PARTICLE ATTRITION: MECHANISMS AND METHODS TO DETERMINE ATTRITION INDICES

Yeook Arrington[1*], S.B. Reddy Karri[1], Ray Cocco[1]

[1]*Particulate Solid Research, Inc., 4201 West 36th Street, Building A, Chicago, IL 60632, USA*

*Email : *yeook.arrington@psri.org*

Abstract – Particle attrition can be a major issue in using catalyst particles in fluidized beds and circulating fluidized beds. Particles tend to break down via two mechanisms – abrasion and fragmentation. Abrasion can be defined as constituent particles attriting off the surface of the parent particles. The resulting size distribution of parent particles shows almost no change in cut sizes under this abrasion attrition mechanism. With the fragmentation attrition mechanism, the parent particles are breaking down to intermediate cut sizes as well generating constituent particles. This results in a shift in the size distribution of parent particles in addition to producing finer constituent particles.

Several methods are available in characterizing attrition characteristics of catalyst particles. Jet cup attrition testing is a common method for ranking of relative attrition characteristics by comparing their attrition indices. PSRI jet cup attrition testing is a two-step process. The first step in jet cup attrition testing is to identify the threshold velocity and to determine the optimum jet velocity for evaluating particle attrition. The threshold velocity represents the gas jet velocity at which the transition of the attrition mechanism from abrasion to fragmentation takes place.

INTRODUCTION

It is important to understand how the particles attrit under the relevant operating conditions in fixed fluidized beds and circulating fluidizing beds since particle attrition usually has a negative effect on product quality as well as on process operation.

There are several methods (ASTM D5757, 2011; Davuluri and Knowlton, 1998; Weeks and Dumbill, 1990) available in characterizing attrition of catalyst particles. Jet cup attrition is the most commonly used laboratory test method for evaluating particle attrition in a fluidized system such as FCC units. However, the jet cup test method does not give a quantitative attrition rate that can be applied towards commercial units, it only provides a relative attrition rate among different materials. That is, the ranking of catalyst attrition can be determined among the same family of several materials by comparing their attrition indices from the jet cup attrition testing under the same test conditions.

In the past, Particulate Solid Research, Inc. (PSRI) conducted both computational fluid dynamic (CFD) and cold flow experimental studies on a jet cup device to obtain a better understanding of particle attrition in a jet cup (Cocco et al., 2010). One major finding was that a significant portion of the material remained stagnant in a conventional Davison type cylindrical jet cup. PSRI explored the several different configurations of jet cups and found that the conical shape cup showed the best performance – all the particles were observed to be in motion – throughout the various jet velocities tested. Another finding was that the conical jet cup attrition data correlated well with cyclone attrition data from a 29.2-cm-diameter fluidized bed-cyclone system in ranking of the relative attrition characteristics with respect to particle attrition.

Particle attrition can be categorized into the two mechanisms of abrasion and fragmentation. In the abrasion attrition mechanism, particles are attriting off the surface of the parent particles. The resulting size distribution of parent particles shows almost no change in cut sizes, showing only a peak of finer constituent particles under this attrition mechanism. With the fragmentation attrition mechanism, the parent particles are breaking down to intermediate cut sizes as well as generating constituent particles. This results in a shift in the size distribution of parent particles in addition to producing finer constituent particles.

Abrasion type attrition tends to be the dominant source of attrition for a well-designed process of fixed fluidized beds and circulating fluidized beds, so that it is crucial to use a more reliable jet velocity in the jet cup attrition test. Otherwise, it might lead to an error in the catalyst selection process in commercial units. A gas jet velocity should be selected in the abrasion dominating region because the ranking of catalyst attrition in the fragmentation region may not be the same as in the abrasion region.

PSRI attrition testing in a jet cup is a two-step process. The first step involves the determination of the threshold velocity, where attrition by abrasion (i.e., removal of protrusions, corners, edges, etc.) transitions to attrition by fragmentation (i.e., splitting of the particle itself). The threshold velocity can be defined as the velocity at which the particles start to attrit so rapidly that the attrition rate vs. gas jet velocity curve is no longer linear. It clearly exhibits a change in slope. The lower first slope indicates the abrasion dominating attrition mechanism, and the second higher slope indicates the fragmentation dominating the attrition region. The threshold velocity signifies the transition of these two mechanisms from abrasion to fragmentation.

In this paper, PSRI jet cup data demonstrates how to determine the mechanisms of particle attrition purely by looking at the particle size distributions, and how the sizes of parent particles shift over the extended period of time for each relevant mechanism.

