90°, the static holdup is the largest value in the packed bed of 14 mm spheres and the smallest value in the packed bed of 20 mm spheres. With wetting angles of 30, 120, 150 and 180°, the effect of packed bed structure on static holdup was smaller.
Figures 11 through 13 show the effects of the packed bed structure on the static holdup. Figure 11 shows the effect of the void fraction of the packed bed on the static holdup. As shown in this figure, no clear relationship between the static holdup and void fraction was observed. Figures 12 and 13 show the influences of the specific surface area and the harmonic mean diameter of the packed materials on static holdup, respectively. Static holdup increased with the increase in the specific surface area and the decrease in the harmonic mean diameter.

To analyze the relationship between the specific surface area and static holdup, the liquid flows in two more different packed bed structures were calculated with the wetting angle of 90° and the kinematic viscosity of 1.39 × 10⁻⁶ m²/s. The packed materials were mixtures of 14 and 20 mm spheres. The shape of the packed bed was same as previous cases, namely, a cylinder with a diameter of 80 mm and a height of 60 mm. The numbers of spheres of 14 and 20 mm were 49:24 and 25:32, respectively. Void fraction, specific surface area and harmonic mean diameter for former bed were 0.376, 200.6 m²/m³ and 16.84 mm. One’s for the later were 0.372, 217.7 m²/m³ and 15.53 mm.

To compare with previous researches, static holdup calculated in this study was compared with that estimated by the static holdup equation (Eq. (14)) proposed by Fukutake et al. ¹ ²

\[ h_s = \frac{1}{(20.5 + 0.263 C_{pm})} \] ........................ (14)

\[ C_{pm} = \frac{\rho_\ell g Y_0 d_0^2}{\sigma (1 + \cos \theta)(1 - e)^2} \] ........................ (15)

where \( C_{pm} \) is modified capillary number [–], and is the ratio of gravity to the surface tension considering the influences of the wetting angle and the void fraction. Figure 15 shows the relationship between static holdup and the modified capillary number \( C_{pm} \). The line in the figure refers to Eq. (14). The solid line is within the experimental range of Fukutake et al., ¹ ² and the dotted part is extrapolated to larger \( C_{pm} \) range. The calculated static holdup increases with the
decrease in the modified capillary number. This tendency has an agreement with Eq. (14). Fukutake et al. mentioned that the amount of static holdup with the same packed material changes with the variation of packed bed structure. Therefore, the difference between static holdup calculated in this study and that derived with Eq. (14) consists of the deviation by packed bed structure and the inaccuracy from numerical discretization and modeling by finite size particles.

5. Conclusions

Numerical simulation focusing on packed bed structures was carried out to analyze the relationship between the packed bed and the liquid flow using a model of a three-dimensional liquid flow by the MPS method, which considered the physical properties of the melt such as wettability with the packed bed material. The conclusions are as follows:

(1) It was confirmed that the packed bed structure influences the dripping rate and holdup phenomena. It is predicted that the diameter of packed material and specific surface area of packed bed have a large influence on a liquid flow and an amount of holdup.

(2) The static holdup and the average dripping rate in various packed structures were calculated from numerical simulation. The simulation results showed that static holdup increased with the decreasing modified capillary number $C_{pm}$. This is in agreement with the results of the cold model experiments performed by Fukutake et al.1,2)

(3) With a smaller wetting angle, the average dripping rate increases with a packed bed structure consisting of larger-diameter packed materials. However, the packed bed structure with the highest average dripping rate changed with other conditions, such as the viscosity and wetting angle. It is considered that the wetting angle which takes largest drag force by the wettability has a variation with packed bed structures.

REFERENCES