Inter-particle Percolation Segregation during Burden Descent in the Blast Furnace

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Inter-particle percolation at the interfaces between burden layers directly influences the permeability of the burden in the shaft of the blast furnace. This paper studies inter-particle percolation of small particles (pellets) into large particles (coke) during the burden descent through small-scale experiments and simulations. A special device was designed for making it possible to consider the effect of the increase in cross-sectional area along with the burden descent. The simulations, which are based on the discrete element method, were first validated using one experimental case. An overall agreement was found between the experiments and the simulations. The velocity distribution of coke and pellet particles in the small bed, the trajectories along the height of the bed and the quantity of percolating particles at different heights of bed were investigated. The results show a considerable inter-particle percolation of pellets into the underlying coke layer at the wall area, but also a percolation over the whole radius of the system. These findings stress the importance of taking measures to prevent percolation by proper design of the charging programs in the operation of the blast furnace.

KEY WORDS: discrete element method; particle percolation; burden descent; blast furnace; packed bed.

1. Introduction

In the blast furnace shaft, the cross-sectional area perpendicular to the central axis increases considerably from the throat to the belly. The descending burden materials therefore spread out and their layer thicknesses become smaller. This is associated with a loosening of the packed bed, and since the descending materials are composed particles of different size in alternate layers (coke and sinter/pellet), smaller particles resting upon larger ones at a layer interface are expected to percolate into the lower layer. Such inter-particle percolation influences the permeability of burden in the shaft, and, in particular, in the cohesive zone. In the latter region, a strong percolation of iron-bearing burden into coke may change the characteristics of the coke slits, through which the ascending gas passes almost horizontally. Much work on burden distribution in blast furnaces has been reported and some papers focus on the conditions at burden descent,1–7 but very few investigations have studied inter-particle percolation6 and there are practically no papers on a quantification of the percolation during burden descent. Li et al.,9 Bridgwater and Ingram,10 Lomine and Oger11 and Zhu et al.12 studied one or a small number of particles percolating into a static particle bed, which is quite different from the situation in an operating blast furnace. Zhu et al.12 and Rahman et al.13 applied the discrete element method to investigate the percolation behavior of one particle, including percolation velocity, residence time distribution and radial dispersion, under various conditions and found the simulation results consistent with the findings by Bridgwater and Ingram.10

The work presented in this paper makes an attempt to study inter-particle interface percolation by means of small-scale experiments and by discrete element method (DEM) simulations. A device for studying inter-particle percolation was constructed and used in a set of experiments, observing the particles through a plexiglass and by measuring the burden surface height. The results provided useful insight into the percolation phenomena, but it was hard to quantify the percolation due to the simultaneous voidage changes of the expanding bed. Therefore, DEM was also applied to study the system. The DEM simulations were first verified by comparison with the experimental results, followed by an analysis of the behavior of the particles in the two layers with respect to percolation. Finally, some conclusions concerning the inter-particle percolation segregation phenomena as well as the applicability of DEM are drawn.

2. System Studied

In order to experimentally investigate the percolation of small particles (sinter or pellets) into an underlying coke layer, a small-scale device simulating the increase in cross-section area associated with the burden descent was constructed, as show in Fig. 1. The initial width of the device (315 mm) was selected in a scale of 1:10 with respect to the throat radius of a reference blast furnace. Instead of arranging for a vertically descending bottom plane, which would increase the physical size of the model, a device was constructed where the plane emulating the furnace wall was
allowed to be shifted both vertically and horizontally. Simultaneously with this expansion, the bottom plate was shifted horizontally to keep its edge in contact with the expanding wall section. This made the burden layers residing in the model expand, mimicking the behavior during burden descent in the blast furnace. The black stripes on the bottom of the device seen in Fig. 1 are made of rubber and stretch as the device expands, which guarantees that the lowest layer of particles will not simply slide on the bottom surface but will instead expand with it. The bed depth (perpendicular to the plexiglass) is 150 mm. Experiments were conducted in the device by inserting layers of blast furnace burden particles, scaled down by a ratio of 1:4, studying the percolation under different circumstances. The reason for not scaling down the particles by the same factor as the geometry of the device was that the same particles had been used for small-scale burden distribution experiments, where much smaller particles would exhibit inter-particle forces and static electricity at the plexiglass, and further, would give rise to dust problems. In the experiments reported in this work, a layer of coke was first deposited on the bottom of the device, and a layer of pellets was added on its top. After that, the device was slowly (1.5 mm/s in terms of the horizontal movement, which can be described by Newton’s second law of motion. The discrete element method, 15 which has become a popular method for describing particle flows, applies an inter-particle contact model composed of spring and dashpot that correspond to the elastic and plastic nature of particles in the normal direction, respectively. In the tangential direction, the model consists of slider, spring and dashpot. The governing equations for a particle (i) interacting with another particle (j) are written 15,17

