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DEM SIMULATION OF A SPOUTED BED WITH DRAFT PLATES

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ABSTRACT

The discrete element method (DEM) has successfully been applied here to investigate the aerodynamics of the particles in a rectangular spouted bed with draft plates. The fluid motion is assumed two-dimensional and is solved simultaneously with the equation of motion of the particles by taking into account the interactions between the fluid and particles. The particle motion is calculated in three-dimensions by solving the Newton's equation of motion for each particle. The spouted bed is a vertical rectangular chamber with a width of 48 cm and a depth of 4 cm. A pair of draft plates are set with an entrance height of 8.3 cm and separation distance of 6.4 cm. The angle of the slanted base is 60 degrees. Several corresponding experiments have been performed using corns particles. The results of the calculation showed that the calculated minimum spouting velocity agrees well with the experimental result. Plug flow occurs at the minimum spouting velocity in the spout region. The plug flow disappears with increasing gas velocity. The distribution of vertical particle velocities and fluid velocities in downcomer are fairly uniform above the slanting base.

INTRODUCTION

Spouted beds are widely used in industry such as drying of granular materials, granulation, tablet coating and solid blending. The conventional spouted bed is formed in conical or conical-cylindrical vessel which has a small opening for gas injection at the center of the vessel. The high gas velocity injected at the bottom lifts and carries particles upwards through the central part of the bed. These particles, after reaching a certain height above the peripheral bed level, fall as a loosely packed bed into the downcomer between the hollowed core and the vessel wall. The overall bed is composed of a dilute phase in the central core (spout region) in which the particles are lifted and moved upward by the injected gas and a dense phase (downcomer) between the spout region and the vessel wall in which the particles are moved down. To improve the bed structure and flow stability, a draft tube is inserted in the core of the spouted bed to separate the spout region from the annulus region, thus eliminating back mixing, stabilizing solids circulation and reducing the bed pressure drop [1]. Among the various modifications of the spouted bed proposed to overcome some of limitations of the conventional design, the most promising appears to be the two dimensional spouted bed in which scale-up can be achieved, to some extent, by a simple multiplication of the apparatus along the bed depth [2].

The observation of the phenomena which occur inside the spouted bed without disturbing the gas flow is difficult. In the present day, numerical simulations have become popular to simulate gas and solid flows not only for dilute-phase flows but also for dense phase-flows. Tsuji et al. [3-6] applied the DEM to plug flows in a horizontal pipe, two-dimensional fluidized bed and a cylindrical spouted bed with slanting base. They found that the calculated results of the formation of bubbles, slugs, particle mixing and velocity profiles of the particles agreed well with the experimental observations.

From these researches, the numerical simulation is found to be a useful tool for investigating the phenomena of gas and particles flows without disturbing the flows in a vessel. The objectives of this work is to investigate the minimum spouting velocity, pressure drop and velocity profiles of gas and particles in a spouted bed with a slanting base and draft plates. Fluid motion is calculated in two dimensions and the particle motion is calculated in three dimensions.

GOVERNING EQUATIONS

FLUID MOTION

The locally phase-averaged equation of continuity and equations of motion are used for calculating the fluid motion. All the quantities of the fluid such as pressure and fluid velocity are considered to be uniform in a cell. The void fraction of each cell can be calculated from the volume of particles contained in each cell. Thus, the position and velocity of an individual particle are not concerned in the equation of fluid motion. Only the volume of the particles and average value of particle velocities are considered. The equations of fluid motion are as follows:

Equation of continuity

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial}{\partial x_j}\left(\varepsilon u_j\right) = 0 \qquad (1)$$

Equation of motion

$$\frac{\partial}{\partial t}\left(\varepsilon u_i\right) + \frac{\partial}{\partial x_j}\left(\varepsilon u_i u_j\right) = -\frac{\varepsilon}{\rho_g}\frac{\partial p}{\partial x_i} + f_{pi} \qquad (2)$$

Fluid is treated as inviscid except the interaction term (f_{pi}) between the fluid and particles.

$$f_{pi} = \frac{\beta}{\rho_g}\left(v_{pi} - u_i\right) \qquad (3)$$

where ?, u, p, $?_g$ and $\bar{v}_{pi}$ are the void fraction, fluid velocity, pressure, fluid density and the average particle velocities, respectively. The coefficient ? is derived from Ergun's equation for dense phase and Wen and Yu's equation for dilute phase.

