Effect of Fines Content on Bubble Properties in a Two-dimensional Fluidized Bed by Digital Image Analysis

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Abstract - The effect of fines content in fluid catalytic cracking (FCC) catalyst on bubble properties was investigated by considering two catalyst batches. One contained fewer fines and had a Sauter mean diameter of 83 µm while the other had a higher fines content with a 74 µm mean diameter. The hydrodynamics were analyzed in a two-dimensional fluidized bed with superficial gas velocities in the bubbling regime. Photos of the bed were analysed by isolating bubble images, after which colour images were converted to binary images by using MATLAB® software. These binary images were used to determine properties such as equivalent bubble diameter, gas fraction, circularity and bubble hold-up in the bed as function of superficial gas velocity and fines content. The results showed that bubble diameter increases with gas velocity for both catalyst batches. A smaller bubble size was observed at all except the highest superficial velocities for the catalyst batch with the higher fines content. However, the high fines content catalyst had a higher gas fraction than the low fines content batch at all gas velocities. This average value was the same regardless of gas velocity, while an increase in superficial velocity resulted in an increase in gas fraction for the lower fines content catalyst. The bubble hold-up for the catalyst batch with the lower fines content was also higher than that of the high fines content catalyst. For both batches an increase in bubble hold-up with velocity was observed. Similar circularity values for both catalyst types were calculated at all superficial velocities.

INTRODUCTION

Fluidization is utilized in industry for a variety of applications which include drying, mixing, as well as catalytic and non-catalytic reactions.[1,2,3] More specific examples include hydrocarbon cracking, thermal treatment of metals, combustion and gasification of biomass and coal, recovery of energy from gases and hot solid particles, coating of particles and synthesis reactions.[4]

A clearer understanding of the hydrodynamics and specifically its effect on mass and heat transfer within these reactors would be most beneficial to industry. The conversion of gaseous reactants in fluidized bed reactors strongly depends on the gas-solids distribution, which in turn is influenced by bubble properties, such as bubble size and solid fraction, as well as gas hold-up.[3] Furthermore, it is known that the particle size distribution (PSD) of the fluidized solid can have a significant effect on the fluidization behaviour and bubble properties in the bed.[5,6,7] It is therefore the aim of this work to investigate the behaviour of a two dimensional fluidized bed in the bubbling regime by evaluating the size of the bubbles, bubble hold-up, gas fraction and circularity of the bubbles as a function of gas velocity (U_0) for two powders with a different fines content.

Digital image analysis has been proven to be an accurate technique to quantify bubble characteristics.[2,8] This technique is non-intrusive, supplies a great quantity of information, permits the investigation of several properties simultaneously, and can be automated to a great extent[9]. It was subsequently used in this work for the investigation of the bubble and bed properties. The method involved taking photos of the bubbling bed after which the images were converted to binary matrices which were used to calculate the parameters under investigation. These parameters were compared at superficial velocities of 0.1, 0.2 and 0.3 m/s. Two batches of FCC catalyst with different PSD characteristics were used as the two fluidization powders with air at ambient conditions as fluidization gas.

EXPERIMENTAL

The reactor used for the experimental study was a Plexiglas two-dimensional (2-D) fluidised bed reactor with thickness 25 mm, width 400 mm and height 4.5 m. A volute-inlet primary cyclone, to handle the high solids loading at the upper gas velocities, and a tangential-inlet secondary cyclone were used. Excess fines that bypassed the secondary cyclone were captured in filter bags connected after the secondary cyclone. Saayman[10] includes the complete engineering drawings for the reactor. The volumetric flow of reactor feed gas was controlled with a vortex flow meter with a linear velocity range of between 0.1 m/s and 0.3 m/s. Constant humidity compressed air at 15°C was used as gas supply. Two batches of FCC particles, each with a different fines content, were fluidised in separate experimental runs. The bed was filled with solids to a height of 39 cm for each of the particle types investigated.

