DEM simulation of agglomerated particle behavior in pan-type pelletizer using liquid bridge model

Daiki Fujihashi[1], Yuki Tsunazawa[1], Kazuki Tahara[1], Chiharu Tokoro*[2] and Shuji Owada[2]

[1] Major in Earth, Resources and Environmental Engineering, Graduate School of Science and Engineering, Waseda University, Okubo 3-4-1, Shinjuku-ku, Tokyo, 169-8555, Japan.
[2] Department of Resources and Environmental Engineering, Faculty of Science and Engineering, Waseda University, Okubo 3-4-1, Shinjuku-ku, Tokyo, 169-8555, Japan

*Corresponding author:tokoro@waseda.jp

Abstract

Particle behavior in a pan-type pelletizer was simulated by Discrete Element Method (DEM). In order to represent the effect of added water to adhesive force, liquid bridge model was also included in the simulation. In this study, to investigate detailed behavior of various sizes of particles in pan-type pelletizer, agglomerated particles in five reprehensive particle sizes were simulated by DEM. Velocity and trajectory of several size of particles were compared with experimental results obtained from image processing using high speed camera and their results were consistent each other. In particular, simulation results showed that large particles tend to be located in bottom side of pan and upper side of particles layer, which coincided with the trend obtained from the experiment.

Keywords: DEM, Agglomeration, Liquid Bridge, Pan Type Pelletizer.

Introduction

A pan type pelletizer or a drum type mixer has been generally used for agglomeration of particle mixture by adding binding liquid, because this agglomeration process is productive and low cost. The formation of particle agglomeration is due to adhesion forces between particles, which are attributed to several kinds of inter-particle forces such as Van der Waals' force, electrostatic force or liquid bridge force.

It is well-known that even a small amount of liquid has a significant effect on particulate flow. The adhesion force due to liquid bridges between particles is one of those factors which have long been attracting attention in the field of powder technology. Theories of the liquid bridge between two particles have been developed by several researchers [Fisher, 1926; Lian, Thornton and Adams 1993]. However, since the agglomeration process is very complicated, agglomeration phenomenon has not been revealed fully. Additionally, effective methods to observe particle flows in a pan type pelletizer have not been established. In order to control this agglomeration process properly in a pan type pelletizer, it is necessary and important to understand the motion of particle flows in a pan more particularly and directly.

Computer simulation is one of the effective tools for scientific research. The discrete element method (DEM) simulation can predict behavior of the particle flows from the motion of individual particles. Therefore DEM has been applied to particle simulation such as fluid bet, ball mill, slope failure, and so on. Several researchers have also been proposed DEM simulation taking into account the liquid bridge force.

The objective of this study is to predict several particle sizes of particle flows in a pan type pelletizer by using DEM simulation. In this study, the motion of different sizes of particles was calculated by DEM simulation taking into account a static model of liquid bridge. In order to compare with simulation results, agglomeration experiment using a laboratory scale pan type pelletizer was also conducted. Trajectory and moving velocity of coarse particle in a pan were measured by using a high speed camera and compared with DEM simulation results.

Materials and Methods

Agglomeration Experiment

Agglomeration experiment was carried out in order to validate and compare the DEM simulation results. A pan type pelletizer (ASONE, Japan, PZ-01R) was used for the experiment. The inner diameter and length of the pelletizer were 280 and 730 mm respectively. Figure 1 shows the schematic diagram of a pan type pelletizer used in the experiment. The granulating time was set 5 minutes and the rotation speed was set at 39.0 rpm. Water was added to powder with a spray bottle. Calcium carbonate particles were used in the agglomeration experiment.

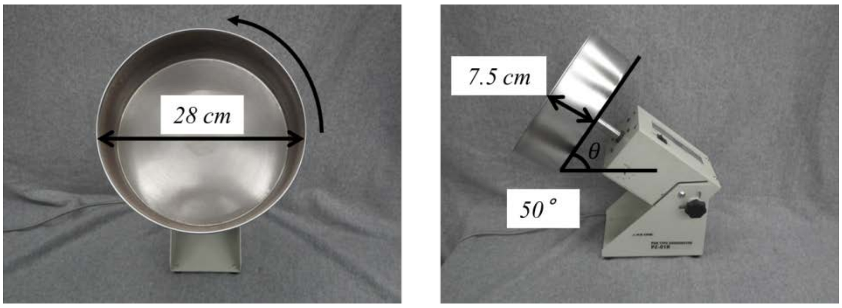
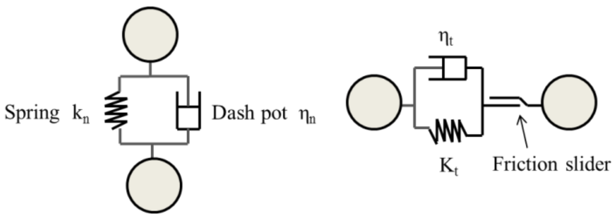