PARTICLE MOTION

The particle motion was calculated by solving the Newton's equation of motion for individual particle with taking into account gravity force (f_g), drag force (f_D) and contact force between the particles (f_C). The drag force is the sum of reaction force from equation (3) and the pressure force [5]. The contact force is calculated by using the DEM. A particle often contacts with many particles or walls. Therefore, the contact force f_C is the sum of all these contact forces. The Newton's equation of motion can be written as follows:

$$\ddot{\boldsymbol{x}} ? \frac{\boldsymbol{f}_C ? \boldsymbol{f}_D}{m} ? \boldsymbol{g} \quad (4)$$

where m is the mass of a particle. The rotational motion of a particle caused by tangential force is derived from

$$\dot{?} ? \frac{\boldsymbol{T}}{I} \quad (5)$$

where T is the torque caused by the tangential components of the contact forces. I is the moment of inertia of a particle.

CONDITIONS OF CALCULATION

The geometry of vessel in this calculation is set as shown in Figure 1. The experimental conditions and the calculation conditions are summarized in Table1. The number of particles corresponding to the same bed height as the experiments are approximately 26,000. The coefficient of friction and the coefficient of restitution of the particles are assumed to be 0.1 and 0.9 respectively. The value of spring constant in the contact force model was determined as the same way of Kawaguchi et al.[5]. The spring constant is 800 N/m. Air at 20^{o}C and 1 atm is used for the fluid in this work. The gas flow is assumed to be two-dimensional. The grid size for calculating gas motion is 16.00 mm x 27.72 mm (dy x dz). Time step for calculation is estimated by using the oscillation period of the spring-mass system as Tsuji et al. [4]. The time step used in this work is 0.0003 s. The properties of particles used for the calculation are set close to shelled corn. The particles are assumed to be spherical and monodisperse.

Table 1. Conditions of calculation and experiment

		Calculation	Experiment [1,2]
Particle			
Diameter, d_p	(mm)	8.0	8.0
Density, ?$_p$	(kg/m^3)	1,231	1,231
Sphericity, ?		1	0.755
Vessel			
Width, W	(mm)	480	500
Depth, L_b	(mm)	40	40
Width of gas inlet, W_i	(mm)	32	33
Width of draft plates, W_d	(mm)	64	50
Entrance height, H_o	(mm)	83.2	100
Spout height, H_b (mm)		887	900
Slant angle, ?		60	60
Dimensionless			
W/W_i		15	15.1
W/d_p		60	62.5
W_i/d_p		4	4.1
W_d/W_i		2	1.5

