1. Introduction

Granular materials may form a stagnant zone in a handling process vessel, which has been recognized as a most striking difference between solid flow and liquid flow. Prediction of the stagnant zone profile and its relation to solid flow pattern is important to the design and control of many industrial processes among which hoppers and blast furnaces are typical examples. Traditionally, continuum models are used to describe solid flow. However, empirical or arbitrary treatments have to be employed in such a model in order to predict the profile of a stagnant zone in a hopper or blast furnace.1–3) In recent years, discrete approaches, often developed on the basis of the so-called Distinct Element Method (DEM),4) have increasingly been used to simulate solid flow. In particular, it has been reported that a stagnant zone can be simulated by means of a modified DEM.5–7)

Often gravity is regarded as the key driving force for solid flow. However, under certain conditions, other forces may also play a role here. For example, the buoyancy force becomes significant when the density of fluid filling the voids among particles is high, even though the flow of fluid can still be ignored. In fact, this has been the case for the flow of coke particles in an ironmaking blast furnace.8) In the hearth of a blast furnace, coke particles are supported by the liquid molten iron and may not touch the hearth bottom;9) their flow may be strongly affected by the buoyancy force. It is important to understand the effect of buoyancy force on the solid flow and stagnant zone or deadman in blast furnace hearth in order to develop a better control strategy.

This paper presents an experimental study of the solid flow under conditions related to ironmaking blast furnace. The flow of particles is driven by the downward gravitational and upward buoyancy forces. Consequently, the flow pattern and stagnant zone profile, strongly affected by the level of liquid and the position of discharging hole, are more complicated than those obtained when the gravitational force is the only force. DEM simulation can reproduce the experimental results well, which provides an effective way to simulate the solid flow and related complicated high temperature phenomena in a blast furnace hearth and understand the underlying physics.

Key WORDS: blast furnace; hearth; buoyancy; liquid; mathematical model; scale model; free space; coke; packed bed; solid flow; stagnant zone; particle.

2. Experimental Method

2.1. Physical Modeling

Physical experiments are carried out using a Perspex water model. As schematically shown in Fig. 1, the model consists of a water vessel, a particle charging pipe and a partition sheet with a particle-discharging hole. Particles are charged from the top of the charging pipe and dis-
charged from the discharging hole. Commercial wooden balls and water are used to simulate coke particles and liquid iron respectively. The physical properties of the wooden balls are shown in Table 1.

The procedures for an experiment are given as follows. First, a specified amount of water is poured into the vessel, with the particle-discharging hole sealed by a stopper. Then two thousands of white color wooden balls are charged slowly though the charging pipe. When the stopper is removed, the balls are manually discharged through the discharging hole to simulate the consumption of coke due to combustion at the raceway or carbon solution in the hearth. At the same time, purple balls are charged into the bed through the charging pipe to substitute the discharged white balls. The charging and discharging operations continue until a steady state flow is reached, which can be judged when the profile between the purple and white balls dose not change. This profile can be used to identify the shape of a stagnant zone if it forms under a given flow condition. In the mean time, the flow pattern of particles is observed.

2.2. Numerical Simulation

This work based on the DEM originally proposed by Cundall and Strack but modified by incorporating a rolling friction model in the rotational equation of a particle. According to this model, the transitional and rotational motions of particle i in a system at time t, caused by its interactions with neighboring particles or walls under gravity and buoyancy force, can be described by the following equations:

\[ m_i \frac{dV_i}{dt} = (m_i - m_l)g + \sum_{j=1}^{N} \left( F_{ci,j} + F_{di,j} \right) \] ............(1)

and

\[ I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{N} \left( T_{ij} + M_{ij} \right) \] ............(2)

where \( m_i, I_i, V_i, \text{ and } \omega_i \) are, respectively, the mass of particle, moment of inertia, translational and rotational velocities of particle i. \( m_l \) is the mass of liquid substituted by particle i. The forces involved are: gravitational force \( m_i g \), buoyancy force \( -m_l g \) (if the particle merges in liquid), and inter-particle forces between particles i and j, which include the contact force, \( F_{ci,j} \) and viscous contact damping force, \( F_{di,j} \). These inter-particle forces are summed over the \( k_i \) particles in contact with particle i. The inter-particle forces are determined from their normal and tangential components, i.e. \( F_{ci,j} \) and \( F_{di,j} \), and \( T_{ij} \), which depend on the normal and tangential deformation. Torques, \( T_{ij} \), are generated by tangential forces and cause particle i to rotate, because the inter-particle forces act at the contact point between particles i and j rather than the particle centre. \( M_{ij} \) are the rolling friction torques that opposes the rotation of the i\(^{th}\) sphere. Equations to calculate these forces can be found elsewhere. The simulation conditions are similar to those used in the physical experiment, as listed in Table 2.

3. Results and Discussion

3.1. Effect of Liquid Level

Figure 2(a) shows the solid flow patterns without liquid. It can be observed that a stagnant zone forms at both sides of the discharging hole. The flow area concentrates at the upper part above the discharging hole. This flow pattern resembles that observed for a funnel flow under gravity in a silo (see, for example, Medina et al.). However, the presence of water and hence the buoyancy force will significantly change the flow pattern. As shown in Fig. 2(b), because of the buoyancy force, the bottom of the packed bed can be lifted up by water, although for this case, it is limited to a small region directly under the discharging hole. This lifting up comes from the discharging process, because a small amount of particles at this area can be discharged. On the other hand, particles move downward a bit to replace some particles at the bottom of the packed bed which move toward to the discharging hole. Consequently, the size of the stagnant zone is reduced, with its profile lower than that without water. Once steady flow is established, the particles in the stagnant zone will not move any more.

