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Jet cup attrition testing

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ABSTRACT

Jet cup attrition testing is a common method for evaluating particle attrition in fixed fluidized beds and circulating fluidized beds. An attrition index, calculated from jet cup data, is used to compare with one or more reference materials. However, this method is far from perfect despite its popularity. Results obtained at Particulate Solid Research, Inc. (PSRI) in different-sized jet cups and a 29-cm (11.5-in.) diameter fluidized bed test unit did not provide the same ranking of catalyst with respect to particle attrition. To obtain a better understanding of attrition in a jet cup, both computational fluid dynamics (CFD) and cold flow studies were performed with a 2.5-cm (1-in.) diameter Davison-type jet cup and PSRI's cylindrical 7.6-cm (3-in.) diameter jet cup. Results showed that a significant amount of material in the Davison and PSRI jet cup remained stagnant. Based on these results and additional CFD modeling, PSRI designed a new jet cup, where most of the material was hydrodynamically active. The new jet cup showed a 25% increase in attrition compared to PSRI's cylindrical jet cup under similar conditions and run times. Results were also compared to cyclone attrition data for several materials at PSRI. The new jet cup provided data that correlated with attrition results from the 29-cm (11.5-in.) diameter fluidized bed unit.

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1. Introduction

The Davison jet cup attrition method is the most common method of ranking particle attrition for fluidized bed, riser, and cyclone applications. The Davison jet cup consists of a 2.5-cm (1-in.) diameter cup [1]. The cup has a tangential gas inlet and is attached to a large disengagement chamber, as shown in Fig. 1. Approximately 5 or 10 g of the test material are placed into the Davison jet cup. Gas is added at high velocities through the tangential inlet. Fines generated in the cup due to attrition enter the disengagement section, where they refluxed back into the jet cup. This process continues until the particles become too small and escape through the outlet. The material loss is related to attrition loss.

PSRI has expanded on this concept by capturing the lost material in a filter and using a 7.6-cm (3-in.) diameter jet cup with 100 g of material [2]. Capturing the entrained material allows for a complete material balance. The larger sample size reduces measuring errors and enables material balances in excess of 95% to be achieved. This is often not the case for the smaller sample sizes in the 2.5-cm (1-in.) diameter Davison jet cup. The larger jet cup size also allows attrition testing of larger Geldart Group B or D materials, such as pelletized high density polyethylene (HDPE).

Both jet cup methods use a tangential gas inlet in a cylindrical cup to produce tangential or swirling flow that mimics the particle–wall impacts in cyclones, fluidized beds and risers. The jet cup method is primarily used to rank catalyst attrition 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. Typically, the particle size used to denote "fines" is at sizes less than 20 or 44 μm.

The Davison or standard cylindrical jet cup method has been found to provide only relative comparisons among different catalysts. It cannot predict the quantitative extent of the attrition or attrition rate that will occur in a commercial process. This limitation was proposed because the prevailing stress mechanisms in the jet cup test differ from those in large-scale processes [3]. PSRI has found similar results. The attrition index data were not useful for predicting absolute attrition values in commercial units. Yet, jet cups are commonly being used to compare ranking of various materials catalyst using the attrition index. In other words, the attrition rate of new material is based on some reference material, perhaps a predecessor of the new material.

However, PSRI has found that the standard jet cup method may not even be suitable for ranking catalyst and other material attrition rates. PSRI used CFD and cold flow experimental studies to discern the underlying hydrodynamics responsible for particle attrition in the jet cup device. Results showed that the standard jet cup design was ineffective in causing all particles to be in motion whether a 2.5-cm (1-in.) or 7.6-cm (3-in.) diameter cup was being used. 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 ranking from the conical cup also agreed well with the attrition ranking from a 29.2-cm (11.5-in.) ID fluidized bed cyclone attrition test unit.

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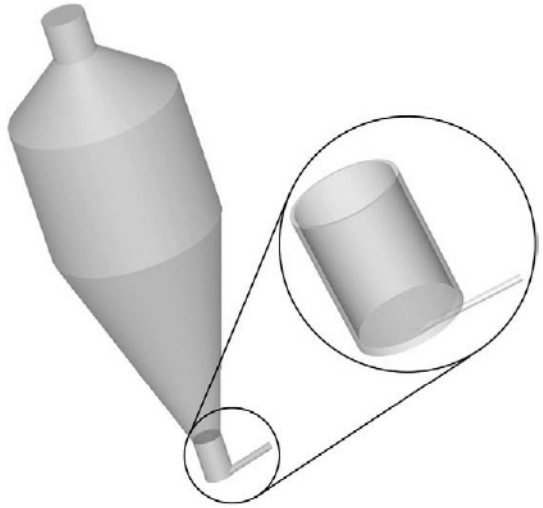

Fig. 1. The overall Davison jet cup (left) and close up of the jet cup (right). Based on Weeks [1].

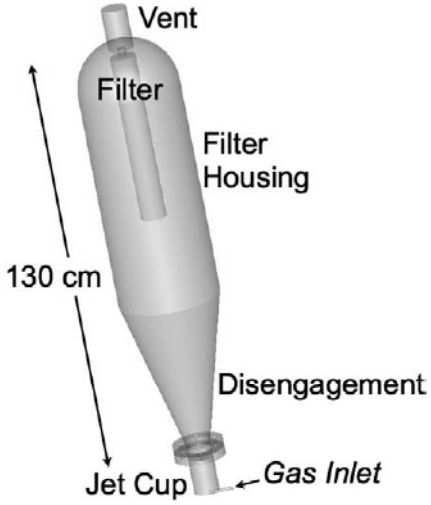

Fig. 3. PSRI's cylindrical jet cup apparatus.

2. Experimental

2.1. Powder material

Equilibrium FCC catalyst powder was used for the cold flow studies and modeled in the CFD studies. The particle density was to be 1492 kg/m^3 (93 lb/ft^3). Fig. 2 shows the particle size distribution of the FCC catalyst material, which had median particle diameter ($d_{p,50}$) of 78 μm and Sauter mean diameter of 81 μm.

Proprietary catalyst used in the 29.2-cm (11.5-in.) ID fluidized bed cyclone attrition study had a d_{p50} of 53 μm and a Sauter mean diameter of 55 μm. The corresponding particle size distribution is also shown in Fig. 2. The proprietary catalyst particle density was 1458 kg/m^3 (80 lb/ft^3).

2.2. Jet cup attrition measurements

Jet cup attrition studies using the 2.5-cm (1-in.) and 7.6-cm (3-in.) diameter standard jet cup were performed in the same test unit. Fig. 3 provides a schematic drawing of the test unit. The 2.5-cm (1-in.) diameter jet cup was typical of a Davison jet cup design. The test procedures were also similar for each cup size except 100 g of sample was used for the 7.6-cm (3-in.) diameter cup instead of the 5 or 10 g used in 2.5-cm (1-in.) diameter cup. The larger sample size reduces measurement error compared to the 2.5-cm (1-in.) diameter or Davison jet cup.