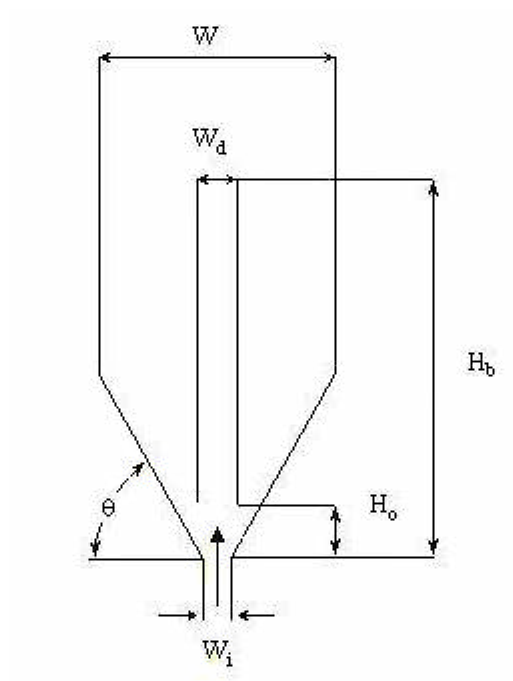


Figure1. Schematics of the two-dimensional spouted bed

RESULTS AND DISCUSSION

MINIMUM SPOUTING VELOCITY

When the gas velocity increases in a spouted bed, a central dilute core region is formed and the pressure drop increases. As the gas velocity further increases, the core region penetrates the bed, forming a spout. A slight further increase in gas velocity leads to steep decrease in pressure drop. After that, the pressure drop is fairly constant although the gas velocity increases. However, as the gas velocity decreases, the pressure drop traces a different path, making a hysteresis loop. The minimum spouting velocity (U_{ms}) is a point at which the pressure drop is beginning to increase steeply when the gas velocity decreases. Figure 2 shows a calculated pressure drop for increasing and decreasing gas velocity. The U_{ms} is obtained from the calculation and experiment are 1.25 m/s and 1.34 m/s, respectively. The U_{ms} of calculation agrees well with that of the experiment. The pressure drop of experiment at the U_{ms} is 1.45 kPa. The calculated pressure drop at U_{ms}, 1.16U_{ms},1.36U_{ms} and 1.6U_{ms} are 1.07 kPa, 1.14 kPa, 1.03 kPa and 0.88 kPa respectively. The pressure drop is fairly constant when the gas velocity increases after a U_{ms} point. The calculated pressure drop at U_{ms} is lower than the pressure drop of the experiment. This disagreement may be caused by the smaller solid concentration in the spout region due to smaller spacing between the draft plates and slanting base in the calculation.

PARTICLE AND FLUID VELOCITY

The present calculated results show that the plug flow occurs at the minimum spouting velocity in the spout region and the plug velocity increases with increasing gas velocity. The plug disappears at a gas velocity 1.9 m/s and the spout is stable for U/U_{ms}>1.6 (U>2 m/s). Figure 3 shows the distribution of vertical particle velocities in spout region at 1.6 U_{ms}. Particles are accelerated to a maximum velocity near the gas inlet and the velocity gradually decreases. The particle velocity decreases with increasing the height. The particle velocity also decreases with increasing distance from the spout axis. The distribution of vertical particle velocities in the downcomer region is shown in Figure 4 (downward velocities are plotted as positive values). In the lower region, the vertical particle velocities are higher than the upper region due to the reduction of cross-sectional area by the slanting base. The distribution of the vertical particle velocities in the downcomer region are fairly uniform at the heights above the slanting base. The vertical particle velocities in the entire downcomer region increase with increasing gas flow rate. Figure 5 shows the distribution of vertical fluid velocities in the downcomer region. The profiles are fairly uniform at the heights above the slanting base. The vertical fluid velocities near the draft plates and the walls are higher than the other region because the void fraction of fluid cell close to the draft plates and walls are slightly higher than the void fraction in the other region. Therefore, gas can penetrate through the region near the draft plates and walls well. The vertical fluid velocities increase with decreasing height at the slanting base region due to the change of the cross-sectional area (of the downcomer region). The vertical velocities in the entire downcomer at 1.16U_{ms} is higher than those of 1.6 U_{ms} because the plug flow which occurs at 1.16U_{ms} makes the flow resistance in the spout region higher.

