Numerical investigation of mixed layer effect on permeability in a dynamic blast furnace

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Abstract
Gas flow distribution in a blast furnace (BF) plays a significant role in BF smooth operation, productivity, and thermal efficiency. It is affected by the distribution of burden materials composed of alternating coke and ferrous ore layers. While moving downward coke and ferrous layers of different sizes can mix and form the so-called mixed layers. Generally, the porosity is lower and hence the pressure drop is higher in the mixed layers. These variations can change the gas flow distribution and BF performance. Previous work tried to quantify the effect of material properties and process conditions on the formation of mixed layers and the resulting local porosity variation. However, these studies were often conducted under simplified conditions. Few were dedicated to the formation of mixed layers in a BF and its effect on BF performance. This work studies the formation of mixed layers in an experimental BF by using a combined computational fluid dynamics and discrete element method approach. The effect on BF performance was evaluated under different operational conditions including different size ratios of coke to iron ore particles, burden distribution, batch weight, and discharge rate. The results obtained were helpful to optimize burden charge for improving BF performance.

KEYWORDS
blast furnace, computational fluid dynamics, discrete element method, mixed layer, permeability

1 INTRODUCTION

Gas flow distribution in a blast furnace (BF) plays a significant role in BF smooth operation, productivity and thermal efficiency. It is affected by the distribution of burden materials composed of alternating coke and ferrous ore layers. Flow distribution and hence pressure drop of gas in the granular zone of BF is dependent on permeability distribution, number, and thickness of alternating layers of coke and ore burden.1

Generally, layered burden structure inside BF above the fusion zone comprises of alternate layers of ore and coke separated by a so-called mixed or “interface” layer as schematically shown in Figure 1. The formation of mixed layers is a significant phenomenon in a BF because the porosity at the interface regions is of major importance in the definition of nonuniform flow through the stack region of a BF. Laboratory-scale experiments,2–4 scaled burden descent models as...
well as industrial measurements\textsuperscript{1,5,6} have been conducted to examine mixed layer formation. These studies revealed that the mixed layer usually has much lower gas permeability compared with the individual layers. Therefore, the pressure drop increases with increasing number of interfaces between the coke and ore layers in a packed bed.\textsuperscript{7} Quantitatively, the interfacial loss would be 20\% to 35\% of the total stack pressure drop. There are several affecting factors on mixed layers formation. In particular, the marked local minima in porosity occur when a layer of smaller particles is placed upon a layer of larger particles, while local minima in porosity are much less marked for other geometric arrangements, for example, the layering of larger particles on smaller, or having a shell-core arrangement with the vertical interface, where the penetration depth of the smaller particles into the larger ones is greatly reduced.\textsuperscript{2} In addition, the exhibited porosity minima depend on the particle size ratio.\textsuperscript{2,3,8} The penetration of smaller particles into the interstices of the larger ones occurs easily when the particle size ratio exceeds approximately two, while the values are typically five in some practical BFs. Therefore, it is of practical importance in estimating the flow resistance of BF burdens because there are many layers and hence many interfaces in a BF.

In recent studies, the effect of particle properties on interparticle percolation of small particles (pellets) into a layer of larger particles (coke) during burden descent in the BF has been comprehensively investigated.\textsuperscript{9,10} It is found that coke shape, pellet diameter, static friction, and interparticle rolling friction and restitution had a marked effect on the percolation, while rate of expansion of the device, density of pellet, and shear modulus proved to be of minor importance. In addition, nonspherical particle percolation behaviors through a packed bed or disordered particulate media are examined.\textsuperscript{11,12} The effects of complicated granular materials state, such as under cohesive or wet/dry conditions, on particulate system mixing and segregation have been widely discussed.\textsuperscript{13-15} Apart from the mixing observation based on solid phase, the gas pressure drop across granulated mixtures is studied as well.\textsuperscript{16} Furthermore, the effect of particles structure on the heat and mass transfer through the packed bed and the effect of high reactivity coke for mixed charge in ore layer on reaction behavior of each particle in BF have been examined.\textsuperscript{17-19} Nevertheless, the cases studied were limited to small scaled local BF area within a short operation period. In practice, modern operating practices have been pursuing higher ore-to-coke ratio through different approaches, causing thinner coke layers relative to the pellet layers, but the charging programs should still yield sufficient coke windows in the cohesive zone.\textsuperscript{20} Therefore, there is need for a deeper understanding of the formation of mixed layers and the impacts on BF operation. Furthermore, while all the previous work tried to characterize the mixed layer characteristics in terms of bulk properties of particles and established the existence of local porosity minima across interface, few of those were conducted with a BF geometry or under a dynamic process. Therefore, it is of great necessity to study the effects of BF related operations on mixing behaviors and further impacts on BF performance in a dynamic BF to improve our understanding for a better control.