Figure 1. Snapshots of a pan type pelletizer

Discrete Element Method(DEM)

The DEM model used in this study is based on the original DEM concept proposed by Cundall and Strack (1979). As shown in Figure 2, contact between particles and between a particle and a wall is modeled using a Voigt model consisting of a linear spring and dashpot in normal and tangential directions. A slip model defined by the friction coefficient is included in the tangential force. A linear contact model is adopted to reduce the computation load. In this study, the particles are considered to be spherical.



(a) Normal direction (b) Tangential direction
Figure 2. Principle of Voigt model

Inter-particle forces

The liquid bridges cause various effects on the particles, such as the adhesion force exerted by the static forces, the dynamic forces exerted by the viscosity of the liquid and relative displacement of the particles. Static strength forces as surface tension and capillary forces are conservative forces in the sense that they always act to pull particles together in wetted systems. In this study, only static strength forces between the particles were considered. Both of the contact force and the adhesion force of a liquid bridge were taken into account for contacting particles. In the case that a liquid bridge was formed between separated particles, only the adhesion force was considered.

Modeling of liquid bridge

The static strength of liquid bridge consists of two components. One is suction pressure caused by the curvature of the liquid interface. The other is force due to the interfacial surface tension acting around the perimeter of the bridge cross-section. In the case that gravitational effects arising from bridge distortion and buoyancy can be neglected, the total force ***F*** acting between two equal-sized spherical particles, whose radius is r_0, is given by the sum of two components; one is the axial component of the surface tension acting on the three-phase (solid / liquid / air) contact line and the other is the hydrostatic pressure acting on the projected area of the liquid contact to each particle. This leads to the following expression,

$$F = \pi \cdot \Delta P \cdot r_0^2 \cdot \sin^2(\varphi) + 2\pi \cdot \gamma \cdot r_0 \cdot \sin(\varphi) \cdot \sin(\varphi + \theta) \tag{1}$$

where φ is the half-filling angle, θ is the contact angle and γ is the liquid surface tension. Schematic representation of a liquid bridge between two equal-sized spherical particles, particle *i* and particle *j*, with definition of these parameters is shown in Figure 3. In this figure, $2h$ is the surface distance between particles.

ΔP in equation (1) is the pressure difference across the curvature of the air-liquid interface. Assuming that the liquid surface has constant mean curvature ΔP is given by the Laplace-Young equation as follows.

$$\Delta P = \gamma \left[\frac{1}{r_1} - \frac{1}{r_2} \right] \tag{2}$$

where r_1 and r_2 are the radius of curvatures of the liquid bridge surface.

There is a general lack of reliable theoretical formulas for the calculation of the liquid bridge force between two unequal-sized spheres. In this case, following approximation is generally used. That is, the radius term r_0 in equation (1) is replaced by an effective particle radius r_{eff} according to the following equation.

$$r_{eff} = \frac{2 r_i r_j}{r_i + r_j} \tag{3}$$

where r_i and r_j are radius of particle *i* and *j*, respectively.

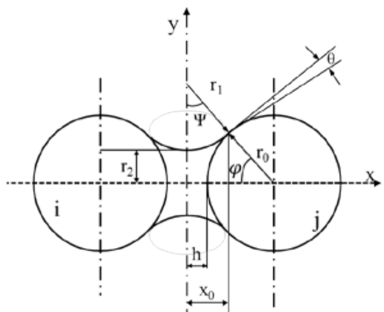


Figure 3. Schematic diagram of liquid bridge

Restriction on liquid bridge formation

Liquid bridges are formed not only between contacting particles, but also between separating particles with a small gap. It is necessary to determine the limit length of the gap in which the liquid bridge is formed.