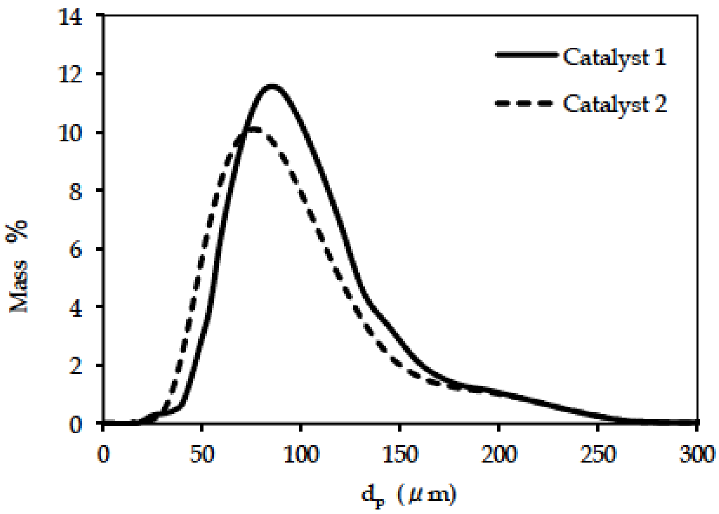

Figure 1. Particles size distributions of the two catalyst particle batches

Catalyst 1 represents the particle batch with the lower fines content and a Sauter mean diameter of 83 µm, while Catalyst batch 2 had a higher fines content and a Sauter mean diameter of 74 µm. Figure 1 shows the particle size distributions of the two different batches.

Photos were taken of the bubbling bed at each of the superficial gas velocities. All photos were of a bed section 24.5 cm above the distributor. These photos were drawn into the Microsoft® Paint application and bubbles were cut out using the free-form selection tool and saved as jpeg files. These jpeg files representing the bubbles were analysed using the image processing toolbox in MATLAB®. Here the pictures were first converted to greyscale images i.e. matrices containing elements that have a value between 0 and 255 where 0 represents black and 255 represents white. A threshold value is selected between 0 and 255 to convert the images to black and white. All the elements with an intensity value less than the threshold are turned to black and those greater than the threshold are turned white. Similar to the work of Shen, *et al.* [11], a threshold value is selected by comparison of a typical photo frame with the binary segmentation mask of bubbles until an accurate portrayal of the visual observation is achieved. The threshold value was different for photos taken on different days to compensate for variation in light intensity in order to capture the same amount of detail. The black and white images are saved as binary matrices from which the parameters under investigation can be calculated. Figure 2 shows the resultant black and white images of a single bubble from each of the catalyst batches isolated and analysed in this manner.

Each batch was fluidised at the three superficial velocities - 0.1, 0.2 and 0.3 m/s. For each of the runs 144 photos were taken of the fluidised bed. For catalyst 1 between 130 and 140 bubbles were isolated from the photos per run, whereas for catalyst 2, 70 to 80 bubbles per run could be used. The average as well as data distribution for each of the properties investigated were calculated for each run and are subsequently summarized in box plots. The 5^{th}, 25^{th}, 75^{th} and 95^{th} percentiles, as well as the median and average values can all be presented in this manner.