$$m_i \frac{du_i}{dt} = \sum_{j \neq i} K_{ij} (F_{x,ij} + F_{y,ij} + F_{z,ij}) + m_i g \quad \ldots (1)$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j \neq i} (T_{ij} + T_{j,i}) \quad \ldots (2)$$

where $u_i$, $I_i$ and $\omega_i$ are the translational velocity, moment of inertia and angular velocity of particle $i$, respectively. The forces involved are the gravitational force ($mg$) and inter-particle forces between the particles, which include the normal force and tangential contact force, $F_{x,ij}$ and $F_{z,ij}$ and damping forces, $F_{d,ij}$ and $F_{b,ij}$. The inter-particle forces are summed over the $K_i$ particles in contact with particle $i$ and depend on the normal and tangential deformations, $\delta_n$ and $\delta_t$. The torque acting on particle $i$ includes two components; one arises from tangential force and the other one is the rolling friction. 16–20

$$T_{ij} = R_i \times (F_{x,ij} + F_{b,ij}) \quad \ldots (3)$$

$$T_{j,i} = -\mu_t F_{b,ij} \cdot \hat{\omega}_j \quad \ldots (4)$$

where $R_i$ is the distance of the contact point from the center of mass, $\mu_t$ is the rolling friction coefficient and $\omega_i$ denotes the unit angular velocity vector of the object at the contact point.

The method tracks each particle by integrating Eqs. (1)–(2), considering interaction with other particles and boundaries (“walls”). The hardness of the particles and the dashpot are related to Young’s modulus and the coefficient of restitution, respectively. The friction between entities is defined with a Coulomb-type of friction law. In this study, the EDEM software was applied to simulate a similar setup as that used in the experiments. The physical properties used for spherical coke and pellet particles, and for the walls, including one moving plexiglass plane and two static ones, are reported in Table 2, where pellet and coke data were taken from the literature. 19,21

![Fig. 1](image)

**Fig. 1.** Experimental device for emulation of particle percolation at burden descent.

### 3. Numerical Simulation Method

Moving granular particles undergo translational and rotational movement, which can be described by Newton’s second law of motion. The discrete element method, 15 which has become a popular method for describing particle flows, applies an inter-particle contact model composed of spring and dashpot that correspond to the elastic and plastic nature of particles in the normal direction, respectively. In the tangential direction, the model consists of slider, spring and dashpot. The governing equations for a particle (i) interacting with another particle (j) are written 15,17

### Table 1. Size distribution of coke used in experiments.

| Particle diameter (mm) | Mass fraction (wt-%) |
|------------------------|----------------------|
| 3–5                    | 2                    |
| 5–10                   | 7                    |
| 10–16                  | 43                   |
| 16–20                  | 32                   |
| 20–25                  | 16                   |

\[ m_i \frac{du_i}{dt} = \sum_{j \neq i} K_{ij} (F_{x,ij} + F_{y,ij} + F_{z,ij}) + m_i g \quad \ldots (1) \]

\[ I_i \frac{d\omega_i}{dt} = \sum_{j \neq i} (T_{ij} + T_{j,i}) \quad \ldots (2) \]

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### 4. Results

#### 4.1. One-Layer Setup

Some results will next be presented from experiments and simulations, where only one layer of particles expands in the experimental rig. These tests were undertaken in order to...
gain an understanding of the bed expansion on the bed’s packing degree. With reference to the regions in the blast furnace, the part close to the moving wall in the experiments will be referred to as the wall while the opposite part, close to the stagnant wall, will be referred to as the center.