In this work, the mixed layer formation and its effects on porosity distributions and pressure drop under different BF operations are mainly investigated using the combined computational fluid dynamics (CFD)-discrete element method (DEM) approach.\textsuperscript{21} Besides analyzing two types of mixed layer formation, the other original contribution is studying the effects of different operations, such as the coke to ore particle size ratio, burden distribution, batch weight, and discharge rate around raceway zone, on mixed layers in a dynamic BF process. Therefore, the findings can be more realistic and applicable for a large/real BF. This paper is organized as follows: in Section 2, the mathematical model is introduced; in Section 3, the simulation conditions are specified; in Section 4, the numerical results are analyzed in terms of the general
characteristics of the mixed layer, and the effects of a mixed layer on porosity distribution and pressure drop; finally in Section 5, the main conclusions are drawn.

2 MODEL DESCRIPTION

The approach used is largely the combined CFD-DEM approach. The dynamic BF model considering stock line for the examination of the effects of the mixed layer is a new development. A discrete solid phase and a continuum gas phase are considered for the gas-solid flow. The models are briefly introduced in this section. In fact, the validations have been confirmed in our previous study.22

2.1 Governing equations for solid phase

The solid phase is described by DEM, originally proposed by Cundall and Strack.23 At any given time \( t \), the equations governing the translational and rotational motions of particle \( i \) can be written as:

\[
\frac{d}{dt} \left( m_i v_i \right) = \sum_j \left( f_{e,i,j} + f_{d,i,j} \right) + f_{pf,i} + m_i g
\]

and

\[
I_i \frac{d\omega_i}{dt} = \sum_j \left( T_{t,i,j} + T_{r,i,j} \right).
\]

The forces involved are: particle-fluid interaction force \( f_{pf,i} \), the gravitational force \( m_i g \) and the forces between particles (and between particles and walls) which include the elastic force \( f_{e,i,j} \), viscous damping force \( f_{d,i,j} \). The torque acting on particle \( i \) due to particle \( j \) includes two components: \( T_{t,i,j} \), which is generated by the tangential force and causes particle \( i \) to rotate, and \( T_{r,i,j} \), which is commonly known as the rolling friction torque, is generated by asymmetric normal contact forces and slows down the relative rotation between contacting particles.24,25 If particle \( i \) undergoes multiple interactions, the individual interaction forces, and torques are summed up for all particles interacting with particle \( i \). The equations used to calculate the particle-particle interaction forces and torques, and particle-fluid interaction forces have been well established, for example, as reviewed by Zhu et al.21 The equations used for the present work are the same as those used in the previous studies.26,27

