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Effects of aggregation on the kinetic properties of particles in fluidised bed granulation

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ABSTRACT

Aggregation in particulate flow affects not only the size but also the pressure, momentum, kinetic energy, mixing and aggregation efficiency of the particles. This paper demonstrates such effects using a kinetic theory of aggregation to study a gas fluidised bed granulation system with a comparison to that of the process without aggregation. The aggregation system showed a decreasing bed pressure and an increasing total momentum and kinetic energy of the particles over time. A continual mixing of the particles between regions from top to bottom of the bed was observed while for the non-aggregation system, after the fluidisation has fully developed, hardly any mixing of the particles between those regions was seen. It was found that the aggregation of particles mainly took place in the middle of the bed while in the top and bottom of the bed, aggregation had a smaller proportion and segregation showed to dominate. The calculated collision success factor suggests that the particles in the top of the bed have the largest probability to aggregate.

1. Introduction

Aggregation is considered as playing a crucial role in the processes of particle size enlargement such as crystallisation [1] and granulation [2–6] and many researchers and research communities have contributed to this area [7–33]. The growth of particle size in the processes undergoing aggregation is typically modelled by a population balance method [3,24,34–48] and for granular flow in such as gas fluidised bed (FB) systems, a kinetic theory approach [12,49–54] can be adopted. For FB systems, the use of the kinetic theory to understand the motion of particles has become a common method [55–58] and experimental measurements [59–64] have validated the applicability of this method to some large extent. It can be said that the majority of the studies on the application of kinetic theory to FB granular flows [65–72] are concerned with the behaviour including mixing and segregation of the particles mostly for non-aggregation systems [51,73–77]. However, for systems of aggregation in FBs, apart from some population balance modelling [54,78] of particle size change, a quantitative description of the impact of aggregation on other important kinetic properties such as pressure, momentum, kinetic energy, mixing and aggregation efficiency has yet to be seen. This is because it is only by knowing that, a thorough understanding of the aggregation effect can be achieved then the process and product quality control in particulate flow can be made possible. This paper is aimed to address these issues using the kinetic theory of aggregation [53] to model a FB system for the case of aggregation. Its results are compared with that of the experiment and a non-aggregation simulation.

The kinetic theory of aggregation is a theory that describes the phenomena of aggregation in terms of the probability of the colliding particles to succeed for aggregates. This probability refers to a collision success factor: ψ, *i.e.*, the aggregation coefficient. This factor has transformed those transport equations from their traditional structure [79] into the ones that demonstrate the effects of aggregation on individual and ensemble properties of the particles such as population, momentum and kinetic energy. These transport equations are given in Appendix I.

2. The collision success factor

The collision success factor—aggregation coefficient, is used in the conservative Eqs. (A.1)–(A.10) to account for the completely inelastic collisions. Its numerical values can be calculated by the known aggregation rate constants that are determined using a Moment method [48] with a discretised population balance technique [80]. The calculation of ψ is given below.

As can be seen from Eq. (A.1), the aggregation kernel $k_{\varepsilon v}{}^{agg}$ for the collisions between particles of volume v and ε is

$$k_{\varepsilon v}{}^{agg} = \left[\frac{8\pi\theta_s m_v + m_\varepsilon}{m_v m_\varepsilon}\right]^{1/2} \psi_{\varepsilon v} g_{\varepsilon v} \sigma_{\varepsilon v}{}^2$$
$$= \psi_{\varepsilon v} g_{\varepsilon v} \sqrt{\frac{\pi\theta_s}{2\rho_s}} \left(\frac{6}{\pi}\right)^{\frac{2}{3}} \left(v^{-1} + \varepsilon^{-1}\right)^{\frac{1}{2}} \left(v^{\frac{1}{3}} + \varepsilon^{\frac{1}{3}}\right)^2 = k_0 f_{\varepsilon v}, \qquad (1)$$

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where

$$k_0 = \psi_{\varepsilon v} g_{\varepsilon v} \sqrt{\frac{\pi\theta_s}{2\rho_s}} \left(\frac{6}{\pi}\right)^{\frac{2}{3}}, \quad (2)$$

$$f_{\varepsilon v} = \left(v^{-1} + \varepsilon^{-1}\right)^{1/2} \left(v^{1/3} + \varepsilon^{1/3}\right)^2, \quad (3)$$

in which $\theta_s = \int_v \theta_v n_v dv / m_0$ (θ_v and n_v are the kinetic energy and number density of the particles of volume v, respectively, and m_0 is the zeroth Moment—the total number of particles) is the mixture kinetic energy of all particles. $g_{\varepsilon v}$ is the radial distribution function accounting for the probability of finding a particle with a reference of a distance to another particle. This distance normally refers to the addition of the radii of the two particles. In a gas FB system where particles are well mixed, $g_{\varepsilon v}$ without losing its general applicability [81–83] can be approximately regarded as $g_s = [1 - (\varepsilon_s/0.64)^{1/3}]^{-1}$ where ε_s is the total volume fraction of the particles in the system, and k_0 can be determined by the technique shown in Appendix II. As k_0 in this study is extracted using the experimental PSDs, it is only a function of time; the calculated $\psi_{\varepsilon v}$ would then become as well only time dependent and is denoted by ψ.