The panels in Fig. 2 show the experimental results from an expansion of a layer of coke. After the initial expansion, only a slight slope of the upper surface is observed, but along with further expansion a bend develops at the moving wall and gets stronger during the final expansion. It is interesting to note that the volume occupied by the layer, approximated from the upper surface and the geometry of the system, increases. Comparing the final state with the initial state, the volume increase is about 15%. Thus, the expansion is accompanied with a voidage increase, caused by a decreasing packing degree of the particles. This is obviously caused by the action of the moving wall and simultaneously by the shear force exerted by the moving bottom plate. Comparing the experimental results with the corresponding ones from DEM simulations (right panels in Fig. 2) it is observed that the beds keep almost the same height at each stage of expansion. Along with the expansion, the left side of the simulated profile begins to bend earlier and it is somewhat more rounded, which may be due to the spherical particle shapes used in the simulation. However, the overall agreement must be considered good.

Figure 3 shows a comparison between simulation and experimental results for a single layer of pellets. Even though there is a slight overestimation of the extent of the bend in the simulations, the overall agreement between the experimental and simulated burden surface profiles must again be considered sufficient. In particular, the profiles for the cases with largest expansion show excellent agreement, which demonstrates that DEM has been able to capture the salient features of the expanding layers. Next, a set of percolation experiments with a double-layer setup will be studied.

### 4.2. Overall Experimental Findings from Two-Layer Setup

The left column of Fig. 4 presents results from a percolation experiment with a pellet layer charged upon a coke layer, where the panels correspond to different expansions.
of the device, starting (at the top) with no (0 mm) and ending (at the bottom) with maximum (200 mm) expansion. It is clearly seen how the extent of inter-particle percolation grows with the expansion of the device, in particular after the 150 mm expansion stage has been reached. The pellet layer in the experiments gradually bends at the moving wall and eventually percolates partially into the coke layer, finally revealing the uppermost coke particles. Even though the view through the plexiglass gives a somewhat exaggerated picture of the extent of the percolation of the visible particles, caused by the larger coke bed voidage at the glass and a possible bulging of it, a rather uniform slope of the upper pellet layer is eventually formed. The right column of Fig. 4 illustrates the results of a DEM simulation of the particles in the expanding device. The experimental and simulated burden profiles are seen to be in good agreement, and the slight differences can be partly ascribed to the fact that the relatively large coke size distribution is described by spherical particles of three diameters. A comparison of the height of the material beds in the experiments and in the simulations is provided in Fig. 5, which shows the agreement, despite some discrepancy for the dimensionless coordinates 5/8 and 7/8 in the last two expansion stages. In summary, the findings indicate that the inter-particle percolation experienced during burden descent in the blast furnace can be simulated by DEM, even though the non-spherical coke particles are represented by spheres in the simulations.

4.3 Detailed Study of Pellet Percolation

A general observation from the experiments is that the over-all volume occupied by the two layers stays relatively constant, despite the obvious pellet percolation into the coke layer. This is due to the simultaneous decrease in the packing degree of the underlying coke layer (mentioned in subsection 4.1). From the experimental results it is only possible to estimate the extent of the inter-particle percolation from the surface height through the transparent wall of device, but not to make observations about the internal structure of the bed or about other bed-internal properties. Therefore, a procedure was developed to roughly estimate the extent of percolation of the pellets. With reference to

Fig. 3. Comparison between experimental (left) and DEM simulation (right) results for a single pellet layer. Expansions of the device are 0 mm (top), 50 mm, 100 mm, 150 mm and 200 mm (bottom).

