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PARTICLE ATTRITION MEASUREMENTS USING A JET CUP

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Particle attrition is usually detrimental as it negatively affects product quality and process cost. Thus, it is important to know how particles attrit under relevant operating conditions. Small jet cup attrition test devices (such as the Davison Jet Cup) are typically used to measure relative particle attrition for fluidized beds and risers. Ideally, the attrition rates measured in these laboratory units provide a relative indication of how the materials will behave in the commercial unit. Most jet cup devices have a cylindrical configuration. However, Particulate Solid Research, Inc. (PSRI) has found that a cylindrical jet cup attrition measurement may not be effective in providing accurate attrition rankings. Attrition index rankings from a cylindrical jet cup and a 0.3-meter (12-inch) diameter, pilot-plant fluidized bed unit did not agree with each other. It was subsequently found in cold flow studies at PSRI in Plexiglas™ jet cup models which showed that many of the solids were nearly stagnant, even at high inlet jet velocities. Approximately 30 to 50% of the particle sample in a cylindrical jet cup was not in motion and was not exposed to the solid stresses needed for accurate particle attrition measurements. Computational Fluid Dynamics (CFD) results confirmed this finding. As a result, it is unlikely that relevant attrition rankings can be reliably determined from cylindrical jet cup studies because a significant portion of the particle sample is not exposed to sufficient solid stresses to cause attrition. Only by insuring that the entire sample is under a similar amount of stress can attrition be accurately linked to inlet jet velocity and directly compared with different materials.

This paper discusses the development of a conical jet cup device that allows all of the sample particles to experience similar solids stresses. The rankings of the attrition indices from the conical jet cup were found to correspond to the rankings observed in pilot-plant attrition tests. The agreement in rankings obtained with the new conical jet cup was not observed with the traditional cylindrical jet cup.

INTRODUCTION

For circulating fluidized beds, the Davison jet cup attrition method is the one of the most common methods of ranking particle attrition. The Davison jet cup consists of a 2.5-cm (1-inch) diameter cup with a tangential gas inlet (1,2). The cup is attached to a large disengagement chamber. Approximately 5 to 10 grams of the test material are placed into the Davidson jet cup. The jet cup method uses a tangential gas inlet in a cylindrical cup to produce a tangential or swirling flow that mimics the particle-wall impacts in cyclones, fluidized beds, and risers. During operation, fines generated in the cup due to attrition enter the disengagement section, where they are either refluxed back into the jet cup or become too small and escape through the outlet and trapped by the filter). The material loss or trapped is related to attrition loss. The jet cup method is primarily used to rank attrition of different materials in terms of an attrition index (AI), where the weight fraction of particles smaller than a specific size is compared before and after the attrition testing.

Jet cups are used to compare the attrition rates of various materials using an attrition index. In other words, attrition rate of a new material is compared to some reference material, perhaps a predecessor of the new material. However, PSRI has found that the standard jet cup method may not be suitable for ranking catalyst and other material attrition rates (3). PSRI used cold flow experimental studies and CFD to discern the underlying hydrodynamics responsible for particle attrition in the jet cup device. Results showed that the standard, cylindrical jet cup design was ineffective in causing all particles to be in motion regardless. Based on these results, PSRI designed a new conical jet cup that was able to achieve better particle mobility and higher attrition rates. The relative cyclone attrition rankings from the conical cup also agreed well with attrition ranking from a 29.2-cm (11.5-inch) ID fluidized bed cyclone attrition test unit.

EXPERIMENTAL

Powder Material

Equilibrium FCC catalyst powder was used both for cold flow studies and modeled in the CFD simulations. The catalyst particle density was assumed to be 1492 kg/m^3 (93 lb/ft^3). The median particle diameter (d_{p50}) was 78 microns, and the Sauter mean diameter was 71 microns. The proprietary catalysts used in the 29.2-cm (11.5-inch) ID fluidized bed cyclone attrition study had a d_{p50} of 55 microns and a Sauter mean diameter of 53 microns. The proprietary catalyst particle density was 1458 kg/m^3 (80 lb/ft^3).

Jet Cup Attrition Measurements

Jet cup attrition studies using the 2.5-cm (1-inch) and 7.6-cm (3-inch) diameter cylindrical jet cups were performed in the same test unit. The smaller jet cup, which most resembles the Davison Jet Cup, was filled with 10 grams of material where as the large jet cup was filled with 100 grams of material. PSRI typically used the larger jet cup to minimize experimental error (i.e., material balance error).

