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Original Research Paper

Effect of collision angle on particle-particle adhesion of colliding particles through liquid droplet

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ABSTRACT

In wet granulation processes, a particle adhesion mediated by a liquid bridge is one of the quite important phenomena. In an actual process, the liquid bridge shows dynamic motion due to continuous motion of the particles. Therefore, understanding of the particle adhesion phenomenon by a dynamic liquid bridge is essential to adequately and precisely control wet granulation processes. This study presents a direct numerical simulation of the particle–particle adhesion by a dynamic liquid bridge. Collision of a dry particle and a wet particle was simulated at various collision angles. In particular, translational and rotational motions of the particle at different collision angles were discussed through comparison with a conventional static liquid bridge force model. As a result, it was found that both translational and rotational motions were largely different between simulation results of the direct numerical simulation and static liquid bridge force model, especially at the tangential collision. To understand these results, we focused on the rotational behavior of the particle and deformation of the liquid bridge. It was concluded that the non-slip behavior of the liquid bridge on the particle surface is a key phenomenon for the particle-particle adhesion by the dynamic liquid bridge at the tangential collision.

1. Introduction

In wet granulation processes, a particle adhesion phenomenon by a liquid bridge, which is the most fundamental phenomenon, is one of the quite important processes to determine physical properties of agglomerated particles. Therefore, understanding of this particle adhesion by the liquid bridge is essential to adequately and precisely control wet granulation processes.

In an actual wet granulation process, the particles are collided with each other through a liquid droplet. Therefore, the deformable liquid bridge, i.e., dynamic liquid bridge, is formed between particles. The dynamic liquid bridge shows compression, elongation, and rupture behaviors due to motion of the particles. So far, numerous studies on a static liquid bridge, which is not considered deformation, have been reported [1–7]. These previous studies on the static liquid bridge cannot cover the particle-particle adhesion by the dynamic liquid bridge. Although there are some experimental and numerical studies on the dynamic liquid bridge [8–17], these studies have not focused on the particle adhesion but on a liquid bridge force and deformation behavior of the liquid bridge.

So far, we have focused on the particle-particle adhesion by the pendular dynamic liquid bridge [18–20], because this particle adhesion phenomenon should be investigated for elucidation of the particle growth mechanism in wet granulations. This particle adhesion phenomenon is difficult to experimentally and analytically investigate due to their complexities. In such a case, a numerical simulation can be a powerful tool. We have developed a direct numerical simulation model to analyze the particle adhesion by the dynamic liquid bridge. In the validation test, our simulation results showed good agreement with experimental results, confirming that the validity of our simulation model [18]. Effects of critical parameters such as collision velocity, contact angle, and droplet size were numerically analyzed by using our simulation model [18–20].

Various factors (e.g. physical properties of the particle and liquid, mode and intensity of the particle-particle collision) can affect the particle adhesion phenomenon by the dynamic liquid bridge. Among these factors, collision angle against a binder droplet on a particle surface can be a critical factor. In an actual wet granulation process, the particle-particle collision mediated by a liquid droplet can occur at various collision angles, because the particles randomly collide with each other in the process. When a particle collides with another particle through a liquid droplet in an oblique

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direction, the liquid bridge force can act not only in the normal direction but in the tangential direction. However, previous studies on the static liquid bridge force can only express a liquid bridge force in the normal direction [3,4,6]. Although the normal and tangential liquid bridge force models were proposed using a lubrication theory [21,22], a capillary force was not considered in these force models, but a viscous force was only considered. Moreover, deformation of the liquid bridge and influence on the collision angle of the particle were not taken into account in these models using a lubrication theory. Therefore, the effect of collision angle on the dynamic liquid bridge force cannot be expressed by the previous models. As a simple experimental study, collision between a dry particle and a thin liquid film at different collision angles has been reported [23–26]. Crüger et al. [26] investigated the effect of critical parameters (e.g. liquid layer thickness, viscosity, and surface tension) on the normal and tangential wet restitution coefficient at different collision angles. They showed that tangential wet restitution coefficient and liquid bridge behavior was varied depending on the collision angle. However, the effect of collision angle on the microscopic particle-particle adhesion by the pendular dynamic liquid bridge cannot be experimentally analyzed due to their complexities.

In this study, the effect of collision angle on the particle-particle adhesion by the dynamic liquid bridge was analyzed using a direct numerical simulation. The particle-particle adhesion between two colliding particles through a liquid droplet was calculated by solving motions of particle, gas, and liquid. In particular, translational and rotational motions of the particle at different collision angles were investigated through comparison with a conventional static liquid bridge force model.

2. Numerical simulation

2.1. Numerical simulation model

To simulate the deformation of liquid bridge and moving particles, motions of gas, liquid, and solid should be solved. In this study, dynamic motion of the liquid bridge, i.e., motions of gas and liquid, was solved by a computational fluid dynamics (CFD) with a constrained interpolation profile (CIP) method. The moving particles were simulated by a Lagrangian approach considering liquid bridge force that is temporally changed due to dynamic behavior of the liquid bridge. In this study, the influence of gravity was negligible, because the Bond number was $8.47 \times 10^{-5} << 1$ [27]. Therefore, the gravity was not considered. A detailed description of our simulation model can be found in Kan et al. [18]. A part changed from the previous model is explained as below.