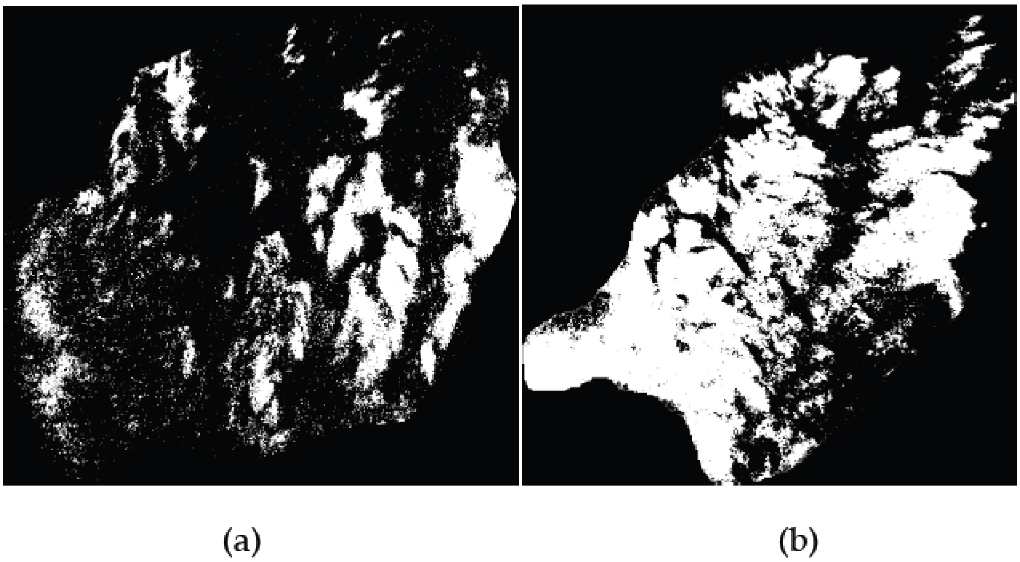

Figure 2. Black and white images of a bubble from the bed with a) catalyst 1 (lower fines content) and b) catalyst 2 (high fines content) particles.

RESULTS AND DISCUSSION

The area based equivalent diameter, D_{eq}, was calculated from the black and white images by using Eq. 1:

$$D_{eq} = \sqrt{\frac{4A}{\pi}} \tag{1}$$

In Figure 3 it can be seen that the average value for D_{eq} increases with superficial velocity for both particle types. This is in agreement with the findings of Mudde *et al.*[2] and Busciglio *et al.*[12] In addition, both Mudde *et al.*[2] and Busciglio *et al.*[12] observed an increase in bubble diameter with bed height, which may explain the wide distribution in bubble sizes found in this study. For both the particle types a wider distribution in bubble sizes is observed as the superficial velocity is increased. This increase in distribution is more significant for catalyst 2, which has a higher fines content. Furthermore, a smaller average bubble diameter was observed for the catalyst batch with the higher fines content except at the highest superficial velocity of 0.3 m/s – where the average bubble diameter of the two particle batches is almost equal. In a reactor, smaller bubbles are preferred since they have a larger surface area to volume ratio. A larger bubble surface area would improve mass transfer of the gaseous reactant to the emulsion phase with a resultant increase in conversion. From the observations on bubble diameter a catalyst type with a higher fines content would therefore be advantageous for reactor efficiency.

Shen *et al.*[11] developed an equation for the bubble diameter in two dimensional beds from their digital image analysis work, given here as equation 2.

$$D_{eq}=0{,}89\left[\left(U_0-U_{mf}\right)\left(h+\frac{3.0A_0}{t}\right)\right]^{2/3}g^{-1/3} \tag{2}$$

In Figure 4 the experimental data for D_{eq} is compared with values predicted for this system by using equation 2. D_{eq} is over predicted for both particle types at all superficial velocities.

