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Effect of droplet size on particle-particle adhesion of colliding particles through droplet

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ABSTRACT

In a fluidized bed spray granulation, a particle-particle adhesion by a liquid bridge, which shows dynamic motion due to moving particles, is the most fundamental phenomenon. Therefore, understanding of the particle-particle adhesion by such a dynamic liquid bridge is very important to elucidate mechanisms of particle agglomeration phenomenon in the wet granulation. In this study, the particle-particle adhesion phenomenon at the individual particle scale was analyzed using a direct numerical simulation. Collision of two particles mediated by binder droplets on a particle surface was simulated. In particular, the effect of droplet size under constant total liquid volume on adhesiveness of two colliding particles was investigated. In the present simulation, multiple liquid bridges were simultaneously formed, and these liquid bridges coalesced into single liquid bridge. The simulation results exhibited that the adhesiveness of particles increased with a decrease in the droplet diameter under a constant total liquid volume. In an initial stage of the particle growth in a fluidized bed spray granulation, the tendency of the calculations was consistent with experimental results. We revealed that the capillary pressure force and shapes of the liquid bridge are key factors for particle-particle adhesion at different droplet sizes under constant total liquid volume.

1. Introduction

Fluidized bed spray granulation processes are widely used in many industries to improve characteristics of agglomerated particles. In this process, the particles are collided with each other mediated by a binder droplet and the particles are adhered by a liquid bridge. This particle-particle adhesion by the liquid bridge is the most fundamental phenomenon in the fluidized bed spray granulation. Because quality of the final products is determined by physical properties of the agglomerated particles, the wet granulation processes are required to be more adequately and precisely controlled. For this sake, understanding of the particle-particle adhesion by the binder droplet is needed to elucidate mechanism of the particle agglomeration in the wet granulation.

In a microscopic particle-particle adhesion by the liquid bridge, the liquid bridge between particles shows dynamic motion (e.g., compression, elongation, and rupture) due to moving particles. This dynamic motion of the liquid bridge cannot be considered by conventional theories and analytical models about the static liquid bridge [1–5]. There are some experimental and modeling studies on the dynamic liquid bridge [6–13]. Recently, the dynamic liquid bridge has been analyzed using a numerical simulation [14–17]. Darabi et al. [14] simulated stretching behavior of liquid bridge and analyzed effects of dimensionless numbers (capillary, Weber, and Bond numbers) on the rupture distance. Sun and Sakai [16] investigated rupture behavior of liquid bridge and dynamic liquid bridge force acting on a particle. Their simulation results showed good agreement with a result obtained by an empirical model. These previous studies focused on deformation behavior of the liquid bridge and dynamic liquid bridge force acting on a particle. However, the particle-particle adhesion of moving particles by the dynamic liquid bridge has not been investigated in the previous studies, although this particle adhesion phenomenon should be investigated for comprehensive understanding of the particle growth in a wet granulation. So far, we have developed a numerical simulation model to analyze the particle-particle adhesion by the dynamic liquid bridge. The validity of our simulation model was confirmed comparing the simulation results with experimental results [18]. Effect of many critical factors (e.g., particle colliding velocity, physical properties of particle and binder liquid) can be directly analyzed by using our simulation model [19].

Various factors, including physical properties of the particle and liquid, mode and intensity of the particle-particle collision, can affect particle-particle adhesion by the dynamic liquid bridge. Among these factors, droplet size of binder liquid can be a critical factor affecting quality of the agglomerated particles. It has been recognized that the nuclei size of granules are determined by size distribution of the droplets [20]. Some experimental studies investigating effect of the droplet size of sprayed binder liquid on performance of the wet granulation have been reported [21–25]. Tan et al. [24] investigated the particle

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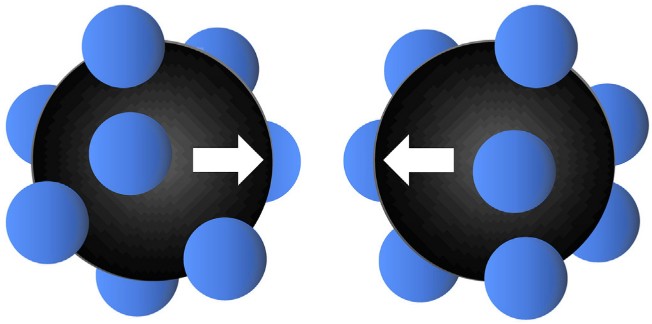

Fig. 1. Schematic of droplets and particles.

growth rate and final granule size at different droplet sizes under constant amount of sprayed binder liquid in the fluidized bed granulation. They found that the overall growth rate and final granule size increased with an increase in the droplet size. However, the effect of the droplet size on the microscopic particle-particle adhesion cannot be quantitatively analyzed by the experimental approaches. We here focused on the particle-particle adhesion under a constant total liquid volume, where number of droplets on a particle surface is varied depending on the droplet size. This results in the formation of multiple pendular liquid bridges between particles. However, the particle-particle adhesion by multiple dynamic liquid bridges cannot be analyzed by experiments and previous theoretical models due to their complexities.