As shown in Fig. 3, the cup is attached to a 130-cm (51-in.) high disengagement section, where the diameter is increased to 30.5-cm (12-in.). A 5 μm sintered metal filter is inserted in the expansion chamber through the outlet port. A pressure gauge is also located on the chamber. The PSRI jet cup is equipped to reach temperatures of 815 °C; however, all measurements conducted in this study were at room temperature.

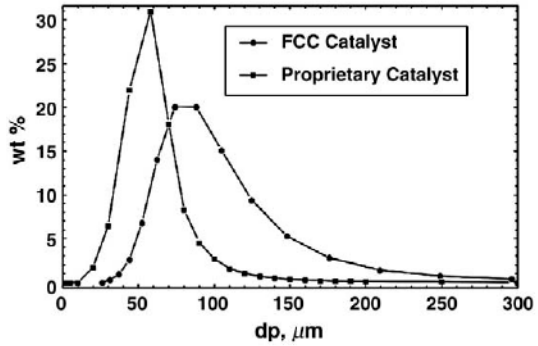

Fig. 2. Differential particle size distribution of the FCC catalyst and proprietary catalyst powder used in the CFD simulations and jet cup experiments.

Gas flow rates were controlled with two Dwyer 50 and 400 SCFH rotameters. Gas flow rates were checked after the first 15 min and then at each hour after that. Flow rates were corrected for error due increasing back-pressure (if any) from the filtering media. Magnehelic and Marsh pressure gauges were used to measure the pressure in the test unit.

Prior to testing, the powder was dried in an oven at 425 °C overnight. The powder was then riffled into equal 10 and 100 g samples. The particle size was analyzed on one of the dried riffled material samples using an electrical zone sensing Coulter Counter (model Multisizer II). The other sample was poured into the jet cup, and the cup was fastened to the attrition test unit shown in Fig. 3.

The rotameter was set such that jet velocities were either 76.2, 137.2 or 182.9 m/s (250, 450 and 600 ft/s). The test was conducted for 1 h and operated below the threshold velocity where fragmentation dominates.

After testing, the jet cup was carefully removed and the contents were weighed. Material collected on the filter media and inside the disengagement section of the jet cup unit was removed and weighed. Particle size analysis was conducted on material left in the jet cup and the material collected from the filter media. 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 at the size of interest after the test to the initial weight percent of that size fraction. Particles smaller than this particle size were considered as fines. For this study, fines were defined as particles smaller than 20 and 44 μm.

2.3. 29.2-cm (11.5-in.) 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 29.3-cm (11.5-in.) ID fluidized bed with primary, secondary, and tertiary cyclones, as shown in Fig. 4. 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/s (40 ft/s), 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.

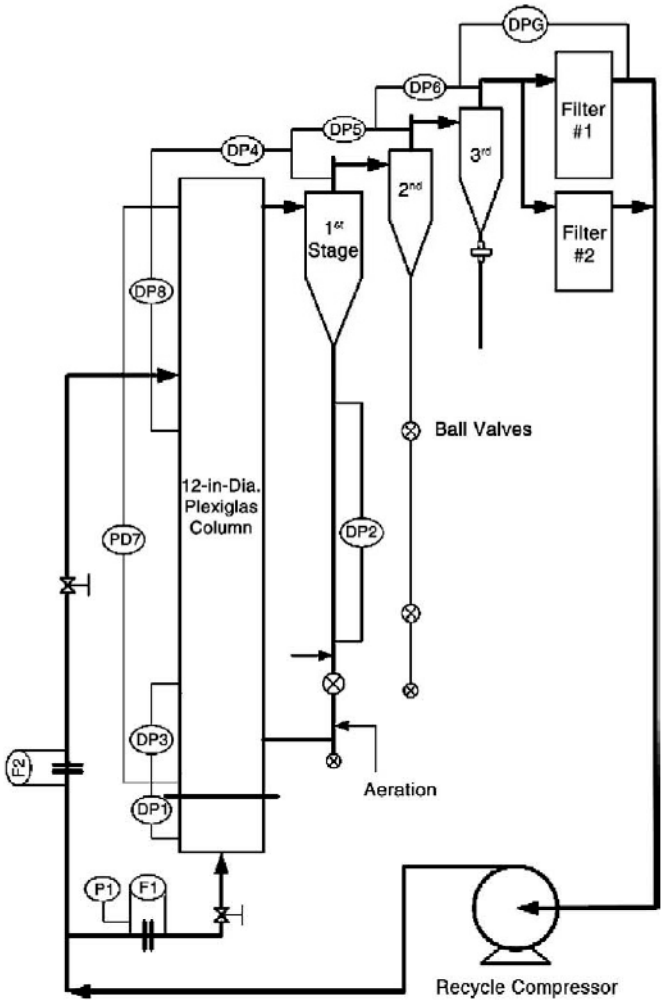

Fig. 4. The PSRI 29.2-cm (11.5-in.) diameter fluidized bed cyclone attrition test unit.

The particles collected from the secondary cyclone were used for the attrition measurements and 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 being measured. Samples were collected periodically from a side port on the bed as well from the secondary cyclone dipleg. Particle size analysis was conducted in a similar method as with the jet cup samples.

2.4. 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 attrition studies. PSRI uses a 7.6-cm (3-in.) diameter jet cup containing 100 g of material. Jet velocities used in this study were at 76, 137, 183, and 274 m/s (250, 450, 600, and 900 ft/s). The axial length from the bottom of the cup to the bottom of the disengagement section was 15-cm (6-in.). The jet orifice inner diameters were 0.24 or 0.48 cm (0.0938 or 0.1875 in.).

The second jet cup was a 2.5-cm (1-in.) diameter cup that represented jet cups typically used in accordance with the Davison methodology [1]. The 2.5-cm (1-in.) diameter Davison jet cup was tested at jet velocities of 76, 137, 183, and 274 m/s (250, 450, 600, and 900 ft/s). The jet orifice inner diameter was 0.24 cm (0.0938 in.). The jet cup height was 8.25 cm (3.25 in.). The axial length from the bottom of the cup to the bottom of the disengagement section was 18 cm (7 in.). A 9.75-cm (3.8-in.) long conical spool piece was inserted between the Davison 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. The Davison jet cup was tested with 5 and 10 g of equilibrium FCC catalyst.

New cup designs were based on improving the standard 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 conical insert jet cup and the conical jet cup. All of these concepts are illustrated in Fig. 5.

All jet cup concepts were designed with a 7.6-cm (3-in.) diameter outlet. The conical jet cup diameter was reduced to 3.8-cm (1.5-in.) 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-in.) ID and fastened 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 Fig. 3.

2.5. CFD simulations of jet cup hydrodynamics

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].

The carrier gas is treated as a continuum in an Eulerian framework using the Reynolds Averaged Navier Stokes (RANS) equations. The particles are treated as discrete entities. In order to track a large number of particles (millions to billions), particles of similar sizes are treated as parcels or "clouds." The drag force between each phase is coupled (two-way). Parcels of N particles are assumed to have a drag force of one similar particle times N. Particle drag within each particle parcel or cloud is assumed to interact with the gas phase independent of other clouds. For this study, both phases were assumed to be isothermal.