EXPERIMENTAL

Test Material

Jet cup attrition testing was conducted using FCC equilibrium catalyst. Fig.1 shows the particle size distribution (PSD) of this material before subjected to a jet cup test. The material had a particle density of about 1500 kg/m^3. The median particle diameter ($d_{p,50}$) was 82.8 μm, and the fines content less than 44 μm was 3.8%.

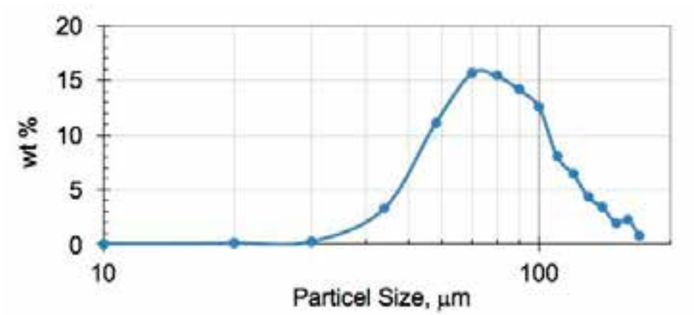


Fig. 1. Particle size distribution of FCC equilibrium catalyst

Jet Cup Attrition Measurements

The PSRI jet cup test unit was fully automated with DasyLab software so that gas flow rates were controlled by a mass flow controller. Based on back pressure build-up in the test unit, gas flow rates were automatically adjusted to maintain a constant gas jet velocity. Fig. 2 shows an overall flow diagram for this test unit.

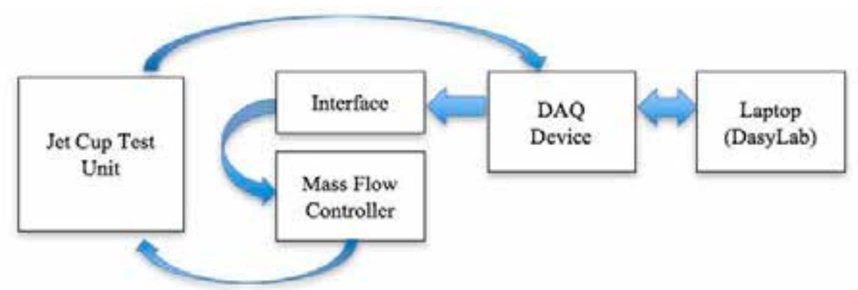


Fig. 2. Overall flow diagram for an automated PSRI jet cup test unit

Fig. 3 shows the PSRI conical jet cup attrition testing unit. The conical jet cup expanded from a 3.8-cm (1.5-in.)-diameter at the bottom to a 7.6-cm (3-in.) diameter at the top. It had a tangential gas inlet of 0.48-cm (3/16-in)-diameter. The conical jet cup is attached to a 130-cm (50-in) disengagement section, where the diameter increased to a 30.5-cm (12-in). Multiple layers of woven wire cloth, sintered into a porous metal structured filter element is inserted into the expansion chamber through the outlet port. This filter element used in the test unit is a 5-cm (2-in)-diameter stainless steel sintered metal candle. The PSRI jet cup attrition unit is equipped to operate at a temperature up to 700°C (1300°F). However, all the measurements conducted in this work were at room temperature.

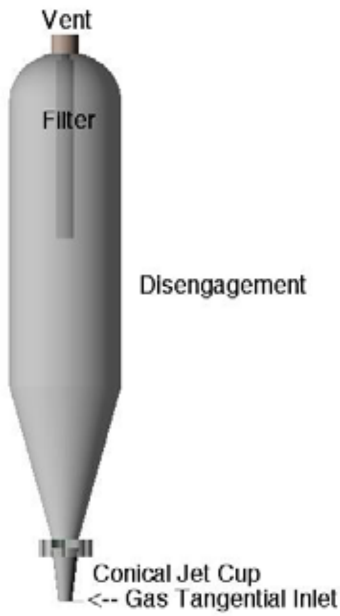


Fig. 3. PSRI conical jet cup apparatus

About 100 grams of dried sample was used in the jet cup attrition testing. The particle size analysis was carried out on this dried sample before subjecting it to the jet cup attrition testing. After the testing, the filter element was carefully taken out from the test unit. The filter element was weighed before and after the test. Fines captured on the filter element were brushed down and saved for the particle size analysis. All the attrited material in the cup and interior wall of the test unit were collected, weighed, and saved for the size analysis. The mass balance was generally 95% to 98%. After the particle size analyses were done for both the filter and cup samples individually, then these two size distributions were mathematically combined to get a final attrited size distribution.