The liquid bridge can be sustained when the capillary pressure is larger than zero. The limit length of gap H_{max} can be derived by solving the Laplace's equations under the condition of the capillary pressure equal to zero. H_{max} of neighboring particles is given by the following formula.

$$H_{max} = r_2 \cdot \ln\left(\frac{1+\sqrt{1-r_2}}{\sqrt{r_2}}\right) + \sqrt{1-r_2} - 1 \tag{4}$$

Determination of Parameters

The DEM parameters used in this study are shown in Table 1. These simulation parameters were determined from experimental results. In particular, the frictional coefficient was determined carefully since it strongly affects granules behavior. Dashpot coefficient was calculated from spring constant and coefficient of restitution. The particle diameter was determined from sieve mesh used in sieving of particles before/after agglomeration test. The number of particles was determined from weight balanced particle size distribution measurement.

Table 1. Calculation condition

Simulation	Time step (s)	1.0×10^{-6}
	Gradient angle (°)	50.0
	Spring constant (N/m)	1000
	Reflection coefficient (-)	0.1
	Friction coefficient (-)	0.484
	Surface tension of liquid (J/m^2)	0.0725
	Water content (-)	0.00, 0.08
Particles	Particle diameter (mm)	16, 8, 4, 2, 1
	Number of particle (-)	2, 43, 1466, 11868, 41823
	Density of particles (g/cm^3)	2.60

Results and Discussion

Behavior of particles in pan type pelletizer

Figure 4 shows the particle size distribution of the feed particles and the agglomerated particles; particle size is normalized by maximum particle size.

The particle size of the agglomerated particles was larger than that of the feed particles, which showed that effective agglomeration was achieved in the experiment.

In order to compare the behavior of particles in an experiment with the behavior calculated from DEM simulation, the behavior of particles in the experiment was taken by a high speed camera. In this study, the behavior of coarse particles was especially focused on. Figure 5 shows the state of calcium carbonate particles after the agglomeration experiment.

Figure 6 shows snapshots of particle motion calculated by DEM simulation. Coarse particles whose diameter were 8 mm, were painted pink color, and coarse particles whose diameter were 16 mm, were painted green color. That is, the particles rose along the pan wall and then fell down on the surface layer of the granules toward the downside. At this time, the particles cascaded on the surface layer of other granules in the pan. This cascading motion of granules would be important for the agglomeration behavior. Additionally, some particles adhered to the bottom wall of the pan by the force of liquid bridge.

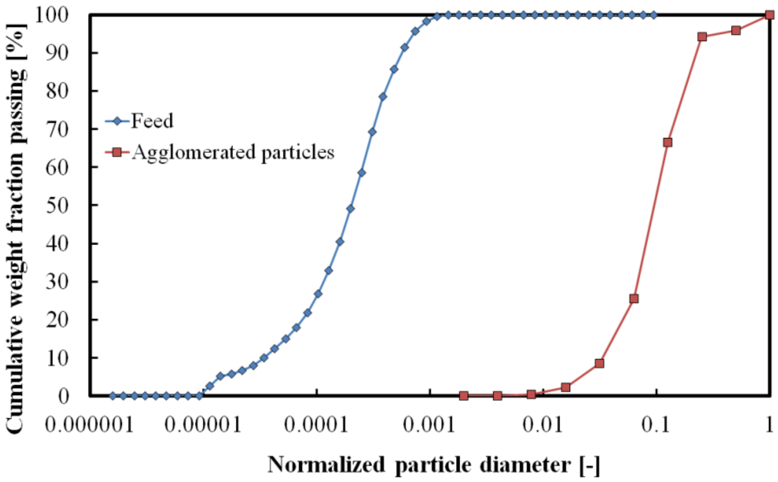
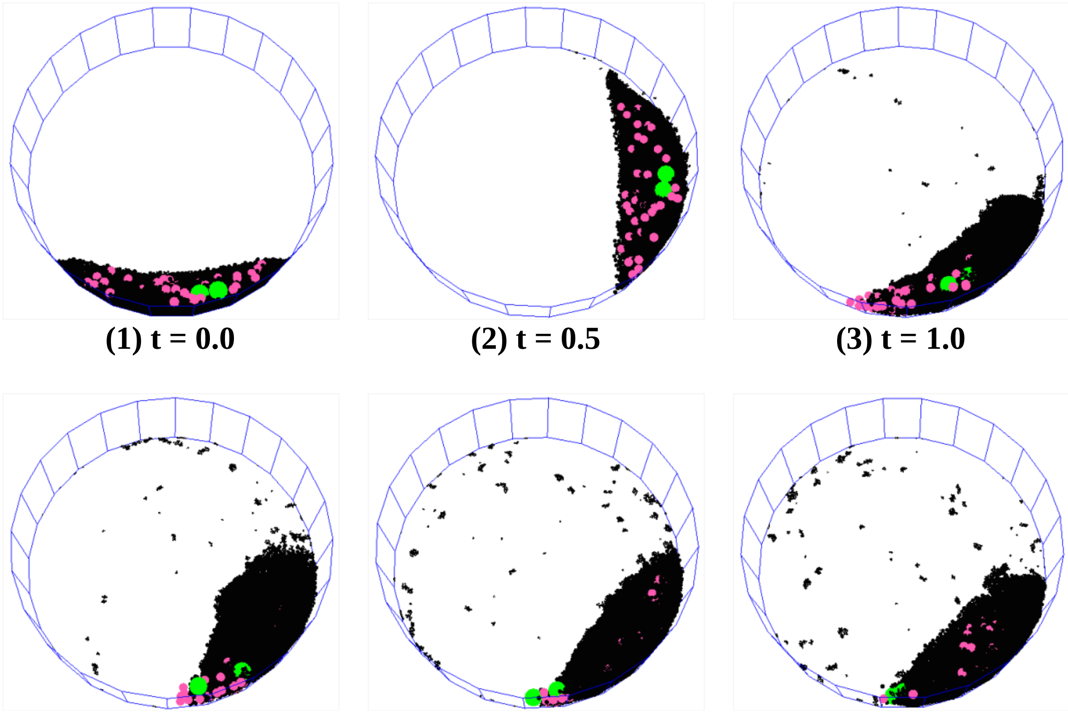