The interparticle, normal stresses for collisions between particles were defined by the relationship of Harris and Crighton [6]. The particle–fluid drag was expressed using the drag law proposed by Gidaspow [7] where drag is described by Wen-Yu and Ergun. A linear

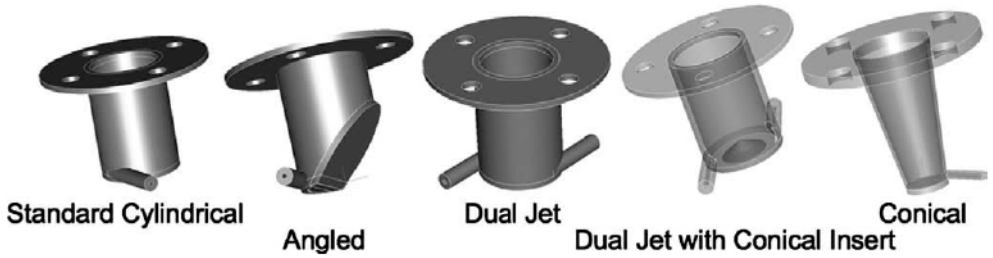

Fig. 5. Five configurations used for evaluating jet cup attrition.

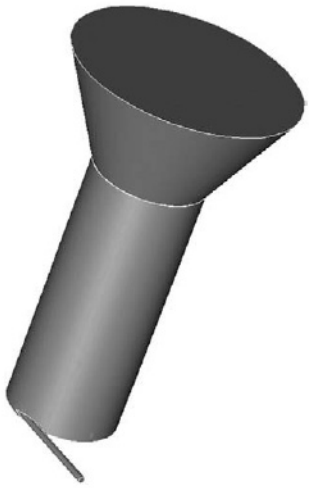

Fig. 6. Grid domain used to simulate the cylindrical jet cup.

transition from one model to the other was used between 75 and 85% of close packed loadings. Details of this can be found in Snider [8].

Barracuda™ 10.0 uses an algebraic gas phase turbulence model. Although this is a rudimentary method for modeling gas phase turbulence, Derksen et al. [9] have shown that for high loadings, the gas phase turbulence is dampened and is not a major contributor to the general hydrodynamics.

Fig. 6 shows the grid domain used to study the PSRI jet cup. Only a portion of the disengagement section was modeled. Any particle that reached the edge of the disengagement section was considered as lost to the domain. Jet cup designs were modeled at near ambient conditions with a temperature of 25 °C and an initial pressure of 104,771 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/s (0.000012 lb/ft/s), respectively.

Particle properties were based on a typical equilibrium FCC catalyst powder discussed above and with the particle size distribution shown in Fig. 2. The particle density was assumed to be 1492 kg/m^3 (93 lb/ft^3). 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/s (450 ft/s) corresponding to one of the experimental jet cup conditions.

3. Results

3.1. Cold flow study

Fig. 7 shows several still shots from the video taken of PSRI's 7.6-cm (3-in.) diameter cylindrical jet cup with a 0.48-cm (0.1875-in.) nozzle diameter at the three jet velocities tested. A significant portion of the material in the jet cup remained stagnant even at a jet velocity of 183 m/s (600 ft/s). Only at a jet velocity of 274 m/s (900 ft/s) were all the particles observed to be in motion (not shown in Fig. 7). However, this was not an ideal case as the material was blown from the cup into the disengagement section after a few seconds of operation at this jet velocity.

Similar particle stagnation was found with the PSRI jet cup having the smaller 0.24-cm (0.0938-in.) jet inlet diameter, as shown in Fig. 8. Here, the extent of the stagnation region was observed to be higher. At 76 m/s (250 ft/s) only a few particles were observed to be in motion.

Fig. 9 shows the still shots of video taken of the Davison jet cup with 5 g of FCC catalyst material. The Davison Jet Cup did better in terms of the amount of particles in motion. At 76 m/s (250 ft/s) jet velocity, most of the particles were still stagnant, similar to that found with the PSRI jet cup having the smaller nozzle size (the same size as the Davison jet cup). At 137 m/s (450 ft/s), only 30% of the particles were stagnant. At 183 m/s (600 ft/s), most of the material was observed to be in motion in the Davison jet cup whereas not all the particles were in motion in the larger PSRI Jet Cup.

Using 10 g of FCC catalyst powder in the Davison jet cup did reduce the size of the stagnant region, as shown in Fig. 10. With a jet velocity of 74 m/s (250 ft/s), 56% of the material was stagnant. At 183 m/s

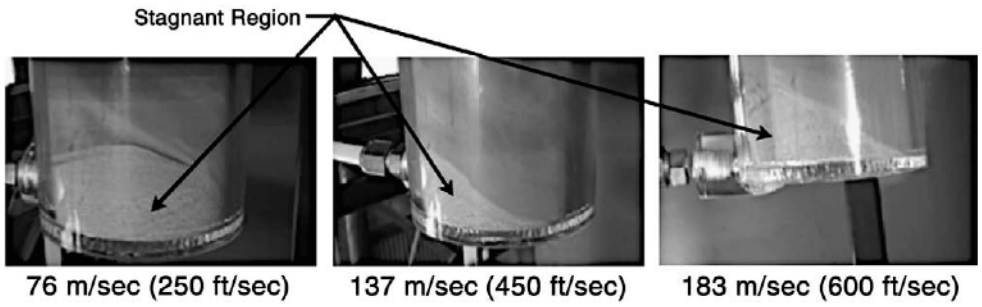

Fig. 7. Still shots from a video of the 7.6-cm (3-in.) ID cylindrical jet cup with a 0.48-cm (0.1875-in.) diameter nozzle.

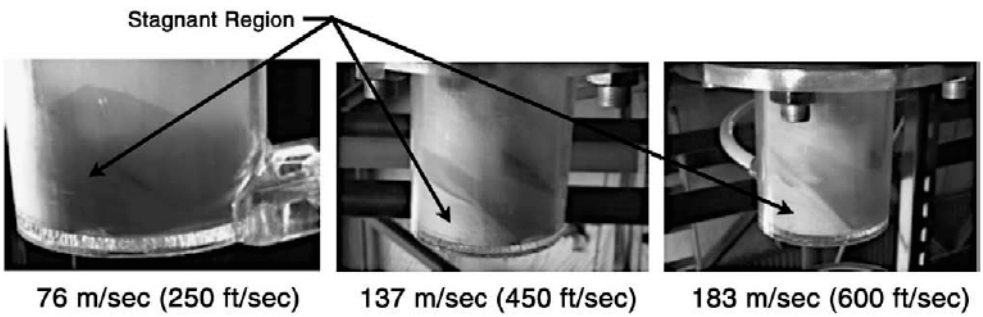

Fig. 8. Still shots from a video of 7.6-cm (3-in.) ID cylindrical jet cup with a 0.24-cm (0.09-in.) diameter nozzle.

