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Experimental and theoretical study on the agglomeration arising from fluidization of cohesive particles—effects of mechanical vibration

Chunbao Xu, Jesse Zhu*

Particle Technology Research Centre, Department of Chemical and Biochemical Engineering, The University of Western Ontario, London, Ontario, N6A 5B9, Canada

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Abstract

A novel technique that can prevent the disruption of agglomerates when sampling the agglomerates from a fluidized bed has been developed and has been applied to the investigation of the agglomeration behaviour of cohesive particles during fluidization with and without mechanical vibration. A new model for the prediction of agglomerate size has also been established on the basis of the energy balance between the agglomerate collision energy, the energy due to cohesive forces and the energy generated by vibration. The accuracy of the model is tested by comparing the theoretical results with the experimental data obtained both in the present work and in the literature. Effects of gas velocity and mechanical vibration on agglomeration for two cohesive (Geldart group C) powders in fluidization are examined experimentally and theoretically. The experimental results prove that mechanical vibration can significantly reduce both the average size and the degree of the size-segregation of the agglomerates throughout the whole bed. However, the experiments also reveal that the mean agglomerate size decreases initially with the vibration intensity, but increases gradually as the vibration intensity exceeds a critical value. This suggests that the vibration cannot only facilitate breaking the agglomerates due to the increased agglomerate collision energy but can also favour the growth of the agglomerates due to the enhanced contacting probability between particles and/or agglomerates. Both the experimental and theoretical results show that a higher gas velocity leads to a smaller agglomerate size.

Keywords: Cohesive particles; Fluidization; Mechanical vibration; Agglomeration; Modelling

1. Introduction

The significance of particle technology is apparent in that approximately one-half of the products in the chemical industry and at least three-quarters of the raw materials are in granular form (Nedderman, 1992) and it is estimated that sales of $61 billion per annum in the chemical industry are linked to particle technology (Ennis et al., 1994). The high surface area-to-volume ratio and other special characteristics of fine particles make them very attractive in the industries of advanced materials, food and pharmaceuticals, etc. However, handling of these fine powders becomes much more difficult as their sizes become smaller. Fine particles, 30 μm or smaller in size, classified as group C (cohesive) particles by Geldart (1973), are generally believed to be unsuitable for fluidization since they tend to form agglomerates as a consequence of strong interparticle forces (Baerns, 1966; Chaouki et al., 1985; Pacek and Nienow, 1990; Ushiki, 1995; Horio et al., 1996). Although for submicron- or nanoparticles where the interparticle force is much stronger than the gravitational forces, the bed of particles may exhibit a state of self-agglomerating fluidization due to the formation of stable and roughly mono-sized agglomerates (Molerus, 1982; Geldart et al., 1984; Rietema, 1984; Jaraiz et al., 1992; Chaouki et al., 1985; Morooka et al., 1988), for most of the group C particles where the interparticle forces are not strong enough, the agglomerates formed in fluidization are unstable and normally have a severe size segregation, leading to partial fluidization or even de-fluidization (Pacek and

* Corresponding author.
E-mail address: jzhu@uwo.ca (J. Zhu).

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Nienow, 1990; Wang et al., 1998; Xu et al., 2004). It thus suggests that the fluidization behaviour of cohesive particles strongly depends on the properties (e.g., strength, size and size distribution, etc.) of the agglomerates arising from fluidization and the agglomeration behaviours during fluidization (Chaouki et al., 1985; Chirone et al., 1993).

Several previous experimental works (Kono et al., 1990; Li et al., 1990; Wank et al., 2001; Xu et al., 2004) have demonstrated that the size/size distribution of agglomerates arising from fluidization of cohesive particles is dependent not only on the properties of the primary particles but also on the fluidization conditions such as parameters of fluidizing gas (gas type, humidity and velocity) and the application of fluidization aids (e.g., mechanical vibration). Mechanical vibration has proved to be an effective means to help fluidization of cohesive solids due to the breaking of channels and agglomerates (Mori et al., 1990; Dutta and Dullea, 1991; Mujumdar, 1983; Wank et al., 2001; Xu et al., 2004). Consequently, vibro-fluidized beds are commonly used in powder processing such as mixing, granulation, drying and coating. So far, however, a comprehensive study on the agglomeration behaviours of cohesive particles during fluidization and the effects of mechanical vibration are still unavailable in the literature.

