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The collision efficiency of liquid bridge agglomeration

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HIGHLIGHTS

- The hard-sphere approach was applied to model agglomeration due to liquid.
- The collision efficiency was extracted from computer simulations.
- The dependence of the collision efficiency on dimensionless criteria was found.
- A new expression for the estimation of the collision efficiency was proposed.
- The expression is validated with experiments.

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ABSTRACT

An understanding of agglomeration in multiphase flows by means of capillary bridges is important for various technical applications. One of the key parameters that describe the process is the probability of agglomeration, usually termed collision efficiency. In the present paper we study the collision efficiency by using Eulerian–Lagrangian computational fluid dynamics (CFD) modelling. The analysis evaluates the dependence of the collision efficiency on various dimensionless parameters that describe the process, including, among others: Reynolds number, bridge capillary number and wetting angle. In addition we further develop a theoretical expression for a priori engineering estimates of the collision efficiency. This expression is validated against numerical, theoretical and experimental results.

1. Introduction

Agglomeration in slurries (Kudrolli, 2008) and aerosols (Chua et al., 2011) takes place when the particles stick to each other during an interparticle collision. This occurs due to the inherent cohesivity of particle surface caused by the van-der-Waals interaction or, as studied in this paper, due to the capillary attraction when the particle surface is covered with tensive fluids. These fluids, often referred to as binders, form the so-called liquid bridges between the particle surfaces.

The phenomenon of liquid bridge agglomeration is important from a technological point of view since the process kinetics could be controlled by varying the main flow parameters and the properties of the binder. The use of oil binders promotes selective agglomeration in coal-water slurries (Netten et al., 2014; Vanangamudi and Rao, 1984; Kawashima and Capes, 1974). Liquid bridging of solid particles dispersed in gas phase (Schaafsma et al., 2006a,b) is used for production of millimetre-size grains from fine micro-particles during fluidization. Moreover, liquid bridges are considered to be a primary cause of petroleum pipe blockage with gas hydrate obstructions (Zerpa et al., 2012). Agglomeration plays an important role in the forced separation technologies (Lee et al., 2003). Finally, the phenomenon of cellular bonding of blood cells (Goto et al., 1998) can also be considered as the liquid bridging.

One of the key parameters that describe the kinetics of the bridge-dominated agglomeration is the collision efficiency. Generally, this can be defined as the probability that the dispersed objects agglomerate in a multiphase system. However, the details of this definition differ in literature. For example, the early works on liquid drop coalescence (Hocking and Jonas, 1970; Pinsky et al., 1999) propose that the collision efficiency is equal to the collisional cross-section of drops, that is, the probability of collision as such. Another definition of collision efficiency is used in the field of the population balance modelling (Hounslow et al., 1988; Balakin et al., 2014a). Here the collision efficiency is defined as the ratio between the

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frequencies of collision and successful agglomeration events, that is, the probability of agglomeration during a collision. This definition is the one we will focus on in the present paper.

The collision efficiency of cohesive particles whereby the van-der-Waals interaction leads to agglomeration is well documented in the literature. Zeichner and Schowalter (1977) and van de Ven and Mason (1977) analysed trajectories of a pair of cohesive particles that interacted in a continuous phase flow. The collision efficiency was found to be dependent on the so-called flow number, that is, the ratio between the cohesive force and the repulsive drag force. These expressions, however, are only capable of predicting collision efficiency during a doublet formation, i.e. they are valid at the early stages of agglomeration when the aggregates are composed of two primary particles. An extended analysis designed to evaluate collision efficiency for fractal agglomerates was performed by Brakalov (1987), Potanin (1991), Kusters et al. (1997) and Babler (2008). Finally our recent work (Balakin et al., 2013) dealt with collision efficiency of van-der-Waals agglomeration determined from a series of Eulerian–Lagrangian simulations.

Initially, the collision efficiency of the liquid bridge agglomeration was defined as the probability that particles contact each other by a binder-wet region during the collision. This probability was set to be proportional to the fractional coverage of the particle surface, that is, the ratio of particle surface covered by the binder to the total particle surface (Smellie and La Mer, 1958; Healy and La Mer, 1962):

$$\tau_0 = \frac{a^2}{d^2}, \tag{1}$$

where d is the particle diameter and a is the radius of the binder drop at the particle surface:

$$a = \left[\frac{3V}{\pi}\frac{\sin^3\theta}{2-3\cos\theta+\cos^3\theta}\right]^{1/3}, \tag{2}$$

where V is the volume of the binder droplet that stays on the particle surface and θ is the binder-particle wetting angle.