Fig. 4. Comparison between experimental (left) and DEM simulation (right) results for a pellet layer (initial height 62 mm) on a coke layer (initial height 144 mm). Expansions of the device are 0 mm (top), 50 mm, 100 mm, 150 mm and 200 mm (bottom). Coke 1 is denoted by white, coke 2 by black, coke 3 by dark gray, and pellets by light gray in the simulations.

Fig. 5. Bed height during the bed expansion process. The abscissa corresponds to the dimensionless width of the bed and the ordinate to the total bed height.
Fig. 6, the (projection) area covered by pellets and coke in a two-layer experiment has been colored white. The lower middle picture shows the area covered by a single coke layer, colored black, while in the pictures to the right are created by overlaying the black area on the white. This gives a rough estimate the layer thickness of the pellet layer: dividing this into 12 vertical slices (cf. rightmost lower figure) provides a quantification, albeit approximate, of the distribution that can be used to estimate the extent of the percolation in different regions of the bed. The remaining white area in each slice now roughly corresponds to the cross-section of the remaining pellet layer, while the rest of the pellets must have percolated into the coke layer below. In the analysis, the two outermost slices were disregarded, because large variations in their surfaces were observed in the experiments, mainly due to the end effect caused by the device corners that locally makes the bed voidage smaller. The left part of Fig. 7 shows the fraction of the pellet layer that has descended into the coke layer, estimated by the method outlined above. It is seen that initially (after charging), about 20% of the pellets have penetrated into the coke layer void. Here it should be remembered that this value contains the volume change caused by the smaller pellets filling the top void of the coke bed, because the average coke-bed height was deduced from its projection onto the plexiglass. Already at 50 mm of expansion the region close to the moving wall shows a dramatic pellet percolation, and along with further expansion the profile gets somewhat distorted, and the difference between the regions at the moving wall and at the stagnant wall further grows. At the largest expansion about three fourths of the pellets have percolated into the bed at the moving wall, while the corresponding value at the other end of the bed is clearly less than a third. The right part of Fig. 7 shows the fraction of the pellet layer that has descended into the coke layer in simulation. It is seen that initially (after charging), about 10% of the pellets have penetrated into the coke layer void except the point at the moving wall where some more percolation is observed. With the increase of expansion, the fraction of percolated pellets increases, especial at the moving wall, similar to the results from the experiments. The final percolation extents at the extremes (i.e., at the moving wall and at the stagnant wall) are also in good agreement with the experimentally observed values. It is also interesting to note that the simulated values also show some fluctuations of the profiles. The reason for these changes may be that pellets on the surface close to the moving wall may roll towards it, which locally increases the apparent percolation extent.

Figure 8 shows the simulated pellet percolation behavior at the dimensionless width positions 1/8, 3/8, 5/8 and 7/8 as cross sections at maximum bed expansion (200 mm). With an increase in the dimensionless width more pellets permeate into the coke space, i.e., the pellets close to the moving wall percolate faster and easier than in the center of the bed. At the moving wall, the (initial) voidage of the whole coke layer is seen to be more or less fully occupied by pellets. This means that the extent of percolation in the true blast furnace is expected to be rather strong at the wall, where, the wall friction may further give rise to a mixed layer. Clearly, the small and spherical size of the pellets promotes the penetra-

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Fig. 6. Method applied to estimate extent of inter-particle percolation on the basis of surface heights of the double layer setup (white) and a single expanded coke layer (black).

Fig. 7. Estimated fractions of pellet layer that have percolated in to the underlying coke layer at different stages of the expansion of the bed.

Experiment

Simulation
tion of these particles. The simulated angular and translational velocity distribution in the last stage of the expansion process is shown in Fig. 9, where the rolling motion of the percolating pellets is clearly observed. The coke particles, in turn, mainly move at the wall due to the motion of the wall, while some rolling is observed at the bottom of the system.