2.2 Governing equations for fluid phase

The fluid phase (air for this study) is treated as a continuum phase and modeled in a way similar to the one widely used in the conventional two-fluid model.28 In this connection, there are three sets of governing equations, developed by Anderson and Jackson.28 Different governing equations may lead to different results, depending on the systems considered. According to Zhou et al.,26 Set II and in particular Set I can be used generally, and Set III can only be used conditionally. In this work, Set I is used. Thus, the conservations of mass and momentum in terms of the local averaged variables over a computational cell are given by

\[
\frac{\partial (\rho_f \epsilon_f)}{\partial t} + \nabla \cdot (\rho_f \epsilon_f \mathbf{u}) = 0,
\]

and

\[
\frac{\partial (\rho_f \epsilon_f u_i)}{\partial t} + \nabla \cdot (\rho_f \epsilon_f u_i \mathbf{u}) = -\nabla p - F_{fp} + \nabla \cdot \tau + \rho_f \epsilon_f g,
\]

where \( \mathbf{u}, \rho_f, p, \) and \( F_{fp} \) are the fluid velocity, density, pressure, and volumetric fluid-particle interaction force, respectively; \( \tau \left( = u_f \left( \nabla \mathbf{u} + \left( \nabla \mathbf{u} \right)^{-1} \right) - \frac{2}{3} u_f \left( \nabla \cdot \mathbf{u} \right) \right) \) and \( \epsilon_f \left( = 1 - \sum_{i=1}^{F} V_i / \Delta V \right) \) are the fluid viscous stress tensor and porosity,
respectively, with $V_i$ representing the volume of particle $i$ (or part of the volume if the particle is not fully in a CFD cell), and $k_V$ the number of particles in the computational cell of volume $\Delta V$. Note that $\epsilon_f$ is determined over a computational cell for fluid phase. The volumetric particle-fluid interaction force $F_{fp}$ in Equation 4 can be determined as the sum of drag ($f_{d,i}$) and pressure gradient forces ($f_{pg,i}$) on individual particles, given by $F_{fp} = \sum_{i=1}^{k_V} (f_{d,i} + f_{pg,i})/\Delta V$.

### 2.3 CFD-DEM coupling scheme

The methods of numerical solutions to problems requiring CFD-DEM coupling have been well established. The coupling scheme used here is the same as before, which is briefly described as follows for completeness. At each time step, DEM will produce information such as the positions and velocities of individual particles, which will be used for the evaluation of porosity and particle-fluid interaction force in a computational cell. CFD will then use this information to determine the fluid flow, which in turn can be used to find particle-fluid interaction forces. Incorporation of the resulting forces into DEM will produce information about the motion of individual particles for the next time step.

### 3 SIMULATION CONDITIONS

In the present work, the BF geometry is set according to that of the LKAB experimental BF, as given in Figure 2A. To reduce computational cost, a two-dimensional slot model is used. Periodic boundary conditions are however, applied to solid particles along the front and rear directions, as done in the previous study. This treatment can help in producing reasonable porosity and account for three-dimensional particle-particle interactions with reduced computational effort. Note that the thickness of the bed facilitated with the periodic boundary conditions may affect the simulation results. Our trial tests indicated that the results did not significantly differ when the bed thickness was varied from four to eight particles diameter. Thus, the bed thickness of four coke particles diameter is used here.

For gas flow calculation, the mesh size in Figure 2B has been examined, and the results did not improve much when a finer mesh was used. The solids in the present model include coke and iron ore, their properties are given in Table 1. For simplicity, the properties of side and furnace center walls are assumed to be the same as particles, but the size of a wall is infinitely large.
TABLE 1  Physical properties of reducing gas, iron ore and coke

| Variables                                      | Values                |
|------------------------------------------------|-----------------------|
| Number of particles \( N \)                   | 30 800                |
| Particle diameter of coke/iron ore \( d_p \), mm | 40/25,40/30,40/35     |
| Particle density of iron ore/coke \( \rho \), kg/m³ | 3500/1081             |
| Particle-particle/wall sliding friction \( \mu_s \), – | 0.3                  |
| Particle-particle/wall rolling friction \( \mu_r \), mm | 0.01d_p              |
| Restitution coefficient, –                    | 0.8                  |
| Particle Young’s modulus \( E \), kg/(m·s²)    | \( 1 \times 10^7 \)   |
| Particle Poisson ratio \( \nu \), –           | 0.3                  |
| Inlet flow rate, m³/s                         | 3.6/8.1/12.6         |
| Fluid density \( \rho_f \), kg/m³             | 1.2                  |
| Fluid molecular viscosity \( \mu_f \), Pa·s    | \( 1.8 \times 10^{-5} \) |
| Discharge rate, kg/s                          | 1.42/1.13/0.95/0.71  |