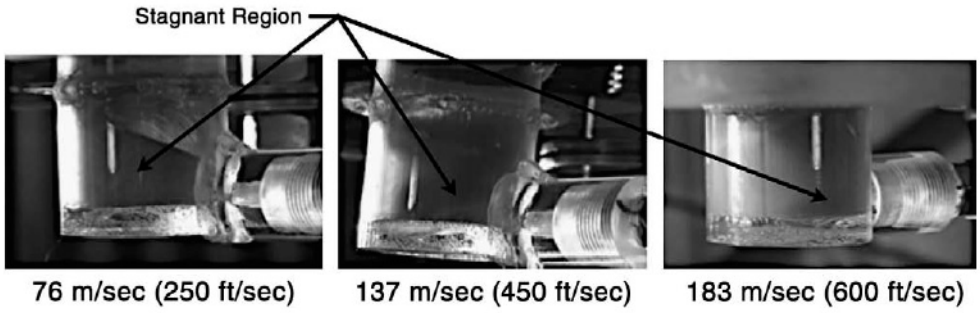

Fig. 9. Still shots from a video of the 2.54-cm (1-in.)ID Davison jet cup with 5 g of material.

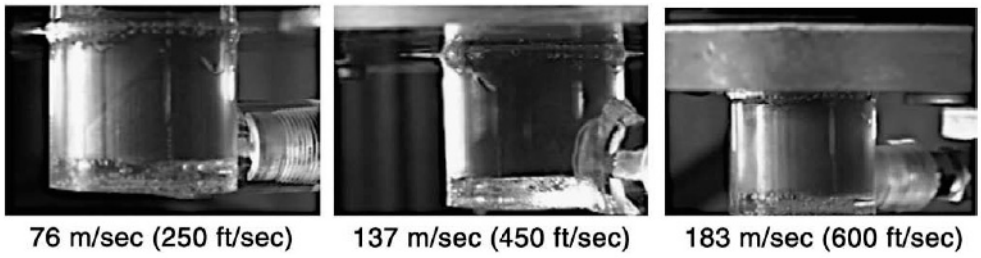

Fig. 10. Still shots from a video of the 2.54-cm (1-in.) ID Davison jet cup with 10 g of material.

(600 ft/s), most of the material was moving, as observed with the 5 g sample. At 274 m/s (900 ft/s), the material was lost from the jet cup after only a few seconds of operation.

By assuming that the stagnant material in the jet cups resembles a cylindrical wedge, as shown in Fig. 11, the volume of stagnant material visually observed was calculated by measuring the height and angle of the wedge with the expression,

$$V = \frac{hR^2}{3}\left(\frac{3\mathrm{Sin}[\phi] - 3\phi\mathrm{Cos}[\phi] - \mathrm{Sin}^3[\phi]}{1-\mathrm{Cos}[\phi]}\right) \quad (1)$$

where R is the radius of the jet cup, h is the height of the highest point of the wedge and ϕ is the angle of repose of the wedge, as shown in Fig. 11.

With Eq. 1, the amount of material observed in the cup was calculated and compared on a relative basis. As shown in Fig. 12, the stagnant material was significant at 76 m/s (250 ft/s) and 137 m/s (450 ft/s) for all cups investigated. This was also true for the PSRI jet cups even at 183 m/s (600 ft/s) jet velocities. More than 50% of the bed was stagnant. The Davison jet cup did better at higher velocities, but to ensure that all the particles were in motion during testing, a jet velocity of 183 m/s (600 ft/s) or higher needs to be employed. However, often this is too high of a jet velocity for realistic attrition testing. Such high velocities may not provide significant attrition results as particles are more likely to be in the disengagement region than in the jet cup.

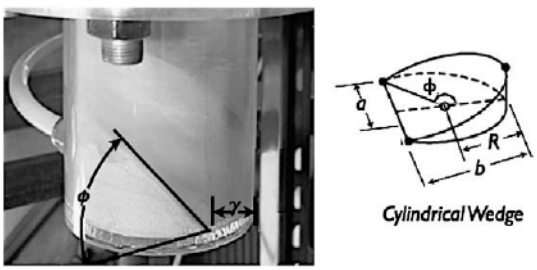

Fig. 11. Estimating the amount of stagnant material in the cylindrical jet cup.

Based on the performance of the standard and PSRI jet cups, the new cup designs shown in Fig. 5 were tested. The first new design tested was the angled jet cup. The angle essentially removed the stagnant region observed in the cylindrical jet cup. From the results with the cylindrical jet cup, a mean jet width of 1.5-cm (0.6-in.) with an angle of repose of ~45° was observed. Thus, the angled jet cup was designed with a similar wedge(angle of "repose" of 45° and jet width or gap of 1.5 cm (0.6 in.)) removed from the PSRI jet cup.

The results of the angled jet cup design are shown in Fig. 13. As with the standard PSRI cylindrical jet cup, 100 g of material was tested at jet velocities of 76, 137, and 183 (250, 450, and 600 ft/s). Although a significant improvement in particle mobility was observed, there were still regions of stagnant particles at the lower gas velocities. At 76 m/s (250 ft/s), 14% of the material was observed to be stagnant at the bottom of the angled jet cup. At 137 m/s (450 ft/s), less than 10% of the material was stagnant. At higher velocities, most of the material was observed to be in motion.

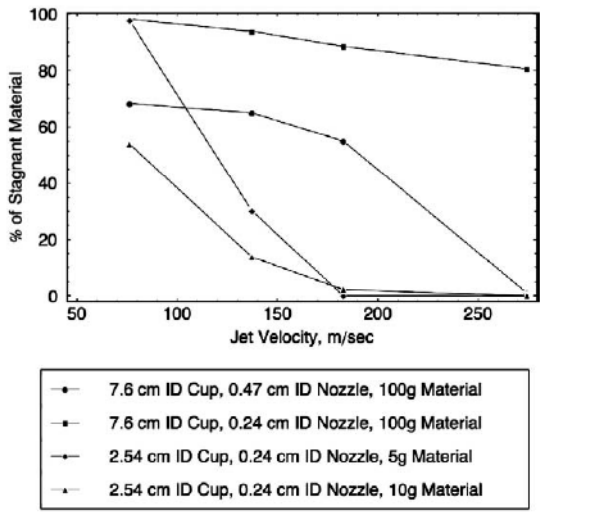

Fig. 12. Amount of stagnant material as a function of gas velocity measured in PSRI's cylindrical jet cups and the Davison jet cups.