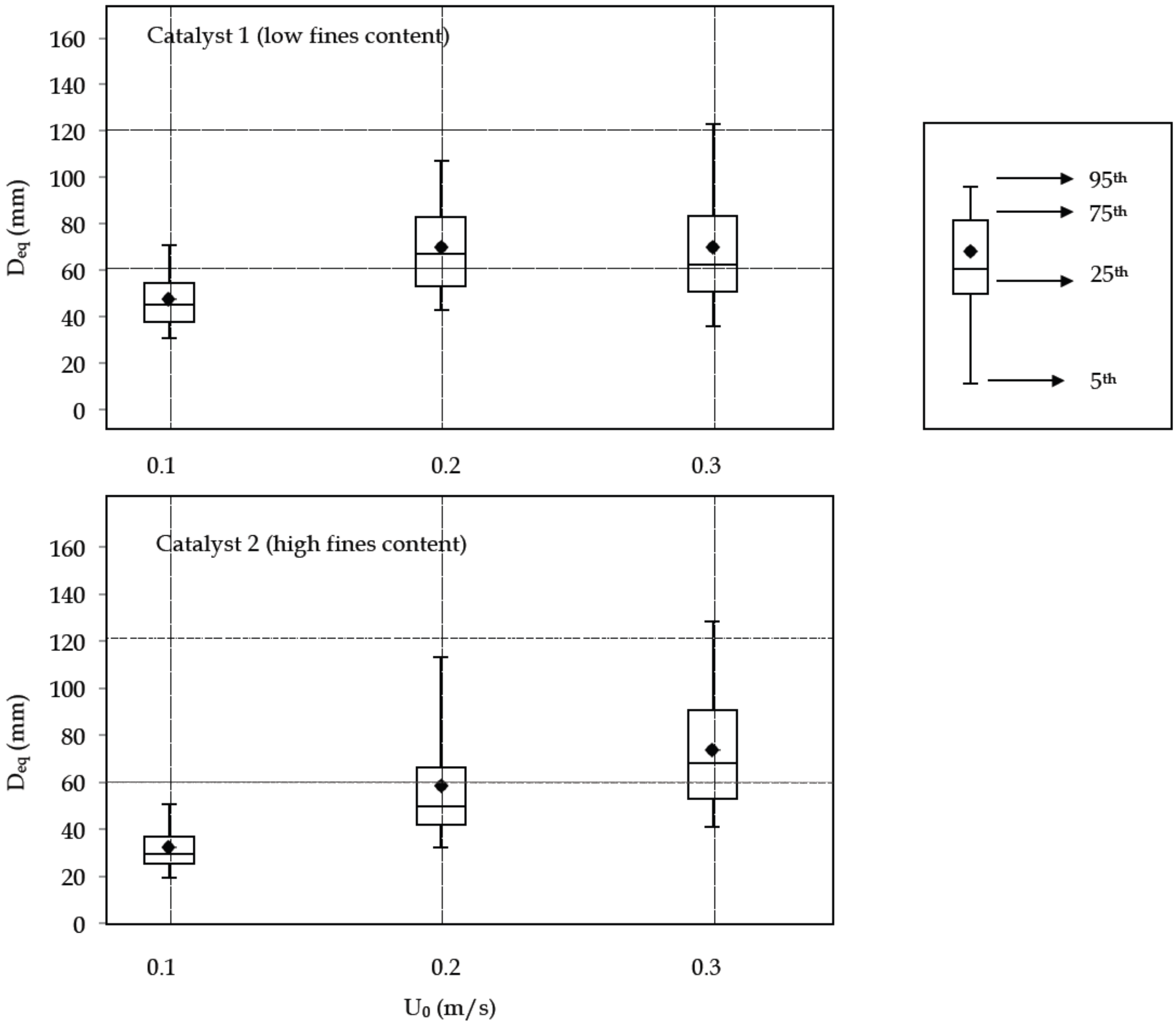

Figure 3. Box plot comparison of D_{eq} for the two catalysts as a function of U_0. Percentiles indicated in legend, (♦) – average, (−) - median

Laverman *et al.*[13], who also found that equation 2 over predicted all their results for bubble diameter, attributed this to the fact that a larger fluidized bed was used by Shen *et al.*[11] for the development of their correlation, since bubbles can grow to a larger diameter in a larger bed. However, Busciglio *et al.*[14] disagrees and found that the correlation by Shen *et al.*[11] underestimates the bubble growth along the bed. The extent to which equation 2 over predicts the data increases with superficial velocity, which is in agreement with the observation by Shen *et al.*[11] that their correlation over estimates bubble sizes at higher velocities.

Bubble hold-up is the amount of gas present in the bubbles per specified area. In this work the bubble hold-up was calculated by adding the areas of all the bubbles and dividing this with the total amount of bed area photographed. The results are given in Figure 5.