Figure 1: Schematic of the jet cup attrition testing unit used at PSRI.

For the 7.6-cm (3-inch) diameter cylindrical jet cups, the axial length from the bottom of the cup to a bottom of the disengagement section was 15-cm (6-inches). The jet or orifice inner diameters were 0.24 or 0.48 cm (0.0938 or 0.1875 inches). The Davison-type jet cup was a 2.5-cm (1-inch) diameter cylindrical jet cup that represented jet cups typically used in accordance with the Davison methodology (1). The jet or orifice inner diameter was 0.24 cm (0.0938 inches). The jet cup height was 8.25 cm (3.25 inches). The axial length from the bottom of the cup to the bottom of the disengagement section was 18 cm (7 inches). A 9.75-cm (3.8-inch) long conical spool piece was inserted between the 2.5-cm (1-inch) diameter cylindrical jet cup and the PSRI jet cup unit to ensure a smooth transition between the cup and disengagement section at the same open angle as the disengagement section.

Figure 1 provides a schematic drawing of the jet cup attrition test unit at PSRI. Both a 2.5-cm (1-inch) diameter jet cup, typical of a Davison jet cup design, and a 7.6-cm (3-inch) diameter cup could be used in the same PSRI unit. The test procedures were also similar for each cup size except that 100 grams of sample were used in the 7.6-cm (3-inch) diameter cup where as 5 to 10 gram samples were used in the 2.5-cm (1-inch) diameter cup. The larger sample size reduces material balance errors compared to the 2.5-cm (1-inch) diameter or Davison jet cup.

As shown in Figure 1, the jet cup was attached to a 130-cm (51-inch) high disengagement section with a diameter of 30.5 cm (12 inch). A five-micron sintered metal filter was inserted into the expansion chamber through the outlet port. Magnehelic and Marsh pressure gauges were also located on the chamber. Gas flow rates were controlled with two Dwyer 50 and 400 SCFH rotameters. The PSRI jet cup was equipped to reach temperatures of 815°C. However, all measurements conducted in this study were conducted at room temperature.

A typical test was conducted for one hour. Jet velocities of 76.2, 137.2 or 182.9 m/sec (250, 450 and 600 ft/sec) where used for all the jet cup studies. A particle size analysis was conducted on material left in the jet cup, and the material collected from the filter media. Particle size analysis was done using an electrical zone sensing Coulter Counter Multisizer II and a Microtrac S3000. A material balance was conducted to ensure that at least 95% of the material was accounted for.

Jet cup results were presented in terms of an attrition index (AI). The attrition index is determined by comparing the cumulative weight percent of the size range of interest after the test to the initial weight percent of that size range. For this study, fines were defined as particles smaller than