Figure 4. Particle size distribution of feed and agglomerated particles

Figure 5. Snapshots of particle behavior (Experiment)



(1) t = 0.0 (2) t = 0.5 (3) t = 1.0

(4) t = 1.5 (5) t = 2.0 (6) t = 2.5

Figure 6. Snapshots of particle behavior (Simulation)

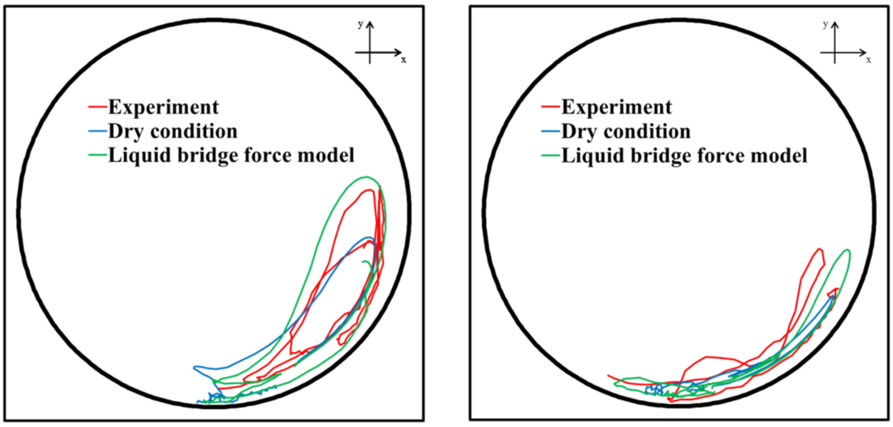
Trajectory and Velocity of Coarse particles

In order to validate simulation results, we focused trajectory and velocity distribution of coarse particles, whose diameters were 8 mm or 16 mm. As shown in Table 1, two different situations in the simulation were compared with experimental results. One was wet condition which was calculated with the liquid bridge model. The other was dry condition which was calculated without the liquid bridge model.

Figure 7 shows the trajectory of coarse particles. Experimental results and simulation results with the liquid bridge model had similarities of the trajectory of coarse particles. In particular, when we focused the maximum height which coarse particle rose up on the surface of particulate bed, simulation results considering the liquid bridge force had almost the same height with experimental results. On the other hand, the maximum height of particles obtained from calculation without the liquid bridge model was much lower than that of experimental results.