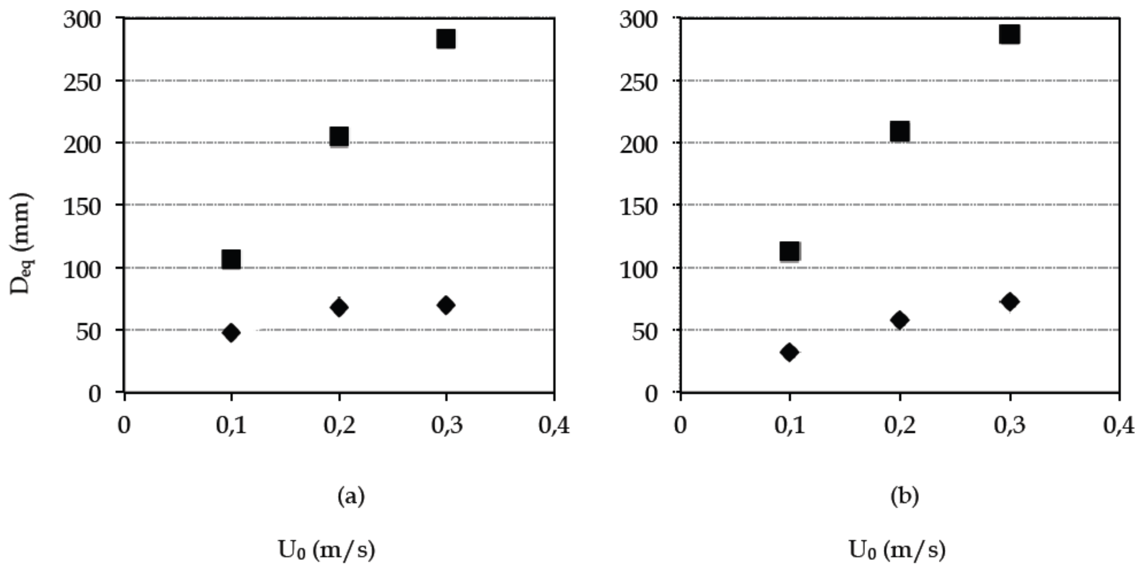

Figure 4. Bubble diameter predicted by the correlation of Shen *et al.* [11] (■) compared to experimental data (♦) for catalyst 1 (a) and catalyst 2 (b)

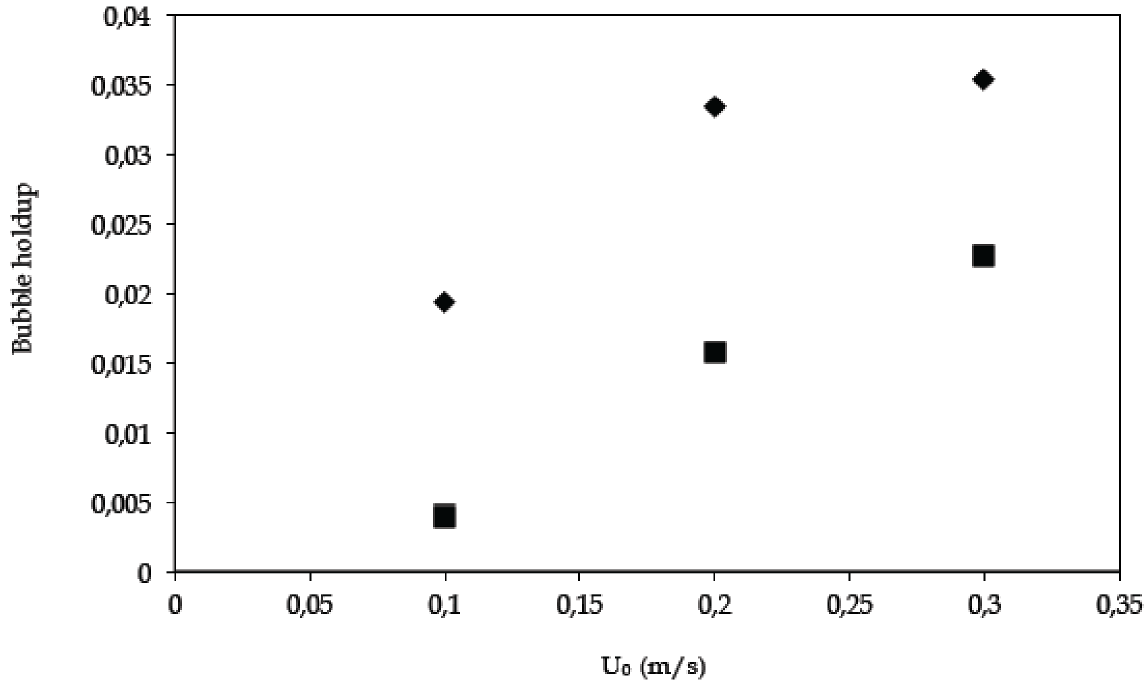

Figure 5. Bubble hold-up for catalyst 1 (♦) and catalyst 2 (■) as a function of superficial velocity

Shen *et al.*[11] found that bubble hold-up increases with particle size. This is also observed here, since the bubble hold-up for catalyst type 1 with the lower fines content is significantly greater than that of the particle batch with the higher fines content. Similar to their results, an increase in bubble hold-up with an increase in superficial velocity is observed. For industrial applications gas hold-up should be maximized [15], since this implies a higher residence time of the gaseous reactant. However, bubble density or hold-up in the emulsion phase does not represent the total gas hold-up in the fluidised bed, and the results are therefore inconclusive regarding the possible implication on reactor performance without combining it with other total gas holdup measurements like bed collapse tests.[16]

The gas fraction is the portion of the total bubble that is occupied gas. Since particles can rain through the roof of a bubble, its gas fraction is not equal to one.[13] The white areas in Figure 2 - the gas phase in the bubble - are represented by 1's in the binary matrix. The gas fraction is then calculated by dividing the sum of all the elements equal to 1 by the total number of elements in the matrix. The results are given in Figure 6.

