Powder Technology 291 (2016) 473–486

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Influence of interparticle forces on attrition and elutriation in bubbling fluidized beds

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ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form 1 December 2015
Accepted 21 December 2015
Available online 23 December 2015

Keywords:
Elutriation
Attrition
Fluidized bed
Electrostatic force
Charge
Faraday cup
Van der Waals force

ABSTRACT

For many reactions performed in fluidized beds, the mechanical stability of particles is of major importance, and yet, despite this, previous studies have disagreed on the elutriated amount and origin of fine particles. This paper therefore investigates the attrition of particles in bubbling fluidized beds in more detail to determine whether these differences are due to electrostatic or other interparticle forces. To achieve this, the forces acting during fluidization are mathematically derived, and two particle types (alumina and dolomite) are experimentally investigated. Based on the results obtained, a simple model is developed to describe the attrition of both particle types.

1. Introduction

Particle attrition and elutriation is always present in fluidized beds, but is of particular concern in catalytic fluidized beds in which chemical conversion is highly dependent on the amount of fines in the bed [1]. Industrial-scale production also needs to consider the need to meet legislative and emission regulations, making the stability and attrition resistance of particles of major importance [2]. Moreover, as the elutriation of fines can influence processes downstream of the reactor, it is something that is usually best avoided. This can be achieved by either preventing the production of fines through the use of attrition resistant particles and/or mild fluidization conditions, or preventing their elutriation by employing cyclones, well designed freeboards, and a filter unit downstream of the fluidized bed [1].

A comparative study of more than 20 existing entrainment correlations has revealed discrepancies in their predicted elutriation rates of up to 8 orders of magnitude [3,4]. Among the various reasons that have been proposed for these discrepancies, such as the usage of non-physically based models to predict particle elutriation, one possibility that has been largely overlooked is the existence of electrostatic forces acting on the particles, preventing elutriation [5]. This paper therefore takes a systematic approach to understanding the different causes of particle attrition by mathematically analyzing the forces acting on particles during fluidization so as to approximate their magnitude and determine their influence on attrition and elutriation. This is followed by experimental measurement of the attrition of alumina (Al) and dolomite (Do) particles over 100 and 500 h in a laboratory-scale bubbling fluidized bed reactor using different gas velocities, during which any electrostatic charge on the particles is assessed. This is aimed at developing a model to accurately predict the attrition rate of both particle types based on published works [6,7] and the assumption that attrition is directly proportional to the excess gas velocity.

2. Theory

2.1. Particle attrition types

Attrition in fluidized beds is a process that reduces the particle size of the bed material, and can be defined as depicted in Fig. 1, either as particle abrasion or fragmentation [8,9]. Particle abrasion is characterized by the production of fines from the surface of a mother particle through rounding of its edges or the chipping off loose material, causing its appearance to change from that of broken glass to more like a grain of rice. Fragmentation, on the other hand, is when fragments are produced by breakage of the whole particle; the mother particle dividing into at least two fragments with little change in overall appearance. The likeliness of the occurrence of these two attritions depends on the intensity of impact and the physical properties of the particle, meaning that laboratory experiments need to be conducted under conditions similar to those the particles experience in reality.

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http://dx.doi.org/10.1016/j.powtec.2015.12.026
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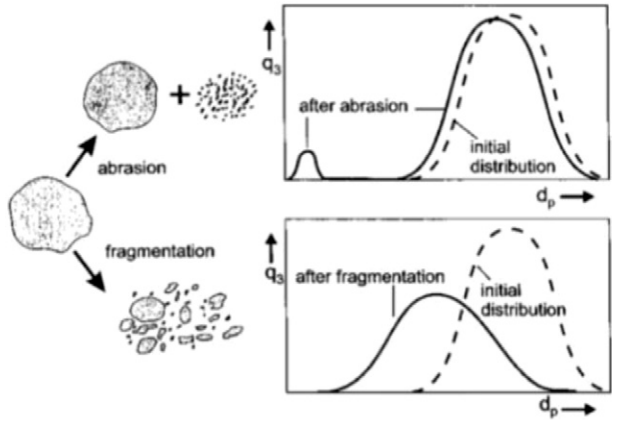

Fig. 1. Attrition modes and their effect on particle size distribution, taken from [10].

2.2. Particle attrition test methods

A frequently quoted thought experiment used to illustrate the difficulties of attrition experiments is that "if we took a batch of rubber pencil erasers and a batch of diamonds, and rubbed them on abrasive paper, we would conclude that the diamonds were more attrition resistant. If we instead struck the particles with a hammer we would conclude that the rubber erasers were more attrition resistant." [11]. It is therefore not surprising that there has been a wide variety of methods developed for the laboratory-scale testing of particle attrition. All, however, share in the fact that they try to predict the behavior of particles in real-world applications by using well-defined test procedures to:

- Reduce the amount of material needed
- Reduce the time for testing
- Reduce the effort involved in testing
- Reduce the working time needed for expensive test rigs by using simpler setups.