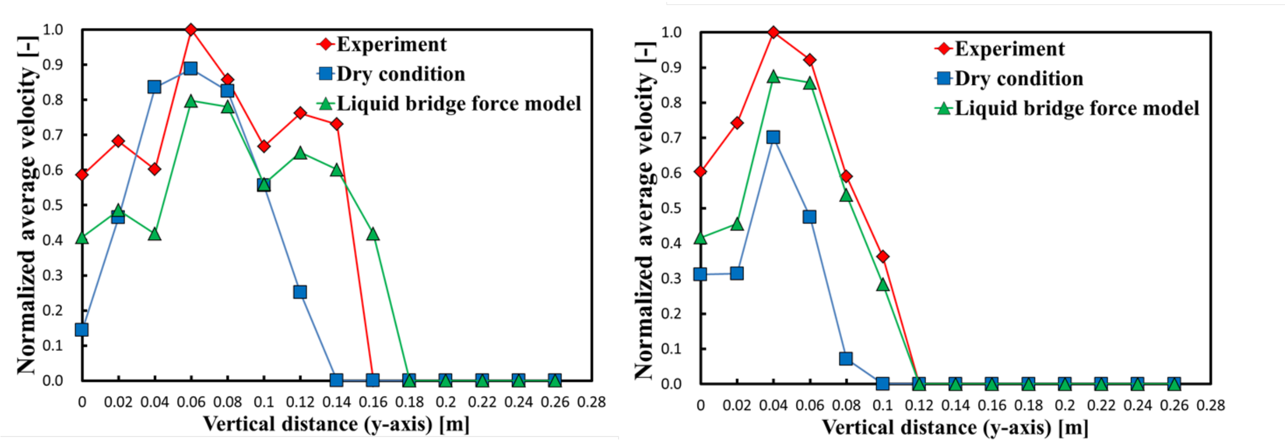
Figure 8 shows the velocity distribution of coarse particles; velocity is normalized by maximum velocity. In the experiment, coarse particles whose diameter were 8 mm, were painted pink color, and coarse particles whose diameter were 16 mm, were painted green color. The velocity of coarse particles was measured by the behavior of particles which was recorded on a high speed camera.

As shown in the figure 9, in the simulation, the x-y plane of the pan was split by square cells, 2 cm on a side, and the velocity was calculated from the average of particle velocity in each cell. Both experimental results and simulation results with the liquid bridge model had similar trend and peak position. Especially velocity distribution of 8 mm coarse particles had unique trend, which could not be represented in the result calculated by the model of dry conditions. These results suggested that the effect of the liquid bridge force was strong for particulate flow in the pan type pelletizer. Comparing between simulation results and experimental ones in Figures 7 and 8, liquid bridge model should be included to DEM simulation in order to represent experimental results exactly.



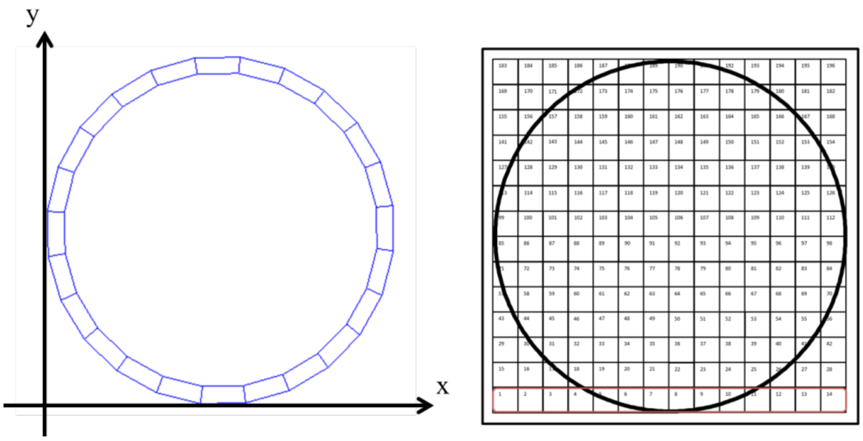
(a) 8 mm **(b) 16 mm**

Figure 7. Trajectory of coarse particles



(a) 8 mm **(b) 16 mm**

Figure 8. Velocity distribution of vertical direction



(a) Coordinate axes **(b) Grid pattern**

Figure 9. Schematic diagram of particle velocity measurement

Conclusion

The behavior of agglomerated particles in the pan type pelletizer with small amount of water was simulated by using the DEM taking account of the adhesion force due to water. The adhesion force acting on two particles was formulated by using the theory of the liquid bridge. The simulation results indicated that the adhesion force due to liquid bridges largely affects particle flows. Concerning the trajectory of coarse particles, both experimental and simulation results with the liquid bridge model had similar trends. Additionally, the velocity distribution also agreed well between both experimental and simulation results when the liquid bridge model was included. These results suggested that the DEM simulation with the liquid bridge model could apply to the determination of appropriate operating condition, such as water content, gradient angle, number of rotations, in the pan type pelletizer.

Reference

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