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PARTICLE CLUSTERS IN FLUIDIZED BEDS

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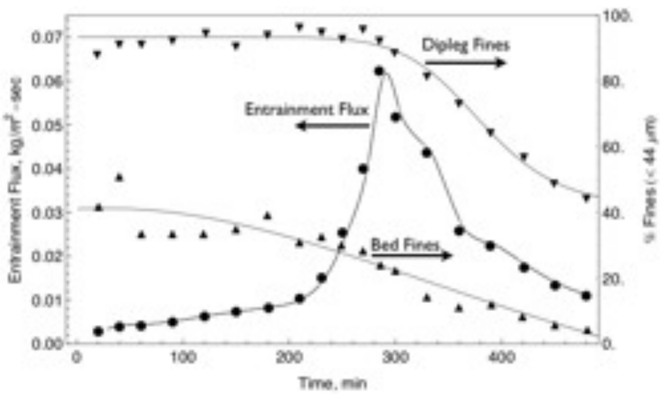
Accurately predicting the entrainment rate is important in designing a commercial fluidized bed. However, most correlations fall short in providing an accurate prediction of the entrainment rate. Many correlations assume that smaller particles have a higher entrainment rate than larger particles; but, this is often not the case. Smaller particles can, and often do, have lower effective entrainment rates than larger particles. This has been presumed from several different experiments. In one case, the entrainment rate of FCC catalyst fines was measured at different fluidized bed heights and found that higher entrainment fluxes were observed at lower bed heights (i.e., higher disengaging heights). In a second case, it was found in a batch entrainment test that with an initial high concentration the fines level in the entrainment flux was very low. As the fines were gradually elutriated away, the entrainment flux increased dramatically. Following a dramatic increase to a maximum, the entrainment flux then exhibited the classical batch exponential decay as the fines were elutriated from the fluidized bed. Recently, high speed video of particles in a fluidized bed freeboard was able to image and track large clusters of particles in the range of 200 microns to 1000 microns when the bed material had a mean particle size of only 25 microns. All of these findings suggests that fine particles in many materials are clumping or clustering. This increases their effective particle diameter which reduces the entrainment rate. The clumps appear to be formed in the fluidized bed, and are ejected into the freeboard. High-speed videos obtained using observations through a borescope inserted into a fluidized bed at PSRI have confirmed the presence of clusters in fluidized beds. Such a phenomenon has many implications regarding how entrainment may be influenced by fines level, bed height, baffles, jet velocity at the distributor, etc.

INTRODUCTION

Particle clustering in fluidized beds has been proposed for since 1948 (1) with others following (2-12). However, little work has been done to measure these cluster properties. Most of the work has been limited to relating clusters to an unexpected increase in the measured particle drag (15-19). The mechanism of formation of these clusters and the underlying dependencies are still unknown. Yet, particle clusters in fluidized beds can have an impact on entrainment and cyclone efficiencies. Based on evidence from pilot and commercial scale plants along with high speed video of a cold-flow fluidized bed, the mechanism of particle clustering in and above fluidized beds and its effect on entrainment were examined.



ρ_p=2300 kg/m3, dp50(initial)=57 µm, Bed Height=1.3 m

Figure 1: Entrainment flux and fines level from a 6-inch (15-cm) diameter fluidized bed at 0.66 ft/sec (0.2 m/sec) superficial gas velocity.

BACKGROUND

Recently, Hays, et al. (20) and Cocco, et al. (21, 22) reported an attempted to reproduce why highly variable entrainment rates were observed in a commercial-scale fluidized bed even though steady state was assumed. Tests were conducted in a 15-cm (6-inch) diameter fluidized column with a static bed height of 132 cm (52 inches) of the same Geldart Group A powder (d_{p50} of 55 to 60 microns) used in the commercial process. The test unit was operated in batch mode at a superficial gas velocity of 0.2 m/sec (0.66 ft/sec).

Figure 1 shows the entrainment flux measured at the outlet and the fines[1] weight fraction for the bed and entrained material as a function of time. As the fines concentration began to decrease in the bed, the entrainment rate increased rapidly to a peak approximately ten times the initial rate. Further depletion of fines from the bed resulted in a subsequent drop in the entrainment rate. For the commercial unit, the highly variable entrainment rates appeared to be due to the extreme sensitivity to the fines concentration. The dipleg was not designed to handle the presumed ten-fold increase in the entrainment rate and sometimes flooded as a result.