Due to the fragile structures of the agglomerates, the biggest challenge in studying the agglomeration during fluidization is the agglomerate–sampling techniques (Noda et al., 1998; Wang et al., 1998; Venkatesh et al., 1998; Castellanos et al., 1999; Wank et al., 2001; Xu et al., 2004). A "freezing" method has been developed by Pacek and Nienow (1990), in which the agglomerate granules were frozen by spraying of a binder solution of wax from the top of the bed before sampling. Another technique, called particle/droplet image analysis, has been recently reported for direct measurement of the agglomerate size in the free board and the region close to the upper surface of the solid bed (Wank et al., 2001). However, there exists an obvious limitation for these two techniques in that they are only capable of the size measurement for the agglomerates in the top bed. It is thus of a great significance to develop other techniques, which are capable of sampling the agglomerates, without disrupting them in either sizes or structures, from any parts of the bed (top, middle or bottom bed). In the present study, a novel "on-line sampling" technique has been developed, the details of which will be described later in the experimental section.

It is well accepted that theoretical study is a very useful means for exploring the mechanism governing the processes of interest. Several theoretical studies on the prediction of agglomerate size have been reported since 1985 (Chaouki et al., 1985; Morooka et al., 1988; Iwadate and Horio, 1998; Zhou and Li, 1999), where most of the models are based on the principle of force balance. Bergstrom (1997) proposed a very simple model, where the agglomerate size was estimated from the force balance between the drag force due to the gas flow and the interparticle force (van der Waals force). Similarly, Iwadate and Horio (1998) predicted the agglomerate size simply by balancing the bubble-causing expansion force and the cohesive force between agglomerates. Zhou and Li (1999) assumed that the drag force due to gas flow and the collision force between agglomerates are balanced with the buoyant gravity and the cohesive force. The predictions using these force-balance-based models have shown various degrees of agreement with the experimental data. On the other hand, Morooka et al. (1988) came up with a model based on an energy balance, in which it is assumed that the agglomerate tends to disintegrate when the energy generated by laminar shear stress and the kinetic energy of the agglomerate are equal to the energy required to break the agglomerate (i.e., the energy due to the cohesive forces). However, in their model, the minimum fluidization velocity (u_{mf}) rather than the superficial gas velocity was used in calculating the energy generated by laminar shear stress and the kinetic energy of agglomerates, which makes the reliability of the model very questionable. Obviously, more studies are needed to ameliorate these models for precise prediction of agglomerate size in fluidization of cohesive particles.

In order to clarify the mechanism governing the formation and failure of agglomerates during fluidization of fine particles under mechanical vibration, the present study will deal with both the measurement and the modelling of the size of agglomerates arising from the fluidization of cohesive particles with and without vibration. A new model for the prediction of agglomerate size is developed based on the energy balance between the agglomerate collision energy, the energy due to cohesive forces and the energy generated by vibration.

2. Theoretical analysis

The phenomenon of size-segregation of agglomerates is often observed in fluidization of cohesive powders, resulting in a layered structure along the bed height: the smaller and usually more stable agglomerates exist at the top, while the larger and looser ones are present at the bottom (Xu et al., 2004). In this regard, the efforts on modelling of the agglomerate size are only meaningful for the top-bed stable agglomerates. To simplify the analysis, the following assumptions are made: (1) the agglomerates formed are all spherical in shape, same in size with a mean diameter of d_a, and of the same properties, (2) the wall effect is neglected and (3) the van der Waals force dominates over other types of the interparticle cohesive forces. It is also assumed that the agglomerate tends to disrupt or break when the total energy due to collision plus external vibration (if applied) is greater than that due to the cohesive forces. Accordingly, the following energy balance may be attained at the breaking point for the agglomerate

$$E_{\mathrm{coll}} + E_{\mathrm{vib,eff}} = E_{\mathrm{coh}}, \tag{1}$$