The bed was initially charged with coke particles to the stock line which is fixed at 6.4 m to simulate practical operations, which is a normal practice to start a BF (Figure 2C). Then, coke particles in the raceway region were discharged at a given rate, resembling the coke combustion. Meanwhile, iron ore and coke particles are charged into the BF top alternatively according to a given batch weight (31.5 kg ore and 10.9 kg coke in this modeling) if the top burden surface is lower than the stock line. Therefore, a layered burden structure and a stable stock line are achieved gradually as shown in Figure 2D.

Generally, the region of the cohesive zone is greatly affected by the burden and operating conditions. However, in this study, a common inverted-V cohesive zone shape shown in Figure 2E was assumed, and its position is preset. The width of the cohesive zone was set as 0.4 m, and the ore particles are discharged when they are lower than the cohesive zone bottom, resembling the melting of iron ore. In the cohesive zone, the Young’s modulus of ore particles was set as 2% of the original value, which was used to consider the softening behaviors as adopted in previous treatment. However, due to the decrease of particle Young’s modulus in cohesive zone, small local porosity leading to low permeability can be observed as a result of the increased overlaps among softened particles.

Furthermore, the packed bed was used as a base \( (t = 0 \text{ s}) \) for the simulation. The time step in each case is constant, which was chosen to ensure the accuracy of the numerical simulation. The coke particles were discharged in raceway zone when the lateral gas jets, which was located at a given height (0.66 m), was introduced. In particular, the discharging rate for the base case (ore/coke particle size 25/40 [size ratio 1.6]) at the raceway zone is 1.42 kg/s, and inlet gas flow rate is 3.6 m³/s. In addition, the simulation cases, except for the case group with different batch weights, were all with the same number of batches for comparative analysis. Here, the different batch weights mean double or triple the base case one but with the same ore/coke ratio. As for the burden distribution types, they are shown in Figure 2F.

4 | RESULTS AND DISCUSSION

In this section, two types of mixed layer formation are discussed. The effects of “interface resistance” resulting from mixed layers, which exist between coke and ore layers, on the porosity distribution and pressure drop were systematically studied. In particular, four BF operating parameters, namely, the particle size ratio, discharge rate around raceway, burden batch weight, and burden distribution type, which may have an effect on mixed layers properties, are discussed here. In order to better understand the underlying relationships among different operations and corresponding BF performances, the performances indices, such as flow pattern, mixed ratio, mixed layer thickness, porosity distribution, and pressure drop are especially focused.
4.1 | General characteristics of mixed layer

4.1.1 | Mixed layer phenomena

In a polydisperse particulate system, such as BF, the burden flow pattern is the primary variable to examine the general performance. Apart from burden pattern, mixed layers, and mixed ratios are also closely related to disparity in particle size or particle size ratio. Figure 3 shows the flow patterns and mixed ratios in different particle size ratios with same horizontal burden distribution. Mixed ratio here is defined as the ratio of ore particle number to total particle number (the sum of ore and coke particles) in a CFD cell during numerical calculations, which is a percentage used to describe mixing state of two types of particle with different sizes, while mixed layer thickness is the height of the interdependent layers of coke and ore. Inspection of these figures particularly from Figure 3D-F indicate that there exists a visible variation in mixed ratio around the cohesive zones due to the intensive mixing of particles in binary size. The larger the particle size ratio, the higher the mixed ratio. At the same time, it can be observed that the ore particle layers consisted of smaller particles exhibit better ductility, which means the layers are not easily pulled apart. In the shaft part, both flow patterns and mixed ratios did not appear to have any notable differences among the different particle size ratios macroscopically and qualitatively. As for the quantitative analysis, it is discussed in following sections in detail.