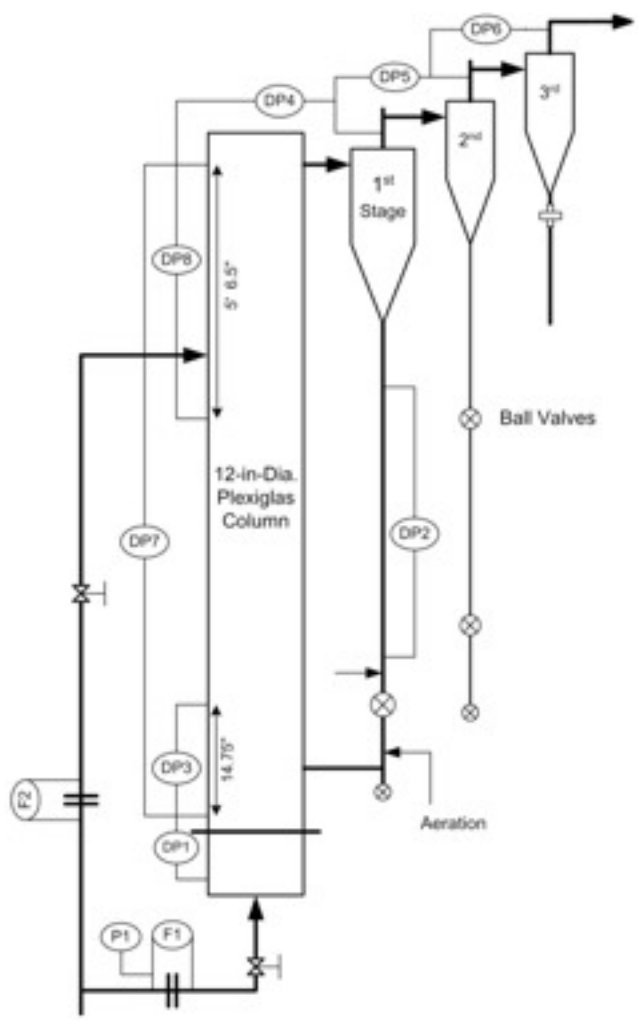

Figure 2: Schematic drawing of the PSRI's 29.2-cm (11.5-inch) diameter fluidized bed cyclone attrition test unit.

either 20 or 44 microns (common but somewhat arbitrary cuts where 44 microns reflects a 350 mesh screen size and 20 microns is something smaller).

29.2-cm (11.5-inch) Diameter Fluidized Bed Cyclone Attrition Test Unit

The attrition indices from the jet cup studies were compared to attrition indices obtained from studies in a 29.2-cm (11.5-inch) ID fluidized bed with primary, secondary, and tertiary cyclones, as shown in Figure 2. The solids loading and inlet gas velocity to the primary cyclone were held constant for each test at 3.2 kg/m^3 (0.2 lb/ft^3) and 12.2 m/sec (40 ft/sec), respectively. The superficial gas velocities in the bed and in the freeboard were varied independently to preserve the loading and gas velocity restrictions on the primary cyclone. Collected particles from the primary cyclone were returned to the fluidized bed. The particles collected from the secondary and tertiary cyclones were used for the attrition measurements and were not returned to the fluidized bed.

The unit was operated for an extended period of time to ensure that the equilibrium attrition rate for each sample was attained. Samples were collected periodically from a side port on the bed as well from the secondary and tertiary cyclone diplegs. Particle size analysis was conducted in a similar method as with the jet cup samples.

Jet Cup Cold Flow Study

Several Plexiglas™ jet cup configurations and test conditions were examined. The Plexiglas jet cups were used for visualization and matched, in design, their stainless steel counterparts used for jet cup attrition studies. Other jet cup were designed based on the observed deficiencies in the cylindrical PSRI jet cup's performance. Plexiglas™ cups were constructed to test various concepts including displacing the stagnant region, adding more jets to reduce the stagnant region and/or increase the axial or lifting velocity in the cup. This resulted in the following alternative cup designs: the angled jet cup, the dual jet cup, the dual jet with cone jet cup and the conical jet cup.

All jet cup concepts were designed with a 7.6-cm (3-inch) diameter outlet. The conical jet cup diameter was reduced to 3.8-cm (1.5-inches) in diameter at the bottom of the cup. The inlet jet diameter was either 0.24- or 0.48-cm (0.0938- or 0.1875-inch) ID and was wielded tangentially to the bottom portion of the cup. The Plexiglas™ cups were attached to the same attrition unit as that used for the attrition measurements shown in Figure 1. Jet velocities used in the cold flow studies were at 76, 137, 183, and 274 m/sec (250, 450, 600, and 900 ft/sec).

CFD Simulations

A CFD model using Barracuda™ version 10.0 from CPFD-Software, LLC. was used to explore gas and solid hydrodynamics in the jet cup attrition test units. Barracuda™ is a Lagrangian-Eulerian hybrid code employing the multiphase particle-in-cell (MP-PIC) numerical method, which has been formulated for dense particle flows (4, 5).

Only a portion of the disengagement section was modeled. Any particle that reached the edge of the disengagement section was considered to be lost to the domain. Jet cup designs were modeled at near ambient conditions with a temperature of 25°C and an initial pressure of 104771 Pa (15.3 psia) and a feed pressure of 172,368 Pa (25 psia). At these conditions, the air density and viscosity were 1.18 kg/m^3 (0.07 lb/ft^3) and 0.000018 kg/m-sec (0.000012 lb/ft-sec),

Figure 3: Still shots from a video of the 7.6-cm (3-inch) ID cylindrical jet cup with a 0.48-cm (0.1875-inch) diameter nozzle at a gas velocity of 137 m/sec (450 ft/sec).

respectively. Particle properties were based on the equilibrium FCC catalyst powder discussed above. The entire particle size distribution was modeled using Barracuda™.