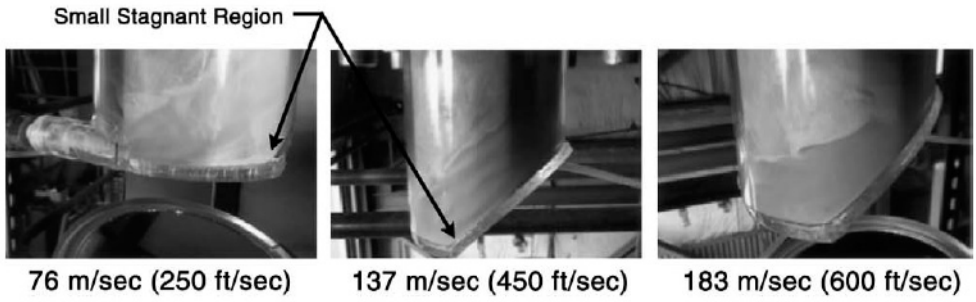

Fig. 13. Still shots from a video of the 7.6-cm (3-in.) ID angle jet cup with 100 g of material.

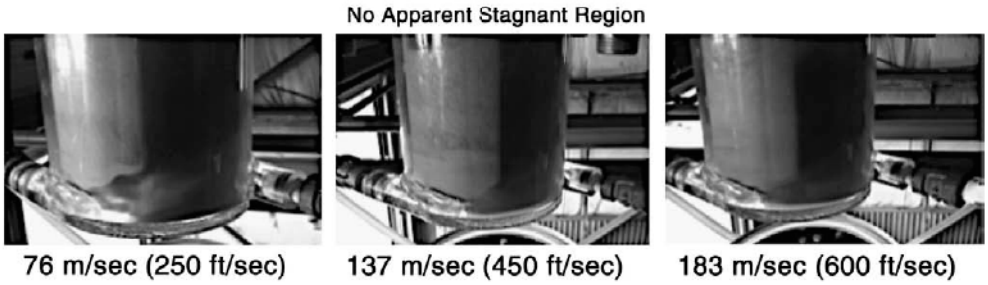

Fig. 14. Still shots from a video of the 7.6-cm (3-in.) ID dual entry jet cup with 100 g of material.

The dual entry jet cup added an extra jet to the PSRI cylindrical jet cup. To use the same gas flow rate as with the cylindrical jet cup, the nozzle diameters for the dual entry jet cup were reduced to 0.24-cm (0.09375 in.), which corresponded to one of the standard PSRI jet cups using the similar smaller nozzle diameter (Fig. 8).

Fig. 14 shows the still photos from the video of the dual entry jet cup with nozzle gas velocities of 76, 137, and 183 m/s (250, 450, and 600 ft/s). The photograph for the 274 m/s (900 ft/s) case is not shown. At 76 m/s (250 ft/s), more than 20% of the material was observed to be stagnant. However, unlike the cylindrical jet cup where the stagnant material formed a cylindrical wedge on one side of the cup, the dual entry cup resulted in a conical-shaped stagnant area in the center of the cup, as shown in Fig. 15. At higher velocities, this conical region reduced in size but was still present even at 274 m/s (900 ft/s). For all jet velocities, the dual entry jet cup performed worse than the angled jet cup, but was still significantly better than the standard cylindrical jet cup.

The conical stagnant region observed at jet velocities of 76 and 137 m/s (250 and 450 ft/s) was measured in terms of angle of repose and the gap between the stagnant material and the jet cup wall. The average gap width was determined to be 1.25-cm (0.5 in.) with an angle of repose of 22°. From these data, the dual entry jet cup was modified with a conical insert similar to that measured as the stagnant region noted above. This modified dual entry jet cup is referred to as the dual entry with insert jet cup.

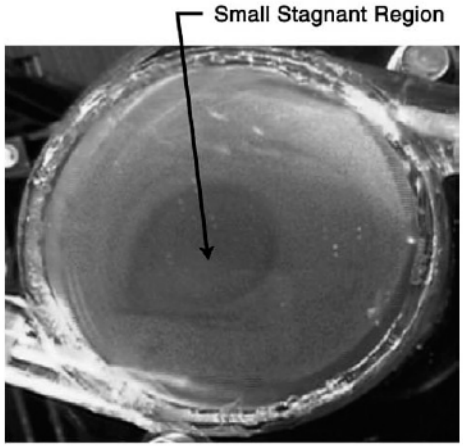

Fig. 15. Bottom view of dual entry jet cup at 137 m/s (450 ft/s) gas jet velocity.

Fig. 16 shows still photos from the video taken for the dual entry with insert jet Cup study. This modified cup performed better than the original dual entry jet cup. However, its performance mirrored that of the angled jet cup.

The last jet cup design investigated was the conical jet cup. 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. The gas jet still entered tangentially at the bottom of the cup with the same inlet diameter of 0.47 cm (0.1875 in.) as that used for the 7.6-cm (3-in.) cylindrical jet cup. Nearly all the particles were in motion in the conical jet cup at gas velocities of 76, 137, 183, and 274 m/s (250, 450, 600, and 900 ft/s) without entraining into the disengagement zone, as shown in Fig. 17. At 76 m/s (250 ft/s), 95% of the material was in motion.

Fig. 18 compares the percentage of stagnant material for each of the jet cups examined. All the new jet cups examined showed significantly smaller stagnant regions than that of the cylindrical jet cup with the 0.48-cm (0.1875-in.) diameter nozzle. However, the conical jet cup measurements were significantly better than the other alternative jet cups tested.

3.2. CFD study

Fig. 19 shows the CFD results from simulating the standard PSRI cylindrical jet cup with 100 g of FCC powder. The simulation was for the operating conditions of 137 m/s (450 ft/s) jet velocity at 25 °C and 104,771 Pa (15.2 psia). The jet cup diameter was 7.6 cm (3 in.) with a nozzle diameter of 0.48 cm (0.1875 in.). As shown in Fig. 19, most of the particles in the cup remained stationary. Simulation times were limited to the first 5 s of operation. Little change was measured in the hydrodynamics after the first second of operation.

Fig. 20 shows the particle velocities in the bottom region of the jet cup for the same simulation shown in Fig. 19. The gray-scale bar indicates the particle velocity where blue represents low particle velocities and red represents high particle velocities. From Fig. 20,

Fig. 16. Still shots from a video of the 7.6-cm (3-in.) ID dual entry jet cup with insert with 100 g of material.

Fig. 17. Still shots from a video of the 3.8-cm (1.5-in.) bottom ID by 7.6-cm (3-in.) top ID conical jet cup with 100 g of material.

several key features are apparent. First, the "stagnant" region is prominent with most of the particles being shown at the near zero velocity magnitude. The few particles that were moving had a trajectory of an inclined, ellipsoidal path from the bottom to the top of the jet cup and back down again. Second, particle velocities were only ~12% of that for the entering gas jet velocity of 137 m/s. At room temperature, the maximum particle velocity was 17 m/s (55.8 ft/s).

Barracuda™ models particle trauma with a wall segment via the expression

$$\Psi = m^a(\vec{v} \bullet \vec{n})^b \tag{2}$$

where m is the mass of the particle, v is the particle velocity crossed with the outward normal vector n of the wall. Parameters a and b are user-defined. For this study, both were set to one so that trauma corresponded to particle momentum. Particle trauma in the cylindrical jet cup was limited to a few select particles, as shown in Fig. 21. The majority of the particles did not appear to have any stress with the wall during the 5 s simulation time. Maximum trauma was measured to be 0.23.