However, one significant point should be noticed that larger mixed ratios occur in the interfacial region when a layer of smaller particles is placed upon the layer consisted of larger ones. In comparison, the mixed ratios are much less marked when larger particles were placed on a layer of smaller ones. This point can be concluded from all the following cases in BF at different operating conditions, that is, the effects of discharge rate in Figure 4, batch weight in Figure 5 and burden distribution in Figure 6. In fact, this phenomena has been observed in the literature as well.2

For qualitative description, mixed layers over and under an ore particle layer, which is located at around 4.4 m, were adopted. Figure 7A-C depict the behaviors of mixed layers where a layer of larger coke particles is placed upon a layer of smaller ore particles (named “large-upon-small” for short) and the reverse cases (named “small-upon-large” for short) of the arrangement given in Figure 7D-F in different the particle size ratios (1.1-1.6). By comparing these two sets of figures, it can be seen that there exists a layer mixture phenomenon in the vicinity of the interface with different size particles. The principal difference of the mixed layers may be described by stating that when smaller particles were placed on a layer of larger particles, penetration will occur; in contrast, only a surface disturbance takes place in the reverse case. This can be more clearly observed in Figure 5.

As for different burden distributions in Figure 6A-C, higher mixed ratios can be observed around sharp boundary in Figure 6D-F. From the force distributions in Figure 6G-I, compared with larger coke particles, the smaller ore particle was
Mixed ratio and mixed layer thickness

To clearly understand mixing characteristics of ore and coke particle layers in a BF, the quantitative results are shown in Figure 8 under the different BF operation conditions. The mixed layers over and under one ore particles layer (located at around 4.4 m in height) were examined in the furnace shaft region. As shown in Figure 8A, the bottom average mixed ratio was around 8% higher than that of the top mixed layer. As for average mixed layer thickness, the value of bottom one is remarkably higher than that of the top one especially when the particle size ratio gradually increases. Generally, it was found that both mixed ratio and mixed layer thickness increased with increasing size ratio for both top and bottom mixed layers. Similarly, it was observed that both mixed ratio and mixed layer thickness increased with increasing batch weights in Figure 8B.
However, the mixed ratio and mixed layer thickness were not always in similar transition trend. In Figure 8C, the mixed ratio value decreased gradually with the increase in discharge rate, while the mixed layer thickness was almost constant. The reason may be that larger discharge rates decrease contact force among the particles, leading to smaller driving force for penetration of the layer interfaces. As for the effects of burden distribution type, the burden layer is much more inclined, the mixed ratio is larger, while mixed layer thickness turns smaller as shown in Figure 8D. The underlying mechanisms have been explained in Section 4.1.1. From the above, it can be generally deduced that the pressure drop would be largely decreased when the mixed ratio and mixed layer thickness were increased at the same time, otherwise, it is difficult to judge the transition trend of pressure drop.

4.2 The effect of mixed layer on porosity distribution

Essentially, the effects of mixed layer on gas flow mainly function through the particle bed porosity. Furthermore, the bed porosity can reflect the pressure drop from another perspective. Figure 9A shows the porosity distributions under different particle size ratios with horizontal burden layer distribution. It shows that porosity increased slightly with the increase of furnace height, which clearly indicated the effect of gravity on porosity distribution. In addition, the porosities of successive layers in larger particle size ratios were slightly lower not just in mixed layers but also in the separated layers especially when mixed layer accounts for larger ratio in layer thickness. Therefore, apart from gravity, the mixed layers also greatly contribute to bed porosities distribution along the vertical direction. In accordance with findings in literature, inspection of Figure 9A indicated that there exists a sharp local minima in the local porosity, which physically
Figure 8  Mixed ratios and mixed layer thickness under varied, A, particle size ratios (1.1; 1.3; and 1.6); B, initial batch weight times (1; 2; and 3); C, discharge rates: (0.71; 0.95; 1.13; and 1.42 kg/s); D, burden distribution (Inclined-S; Inclined-M; and Inclined-L); respectively

is attributable to the penetration of the smaller ore particles into the void space of its lower layer which composes of the larger coke particles. As expected, when the disparity in particle size is larger, the penetration is deeper, and hence the local porosity minimum is smaller.