The boundary conditions for the simulation were a pressure boundary condition at the top of the disengagement region and a velocity boundary condition at the tangential jet. The pressure boundary condition was set at 104,771 Pa (15.3 psia). The velocity boundary condition was set at 137 m/sec (450 ft/sec) corresponding to one of the experimental jet cup conditions.

RESULTS AND DISCUSSION

Figure 3 shows a selected still shot from a video taken of the Plexigas™ 7.6-cm (3-inch) diameter cylindrical jet cup filled with 100 grams of FCC catalyst powder at a gas jet velocity of 137 m/sec (450 ft/sec). A significant amount of material remained stagnant at the bottom of the jet cup despite the length of time in operation. A similar performance was observed at 76.2 and 183 m/sec (250 and 600 ft/sec) gas jet velocities. Only at gas jet velocities exceeding 274 m/sec (900 ft/sec) did most of the material appear to be in motion. However, at this velocity, most of the material was also blown out of the cup into the disengagement region, which is inappropriate for these type of jet cup studies.

Similar behavior was observed when studying the hydrodynamics in the 2.5-cm (1-inch) diameter cylindrical jet cup. At jet velocities of 76.2 and 137.2 m/sec (250 and 450 ft/sec), a significant amount of material remained stagnant at the bottom of the cup -- albeit less than that observed for the larger cylindrical jet cup. At higher gas jet velocities, most of the material was blown out of the jet cup into the disengagement region Although more of the material was in motion compared to similar jet velocities

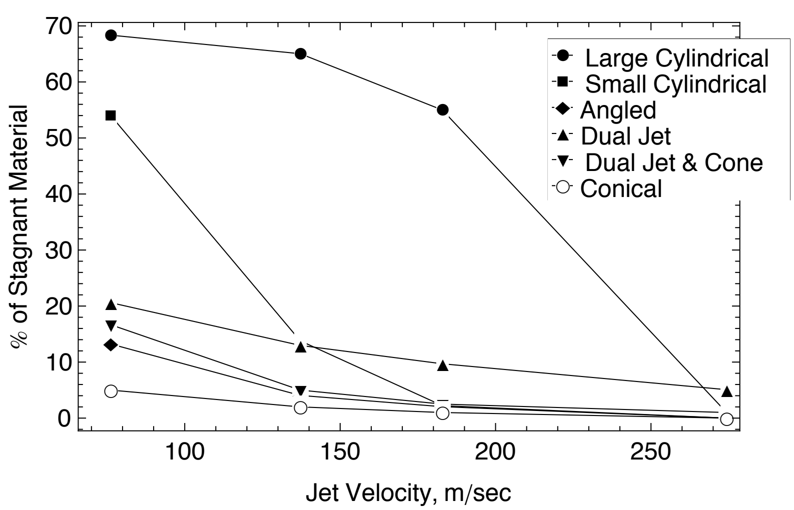

Figure 4: Amount of stagnant material, assuming it has a cylindrical wedge shape, estimated for various Plexiglas jet cup designs.

in the 7.6-cm (3-inch) ID cylindrical jet cup, it was still not satisfactory for a particle attrition test.

By assuming that the shape of the stagnant material in the jet cup resembles a cylindrical wedge, the amount of stagnant solids and the spacing between the stagnant material and the jet cup wall. Figure 4 shows the amount of stagnant material quantified for both the small and large cylindrical jet cups. At jet velocities of 76.2 m/sec (250 ft/sec), more than 50% of the material remained stagnant at the bottom of both the cups. At 137.2 m/sec (450 ft/sec), the smaller cylindrical jet cup appeared to be better than the larger jet cup; but more than 10% of the material still remained stagnant.

Figure 5: Still shots from a video of the 7.6-cm (3-inch) ID conical jet cup with a 0.48-cm (0.1875-inch) diameter nozzle at a gas velocity of 137 m/sec (450 ft/sec).