Any test system for particle attrition only makes sense if the results are directly transferable to a real system; i.e., different materials can respond very differently to applied forces, and therefore, any deviation can produce results that are inaccurate and not transferable. Bemrose et al. produced a very thorough review of the different attrition test methods [8], dividing them into *single particle* (crushing or impact) and *multiple particle* tests. As abrasion requires the interaction of more than one particle, it obviously can only be tested in multiple particle tests, whereas fragmentation is mainly defined by the properties of the material itself, making single particle tests possible.

2.3. First hours during fluidization

The attrition of fresh material in fluidized beds is much higher during the first hours of operation; and depending on the production method, there can also be an increased fines content in the fresh material. This is especially true in the case of brittle and milled materials, which usually have a particle form that is far from spherical. Similarly, crystallized pure materials can form crystals with sharp edges or elongated needle structures that make them susceptible to generating fines. Even more spherical extruded or spray dried material can have a high surface roughness and can contain very weakly bound agglomerates. Introducing fresh material to a fluidized bed therefore tends to produce a high attrition and elutriation rate due to a combination of fines initially present in the bed from production or handling, sharp edges moving against each other, and the breakage of weak agglomerates or crystals with defects.

2.4. Causes of particle attrition in fluidized beds

Gases are fed into the fluidized bed using various different gas distributor systems such as spargers, grid plates, slit plates, and perforated/porous plates [4], which, depending on their design, can be a significant cause of particle attrition. Fluidization was initially achieved by Forsythe using just a few small holes drilled into a steel plate, a method which later became the standard attrition test for a fluid catalytic cracking (FCC) catalyst [12,13]. However, the small holes indicate that the gas enters the system at a speed of hundreds of meters per second (487 m/s in the ASTM standard test), resulting in a very high mechanical stress on the material. Other distributor plate systems are therefore usually constructed of porous, sintered materials that soften fluidization by reducing the speed of the gas. This lowers the internal shear generated between accelerated particles and the rest of the bed. However, the pressure drop above the porous distributor plate still needs to be sufficiently high to prevent the development of gas shortcuts.

Bubbling fluidized beds using porous sintered materials typically have no jet grids, with bubbling tending to start out very homogeneous slightly above the distributor [11]. Depending on the particle type and reactor design (e.g. internals), these bubbles grow and rise through the bed to create particle movement and abrasion. The presence of internals such as heat exchanger tubes can influence the movement of these gas bubbles, and therefore also the attrition rate [14]. Bubbles erupting at the surface of the bed can also lead to additional attrition through the collision of accelerated particles with the walls of the fluidized bed.

2.5. Particle elutriation

Fines and particles in fluidized beds can become entrained in the excess gas leaving the reactor. The easiest model for calculating the maximum size of a particle, that is certain to be elutriated, is based on a force balance around a single particle. For smaller particles and fines the Stokes' law can be applied to calculate the drag force and gain an estimate of the maximum particle size elutriated.

In practice, gas jets from erupting bubbles or gas channels in the bed can lead to much higher localized gas velocities in the freeboard [4] that allow larger particles to be elutriated. These additional factors need to be considered through more complex elutriation models [15–17], with Chew et al. [3] providing a critical review of different entrainment correlations. In the present manuscript, the most conservative assumption was used to calculate the maximum elutriated particle size by combining Stokes' law with the superficial gas velocity in the fluidized bed.

To prevent particle elutriation, it is important to also consider the geometry above the bed; i.e., the freeboard used to separate the particles from the gas stream. For example, increasing the column diameter in this region reduces the gas velocity and allows particles to fall back into the bed. This means that fines above a certain minimum size are decelerated to such an extent that they could fall back into the reactor. Thus, the design of the freeboard can dramatically effect elutriation, even if attrition within the bed remains unchanged [18]. Cyclones and filters can, however, be used under such conditions to prevent fines from leaving the system [4].

2.6. Forces arising during fluidization

In a fluidized bed reactor, different forces are generated by the various interactions between the fluid, particles and the reactor itself, making a theoretical analysis of these forces important to understand how they can effect attrition and elutriation. These forces can be classified as being either mechanical or interparticle in nature.

2.6.1. Interparticle forces

Interparticle forces are responsible for the agglomeration or adhesion of particles, which can affect their fluidization and the elutriation