These results are consistent with the earlier studies of Geldart and Wong (16), Baeyens et al. (17) and Li et al (19). They found that the addition or presence of fines in a fluidized bed of Geldart Group A powder can result in a lower entrainment rate. Hays' study further confirmed the role of fines by showing that the removal of fines from a fluidized bed resulted in a significant increase in the entrainment rate, presumably resulting from a decrease in particle clustering.

Until recently, no direct evidence of particle clusters existing in the fluidized bed has been presented. In order to provide more conclusive evidence of the nature of particle clusters, a special optical system was developed and used to examine particle cluster behavior in and above a fluidized bed. The results of this study are presented below.

EXPERIMENTAL

Powder Materials

For this study, three materials were used: polyethylene, FCC catalyst fines, and FCC catalyst powders. The polyethylene powder is commonly used for coatings and listed under the name of Plascoat™ PPA 571 (Punda Mercantile Inc). The polyethylene powder has a particle density of 400 kg/m^3. The FCC catalyst fines had a median particle size, d_{p50}, of 27 microns with a particle density of 1493 kg/m^3. The

[1] defined as particle sizes smaller than 44 microns

FCC catalyst powder was material obtained from a commercial FCC unit and is commonly called equilibrium FCC catalyst powder (Rocky Mountain Salvage). The particle density for the FCC catalyst powder was 1500 kg/m^3.

Fluidized Beds

Experiments were carried out in a 15-cm (6-inch) diameter by 4.6-meters (15-feet) tall unit constructed of acrylic tubing. The distributor consisted of a perforated plate with 61 holes each with a diameter of 0.47 cm (3/16 inches). Filter cloth was positioned below the perforated plate to prevent solids weepage into the plenum region. The outlet consisted of a 5-cm (2-inch) diameter port on the top of the unit. Two 1.2-cm (0.5-inch) diameter ports were added to the unit to allow access for the high speed video imaging. One port was located 15 cm (6 inches) above the perforated plate. The other port was located 20 cm (8 inches) below the top of the unit. Compressed air at room temperature was used as the fluidizing gas.

Probe Design

An Olympus R100-038-000-50 Industrial Rigid Borescope was modified to image particles and clusters in the freeboard and in the bed. This boroscope had a depth of field of 5 mm to infinity. The boroscope was fitted with a 6-mm diameter optical spacer (Melles Griot) to account for the distance between the boroscope face and the focal length. This prevented particles closer than the focal length from blurring the images or reducing the lighting for the imaged particles. The spacer was secured using a stainless steel guard collar to protect the instrument when in the fluidized bed.

The Olympus R100-038-000-50 boroscope allows for internal lighting. A xenon light sources with an Olympus Liquid-Filled Light Guide was used to supply lighting through the boroscope probe. External lighting was used whenever possible.

High-speed video images were obtained using a Vision Research Phantom v7.2 camera. Although the camera is capable of 75,000 frames per second, only frame rates ranging from 3,000 to 6,000 frames per second were used. The camera was fitted with a C-mount fitting to connect to the boroscope that was inserted into the fluidized bed.

Vision Research Phantom Camera Control Software (version 9) was used for image downloading. Particle size analysis of the high speed video images was conducted using ImageJ software (http://rsbweb.nih.gov/ij/) using a Waterfall filter. Particle tracking was conducted using proprietary software from the National Energy Technology Laboratory (NETL).

RESULTS

FCC Catalyst Fines

Figure 2 shows a high speed video capture of FCC fines at the wall of the 15-cm (6-inch) diameter fluidized bed. The superficial gas velocity was 0.6 m/sec (2 ft/sec). Details of this procedure can be found in Cocco, et al. (21). Figure 2 clearly indicates that particle clustering is occurring since the FCC fine particles with a d_{p50} of 27 microns should not even be visible to the camera. Clusters on the order of several hundred microns were readily observed.

Hays et al. (20) found that as the bed height in this unit decreased slowly, the measured entrainment rate increased with time. To determine if it was the decrease in bed height that was causing the increase in entrainment, material was removed from the dense phase region of the bed while it was fluidized after 4500 seconds. As shown in Figure 2, the removal of bed material from the column caused a significant increase in the entrainment rate.

In separate fluidization experiments, the entrainment rate at six different bed heights was explored. As shown in Figure 3, an inverse linear relationship exists between the fluidized bed height and the corresponding entrainment rate. This dependence suggests that clustering was occurring, and that the size of the particle clusters might have been dependent on bed height.