$$\psi = k_0 \bigg/ \left[g_{\varepsilon v} \sqrt{\frac{\pi\theta_s}{2\rho_s}} \left(\frac{6}{\pi}\right)^{\frac{2}{3}} \right]. \quad (4)$$

Eq. (4) shows how the numerical values of ψ can be calculated in the population balance analysis. The collision success factor derived from the kinetic theory of aggregation is given in Eq. (5).

$$\psi = 1 - (1 + \theta^*/\theta_s) \exp(-\theta^*/\theta_s) \quad (5)$$

where θ^* (J) is the critical relative kinetic energy describing the energy at the force balance between the attraction and repulsion after a collision occurred to a particle and can be approximately assumed to be the same for the particles in an isotropic turbulent system as studied in this paper. This means that any relative collision energy between the colliding particles less than that would succeed for aggregation [53]. It is worth mentioning that this energy can be explored to include the rotation [84,85] of the aggregating particles. However, the calculation of θ^* is not the scope of this article so will not be sought. Nevertheless, Eq. (5) is to be used to explain the physical insights for the change of ψ that takes place during aggregation. This will be seen later in this paper from Fig. 16.

3. The experimental

3.1. Equipment and setup

The experiment was carried out in a top spray FB granulation system that is represented by Fig. 1a.

As seen from Fig. 1a, a gas flow passes through the distributor to fluidise the silica particles. The liquid binder (PEG 1500) is atomised by an air compressed nozzle (JW–10, Sealpump Engineering Ltd) into the droplets of diameter of 7–25 μm and sprayed onto the fluidised particles. The samples of granules are taken from the sampling point. The key properties of the materials and experimental settings are given in Table 1. The initial particle size distribution (PSD) is shown by Fig. 1b.

The fluidisation mode of the gas FB was determined by the product of four dimensionless numbers [86]: $Fr_{mf}\mathrm{Re}_{mf}[(\rho_p - \rho_g)/\rho_g](H_{mf}/D_{FB}) = 4121 \gg 100$, where $Fr_{mf} = u_{mf}{}^2/(gl)$ is the Froude number and $\mathrm{Re}_{mf} = u_{mf} l \rho_g / \mu_g$ is the Reynolds number of particles at the minimum fluidisation velocity u_{mf}; l is the diameter of the particles; H_{mf} is the bed height at the minimum fluidisation velocity and D_{FB} is the diameter of the FB. In the case studied in this paper, approximately $H_{mf}/D_{FB} = 1.6$. According to Kunii and Levenspiel [87], the FB can be considered as a bubbling or aggregative fast fluidisation which suggests an isotropic turbulence.

The PSD of the samples collected from the sampling point during the experiment were measured by a Camsizer (Retsch Technology, Germany). This equipment is an optical-electronic instrument for measuring the distribution of particle sizes of free flowing materials. The measuring principle of this device is imaging processing. While a particle is passing through, images are generated by two Charge-Coupled Device cameras, these images are then analysed to determine the particle's volume equivalent spherical diameter and then a size distribution of the particles.

3.2. The experimental results

Fig. 2 shows the main experimental results: (a) the size distributions, (b) the total number of the particles and (c) the mass mean sizes of the particles changing with time.

The general shift of the PSD from a smaller to a larger size region as seen from Fig. 2 corresponds to the process of aggregation.

The aggregation rate constant quantifies the rate of successful aggregations and is used to calculate the birth and death rates of the particles in population balance modelling for eventually obtaining the numerical solutions of the number density n. These constants are calculated using the zeroth Moments (Fig. 2b) and are shown in Fig. 3.

The rate constants can then be taken to the modelling described below for a full simulation of the particle size distribution across the

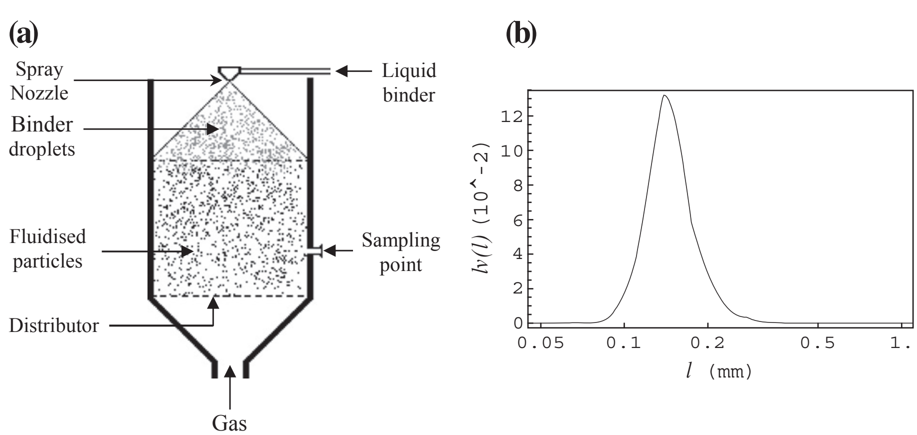

Fig. 1. (a) The schematic representation of a top spray fluidised bed granulation system; (b) The initial size distribution of particles in volume fraction. Note, l (mm) is the particle size in diameter, $v(l)$ (mm^{-1}) is the volume density of the particles of diameter l.