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Attrition of catalyst particles in a laboratory-scale fluidized-bed reactor

Dongfang Wu [a,*], Zhengdong Gu [a], Yongdan Li [b]

[a] Department of Chemical Engineering, School of Chemistry and Chemical Engineering, Southeast University, Jiangning District, Nanjing 211189, China
[b] Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), Tianjin Key Laboratory of Applied Catalysis Science and Technology, and State Key Laboratory of Chemical Engineering, School of Chemical Engineering, Tianjin University, Tianjin 300072, China

HIGHLIGHTS

- Catalyst attrition arises from mixed particle fragmentation and surface abrasion.
- A relative attrition rate is suggested to represent the attrition process.
- The relative attrition rate tends to a constant after nonsteady-state attrition.
- An exponential decay model is proposed to describe the time-dependent attrition.

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ABSTRACT

Attrition of fluid catalytic cracking catalysts is investigated in a laboratory-scale fluidized bed. It is shown that the catalyst attrition arises from a mixed mechanism of particle fragmentation and surface abrasion. The measured conventional attrition rate always decreases with time, even for a long-time attrition; therefore, a relative attrition rate is suggested. Experiments indicate that after a nonsteady-state attrition where the measured relative attrition rate decreases with time, the attrition gets into a steady state and the measured relative attrition rate tends to a constant value. Furthermore, the time-dependence of particle attrition is discussed. It is seen that the widely-used Gwyn equation cannot model the catalyst attrition accurately. Alternatively, an exponential decay attrition model is proposed and confirmed to describe the time-dependent attrition behavior. It is found that the model parameters have definite meanings and are strongly related to the particle properties, fluidization conditions and fluidized bed structure.

1. Introduction

Fluidized beds are widely used in industrial processes such as drying, granulation, combustion, polyethylene production and fluid catalytic cracking (FCC), mainly because of their good mixing abilities, excellent heat transfer, and efficient gas-solid contacting (Bi et al., 2000; Muroyama and Fan, 1985). However, one of serious disadvantages of fluidized beds is that bed particles are subjected to high mechanical stresses caused by interparticle collisions and bed-to-wall impacts, thereby resulting in particle attrition (Bemrose and Bridgwater, 1987; Boerefijn et al., 2000; Wei et al., 1977; Werther and Reppenhagen, 1999). For example, in a fluidized-bed reactor, catalyst attrition will cause the generation of fines, loss of valuable material, degradation of catalyst efficiency, potential damage for downstream equipment, and environmental pollution. Any attrition to smaller sizes may also affect the fluidizing properties and process operating conditions (Bemrose and Bridgwater, 1987; Werther and Reppenhagen, 1999). Therefore, catalyst attrition is a major issue for the reliable and efficient performance of an industrial fluidized-bed reactor, and efforts have to be made to produce sufficiently attrition-resistant catalysts.

Attrition can be divided into two main types: particle fragmentation and surface abrasion (Chen et al., 2011; Choi et al., 2010; McMillan et al., 2007a; Ray et al., 1987; Stein et al., 1998; Tardin et al., 2001; Teng, 2008; Thon and Werther, 2010). Fragmentation occurs when a particle breaks into two or more fragments of similar size. Alternatively, abrasion occurs when a lot of fines are removed from the surface of a particle, while the size distribution of mother particles is only slightly changed or remains unchanged obviously. There are three categories of factors that affect the attrition process in a fluidized bed, i.e., 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

* Corresponding author. Tel.: +86 25 52090620; fax: +86 25 52090618.
E-mail address: dfwu@seu.edu.cn (D. Wu).

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structure parameters (most importantly, orifice number and diameter for multi-orifice distributor plates) (Boerefijn et al., 2000; Chen et al., 2008; Choi et al., 2010; Li et al., 2012; McMillan et al., 2007a; Pougatch et al., 2010; Stein et al., 1998; Tardin et al., 2001; Thon et al., 2011; Thon and Werther, 2010; Tomeczek and Mocek, 2007; Valverde and Quintanilla, 2013; Zhang et al., 2012). Furthermore, 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 (Klett et al., 2007; Werther and Reppenhagen, 1999; Werther and Xi, 1993). For these attrition sources, various models have been presented to relate the measured attrition rate to the jet/superficial gas velocity, density, orifice diameter, etc (Bentham et al., 2004; Boerefijn et al., 2000; Ghadiri et al., 1994; Jiang et al., 2009; McMillan et al., 2007b; Montagnaro et al., 2011; Thon and Werther, 2010; Werther and Reppenhagen, 1999; Werther and Xi, 1993).