Polyethylene

Figure 4 shows an image taken at the center of the fluidized bed in the freeboard region 20 cm (8 inches) from the top of unit) using the Phantom v7.2 and modified boroscope. Particle tracking has been added for each cluster. Although the polyethylene powder had a mean particle size of 70 microns, clusters on the order of 100 to 500 microns and larger were readily observed. Since the modified boroscope arrangement was used, wall effects were minimal.

The size of the clusters was

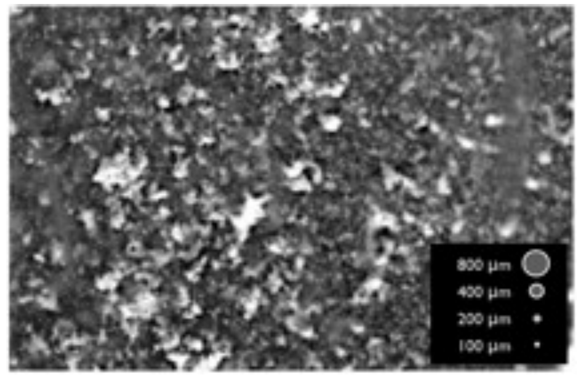


Figure 1. Frame capture from high-speed video imaging of FCC catalyst fines (d_{p50} = 27 microns) in the freeboard region of a 6-inch (15-cm) diameter fluidized bed at a superficial gas velocity of 2 ft/sec (0.6 m/sec). Video taken with University of Chicago (from Ref 20).

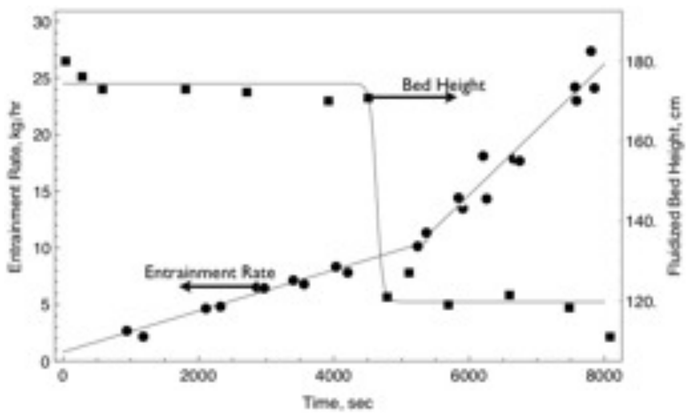


Figure 2: Entrainment rate from a bed of FCC catalyst fines when bed height was decreased by 25% at 4500 seconds. The superficial gas velocity was 0.56 m/sec (1.8 ft/sec) at room conditions.

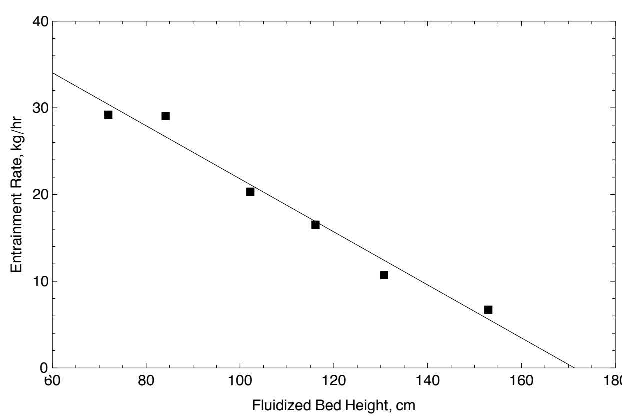


Figure 3: Entrainment flux from a 15-cm (6-inch) diameter bed of FCC catalyst fines with a superficial gas velocity of 0.61 m/sec (2 ft/sec) at various fluidized bed heights.

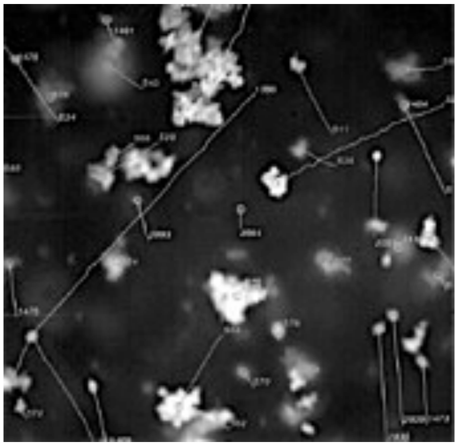


Figure 4: High-speed video frame of Plascoat™ 571 polyethylene in the freeboard region of a 6-inch (16-cm) diameter fluidized bed at a superficial gas velocity of 2 ft/sec (0.61 m/sec). Images were collected at 4000 frames per second with a 20 μs exposure time.

obtained from 100 different images from high speed video frames. Figure 5 shows the particle size distribution of the entrained material obtained from image analysis along with the particle size distribution of the bed material using a Microtrac™ S3000 laser diffraction analyzer. The median size for the freeboard material was measured to be 175 microns. However, this distribution also includes particles that were not part of any clusters.