Jet cup results were presented in terms of an attrition index (AI). AI is determined by comparing the initial size distribution to the final attrited size distribution at the size of interest. For the PSRI jet cup testing, fines were defined as particles smaller than 20 μm or 44 μm, and they were typically referred to as AI (20) and AI (44), respectively.

Particle Size Analysis

The particle size was analyzed using a Beckman Coulter Counter Multisizer III that applies an electro-sensing zone technique in a wet system.

RESULTS

Threshold Velocity

Fig. 4 shows the attrition index of particles smaller than 44 μm (AI (44)) at different jet velocities for FCC equilibrium catalyst. Testing was conducted at room temperature for 1 hour over the jet velocity range of 46 m/s (150 ft/s) to 183 m/s (600 ft/s) to determine the transition between abrasion and fragmentation.

The results of the conical jet cup testing showed that the attrition index increased with increasing jet velocities, and there was a change in slope of the AI (44) vs. jet velocity curve. Typically, the attrition index starts slowly increasing at low jet velocities. At these jet velocities, the abrasion type of attrition is dominating. When attrition by fragmentation starts dominating, the attrition index rapidly increases which happens at high jet velocities. The conical jet cup data indicated that the transition from abrasion to fragmentation mechanisms occurred at a threshold velocity of about 110 m/s (360 ft/s) for FCC equilibrium catalyst. Based on PSRI's internal testing, it can be said that similar behavior was observed with different test materials commonly used in the industry.

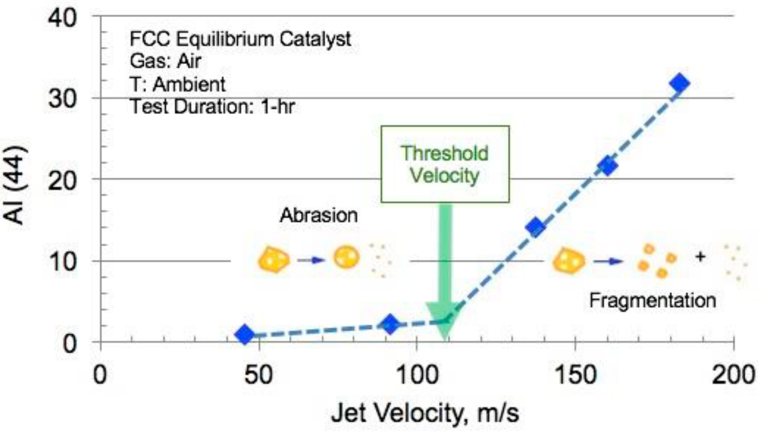


Fig. 4. Threshold velocity of FCC equilibrium catalyst-1 tested at room temperature for 1 hour

Effect of Jet Velocities on Size Distributions of Parent Particles

Fig. 5 shows the initial PSD and final attrited PSDs at different jet velocities for FCC equilibrium catalyst-1 at room temperature for 1 hour testing. At both low jet velocities of 46 m/s (150 ft/s) and 91 m/s (300 ft/s), the attrited PSDs implied that the particle breakage was mainly due to the abrasion type of attrition mechanism since there was nearly no change in parent particle sizes and only small fines were generated. These jet velocities were below the threshold velocity that was determined from the AI (44) vs. jet velocity curve.

A significant shift in the attrited PSDs was observed at jet velocities of 137 m/s (450 ft/s) and higher, and these velocities were above the threshold velocity. This implied that the particle breakage was mainly occurring due to a fragmentation type of attrition mechanism. The parent particles were breaking down to intermediate cut sizes as well as generating constituent finer particles.