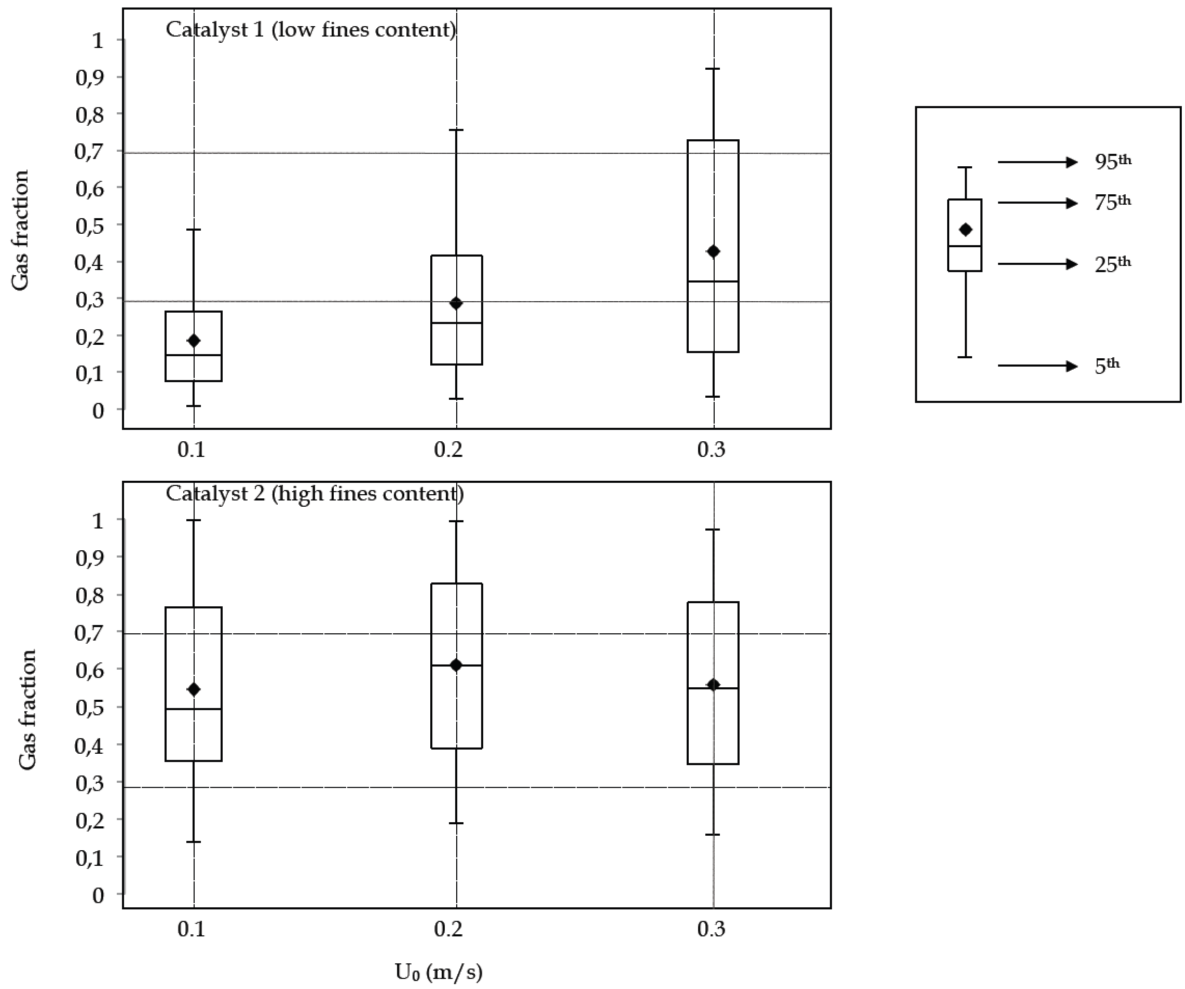

Figure 6. Box plot comparison of gas fraction for two catalysts as a function of U_0. . Percentiles indicated in legend, (♦) – average, (−) - median

