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Jet cup attrition testing

R. Cocco *, Y. Arrington, R. Hays, J. Findlay, S.B.R. Karri, T.M. Knowlton

Particulate Solid Research, Inc., Chicago, IL, United States

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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.

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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* Corresponding author. Tel.: +1 773 523 7227.
E-mail address: ray.cocco@psrichicago.com (R. Cocco).

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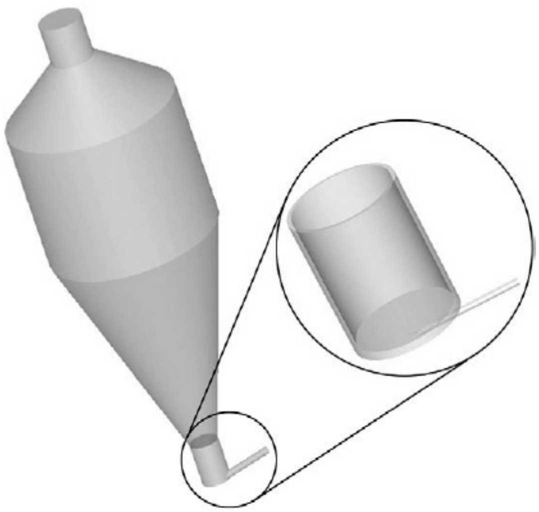


Fig. 1. The overall Davison jet cup (left) and close up of the jet cup (right). Based on Weeks [1].

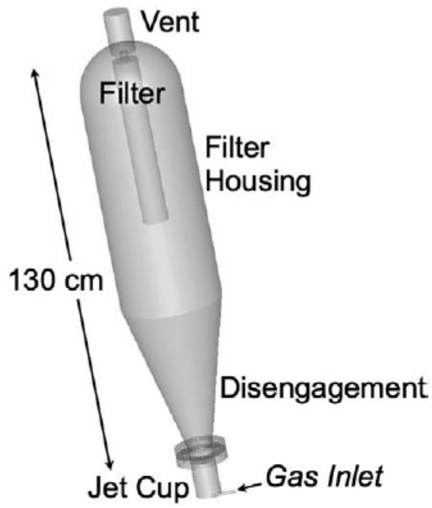


Fig. 3. PSRI's cylindrical jet cup apparatus.

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.

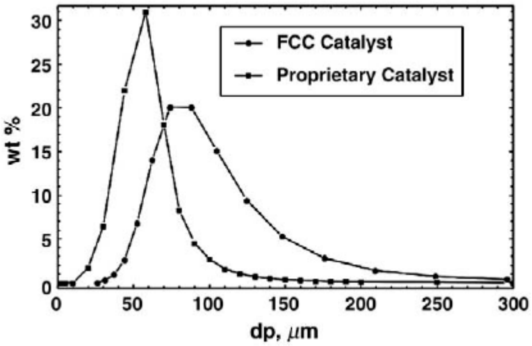


Fig. 2. Differential particle size distribution of the FCC catalyst and proprietary catalyst