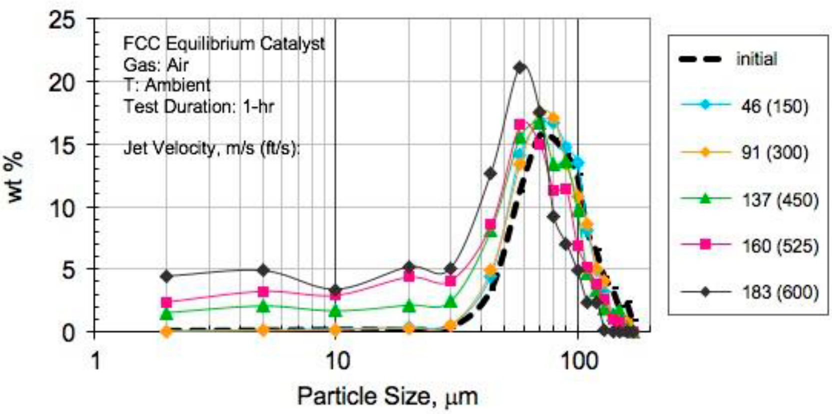


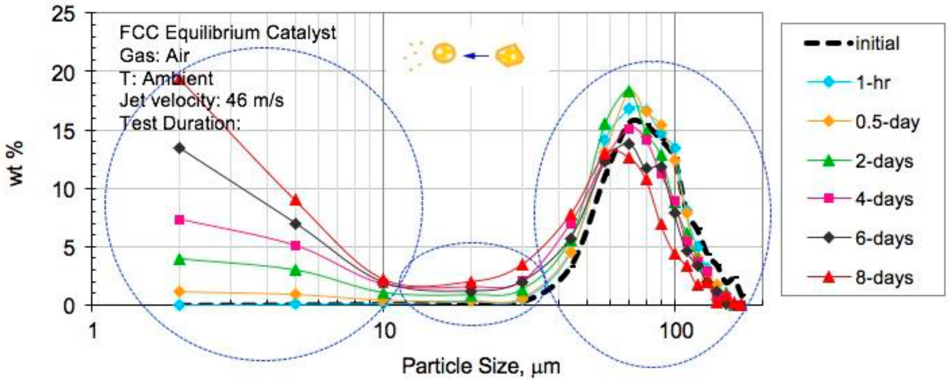
Fig. 5. Initial and final attrited size distributions at different jet velocities (FCC equilibrium catalyst-1)

Effect of Elapsed Time on Parent Particle Sizes

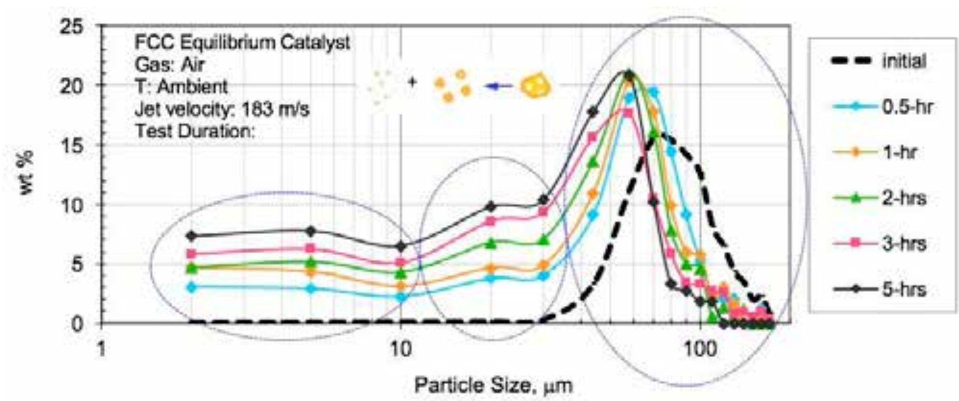
Figs. 6(a) and (b) present how the size distributions of parent particles progress over the extended longer durations at two different jet velocities that represents abrasion and fragmentation type mechanisms, respectively. FCC equilibrium catalyst-1 was used in the jet cup test at room temperature.

Fig. 6(a) clearly shows that the fines (constituent particles) were growing over time by attriting off the surface of the parent particles. The resulting size distributions of parent particles did not change much because the tested jet velocity of 46 m/s (150 ft/s) was below the threshold velocity. This was clearly abrasion type attrition behavior.

Fig. 6(b) shows that a peak of intermediate cut sizes was growing over time caused by the breaking down of the parent particles. It was also observed that the fines peak was growing over time. This resulted in significant shifts in the size distribution of parent particles as well as producing finer constituent particles. The jet velocity was 183 m/s (600 ft/s), and it was above the threshold velocity. The material clearly demonstrated fragmentation type of attrition behavior at these conditions.



(a) Jet velocity of 47 m/s (150 ft/s)



(b) Jet velocity of 183 m/s (600 ft/s)

Fig. 6. Distributions of parent particle sizes over extended durations at different jet velocities

CONCLUSION

Finding the threshold velocity where the attrition by abrasion mechanism transitions into the attrition by fragmentation mechanism is the first step in jet cup attrition testing. Choosing a jet gas velocity in the abrasion dominant region is the next step for the determination of a material's relative attrition characteristics. By looking at the progress of the particle size distribution, it can be determined what attrition mechanism is dominating.

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