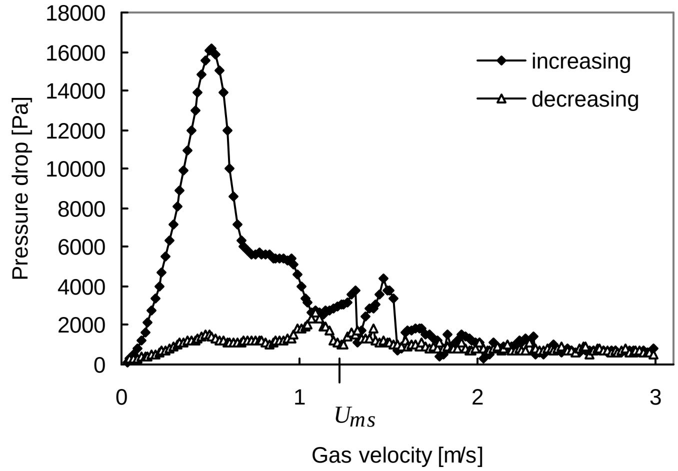


Figure 2. Pressure drop and gas velocity

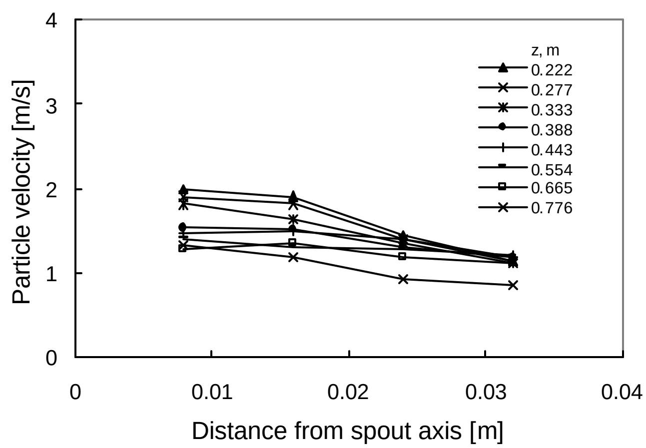
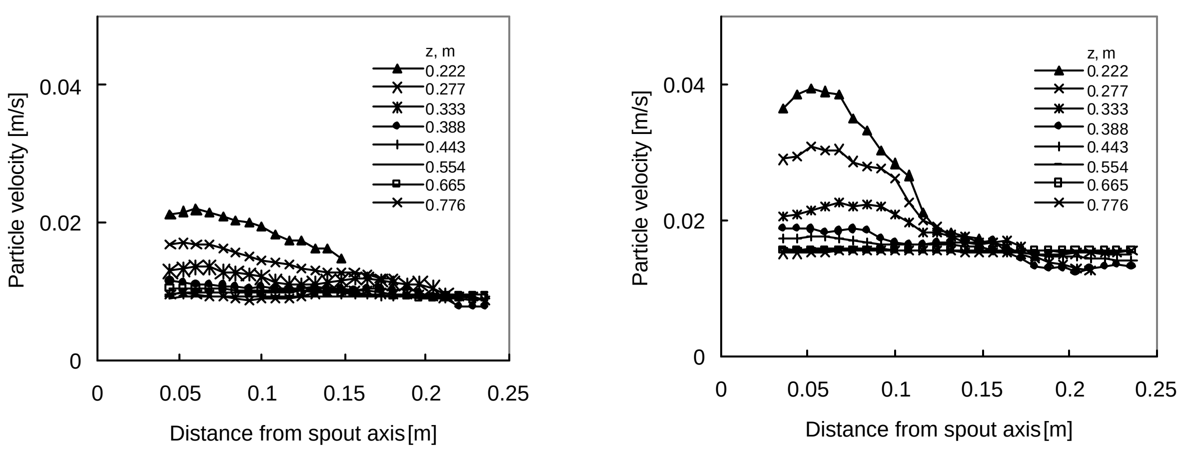


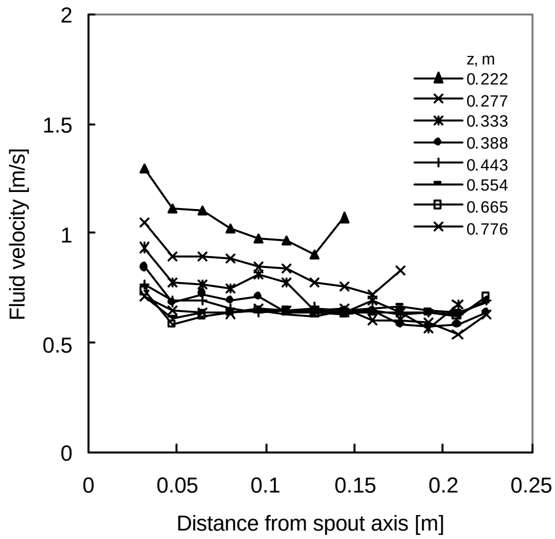
Figure 3. Profiles of vertical particle velocities in the spout at U/U_{ms}=1.6