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

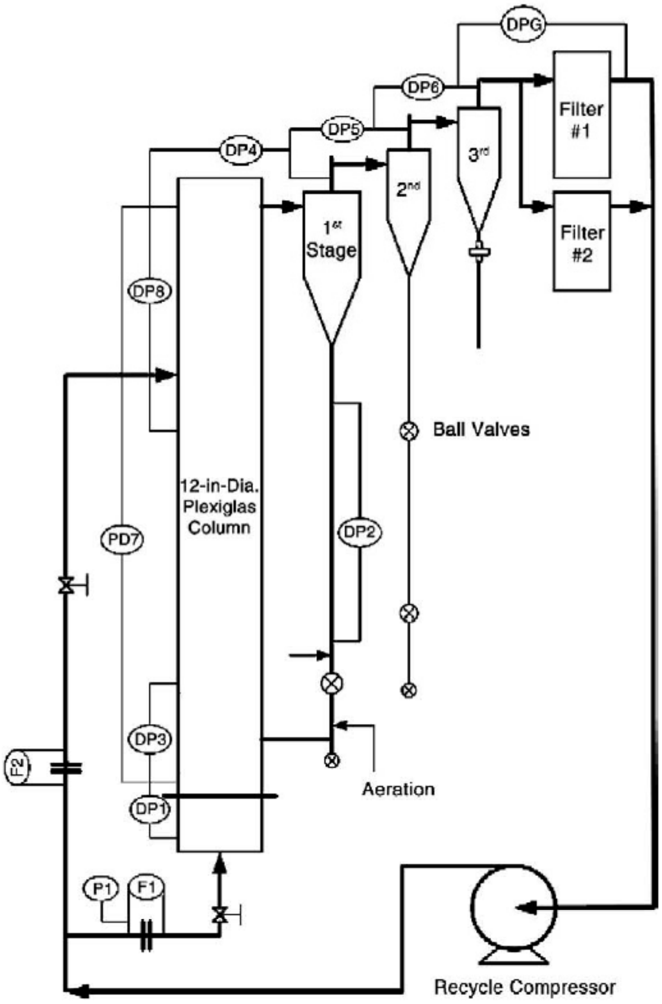


Fig. 4. The PSRI 29.2-cm (11.5-in.) diameter fluidized bed cyclone attrition test unit.

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.

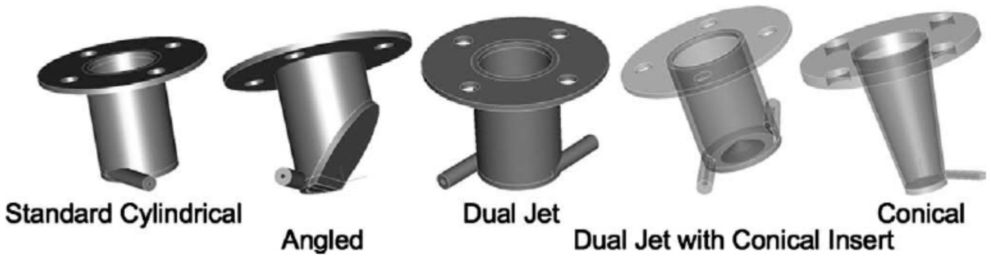
All jet cup concepts were designed with a 7.6-cm (3-in.) diameter outlet. The conical jet cup diameter was reduced to 3.8-cm (1.5-in.) in diameter at the bottom of the cup. The inlet jet diameter was either 0.24- or 0.48-cm (0.0938- or 0.1875-in.) ID and fastened tangentially to the bottom portion of 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



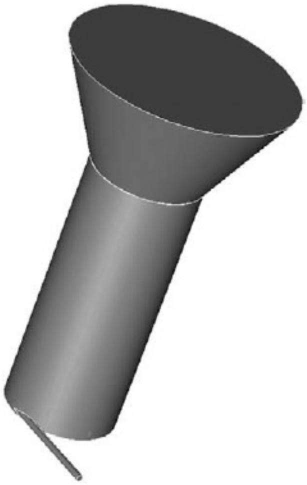


Fig. 6. Grid domain used to simulate the cylindrical jet cup.

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

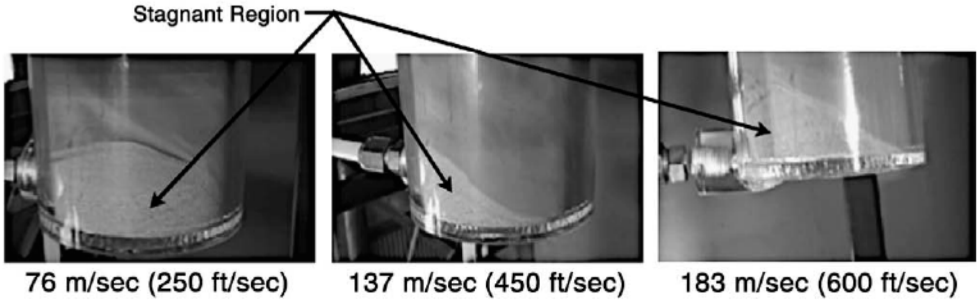
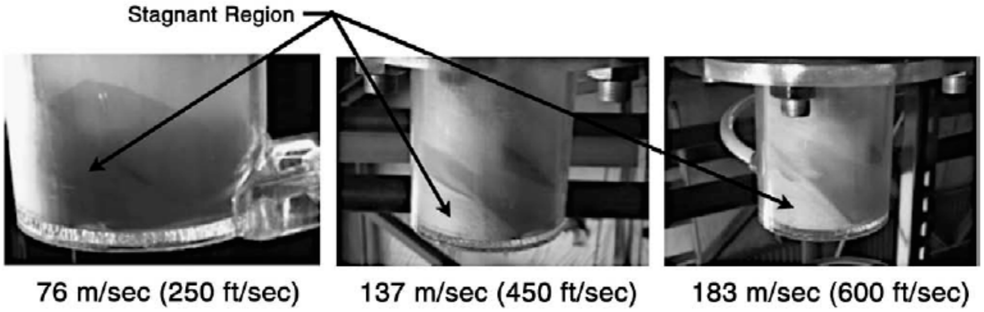
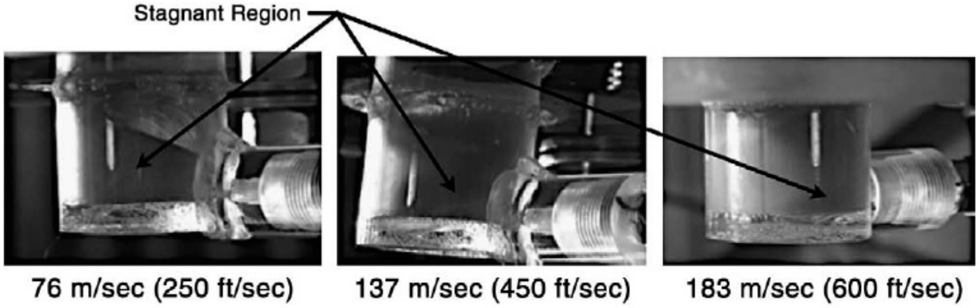