The actual cluster size distribution was obtained by deconvoluting the particle component from the high speed video curve shown in Figure 5. If a log normal distribution is assumed along with the constraints that the particle component does not move the peak position, and the peak width at half maximum is constant, then the cluster size distribution can be deconvoluted from the high speed video curve. The result of that deconvolution process suggests that the cluster size distribution ranges up to 700 microns with a median cluster size of 240 microns, as shown in Figure 5.

A ratio of the presumed particle peak and the deconvoluted peak in Figure 5 suggests that 75% of the material observed in the freeboard is clusters with the remaining 25% being single particles. If it is assumed that both particles and clusters are spherical, and clusters are arranged in a close pack configuration with a solids volume fraction of 0.65, the mean cluster size of 240 microns suggests that the number of particles per cluster is on the order of 26 particles.

FCC Catalyst Powder

The modified boroscope and Phantom v7.2 camera arrangement were also used in the 15-cm (6-inch) diameter fluidized bed containing FCC catalyst. The boroscope was first inserted in the top port at the center of the freeboard. Figure 6 shows a frame of the video obtained for particles and clusters in the freeboard region. The FCC catalyst also tended to cluster in the freeboard region but not to the same extent as the polyethylene. A statistical analysis of the video frames suggested that 30% of the material in the freeboard existed as particle clusters having an average size of 11 ± 5.0 particles.

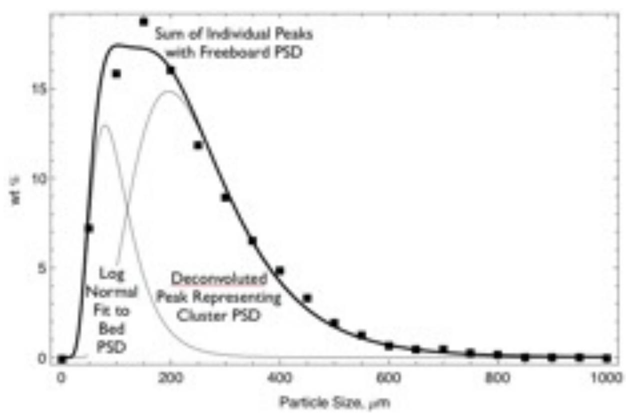


Figure 5: Particle size distributions of bed material (from a Microtrac) and of freeboard material from high-speed video analysis and the deconvolution of the distribution representing the freeboard material into particle and clusters size distribution.

Figure 6: High speed video frame of FCC catalyst in the freeboard region of a 16-cm (6-inch) diameter fluidized bed at a superficial gas velocity of 0.61 m/sec (2 ft/sec). Images were collected at 4000 frames per second with a 20 µs exposure time.

This was less than half the cluster concentration and half the cluster size of the polyethylene powder.

The boroscope and Phantom camera arrangement were also inserted into the dense phase at the bottom of the fluidized bed. The boroscope was positioned at the center of the bed to ensure that wall effects were not an issue. Because of the bed density, cluster imaging was conducted during the period when a gas bubble passed the face of the boroscope where the solids concentration is lower than that in the emulsion phase.

Figure 7 shows a corresponding video frame taken in the fluidized bed. Larger and more clusters were observed in the bed than in the freeboard. A statistical analysis of the video obtained in the fluidized bed suggested that 41% of the FCC catalyst material existed as clusters with an average cluster size of 21 ± 1.7 particles. The clusters existed as both large particles with fines or as many fines. Rarely was a cluster of only large particles observed. In some cases, large strands of ten or more particles were observed consisting of both large and small particles.

DISCUSSION

Using the modified boroscope with a Phantom v7.2 high speed video camera, both the freeboard and bed region can be imaged with good resolution for Geldart Group A powders. From this system, particle clusters were readily observed in the freeboard region, as shown in Figure 4 for polyethylene powder, and Figure 6 for the FCC catalyst powder. This is consistent with the earlier results observed for FCC catalyst fines, as shown in Figure 1. In addition, clusters were observed in the bed region, near the distributor, as shown in Figure 7. The boroscope allowed for imaging away from the wall where other factors such as electrostatics could be an issue.