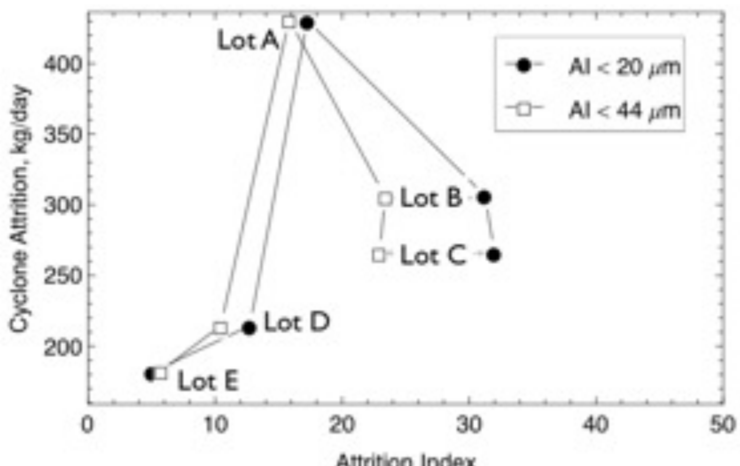

Figure 6: Parity plot of the Attrition Index from the 7.6 cm (3-inch) diameter cylindrical jet cup to attrition loss rates from the PSRI fluidized bed cyclone attrition test unit.

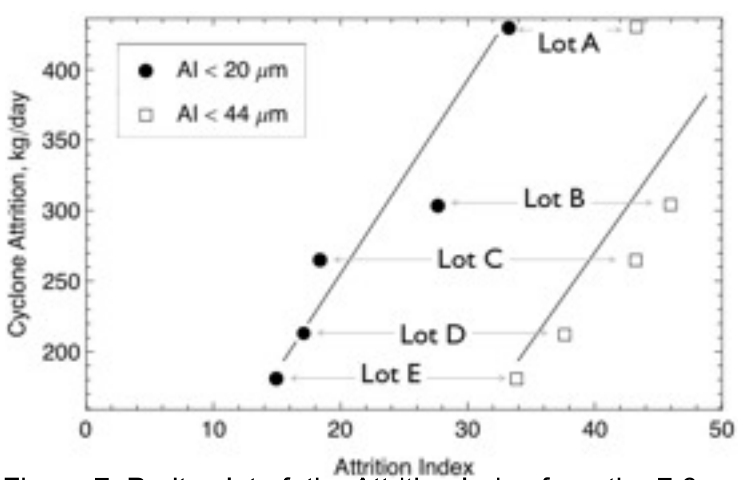

Figure 7: Parity plot of the Attrition Index from the 7.6 cm (3-inch) diameter conical jet cup to attrition loss rates from the PSRI fluidized bed cyclone attrition test unit.

In view of these results, several jet cup design configurations were tested using the Plexiglas™ jet cups. The configurations included an angled jet cup, a jet cup with two tangential jets, a jet cup with two tangential jets and a conical center and a conical jet cup. Testing was conducted in a similar fashion as with the small and large cylindrical jet cups. The quantification of stagnant material was done in a similar fashion except that a cone volume instead of a cylindrical wedge was used for the jet cups with the dual tangential jets.

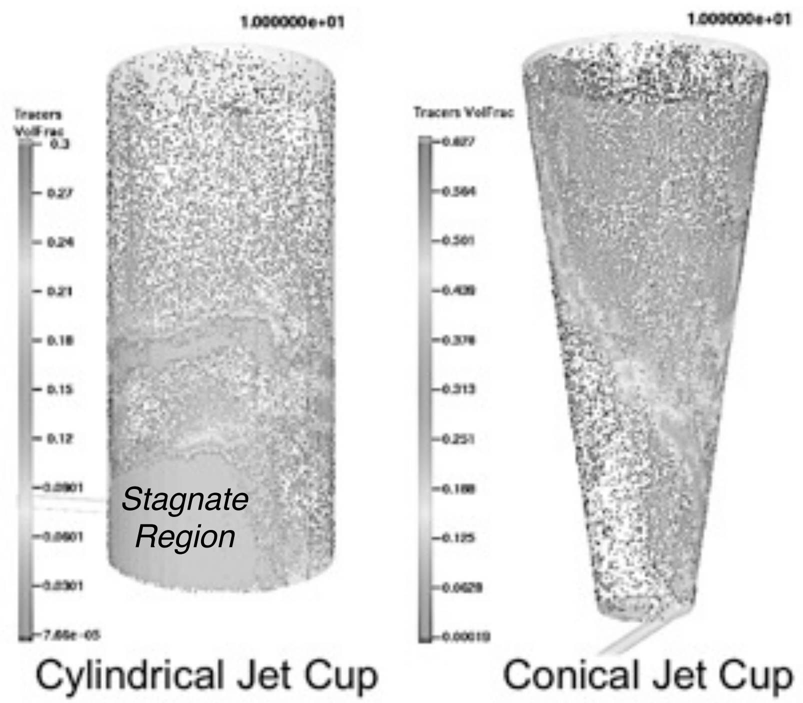

Figure 8: Simulated solids volume fraction for 7.6-cm (3-inch) diameter cylindrical and conical jet cups at a gas jet velocity of 76.2 m/sec (250 ft/sec) with FCC catalyst powder.