For catalyst 1, with the lower fines content, there is a definite increase in gas fraction and an associated wider distribution in the data with an increase in U_0. However, catalyst 2 with a higher fines content showed little change in gas fraction and data distribution across the range of U_0. Furthermore, despite the increase in gas fraction with superficial velocity for catalyst 1, the gas fraction calculated for the high fines content catalyst is still significantly higher - even at the highest superficial velocity investigated. In a reactor, a higher solids fraction (i.e. lower gas fraction) is preferential, since this will result in higher interaction between gas phase reactants and solid catalyst particles. Therefore, when gas fraction is considered, the catalyst with a lower fines content should be advantageous. This is contrary to previous experimental results which show that reactor performance with Geldart A particles actually improves with the addition of fines[17]. The two-dimensional nature of this technique may therefore make it unsuitable to give a true representation of the bubble gas fraction, or it may suggest that mass transfer effects between the bubble and emulsion phase dominate reactor performance. The smaller bubbles observed with the high fines content catalyst 1 would then explain the actual reactor behaviour.

Circularity is the ratio of the circumference of a sphere with the same cross-sectional area of the shape cross section and the actual circumference of the shape cross section and is therefore given by

$$\text{Circularity} = \frac{D_{eq}\,\pi}{\text{Shape circumference}} \tag{3}$$

The range and distribution of circularities were found to be relatively similar for the different catalysts and gas velocities. As illustrated in Figure 7, the average circularity of the bubbles for both catalysts was found to decrease slightly when the gas velocity was increased from 0.1 m/s to 0.2 m/s, after which it remained fairly constant with a further increase in gas velocity. Caicedo *et al.*[9] found that circularity as a function of U_0 follows a normal distribution in a two dimensional bed.