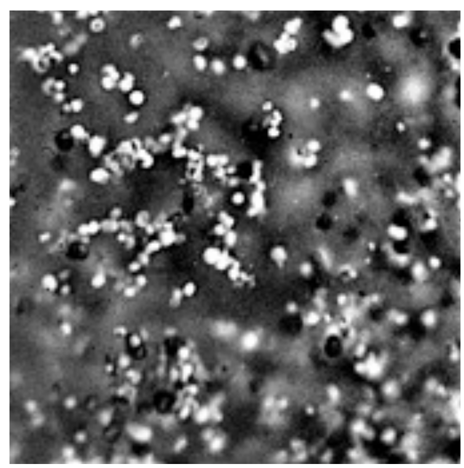


Figure 7: High-speed video frame of FCC catalyst in the bed region of a 6-inch (16-cm) diameter fluidized bed at a superficial gas velocity of 2 ft/sec (0.61 m/sec). Images were collected at 4000 frames per second with a 20 µs exposure time.

For polyethylene powder, the average cluster size was calculated to be 240 microns corresponding to approximately 29 particles, but clusters as large as 700 microns were measured. Assuming a packing fraction of 0.65, this corresponds to clusters containing 650 particles. Based on the probe measurements, more than 75% of the freeboard were particle clusters. Thus, this phenomenon is not only evident; it appears to be prevalent. In all cases, the clusters were not spherical or rigid. Similar findings were found for the FCC catalyst particles although smaller and fewer clusters were observed.

The measured evidence of particle clusters reveals why lower than expected entrainment rates were observed for both these materials. As expected and postulated by Hays (20), Geldart and Wong (16) and Choi et al (18), particle clustering results in particle sizes too large for the drag force to carry the particles sizes out of the unit. Thus, fines that would have been easily entrained out of the unit now fall back into the fluidized bed.

Figure 7 show that particle clusters exist in the fluidized bed, even near the grid plate. However, it is uncertain if these clusters occur only in the bubble region (cloud phase) or in the emulsion phase. The particle concentrations were too high to discern if clusters were in the emulsion region. Only with the occurrence of a bubble near the probe could particle clusters be observed. Thus, for Geldart Group A powders with fines, particle clustering does occur in fluidized beds either in the emulsion and bubble regions or just the bubble regions. Subbarao (23) originally postulated that there was a relationship between bubbles and cluster formation. Perhaps the bubble serves as a concentrator of fines, which better promotes clustering. Another explanation could be that the bubbles serve as a concentrator of clusters that were initially made in the emulsion phase.

Figures 2 and 3 also suggest that particle clusters form in the fluidized bed and get ejected into the freeboard instead of clusters forming only in the freeboard region. If clusters were made only in the freeboard, then the bed height should not affect cluster formation and the resulting entrainment rate. In addition, particle concentrations in the freeboard may be too low to support sufficient particle cluster formation. Kaye and Boardman (12) noted that loadings greater than 0.05% are needed for clustering to occur.

The height of the fluidized bed may control the cluster size or frequency. The formation of large clusters may not occur instantaneously, and sufficient time in the emulsion or bubble region may be needed for large particle clusters to form. A particle cluster may form near the bottom of the bed and continue to grow as it migrates to the top of the bed, possibly with the help of bubbles. At the top of the bed, it is either entrained or circulates back down to the bottom of the bed. As bed height is increased, this large circulation zone becomes more dominant and the possible residence time of a particle cluster in the bed becomes extended.

CONCLUSIONS

A high-speed video camera with a modified rigid boroscope has been developed that allows particle clusters to be visualized, beyond the column wall and, in and above a fluidized bed of polyethylene and FCC catalyst powders. With this technique, it was found that a significant portion of the freeboard contained clusters for both materials. However, the FCC powder had only half the number and size of clusters as the polyethylene material. Results from video taken in the bed suggest that particle clusters may be formed in the bed and are entrained into the freeboard. Data showed that the shorter the bed, the higher the entrainment rate suggesting that the size of the clusters may be linked to the residence time of the clusters in the fluidized bed. Bubbles may also provide the mechanism for particle cluster formation and/or stability.

Particle clustering could have a significant impact on how entrainment is calculated. Currently, no one literature correlation appears to predict entrainment accurately, especially for Geldart Group A powders. Experimental measurements still seem to be the best way to predict entrainment rates for commercial units. However, care needs to be taken when adding or removing fines from a fluidized bed of Geldart Group A particles. Adding fines could lead to reduced solids loss rates because of increased particle clustering. Reducing fines levels could result in an increase in the entrainment rate. It all appears to be dependent on microscopic properties as well as particle size and concentration.

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