Figure 9B illustrates the bed porosity distributions under different raceway discharge rates. Generally speaking, when the discharge rates varied from 0.71 to 1.42 kg/s, the porosity distributions did not show distinct differences in both the variation trend and average value of the furnace height from 4 to 6 m. To some extent, the results did not superficially match with the expected case, which is that, the larger the raceway discharge rate, the larger the bed porosity. The reasoning behind this will be discussed later in Section 4.3. In Figure 9C, the case in normal batch weight (one time of batch weight) shows the lowest porosity distribution compared with the cases in two or three times of batch weight. The main reason is due to that there exists more mixed layers in the former operation, and mixed layers are the main contributors of local minima in the local porosity. As shown in Figure 9D, there are no significant differences among the varied burden inclinations from the perspectives in both transition trend and average porosity value.

4.3  The effect of mixed layer on pressure drop

In a BF process, pressure can directly affect the flow patterns and chemical reactions of its inner multiphases flow. Therefore, it is one of the focused variables in BF operations. In fact, the pressure drop is affected by the resistance caused by the alternative burden layers in BF. In particular, the pressure drop across layered burden structure greatly depends on the number of alternate layers because the “interface resistance” caused by mixed layer has significant contributions to it. Furthermore, the gas flow resistance primarily relies on bed porosity or permeability distribution, while there exist local porosity minima in the interfacial region due to the presence of layers with different size particles.1

For these operations with the same number of burden layers but different size ratios, it can be observed that there were distinct differences in pressure drop as shown in Figure 10A. The pressure drop increases significantly with the increase of particle size ratio. This is because the porosity of mixed layer with larger size ratio was in smaller value due to extensive mixing between the two types of particles as given in Figure 9A.

It is well known that the interactions between gas and solid flow vary directly and simultaneously if any one of them has been changed. Considering this fact, the effect of gas flow rate on the pressure drop is discussed. The operations with the same particle size ratio but different gas flow rates were conducted, and the results are depicted in
FIGURE 9  Porosity distribution under varied, A, particle size ratios (1.1; 1.3; and 1.6); B, discharge rates: (0.71; 0.95; 1.13; and 1.42 kg/s); C, initial batch weight times (1; 2; and 3); D, burden distribution (Inclined-S; Inclined-M; and Inclined-L); respectively

Figure 10B. Here, the relative pressure drop, which represents the radially average pressure based on the referring pressure near the stock line, is adopted for clarity in presenting the effect of gas flow rate. It was found that the increase in flow rate usually results in the increase of relative pressure drop along the vertical direction, and one of the reasons may be the strong mixing and filling of interstitial voids at the interface due to intensive interactions between particles and gas flow because the mixed layer porosities (corresponding to Figure 9A) would have a gradual decrease from 0.457 to 0.432, 0.423 when the flow rate increases from 3.6 to 8.1, 12.6 m$^3$/s. Therefore, it is revealed that gas flow rate can significantly affect the mixed layer properties, such as the mixed ratio and layer porosity, which is consistent with the previous work.\(^1\)

In fact, the coke discharge rate around raceway is also an important parameter affecting gas-solid interactions. However, it has never been discussed in the previous studies from the perspective of its effects on mixed layers in a BF.
Therefore, it is analyzed here to provide fundamental information for understanding the underlying relationships. In these studies, the pressure drop was almost kept constant at different discharge rates from 0.71 to 1.42 kg/s. It is noted that the coke discharge rate around raceway did not affect the pressure drop significantly, and it only has slight impacts on mixed layers as shown in Figure 9B. One possible reason is that the acting part, that is, raceway, is far away from upper mixed layers. In particular, the effects of discharge rate in a certain range on the upper mixed layers are gradually weakened by a large number of particles during the propagation process.