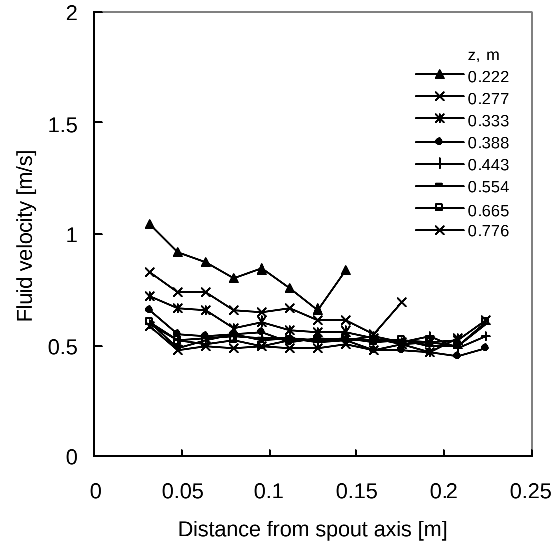
(a) U/U_{ms} =1.16

(b) U/U_{ms}=1.6

Figure 4. Profiles of vertical particle velocities in the downcomer



(a) U/U_{ms} =1.16



(b) U/U_{ms}=1.6

Figure 5. Profiles of vertical gas velocities in the downcomer

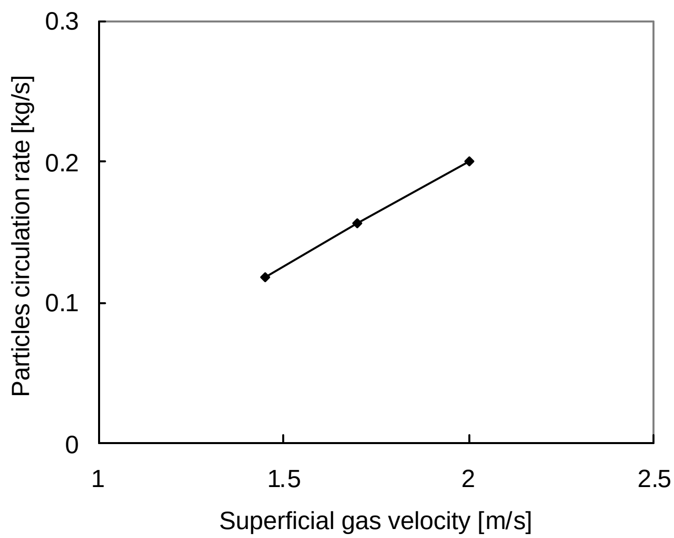


Figure 6. Particle circulation rates and superficial gas velocity

PARTICLE CIRCULATION RATE

The particle circulation rates are estimated by using the particles' velocities, voidage and the cross-sectional area of the downcomer region. The calculated particle circulation rates are shown in Figure 6. The particle circulation rate increases with increasing gas flow rate.

CONCLUSION

The DEM has been introduced for investigating the aerodynamics of spouted bed with draft plates in this work. The calculated minimum spouting velocity agreed well with the experimental result of Kudra et al.[1,2]. The distribution of the vertical particle velocities in the downcomer region are fairly uniform in the region above the slanting base. In the calculation, the plug flow occurs in the spout region at the minimum spouting velocity. The plugs disappear when the gas velocity increases. The spout is stable for U/U_{ms}>1.6. The distribution of the vertical fluid velocities in the downcomer region is fairly uniform in the region above the slanting base.

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