The collision efficiency was then given by Smellie and La Mer (1958):

$$\alpha = \psi_1 = \tau_0 \cdot (1-\tau_0), \tag{3}$$

where ψ_1 is the probability of a binder-wet collision. It was therefore assumed that, once the particles contacts another by a binder-wet region, this always leads to agglomeration. The approach however, is valid only for small particles where their inertia does not play any role during rebound and an agglomerate is therefore formed automatically.

Agarwal (2002) performed experimental studies of the bridge-dominated agglomeration of particles covered by a liquid flocculant. A model was proposed assuming the agglomeration was driven by the superposition of the van der Waals interaction and bridge-induced forces. The derived collision efficiency was proportional to the flow number and the fractional coverage. The collision efficiency was extracted from experimental data using the approach based on Smoluchowski (1927) theory of agglomeration:

$$\alpha = \frac{\pi}{4\gamma\phi t}\ln\frac{n_0}{n(t)}, \tag{4}$$

where α is the collision efficiency, $n(t)$ is the number density of agglomerates at time t, n_0 is the initial number density of primary particles, γ is the shear rate and ϕ is the volume fraction of particles. Agarwal (2002) used this relation to estimate the efficiency of the doublet formation.

Thielmann et al. (2008) and Chua et al. (2013) considered the fractional coverage as well as the viscous effects of the bridge in their expression for collision efficiency:

$$\alpha = \exp[\nu(St^* - St)]\psi_2, \tag{5}$$

where ν is an empirical parameter (Thielmann et al., 2008 used the value $\nu = 1$) and $\psi_2 = 1-(1-\tau_0)^2$ is the probability of both particles colliding by the binder-wet region. St is the Stokes number of the bridge, i.e. the ratio of the characteristic times of the particle and binder flow in the bridge:

$$St = \frac{8mv_0}{3\pi\mu_b d^2}. \tag{6}$$

In the above m is the mass of the particle, v_0 is the absolute value of the particle pre-collisional velocity, μ_b is the viscosity of the bridge and d is the diameter of the particles.

The critical Stokes number responsible for the viscous dissipation of the particle kinetic energy is given by

$$St^* = \left(1+\frac{1}{\epsilon}\right)\ln\left(\frac{X_{max}}{X_{min}}\right), \tag{7}$$

where ϵ is the restitution coefficient of particle material, X_{max} is the rupture distance of the bridge and X_{min} is the roughness of the particle surface. Capillary effects are however, not considered in Eqs. (5)–(7).

In the present paper we study agglomeration by means of numerical modelling. The collision efficiency extracted from the numerical simulations was averaged over the temporal scale of the agglomeration process. This allowed an analysis of efficiency as for large agglomerates as for the doublets and hence to account for longer stages of agglomeration. The model was compared to Eq. (5) and experimental results reported in Heath et al. (2006a). The collision efficiency found in the present paper considered capillary effects and therefore the simulation results were supposed to be physically credible. Moreover, an expression was proposed for fast engineering estimates of the collision efficiency.

2. Methodology

2.1. Numerical simulations

The simulation strategy used in the present work incorporates two techniques developed previously in a way similar to one reported recently in Balakin et al. (2014b). The first is based on the Eulerian–Lagrangian computational fluid dynamics (CFD) model shown in Kosinski et al. (2009). The technique treats the fluid by a set of Navier–Stokes equations for the viscous incompressible flow:

$$\nabla\vec{u} = 0, \tag{8}$$

$$\rho_f\left[\frac{\partial\vec{u}}{\partial t} + \vec{u}\nabla\vec{u}\right] = -\nabla p + \mu_f\nabla^2\vec{u} - \vec{f}_{p,\Sigma}, \tag{9}$$

where $\vec{u}$ is fluid velocity, ρ_f is its density, p is pressure and μ_f is dynamic viscosity.

Eq. (9) is coupled with the flow of the dispersed phase via the interphase momentum transfer term, that is, the summarized drag force, applied to the fluid from all the particles located within a computational cell $\vec{f}_{p,\Sigma}$. An isothermal flow is suggested for both phases and the energy equation is therefore excluded.

Motion of i-th particle in the fluid flow is described by the classical Newtonian mechanics:

$$m_i\frac{d\vec{v}_i}{dt} = \vec{f}_{p,i}, \tag{10}$$