Attrition is a time-dependent process and may change systematically with time (Klett et al., 2007; Stein et al., 1998). Previous investigators have found different stages in the attrition process. For instance, many materials show an early nonsteady-state attrition behavior, after which attrition decreases to a constant value (Klett et al., 2007; Stein et al., 1998). From studies on jetting fluidized beds, Gwyn (1969) proposed a simple time-dependent formulation for attrition, i.e., the mass of the attrited fines has a power law relation with the attrition time (See Eq. 5). Nevertheless, Xiao et al. (2012) considered that there existed a critical point in the time-dependent attrition behavior and that a piecewise function should be used to describe the time-dependence of attrition. For the attrition time greater than or equal to the critical-point time, the attrition rate gradually tends to a constant, and thus a constant function is used; however, for the attrition time less than the critical-point time, the attrition rate decreases sharply with time, and thus a power function similar to Gwyn equation is used. Furthermore, Klett et al. (2007) examined the time-dependence of attrition separately for different attrition sources occurring in a fluidized bed/cyclone circulation system. They introduced a dimensionless stress-history parameter and developed another complex piecewise function to model the time-dependence of attrition rate.

In the literature (Bemrose and Bridgwater, 1987; Boerefijn et al., 2000; Weeks and Dumbill, 1990), several methods are available for assessing and studying the attrition resistance of catalyst particles. For powdered catalysts used in fluidized-bed reactors, two methods are often used: ASTM air-jet attrition test (ASTM, 2011) and jet-cup attrition test (Cocco et al., 2010). Zhao et al. (2000) made a comparison between the two methods and found that the jet-cup test needed less catalysts and was as adequate as the ASTM standard test for the prediction of the attrition resistance. However, attrition mechanism in ASTM fluidized bed is much closer to that in an industrial fluidized bed. In the present article, ASTM standard fluidized bed was, therefore, used to examine the time-dependent attrition behavior of commercial FCC catalysts. A relative attrition rate was suggested to describe the particle attrition, and then a new time-dependent attrition model was proposed. The attrition characteristics and model parameters were also discussed.

Table 1
Physical properties of the catalyst samples under investigation

Sample	Packing density, g/cm^3	Surface area, m^2/g	Pore volume, mL/g	Mean pore diameter, nm	Percent of pore volume in a specific diameter range, %	
					>5 nm	>20 nm
1	0.940	206	0.172	5.76	57.9	14.4
2	0.874	165	0.157	6.52	70.1	11.6
3	0.885	169	0.158	5.82	58.3	14.4

2. Experimental

2.1. Catalyst samples

Three commercial FCC catalysts, available in the Chinese market, were used in this study. They serve in different FCC units in petroleum industry, though they have similar chemical compositions (mainly Y zeolite and kaolin) and similar particle size distributions ranging from about 10–200 μm. Their densities and textural properties are listed in Table 1. Prior to attrition tests, these samples were 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.

2.2. Apparatus

A laboratory-scale fluidized bed was designed according to ASTM D 5757-11 standard (ASTM, 2011), as shown in Fig. 1. It consists of six parts: gas distribution chamber, three-orifice distributor plate, attrition tube, gravitational separator, fines collector, and air supply system. The gas distribution chamber, similar to a buffer tank, can stabilize the air pressure under the gas distributor and then maintain fluidization conditions steady. The distributor plate contains three upward-facing holes with diameter 0.381 ± 0.005 mm, which are symmetrically arranged and 10 mm distant from the plate center. The distributor plate is attached to the bottom of the attrition tube, a 710-mm-long stainless cylindrical column with an inside diameter of 34 mm. The quartz gravitational separator is mounted to the top of the attrition tube. It involves a 230-mm-high lower cone converging to an inside diameter of 35 mm, a 300-mm-long cylinder with an inside diameter of 110 mm, and a 100-mm-high upper cone converging to an inside diameter of 30 mm. The fines collector is connected to

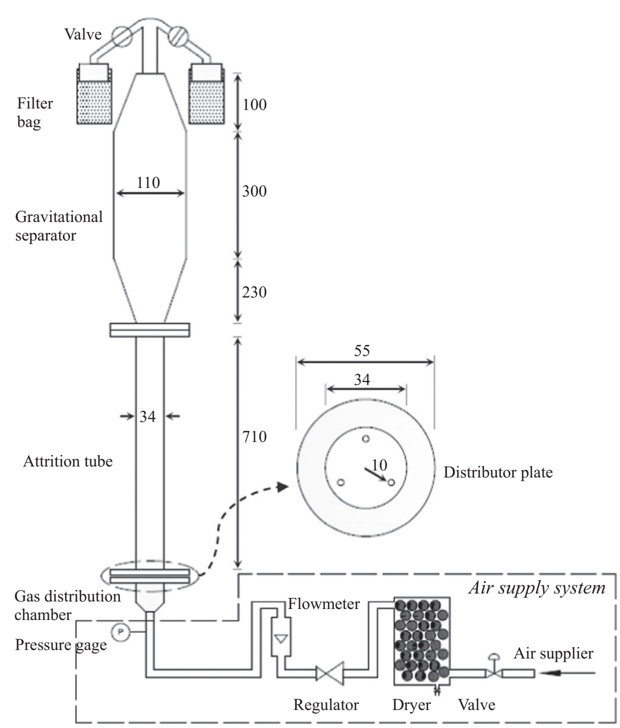

Fig. 1. Schematic diagram of the attrition test apparatus. The physical unit of data is millimeter.