Catalysis Today 264 (2016) 70–74

Contents lists available at ScienceDirect

Catalysis Today

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

Catalyst attrition in an ASTM fluidized bed

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ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form 21 August 2015
Accepted 1 September 2015
Available online 26 September 2015

Keywords:
Fluid catalytic cracking
Fluidized bed
FCC catalyst
Particle attrition
Attrition rate
Attrition source

ABSTRACT

Catalyst attrition is a major issue for the reliable and efficient performance of a fluidized-bed reactor. In this study, attrition behavior of a commercial FCC catalyst is examined in a laboratory-scale ASTM fluidized bed. An attrition rate model that combines the jet attrition and bubble-induced attrition is derived and confirmed to represent the measured total attrition rate versus the superficial gas velocity. The model parameters systematically vary with time, since the properties of the attrited particles change progressively. It is also shown that the minimum bubble attrition velocity is far larger than the minimum fluidizing velocity because energy is required to produce attrition. Furthermore, jet and bubble attritions are separated and their contributions are discussed. The contribution of jet attrition increases rapidly with increasing the gas velocity, and the fast increase in the jet attrition rate is the major cause of the increasingly serious catalyst attrition with increasing the gas velocity. It is also seen that regression analysis is an effective tool to the separation of attrition sources.

1. Introduction

Fluidized beds are widely used in industrial processes such as drying, granulation, combustion, and fluid catalytic cracking (FCC), because materials mix and contact adequately with each other and heat transfers excellently [1,2]. However, particle attrition always exists in fluidized beds [3–6]. For example, in a fluidized-bed reactor, catalyst attrition will result in the generation of fines, loss of valuable material, degradation of catalyst efficiency, environmental pollution, etc. Furthermore, new-born small particles brought by attrition may damage fluidizing properties and process operating conditions [3,6]. Catalyst attrition is, therefore, a major issue for the reliable and efficient performance of an industrial fluidized-bed reactor.

Several methods have been developed to assess and study the attrition resistances of particle materials [7–9]. For powdered catalysts used in fluidized-bed reactors, two methods are often used in laboratory: ASTM air-jet attrition test [7,8] and jet-cup attrition test [9]. They are usually intended to rank different candidate catalysts with respect to their attrition resistances. Zhao et al. [10] reported that the jet-cup test needed less catalysts and was as adequate as the ASTM standard test for the prediction of the catalyst attrition resistance. However, attrition mechanism in an ASTM standard fluidized bed is much closer to that in an industrial fluidized bed.

There are two main types of attrition: particle fragmentation and surface abrasion [11–18]. Abrasion means the loss of edges and corners of particle surfaces, generation of son particles which are approximately the same size to the mother ones and a lot of fines, while fragmentation refers to a particle breaking into several son particles smaller than the mother one. Several sources of attrition can be identified in a fluidized bed system, e.g., grid jet attrition, bubble-induced attrition, and attrition in the cyclones [6,19]. For these attrition sources, several correlations have been developed to relate the measured attrition rate to the jet/superficial gas velocity, density, orifice diameter, etc. [4,12–15,20–24]. Attrition is also a time-dependent process and may change systematically with time [8,19,25,26]. Many materials show an early nonsteady-state attrition behavior, after which attrition decreases to a constant value [19,25,26]. Several models have been proposed to describe the time-dependence of attrition behavior, e.g., Gwyn equation [8] and exponential decay equation [26]. Moreover, in a fluidized bed, attrition is influenced by three categories of factors including particle properties (material properties, textural properties, mechanical strength, shape, size, and surface roughness, hardness, microcracks, etc.), fluidization conditions (gas velocity, pressure, temperature, density, humidity, etc.), and fluidized-bed structure parameters (most importantly, orifice number and diameter for multi-orifice distributor plates) [4,11–15,20–24,27].

Academic institutions active in catalysis research generally concentrate on the chemistry rather than the catalyst mechanical properties. Less effort has been made to investigate the attrition behavior and mechanism in fluidized beds, although a reasonable

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http://dx.doi.org/10.1016/j.cattod.2015.09.007
0920-5861/

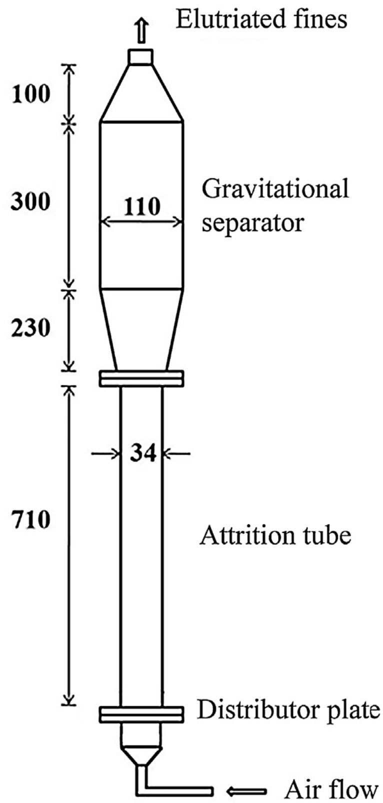

Fig. 1. Schematic diagram of attrition apparatus (The physical unit of data is millimeter.).

amount of information is already available concerning the particle attrition. To our knowledge, no article is available so far in the open literature about the scientific basis for the ASTM air-jet attrition test; therefore, an interest in studying the attrition behavior in an ASTM fluidized bed arises. Moreover, sources of attrition in fluidized beds should be examined, and there is a lack of an efficient and quick method to separate the total attrition rate into contributions of different sources. Therefore, the issues of catalyst attrition call yet for further elucidation and advancement. In this work, dependence of attrition behavior of a commercial FCC catalyst on superficial gas velocity was examined in a laboratory-scale fluidized bed designed according to ASTM standard. The total attrition rate was correlated with a derived attrition rate equation. Sources of attrition were separated by a simple regression analysis method, and their contributions were discussed.