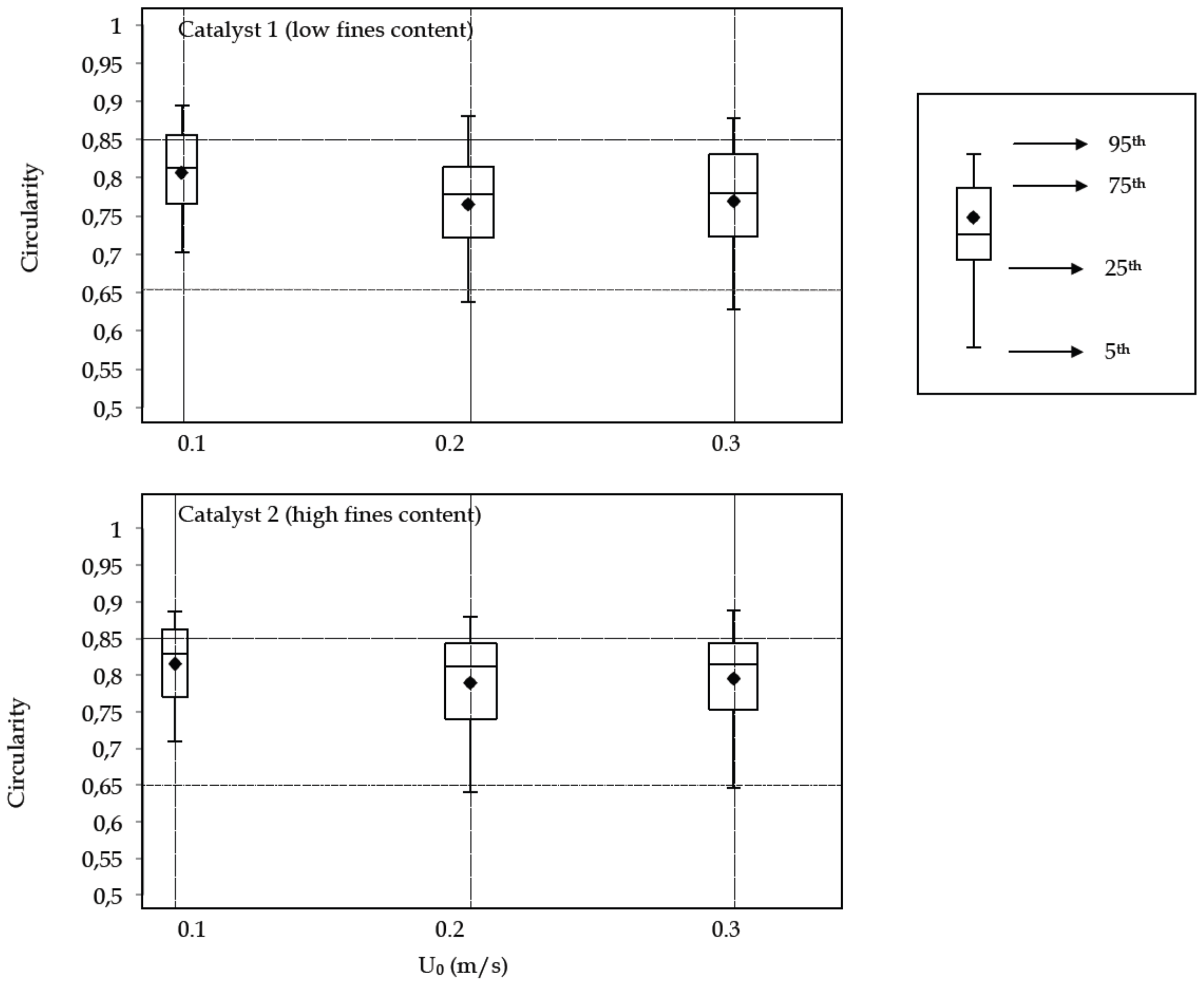

Figure 7. Box plot comparison of circularities for the two catalysts as a function of U_0. Percentiles indicated in legend, (♦) – average, (−) - median

CONCLUSIONS

The bubble properties of two FCC catalyst powders with different PSD's were investigated in a two dimensional bubbling fluidised bed using digital image analysis. The results showed that the average equivalent bubble diameter, D_{eq}, increases with an increase in superficial gas velocity for both particle batches. This increase is more significant for the catalyst batch with the higher fines content. Although the correlation developed by Shen *et al.*[11] for D_{eq} in two-dimensional beds also predicts an increase in diameter with an increase in superficial velocity, it overestimated the experimentally observed diameter for both catalyst types. The particles with a higher fines content had a smaller average D_{eq} at the lower superficial velocities investigated – a desirable property in terms of mass transfer in catalytic reactors since it implies a larger interphase contact area. However, the bubble hold-up was found to be greater for the catalyst containing less fines. This suggests a higher residence time for the gas phase and in terms of hold-up a catalyst with a lower fines content should therefore be advantageous. However, the bubble holdup determined in this work does not represent the overall gas holdup, which is known to increase with an increase in fines content. In addition, the catalyst batch with the lower fines content had a lower average gas fraction in the bubbles. This was observed at all superficial velocities investigated, regardless of the fact that a definite increase in gas fraction values and data distribution was observed for the low fines content catalyst with an increase in superficial velocity, while these values for the higher fines content catalyst stayed relatively constant. Here again the lower fines content catalyst would seem the better choice in terms of interphase mass transfer since a high solids content in the bubble would imply better contact. This is in contradiction with results from previous reaction studies in gas solid fluidized beds, where solids with a higher fines content proved to increase reactor efficiency. This implies that either this method is not suitable to determine bubble gas fraction or that the smaller bubbles observed with the higher fines content catalyst, and the resultant better interfacial mass transfer, dominates the contribution of the higher solids content in bubbles for catalysts with a lower fines content. The suitability of this method for the measurement of bubble hold-up and gas fraction therefore needs to be tested by direct comparison with results from other techniques on the same catalyst type under similar operating conditions.

NOMENCLATURE

Symbol	Description	Units
A	area of bubble	m^2
A_0	area of distributor per orifice	m^2
D_{eq}	equivalent diameter of bubble	mm
g	universal gravity constant	m^2/s
h	height of bed	m
t	thickness of bed	m
U_0	superficial velocity	m/s
U_{mf}	minimum fluidization velocity	m/s
U_t	terminal velocity	m/s

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