Barracuda™ provides wall impact measurements as the number of hits in the cell domain bordering the wall boundary condition. A 5-s simulation resulted in 48,100 hits (with clouds not particles). In addition, a secondary impact with the wall was detected further down the particles path. Fig. 22 shows the wall impact for the cylindrical jet cup simulations. These results suggest that in a jet cup, particles tend to collide (or impact) with the wall instead of grazing the wall.

As with the cold flow observations, the CFD model predicted the stagnant regions in the PSRI jet cup. This suggested that particle concentration, particle velocity, wall impact, and trauma might be good metrics for jet cup design. Thus, a Barracuda™ model was employed also for the new conical jet cup design using the same metrics.

Fig. 23 shows the results of the CFD modeling for the conical jet cup. Nearly all the material was in motion at a gas inlet velocity of 137 m/s (450 ft/s). Simulations also showed that with the exception

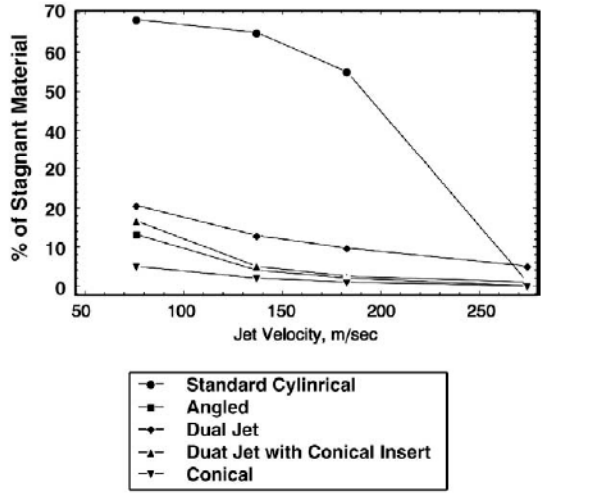

Fig. 18. Amount of stagnant material measured in all the 7.6-cm (3-in.) diameter jet cups tested including the new conical jet cup.

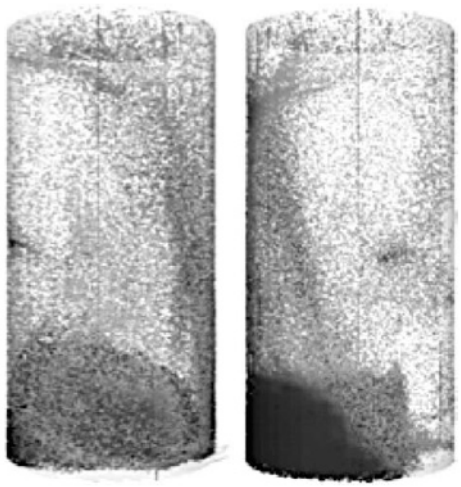

Fig. 19. Simulations of the standard cylindrical jet cup with FCC catalyst powder.

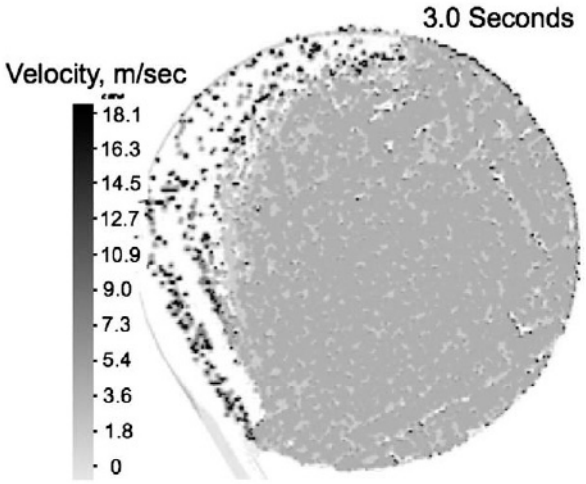

Fig. 20. Simulation results for particle velocities for the standard cylindrical jet cup with FCC catalyst powder at a gas jet velocity of 137 m/s (450 ft/s).

of absent stagnant material, the solids hydrodynamics were similar to the few particles that were moving in the cylindrical PSRI jet cup. The particle trajectory followed an inclined, ellipsoidal path from the bottom to the top of the jet cup and back down to the bottom. Similarly, the maximum particle velocity was approximately 12% of the gas inlet velocity. The maximum particle velocity was measured at 17 m/s (56 ft/s), similar to that observed for the cylindrical PSRI jet cup. Fig. 24 shows the particle velocity at the bottom of the conical jet cup.

The most revealing of the CFD simulations was the particle trauma results. Unlike the particle trauma shown in Fig. 21 for the cylindrical PSRI jet cup, most of the particles in the conical jet cup experienced higher trauma, as shown in Fig. 25. Maximum particle trauma was measured at 1.4 for the conical jet cup compared to 0.23 for the cylindrical PSRI jet cup. Thus, not only were more particles exposed to trauma, the magnitude of the trauma was higher in the conical jet cup for at least a few of the particles. Fig. 26 shows the particle trauma for the bottom portion of the conical jet cup.

Hence, CFD simulations supported the observations of the cold flow study. Most of the particles were stagnant in the cylindrical jet cup. Simulations of the conical jet cup showed that more particles were in motion but with similar maximum particle velocities. The

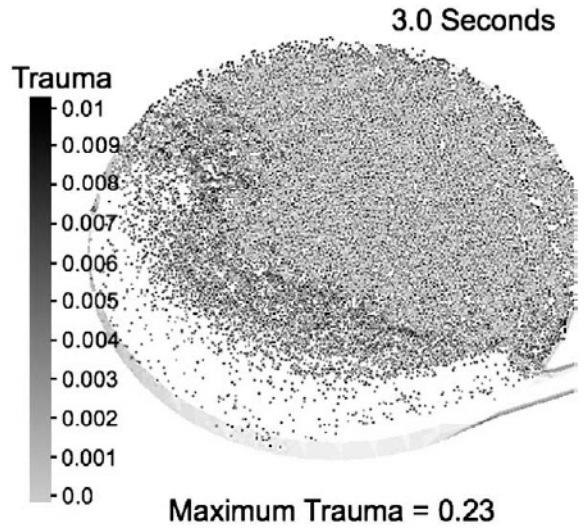

Fig. 21. Simulation results of particle trauma with wall segments for the standard cylindrical jet cup with FCC catalyst powder at a gas jet velocity of 137 m/s (450 ft/s).