In a real BF operation campaign, coke ratio is normally known prior to the “start-up,” which is commonly given by the theoretical and empirical calculations. Furthermore, batch weight can be determined accordingly and comprehensively. The effects of batch weight on pressure drop are discussed here in detail from the perspective of mixed layers formation. For a given stock line with different batch weights, the pressure drop decreases with the increase in batch weight or the decrease in the number of mixed layers as shown in Figure 10C. These observations prove that the mixed layer numbers contribute to the pressure drop due to additional resistance components from more interfacial mixed layers. Theoretically, the number of mixed layers will have significant effects on the pressure drop, however, from our observation, this effect is not significant. This may be due to the simulation limitation, for example, the small particle size ratio used in the studies, which may have weakened the effect of “interface resistance,” hence has caused the pressure drop to be not sufficiently sensitive to mixed layer number.

Physically, the mixed layer would exhibit different characteristics when the successive two burden layers were structured differently. In a BF, the burden distribution needs to be adjusted according to different burden materials and inner running conditions. To examine its effects on pressure drop, several types of burden distribution are examined here. Figure 10D shows the pressure drop under different mixed layer structures, which corresponds to different burden distributions in a BF. Burden layers are distributed with different inclinations or slopes, which are normally adopted in real BF operation practice. As shown in Figure 10D, the pressure drops in the layers with larger inclination are much less pronounced than the horizontally layered one due to the reduced particle penetration as shown in Figure 8D. This is consistent with the previous research in packed bed systems, in which, it is an extreme case of this study in terms of core and shell arrangement of particles.
5 | CONCLUSIONS

In the current research, a DEM-based model, by considering stock line and the cohesive zone together, was successfully developed. This newly developed model has been used to investigate the mixed layer formation, and the effects of BF operation parameters on mixed layers in a dynamic BF process. From the above results, two types of mixed layer formations were observed, namely, “large-upon-small” type and “small-upon-large” type. Especially, the “interface resistance” resulting from mixed layers was found to have varied contributions to pressure drop under different operational conditions. The following conclusions can be drawn.

- There exists layer mixing phenomena in the vicinity of the interface with different size particles. Larger mixed ratio and mixed layer thickness, and smaller local porosity occur in the interfacial region when a layer of smaller particles is placed upon a layer of larger ones; in contrast, only a surface disturbance takes place in the reverse case.
- The mixed ratio and mixed layer thickness vary differently. The pressure drop will be larger when the mixed ratio and mixed layer thickness increase at the same time; otherwise, there is no direct connection among pressure drop, mixed ratio, and mixed layer thickness.
- Gas flow rate can significantly affect the mixed layer properties. Larger gas flow rate leads to larger pressure drop due to strong mixing and filling of interstitial voids at the interface due to intensive interactions between particles and gas flow.
- In the BF operations mentioned above, when the number of mixed layers in the furnace is constant, the pressure drop increases with the increase of size ratio, and the decrease of burden layer inclination. The pressure drop is insensitive to coke discharge rate around the raceway. When the number of mixed layers in the furnace varies with the batch weight, the pressure drop increases with the decrease of batch weight, this is possibly due to more mixed layers.

These findings are meaningful both scientifically and practically. New insights into the mixed layers under different particle size ratios, discharge rates, batch weights, and burden inclinations in a dynamic BF are provided, in addition to their practical importance to provide guidance for the optimization of operating conditions in a real BF campaign.

Please note that the particles considered in this thesis work are spherical only. The effects of some other parameters (materials properties and operational parameters), such as particle shape, on mixed layer formation may be worth for further investigation. Furthermore, some quantitative descriptions of mixed layer are also necessary. For example, the connection between the local porosity and mixed layer characteristics (eg, mixed ratio and mixed layer thickness) is not clear. Apart from these, the mixed layer has significant effects on the gas-solid flow and hence thermochemical behaviors in the BF. Therefore, mixed layer study should be extended further to include heat and mass transfer in the future.

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CONFLICT OF INTEREST

Note that the author has no conflict of interest relevant to this article.

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