In this study, the effect of the droplet size of binder liquid under constant total liquid volume on the particle adhesion by the dynamic liquid bridge was analyzed using a numerical simulation. By solving motions of particle, gas, and liquid, the particle-particle adhesion between two colliding particles through binder droplets was simulated. In particular, the effect of the droplet size on a critical velocity for particle adhesion was investigated and microscopic mechanism of the particle adhesion by the dynamic liquid bridge was discussed.

2. Numerical simulation model

Motions of three phases including gas, liquid, and solid should be solved to simulate the particle-particle adhesion by the dynamic liquid bridge. In this study, a computational fluid dynamics (CFD) with a constrained interpolation profile (CIP) method was used to solve motions of gas and liquid. A Laglangian approach taking into account liquid bridge force, which is dynamically changed due to dynamic motion of the liquid bridge, was used to solve the particle motion. In this study, the gravity was not taken into account, because Bond number was $8.47 \times 10^{-5} \ll 1$ and the influence of gravity can be ignored [26]. Briefly, our simulation model is shown below. A detailed description of the simulation model can be found in Kan et al. [18].

2.1. Governing equations for motions of gas and liquid

The governing equations of motions of gas and liquid are given as follows:

Equation of continuity

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

Equation of motion

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho_\mathrm{f}}\nabla p + \frac{1}{\rho_\mathrm{f}}\nabla \cdot \mu_\mathrm{f}\left[\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^\mathrm{T}\right] + \boldsymbol{f}_\mathrm{sf} + \boldsymbol{f}_\mathrm{p} \tag{2}$$

Advection equation for color function

$$\frac{\partial \phi}{\partial t} + (\boldsymbol{u} \cdot \nabla)\phi = 0 \tag{3}$$

where $\boldsymbol{u}$, t, ρ_f, p, and μ_f are the fluid velocity, time, fluid density, fluid pressure, and fluid viscosity, respectively. $\boldsymbol{f}_\mathrm{sf}$ is the surface tension force which was calculated by a continuous surface force (CSF) model [27]. $\boldsymbol{f}_\mathrm{p}$ is the interaction force from particle to fluid which was calculated by an immersed boundary (IB) method [28]. ϕ in Eq. (3) is a color function, which was used as a parameter to distinguish gas or liquid, i.e., $\phi = 0$ means gas, while $\phi = 1$ means liquid. Eq. (3) expressed unsteady motion of gas-liquid interface, and CIP method [29] was adapted to solve.

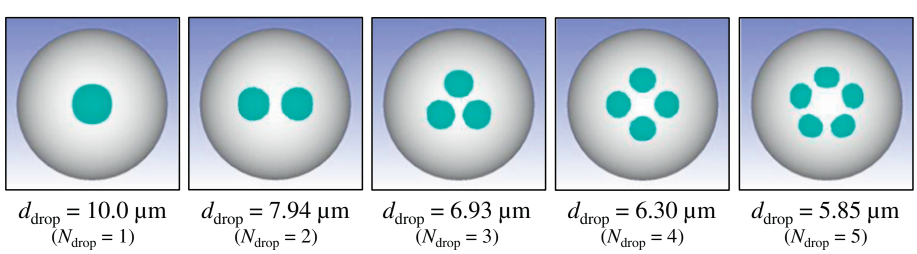

Fig. 2. Initial arrangement of droplets on particle surface at various droplet diameters.

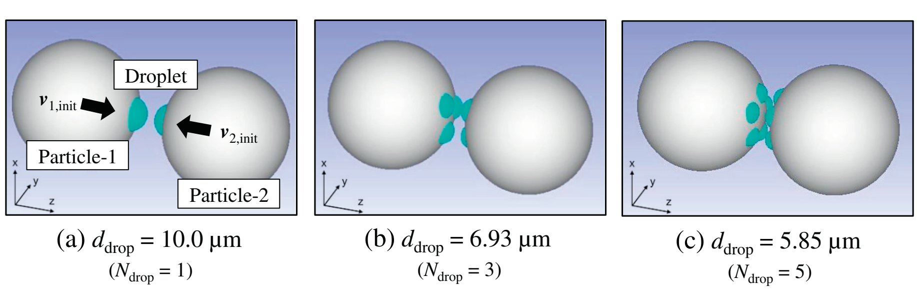

Fig. 3. Initial configurations at various droplet diameters.