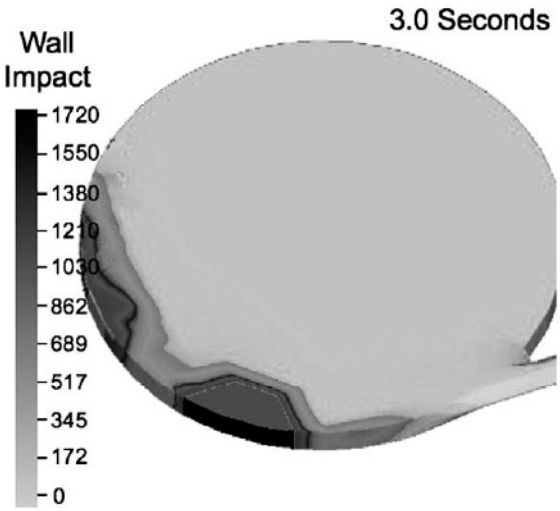

Fig. 22. Simulation results of wall impact in terms of cumulative number of hits with the wall for the standard cylindrical jet cup with FCC catalyst powder at a gas jet velocity of 137 m/s (450 ft/s).

particle trauma indicated more particles may be experiencing more wall attrition and a higher magnitude of that stress.

3.3. Attrition study

Attrition loss rates collected from the secondary cyclone of the fluidized bed cyclone attrition unit shown in Fig. 4 were compared to the attrition indices obtained from the cylindrical 7.6-cm (3-in.) diameter jet cup for several lots of a catalyst material labeled Lots A through F. The only difference in the catalyst lots was particle strength. Thus, different attrition rates or attrition index numbers were expected. As shown in Fig. 27, the loss rates for the materials due

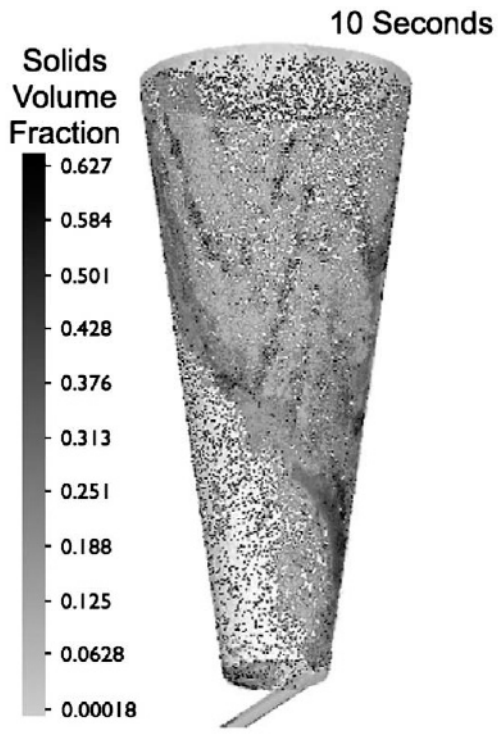

Fig. 23. Simulation results of solids volume fraction (side view) in the conical jet cup with FCC catalyst powder at a gas jet velocity of 137 m/s (450 ft/s).

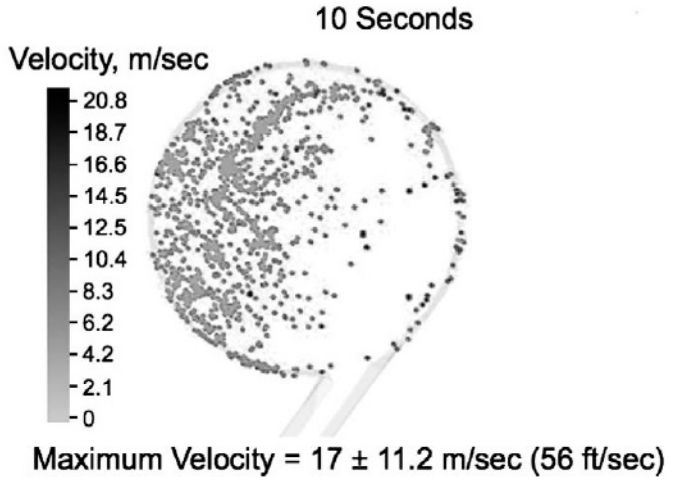

Fig. 24. Simulation results of particle velocity (bottom view) in the conical jet cup with 100 g FCC catalyst powder at a gas jet velocity of 137 m/s (450 ft/s).

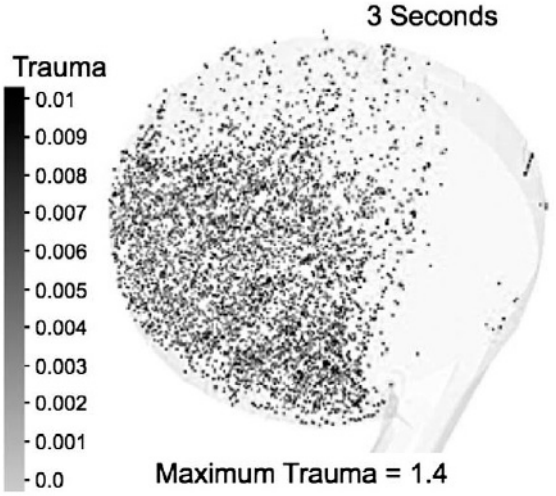

Fig. 26. Simulation results of particle trauma (bottom view) in the conical jet cup with 100 g FCC catalyst powder at a gas jet velocity of 137 m/s (450 ft/s).

to attrition in the cyclones did not correlate with the corresponding cylindrical PSRI jet cup results. Thus, even qualitatively, the attrition results from the standard jet cup may not be applicable to a large fluidized bed unit despite the popularity of this method.

In contrast, the results from the conical jet cup were found to be comparable to the attrition loss rates from the fluidized bed cyclone attrition test unit. The AI<20 μm data from the conical jet cup correlated well with the attrition loss rate data. However, complete agreement was not observed for the AI<44 μm data. Data for Lot A appeared to be an outlier. These results are shown in Fig. 28.

Fig. 29 shows Tukey–Kramer (Student t) test for the attrition index from the cylindrical PSRI jet cup and the conical jet cup for the six catalyst lots (six lots of proprietary catalyst). The conical jet cup exhibited higher attrition rates compared to the standard cylindrical jet cup. This was even more significant where fines levels were defined as particle diameters less than 44 μm. Results suggest that the

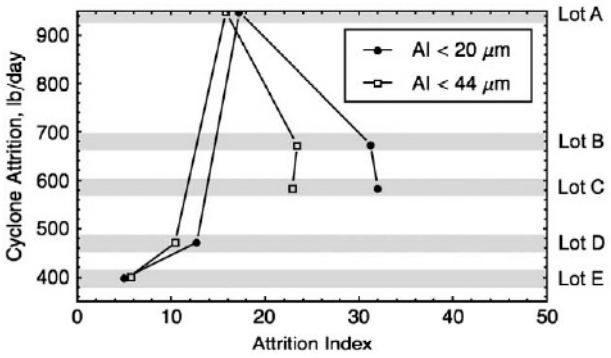

Fig. 27. Correlating the cylindrical jet cup attrition data to the cyclone flow loop attrition data.

conical jet cup provided a higher attrition rate than the cylindrical jet cup. However, the variation in the attrition indices was similar with respect to both jet cups.