2. Experimental

2.1. Catalyst sample, apparatus, and attrition tests

A commercial FCC catalyst was used in this study. It consists mainly of Y-zeolite and kaolin, and is serving in a FCC unit in China petroleum industry. Its mean particle diameter, packing density, and surface area are about 109 μm, 0.885 g/cm^3 and 168.7 m^2/g, respectively. Other physical properties have been described elsewhere [26]. Prior to attrition tests, the catalyst was sieved by a 61-micron sieve to eliminate pre-existing fine particles, and then dried at 120 °C in air for 2 h to remove the effect of humidity.

A laboratory-scale fluidized bed, shown in Fig. 1, was employed as an attrition test apparatus. It was designed according to ASTM D 5757-11 standard [7], consisting of six parts: air supply system, gas distribution chamber, three-orifice distributor plate, attrition tube, gravitational separator, and fines collector. The distributor plate contains three symmetrically arranged upward-facing holes with diameter 0.381 ± 0.005 mm, and these holes are 10 mm distant from the plate center. Other dimensions are marked in Fig. 1. For more information on the attrition apparatus, see ASTM standard [7] or one of our previous publications [26].

Attrition tests were carried out at room temperature. After 50 g of a dried catalyst was charged, an air flow was produced by air compressor and fed to the attrition apparatus to fluidize catalyst particles. Elutriated fines were collected, dried, and then weighed. Detailed operating steps were described in previous article [26]. It should be mentioned that after fines collector, air flow was directly emitted into the atmosphere; therefore, the temperature and pressure in the fluidized bed could be approximately regarded as normal temperature and pressure (NTP), i.e., 20 °C and 101.3 kPa. Under the operating condition, seven superficial gas velocities (0.0834, 0.0981, 0.1155, 0.1337, 0.1528, 0.1746, and 0.1951 m/s) were examined in this work. For each gas velocity, the mass of the elutriated fines was determined as a function of the attrition time, and then the total attrition rate was calculated.

2.2. Data analysis

In the literature [6,12,19,22,27,28], attrition rate is often defined as the mass of the elutriated fines per unit time:

$$R_{\mathrm{a}} = \frac{\mathrm{d}m_{\mathrm{e}}}{\mathrm{d}t} \tag{1}$$

where R_{a} is the attrition rate at attrition time t, and m_{e} the cumulative mass of the elutriated fines at time t. In a fluidized bed, two sources of attrition, i.e., grid jet attrition and bubble-induced attrition, can often be identified; therefore, the total attrition rate in the bed is the sum of the attrition rates of the two sources [6,19].

Grid jet attrition has been studied by several authors [9,10,23–25,27–31]. Considering the energy utilization of abrasion process, Werther and Xi [28] derived a relationship for grid jet attrition rate, which can be rewritten as

$$R_{\mathrm{a,j}} = C_{\mathrm{j}} \cdot d_{\mathrm{pb}} \cdot \rho_{\mathrm{f}} \cdot \frac{D_{\mathrm{t}}^{6}}{d_{\mathrm{or}}^{4} \cdot n_{\mathrm{or}}^{2}} \cdot u^{3} \tag{2}$$

where $R_{\mathrm{a,j}}$ is the jet attrition rate, C_{j} the jet attrition constant, d_{pb} the surface mean diameter of bed particles, n_{or} the number of orifices in the distribution plate, d_{or} the diameter of orifices, ρ_{f} the density of jet gas, D_{t} the diameter of fluidized-bed column, and u the superficial gas velocity. The mechanisms of bubble-induced attrition are not quite clear. There are various theoretical and empirical approaches [6,14,32] that can be summarized as

$$R_{\mathrm{a,b}} = C_{\mathrm{b}} \cdot m_{\mathrm{b}}^{n} \cdot (u - u_{\mathrm{min}})^{m} \tag{3}$$

where $R_{\mathrm{a,b}}$ is the bubble attrition rate, C_{b} the bubble attrition constant, n and m the two power exponents, u_{min} a threshold velocity above which bubble-induced attrition occurs, and m_{b} the decreasing catalyst bed mass due to attrition ($m_{\mathrm{b}} = m_0 - m_{\mathrm{e}}$, where m_0 is the initial catalyst bed mass, i.e., the catalyst bed mass at time $t = 0$. $m_{\mathrm{o}} = 50$ g in this study). Combining Eqs. (2) and (3), the total attrition rate in a fluidized bed can, therefore, be expressed as

$$R_{\mathrm{a,tot}} = R_{\mathrm{a,j}} + R_{\mathrm{a,b}} = C_{\mathrm{j}} \cdot d_{\mathrm{pb}} \cdot \rho_{\mathrm{f}} \cdot \frac{D_{\mathrm{t}}^{6}}{d_{\mathrm{or}}^{4} \cdot n_{\mathrm{or}}^{2}} \cdot u^{3} + C_{\mathrm{b}} \cdot m_{\mathrm{b}}^{n} \cdot (u - u_{\mathrm{min}})^{m} \tag{4}$$

It should be mentioned that the catalyst bed mass, m_{b}, decreases as the attrition time increases. Nevertheless, for a given attrition time, it will also decease probably with increasing the superficial gas velocity. Suppose the decreasing catalyst bed mass (or the