| Table 2. Simulation condition. |
|-----------------------------|
| Number of particle N | 2000 |
| Particle diameter D | 0.02 m |
| Particle weight m | 2.7×10^{-3} kg |
| Sliding friction coefficient \( \mu_s \) | 0.5 |
| Rolling friction coefficient \( \mu_r \) | 0.015D |
| Time step \( \Delta t \) | 10^{-5} |
| Poisson’s ratio \( \nu \) | 0.3 |
| Restitution coefficient | 0.5 |
| Normal spring constant \( k_n \) | \( m_i^2/(10M_1^3) \) |
| Shear spring constant \( k_s \) | \( k_n/[2(1+\nu)] \) |

| Table 1. Properties of the wooden balls. |
|-----------------------------|
| Diameter | 0.02 m |
| Particle density | 770 kg/m³ |
| Bulk density | 370 kg/cm³ |
| Restitution coefficient | 0.5 |
| Colors | white and purple |
Two forces are here effective to make particles flow: the gravitational force and the buoyancy force. The former leads to the downward flow while the latter the upward flow of particles. The effect of buoyancy force will become more obvious if the liquid level is higher than the discharging hole. Figure 3 shows the observation for such a case. It can be seen that the solid flow pattern becomes very complicated. Driven by the buoyancy force, particles below the discharging hole will move toward to the discharging hole. On the other hand, particles above the discharging hole are driven by the gravity and move mainly downward to replace those discharged. All the white particles initially packed in the bed can be replaced by purple particles, meaning that no stagnant zone is formed under this flow condition.

3.2. Effect of Discharging Position

Figure 4 shows the flow patterns for three different discharging positions. When the discharging hole is at the center or the opposite side of the charging pipe, there is not a stagnant zone (Figs. 4(b) and 4(c)). When the discharging hole is directly below the charging pipe, there is a stagnant zone (Fig. 4(a)). This stagnant zone is different from that formed without buoyancy effect shown in Fig. 2(a). This stagnant zone does not touch the bottom plate, and isolates from discharging hole. In all cases, relatively complicated flow patterns are observed, as a result of particle-particle and particle-fluid interactions.

Different from liquid, particles can heap, giving an angle of repose. The heaping phenomenon is obvious in Figs. 2–4. Two free surfaces are found in some experiments: one is at the top and controlled by the gravity, and another is at the bottom and controlled by the buoyancy force. For all the cases considered, there is no much difference at the top surface; and the average angles of repose is 28.5 degrees. The surface at the bottom varies, depending on the flow conditions. However, it appears that the angle of repose corresponding to a bottom free surface is the same as that corresponding to the top surface. This fact suggests that the downward gravitational force and the upward buoyancy force provide a similar effect and the angle of repose is mainly related to the properties of solid particles. Once a stagnant zone forms, there is another angle of repose that divides the bed into flow and stagnant regions. The present results suggest that this angle is equal to around 70 degrees if the gravity is dominant (Fig. 2). However, if a stagnant zone is present when both the gravitational and buoyancy forces are important, its formation must be related to the particle–particle and particle–fluid interactions that heavily depend on the flow conditions (Fig. 4(a)). Further work is necessary in order to understand the formation of this complicated profile.

3.3. Physical vs. Numerical Experiments

Numerical and experimental results have been compared under the same flow conditions. Figure 5 shows a flow pattern when the discharging hole is lower than liquid surface. The numerical results are the snapshots at \( t=55 \) s, set to match the experimental observation. The agreement between them is quite acceptable. It can also be observed that the angle of repose is slightly smaller than that simulated.
This was mainly due to the error induced when taking a photo. When a photo was taken, manual particle discharging had to be stopped in experiment, which changed the profile of the top surface. The angle of repose is mainly controlled by the rolling friction coefficient, which is similar to that formed by discharging method.\textsuperscript{12}

The simulated results (Fig. 5(c)) clearly demonstrate that the discharged particles are mainly supplied from the regions above and below the discharging hole. These particles are substituted by their above and underneath particles, driven by the downward gravitational and upward buoyancy forces, respectively. Horizontal movement is also present because of the unconfined free surface at the top and bottom of the particle bed. Confined by the wall and other particles, particles in the left corner have a relatively long resident time and their movement/consumption is very slow.

Figure 6 shows another comparison between the physical and numerical experiments. The flow conditions are the same as those for Fig. 4(a). The figure shows that the simulated distribution of residence time agrees well with the experimental observation; so is the case in flow pattern and profile of stagnant region. When the discharging hole is directly under the discharging pipe, solid flow is limited to the left part of the bed and a stagnant zone can form at the right side. The horizontal movement of particles results from the interaction between particles which is relatively vigorous only for particles close to the free surface. For particles far way from the discharging hole, driving force for horizontal movement is not available; consequently they are simply stationary under the balance between the gravity and buoyancy force. While the profile of a free surface is mainly controlled by particle properties, for the stagnant part (the right part in Fig. 6), it is this force balance that produces a curved bottom profile of the particle bed.

4. Conclusions

An experimental and numerical study has been conducted of the solid flow under conditions related to an ironmaking blast furnace where the flow of particles is driven by both the downward gravitational and upward buoyancy forces. The results indicate that the flow pattern and stagnant zone profile are strongly affected by the level of liquid and the position of discharging hole and more complicated than those obtained when the gravitational force is the only driving force. DEM simulation can reproduce the experimental results well. Future work is to extend this numerical approach to simulate the solid flow under more complicated conditions related to blast furnace operation and generate particle scale information that can lead to a better understanding of the underlying physics and control strategy.
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