4. Discussion

The attrition index data from cylindrical jet cup tests may not be useful for predicting attrition in commercial units. There is doubt that the cylindrical jet cups can even provide proper ranking of particle attrition with respect to the performance in a commercial-scale unit. This limitation has been proposed as the result of the prevailing stress mechanisms in the test differing from that in the process [3]. CFD

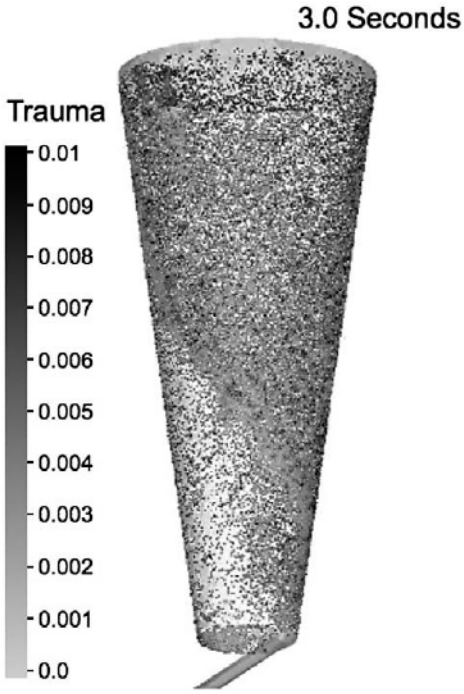

Fig. 25. Simulation results of particle trauma (side view) in the conical jet cup with 100 g material FCC catalyst powder at a gas jet velocity of 137 m/s (450 ft/s).

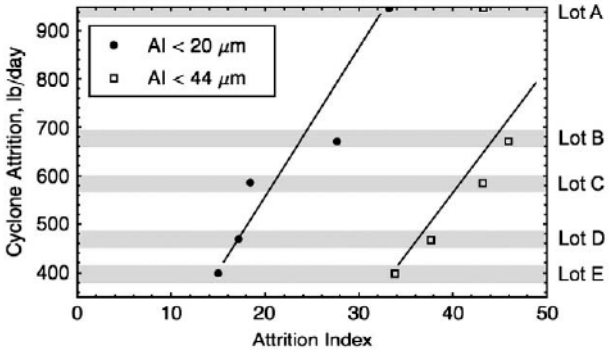

Fig. 28. Comparison of attrition index from a conical jet cup to attrition loss rates from the PSRI fluidized bed cyclone attrition test unit.

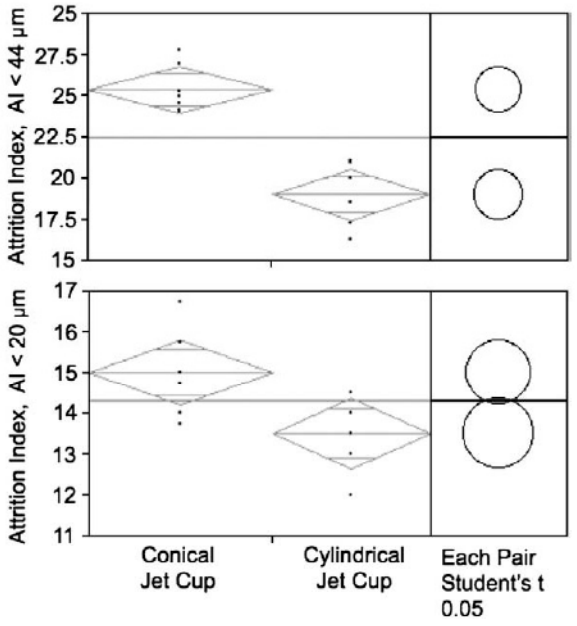

Fig. 29. Student t or Tukey–Kramer test on AI<20 µm (left) and AI<44 (right) µm from cylindrical and conical jet cups at 137 m/s (450 ft/s) with 100 g of FCC catalyst powder. Analysis via JMP™ Statistical Software from SAS™.

results certainly suggest this as particles in a cylindrical jet cup did not resemble the hydrodynamics in a fluidized bed, riser, or cyclone. However, it may also be a sampling error issue. With a certain percentage of material remaining stagnant in the cylindrical jet cup, attrition index results may be based on the wrong sample size. The actual sample size may be significantly smaller than what is measured and reported.

This deficiency with the cylindrical jet cups was an issue in the Davison jet cup as well. It is possible that the convention of only using the Davison jet cup data for relative comparison with other material may be due to a poorly designed experiment. The new PSRI conical jet cup may change this limitation. Cold flow and CFD findings suggest that nearly all the particles are in motion for gas jet velocities of 76 m/s (250 ft/s) or more. CFD results also showed that particle trauma is four- to six-times higher with the new jet cup at gas jet velocities of 137 m/s (450 ft/s). With the maximum particle velocity being similar for both jet cup designs, the increase in particle trauma is because of more particles experiencing collisions with the wall and some of those collisions may be at higher velocities. Unlike the cylindrical jet cups, particles in the conical cup did not have significant amounts of stagnant material to buffer the particle–wall and possibly the particle–particle collisions. The attrition index data support this concept as well. The conical jet cup resulted in 11% and 33% increases in attrition based on the AI<20 and AI<44 µm tests, respectively, as shown in Fig. 29. This difference can be viewed as statistically significant based on the Tukey–Kramer (Student t) test with a 95% confidence level.

Thus, particles in the conical jet cup experience higher attrition than in the cylindrical jet cup presumably because more particles are mobile and exposed to a higher shear at the walls. The intensity of the shear in the jet, however, may be similar for each type of jet cup as the maximum particle velocity remained constant according to CFD results.

Figs. 27 and 28 further demonstrate the merits of the conical jet cup. With the cylindrical jet cups, attrition loss rates could not be correlated to attrition index data from the fluidized bed cyclone attrition test unit. The conical jet cup AI<20 µm data correlated to the attrition loss rates from the fluidized bed unit; but, the AI<44 µm results did not correlate as well. This discrepancy is further confounded because the conical jet cup provided a 30% increase in the AI<44 µm test, as shown in Fig. 29. Hypothetically, the higher attrition rates in the conical jet cup should lead to a better correlation with the attrition loss rate data. Thus, data and simulations suggest the conical jet cup may be more suited for quantifiable attrition measurements, but its limits regarding accuracy and reproducibility need further study. Certainly, additional (and different) materials need to be tested with the new jet cup against the fluidized bed cyclone attrition test unit or a similar unit.

5. Conclusions

CFD simulations revealed that particle velocities in the cylindrical PSRI jet cup may be as low as 12% of the gas inlet velocity. In addition, CFD simulations revealed that less than 50% of the bed in the cylindrical PSRI jet cup may be in motion. The remaining portion of the material is stagnant. Cold flow studies confirmed this result and indicated that even the traditional Davison jet cup has issues with stagnant material.

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/s (250 ft/s). Attrition values were 10 to 30% greater in the conical jet cup compared to the cylindrical jet cup. CFD results confirmed these findings based on particle trauma and wall impact.

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.

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