Figure 10 shows the number of pellets that has percolated to different horizontal planes in the coke layer during the expansion process, for three different vertical distances from the original coke-pellet interface. The number of pellet permeating through the planes and the slopes of the curves both increase along with the bed expansion, although there are some regions of stagnation. At final bed expansion, about 6% of the pellets have descended to a plane 79 mm below the initial coke-pellet interface, while almost 4% of the pellets have descended 140 mm into the coke bed. Thus, along with the burden descent more pellets are expected to percolate into the underlying coke layer. However, one should note that also the upper surface of the coke layer simultaneously descends, particularly at the moving wall. For an expansion exceeding 85% of the maximum one, it seems that the region between the planes 79 mm and 140 mm from the initial coke surface becomes saturated with pellets, so the number of percolated pellets in it stays constant. Still, pellets continue to percolate to the lower levels.

In order to throw further light on the behavior of the percolating pellet particles, twenty pellets that eventually percolated throughout the whole coke layer to the bottom plate were selected, with ten from the region close to the moving wall and ten from the center part of the bed (close to the static wall). The traces of these particles are presented in Fig. 11, using dashed-dotted lines for the particles near the moving wall and solid lines for the particles in the center. The percolation behavior is observed to be fundamentally different for the two zones: Close to the moving wall the particles start a rapid descent immediately and five of the particles have reached the bottom plate during the initial 80 mm of expansion. As for the particles near the stagnant wall, a very slow descent is observed, which after 50–70% of expansion is followed by a more rapid descent. These particles reach the bottom plate during the last 50 mm of expansion. These findings indicate that the initial increase in voidage at the moving wall makes the pellets in the region permeate. After the loose coke bed in the region has been saturated by pellets, and the bed expansion still continues, more space in the center part is revealed, which facilitates percolation in the region. Another finding is that percolating pellets in the center part are mainly found at the walls, while the percolating pellets in the region close to the moving wall originate from the whole pellet layer. Finally, it should be noted that there are some pellets that permeate through the coke layer at almost constant velocity (as indicated by the trace denoted by stars in Fig. 11). This is consistent with experimental

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Fig. 8. Cross sections of the bed in the depth direction for dimensionless bed widths of 1/8, 3/8, 5/8 and 7/8 at maximum expansion. Coke 1 is denoted by white, coke 2 by black, coke 3 by dark gray, and pellets by light gray in the simulations.

Fig. 9. Angular velocity (top panels) and translational velocity (bottom panels) velocity distribution in the final stage of the bed expansion.

Fig. 10. Number of pellets that percolate through different horizontal planes in the burden versus the dimensionless time of the expansion process.
5. Conclusions

This paper has studied inter-particle percolation of small particles (pellets) from an upper layer into large particles (coke) in a lower layer in an experimental device, where the effect of the increase in shaft radius during burden descent in the blast furnace was emulated in small scale. In order to quantify the extent of the pellet percolation and to study the detailed behavior of the percolating particles, the system was simulated by the discrete element method after validating the computational model. From the results the following conclusions can be drawn:

(1) The experimental results demonstrate that a considerable inter-particle percolation must appear during burden descent in the blast furnace.

(2) The discrete element model for inter-particle percolation can successfully reproduce several features of the experimental results.

(3) The complex pellet percolation process continues with the growth of the cross section area, but the number of particles in the upper part of the coke bed seems to saturate, so the available void between the coke particles is efficiently filled by a constant number of pellet particles at larger bed expansions.

(4) The coke particles mainly move at the wall due to its motion, while the pellets are observed to be in rolling motion. There are two different zones for the percolation behavior: The pellets near the moving wall start a rapid descent immediately at the initial expansion, while the pellets in the center part percolate after 50–70% of expansion.

(5) The strong percolation observed at the wall is likely to reflect the conditions for the layers in the regions close to the blast furnace wall. However, the different down-scaling of the geometry and the particles in the experiments exaggerates the extent of the region with strong percolation at the wall: In practice, the bend point observed at the pellet surface is expected to appear at a larger dimensionless radius (cf. Fig. 12) in the true process.

The findings of the work carried out have provided new insight into the complex percolation mechanisms and also new ideas on how to prevent percolation in the blast furnace. These ideas will be elaborated in further work.

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