Calculation method for motions of gas and liquid was the same as our previous model [18]. In the calculation of particle motion, rotational particle motion expressed by the following equations was added:

$$I_p \frac{d\boldsymbol{\omega}_p}{dt} = \boldsymbol{M}_d + \boldsymbol{M}_{sf} \tag{1}$$

$$\boldsymbol{M}_d = -\int_{V_p} \rho_f \boldsymbol{r} \times \boldsymbol{f}_p dV \tag{2}$$

$$\boldsymbol{M}_{sf} = \int_{V_p} \boldsymbol{r} \times \{\sigma \boldsymbol{t}_c (\nabla\phi \cdot \boldsymbol{t}_s)(\nabla\phi_s \cdot \boldsymbol{n}_s)\} dV \tag{3}$$

where I_p means the particle inertia, and $\boldsymbol{\omega}_p$ means rotational velocity of particle. $\boldsymbol{M}_d$ and $\boldsymbol{M}_{sf}$ mean the torque associated with the viscous drag force, and torque associated with the surface tension force, respectively. $\boldsymbol{M}_d$ was calculated by integrating the interaction force from particle to fluid ($\boldsymbol{f}_p$) over the volume of the particle (V_p) [28]. $\boldsymbol{r}$ is the relative position from the center of gravity of the particle to the fluid cell. $\boldsymbol{M}_{sf}$ was calculated by a continuous capillary force (CCF) model [29]. ϕ and ϕ_s are the color function and volume fraction of the solid in a fluid cell. $\boldsymbol{n}_s$ and $\boldsymbol{t}_s$ are the normal and tangential unit vectors at the solid surface, respectively.

A hard sphere model was adapted to calculate translational and rotational rebound velocities of particles at the particle-particle binary collision. The translational and rotational rebound velocities of the two particles ($\boldsymbol{v}_{1,re}$, $\boldsymbol{v}_{2,re}$, $\boldsymbol{\omega}_{1,re}$, and $\boldsymbol{\omega}_{2,re}$, respectively) were calculated by the following equations [30]:

2.1.1. Translational rebound velocity

$$\boldsymbol{v}_{1,re} = \boldsymbol{v}_1 - \left\{(1+e)(\boldsymbol{n}\cdot\boldsymbol{G})\boldsymbol{n} + \frac{2}{7}|\boldsymbol{G}_t|\boldsymbol{t}\right\}\frac{m_{p2}}{m_{p1}+m_{p2}} \tag{4}$$

$$\boldsymbol{v}_{2,re} = \boldsymbol{v}_2 + \left\{(1+e)(\boldsymbol{n}\cdot\boldsymbol{G})\boldsymbol{n} + \frac{2}{7}|\boldsymbol{G}_t|\boldsymbol{t}\right\}\frac{m_{p1}}{m_{p1}+m_{p2}} \tag{5}$$

2.1.2. Rotational rebound velocity

$$\boldsymbol{\omega}_{1,re} = \boldsymbol{\omega}_1 - \frac{5}{7R_{p1}}|\boldsymbol{G}_t|(\boldsymbol{n}\times\boldsymbol{t})\frac{m_{p2}}{m_{p1}+m_{p2}} \tag{6}$$

$$\boldsymbol{\omega}_{2,re} = \boldsymbol{\omega}_2 - \frac{5}{7R_{p2}}|\boldsymbol{G}_t|(\boldsymbol{n}\times\boldsymbol{t})\frac{m_{p1}}{m_{p1}+m_{p2}} \tag{7}$$

where $\boldsymbol{v}_1$ and $\boldsymbol{v}_2$ are the translational velocities of the particle-1 and particle-2 just before collision, $\boldsymbol{\omega}_1$ and $\boldsymbol{\omega}_2$ are the rotational velocities just before collision. e, $\boldsymbol{G}$, $\boldsymbol{G}_t$, $\boldsymbol{n}$ and $\boldsymbol{t}$ are the restitution coefficient between solid particles, relative translational velocity between two particles, tangential relative translational velocity between two particles, unit normal vector from the particle-1 to particle-2, and unit vector in the tangential direction, respectively.

2.2. Simulation set-up

Fig. 1 shows a collision angle α used in this study. $\boldsymbol{v}_{1,init}$ and $\boldsymbol{v}_{2,init}$ are the initial translational velocities of the particles. The particle-2 collided with the stationary particle-1 ($|\boldsymbol{v}_{1,\ init}| = 0$) at collision velocity $v = |\boldsymbol{v}_{2,\ init}| = 3.0$ m/s. The point O is center of mass of particle-2 when the two particles contact. Based on this point O, collision angle α was defined. The collision angle was set from 0 deg (collision in the normal direction) to 90 deg (collision in the tangential direction). Fig. 2 shows initial configurations at $\alpha = 30$ deg and $\alpha = 90$ deg. In this study, a droplet was only set on the particle-1 to simply define collision angle. The x-component of the initial velocity of the particle-2 ($\boldsymbol{v}_{2,init}$) was set as zero, i.e., the particles can only move in the y- and z-direction during simulation. The initial rotational velocities of the two particles were set as zero. Table 1 shows calculation conditions. The physical properties of water were set as calculation conditions of the liquid. The droplet volume was determined based on a typical mist volume used in a fluidized bed spray granulation [31]. The physical properties of a lactose were set as calculation conditions of the particle. In the present study, restitution coefficient between solid particles was set as 1.0 to clearly investigate the acceleration and dissipation of the particle motion derived from the liquid bridge force.

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