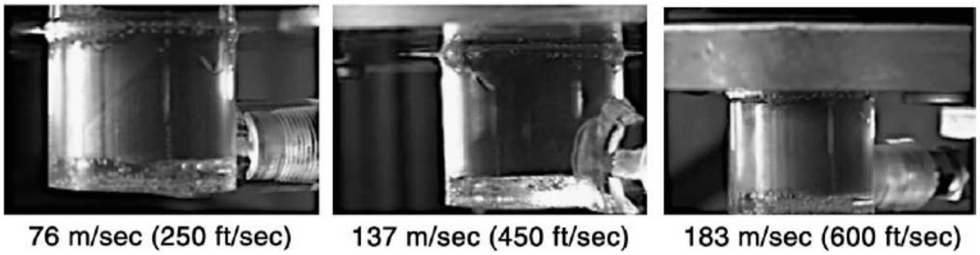
Fig. 7. Still shots from a video of the 7.6-cm (3-in.) ID cylindrical jet cup with a 0.48-cm (0.1875-in.) diameter nozzle.





76 m/sec (250 ft/sec) 137 m/sec (450 ft/sec) 183 m/sec (600 ft/sec)

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



76 m/sec (250 ft/sec) 137 m/sec (450 ft/sec) 183 m/sec (600 ft/sec)

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

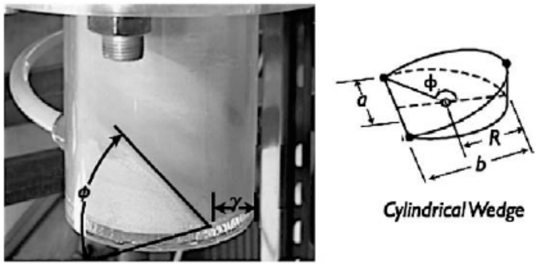
(600 ft/s), most of the material was moving, as observed with the 5 g sample. At 274 m/s (900 ft/s), the material was lost from the jet cup after only a few seconds of operation.

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,

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

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.



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.

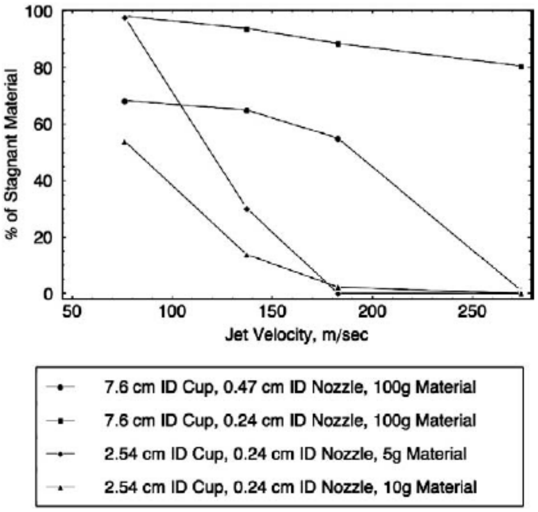


Fig. 12. Amount of stagnant material as a function of gas velocity measured in PSRI's

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