The results from this procedure are shown in Figure 4. All the new designs performed better than the small and large cylindrical jet cups. The conical jet cup design provided the best performance with respect to minimizing the amount of stagnant material. The conical jet cup had a 7.6 cm (3-inch) diameter upper diameter and a 2.54-cm (1-inch) bottom diameter with a 11.4-cm (4.5-inch) vertical length. Both the large cylindrical and the conical jet cup used 100 grams of material. Figure 5 shows a still shot from a video taken in the conical jet cup experiment.

Actual attrition testing with the large cylindrical jet cup and the new conical jet cup confirmed the Plexiglas™ testing observations. The conical jet cup had a 10 to 40% increase in the attrition index compared to the 7.6-cm (3-inch) diameter cylindrical jet cup. Figures 6 and 7 further demonstrate the merits of the conical jet cup based on the ranking of the proprietary powders. The results from the conical jet cup were found to be comparable to the attrition loss rates from the cyclone attrition test unit. The conical jet cup AI<20 micron data correlated well with the attrition loss rates from the cyclone attrition test unit. The conical jet cup AI<44 micron results were also in agreement with the fluidized bed cyclone attrition data except for Lot A. With the cylindrical jet cups, attrition loss rates could not be correlated to Attrition Index data from the cyclone attrition test unit.

Figure 8 shows the CFD results for the model of the 7.6-cm (3-inch) diameter cylindrical and conical jet cups for a gas jet velocity of 76.2 m/sec (250 ft/sec) and 100 grams of FCC catalyst particles. The Barracuda CFD results were in good agreement with cold flow observations. For the cylindrical jet cup, a significant portion of the particles remained stagnant at the bottom of the cup.

Table 1: Maximum particle velocity and particle-wall trauma for cylindrical and conical jet cup model.

Model	Max. Particle Velocity	Trauma
Cylindrical	17 ± 9.2 m/sec	0.23 kg m/sec
Conical	17 ± 11.2 m/sec	1.4 kg m/sec

In contrast, simulation results for the conical jet cup showed that almost all of the particles were in motion.

Assuming accurate CFD models, Table 1 presents the particle velocity, and trauma (i.e., momentum exchange with the wall) predicted by the CFD model for the two jet cup configurations. The conical jet cup resulted in over six times more particle trauma than the cylindrical jet cup. The level of trauma is dependent on the magnitude of the particle velocity and the number of hits on the wall as an additive quantity. As shown in Table 1, the particle velocities appeared to be comparable with respect to both jet cups. Yet, CFD simulations suggested that more particles are hitting the wall in the conical jet simulations than in the cylindrical jet cup simulations. This is significant because CFD results suggest that the conical cup is not artificially inflating the particle velocities to provide a high attrition index. The conical cup is simply allowing for more particle to wall collisions for more particles. Thus,better results are obtained because the conical jet cup allows more of the sample particles to contact the wall.

CONCLUSIONS

Cold flow testing revealed that less than 50% of the bed in the 2.5-cm (1-inch) and 7.6-cm (3-inch) diameter cylindrical jet cup appeared to be in motion. The remaining portion of the material was stagnant. Cold flow studies were used to develop a new conical jet cup, which resulted in nearly all the particles being in motion for gas inlet velocities exceeding 76 m/sec (250 ft/sec). Attrition values were 10 to 30% greater in the conical jet cup compared to the cylindrical jet cup. CFD results confirmed these findings. In addition, particle velocity and particle trauma results from CFD simulations suggested that the conical cup simply provides more opportunities for particle-wall collisions and does not artificially inflate the particle velocity.

The conical jet cup shows promise in providing more reliable attrition results that may be more relevant to commercial units. However, only two catalyst systems (FCC catalyst and a proprietary catalyst powders) have been tested to date. Additional data are needed to ensure that the new jet cup design can provide quantifiable results over a wider range of particles.

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