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ANALYSIS OF LENGTH SCALES OF SOLIDS VOLUME FRACTION VARIATIONS IN A CIRCULATING FLUIDIZED BED OF GELDART B PARTICLES

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ABSTRACT

The flow pattern in a circulating fluidized bed (CFB) is characterized by clusters of particles. In the present study, the length scales of the variations in solids volume fraction were analyzed from a number of experiments carried out with Geldart B particles in a 2D CFB. Large length scales are typical for the bottom region above which more narrow dense clusters are common.

INTRODUCTION

The flow pattern in a circulating fluidized bed (CFB) is characterized by a complicated structure with continuously forming and vanishing clusters of particles. For Geldart B particles the shapes of the clusters are obscure and long narrow strands of particles are typical while Geldart A particles form also small packed clusters (Cocco et al., (1)) in addition to larger looser structures.

Computational fluid dynamic (CFD) simulations have become an important tool in the development of CFB processes. To accurately describe the flow patterns, the simulations should be carried out as transient in a fine computational mesh. In practice computational resources limit the feasible mesh size. Thus it becomes important to understand, what length scales of the flow field can be resolved by the simulation and what scales should be covered by sub-grid scale equation closures (see e.g. Igci et al (2)). Typically the thinnest clusters are narrower than the mesh spacing, but their importance is not clear, i.e. it is not well known, how big a portion of the flow field is covered by such narrow clusters.

In case of Geldart A particles, the size of a cluster formed due to cohesive forces can sometimes be easy to measure. For Geldart B particles it is not easy to define a cluster size, although such attempts have been made using e.g. optical probes (Xu & Kato (3)). Instead of defining a cluster size we can try to analyze the widths and lengths of the particle strands and other regions with high solids content. Actually the measurements made with optical probes correspond to these length scales, typically the vertical ones.

In the present study, length scales of the variations in solids volume fraction were analyzed from two experiments carried out with B particles at different conditions in a 0.4 m wide 2D CFB. Laboratory scale 2D devices of this type are commonly used to produce data for CFD model validation. CFD simulations indicate that the width of the process does not significantly affect the local flow structure (Peltola & Kallio, (4)) and thus the small size is acceptable for the present purpose.

Since the drag force in the vertical direction largely determines the vertical solids distribution in a CFB, the lateral division of the solids in dense clusters and dilute suspension plays a vital role in CFB hydrodynamics. Thus we concentrate in this work on the lateral length scales.

EXPERIMENTAL

A 2D CFB unit at Åbo Akademi University (Guldén, (5)) was used to study the length scales of variations in solids volume fraction. The height of the riser is 3 m and width 0.4 m. The distance between the riser walls is 0.015 m which renders the unit fairly two-dimensional. The air distributor consists of 8 equally spaced air nozzles. The front and back walls are made of polycarbonate plates allowing visual observation and image analysis. In the experiments the bed is illuminated from behind for video recording.

The bed material consisted of spherical glass particles with material density 2480 kg/m^3. The bed material was sieved to a narrow size range with a Sauter mean diameter of 0.255 mm. The total amount of bed material was 4 kg. Three experiments with superficial gas velocities 1.75 m/s, 2.25 m/s and 2.75 m/s were conducted.

Figure 1 illustrates the flow structure at three heights at fluidization velocity 2.75 m/s. The figures show long narrow clusters and strands everywhere in the bed, except at walls in the bed bottom region where wide dense sections occur. The behavior of the CFB at bed bottom up to 0.73 m, in the middle up to 1.47 m and at the top up to 2.2 m was video recorded in all the experiments. From each case a 3 min video was analyzed in this work.

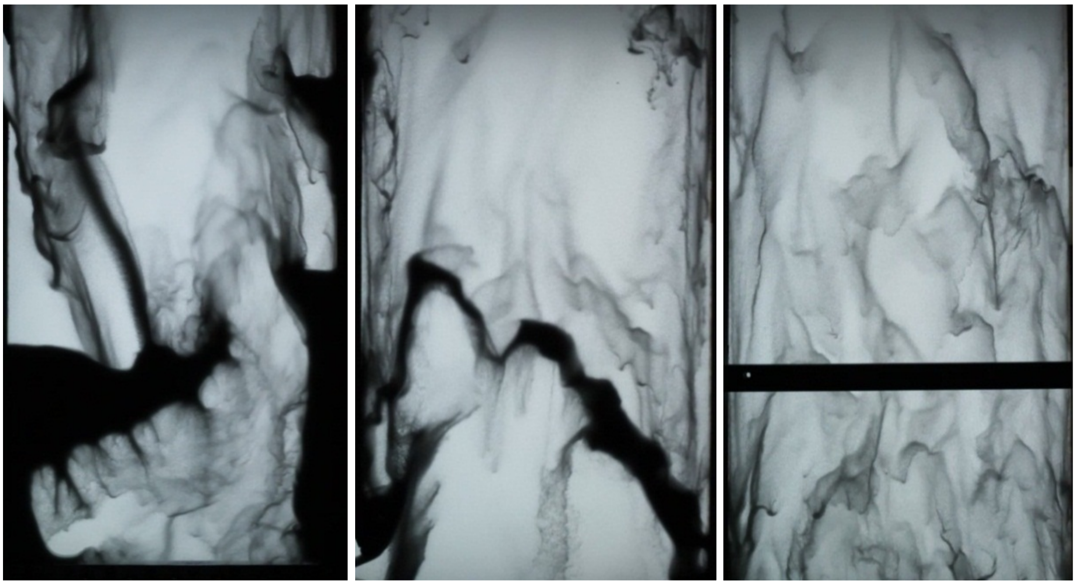


Figure 1. Flow structure at heights 0-0.73 m, 0.74-1.4 m and 1.4-2.2 m at fluidization velocity 2.75 m/s.

ANALYSIS METHOD

Videos were recorded during the experiments at the frame rate of 50 per second. The videos were then converted to sequential images in Adobe Photoshop premiere pro, after which the individual images were analyzed in three steps: a) image thresholding, b) cluster identification and c) measurement of length scales.

Image thresholding

To separate the clusters, the images had to be converted into binary images by using a proper threshold gray-scale value. To sustain significant cluster detail the threshold parameter was determined through an optimization procedure.

The criteria for treshold selection applied in this work (Soong et al.(6)) are as follows:

- The solid density in the cluster must be significantly higher than in the rest of the suspension. In case of grayscale images the grayscale intensity values inside the clusters must be above the local average intensity values.
- In the tresholding procedure, the image portions having a grayscale value δ above $\mathrm{F}\sigma_{\delta} + \bar{\delta}$ are marked as cluster regions. Here σ_{δ} is the standard deviation of local grayscale intensity, $\bar{\delta}$ is the local avarage grayscale intensity and F is a factor to be chosen to produce good separation of clusters.
- Instead of doing the calculation for the whole image at a time, the calculation was also done for variable fractions of the original images to test if that would result in a better separation. The image fraction is thus a small rectangular segment of an image which was used to calculate the local average intensity and its standard deviation. The image segment was moved across the entire image to separate the clusters from the background noise. The selection of this image fraction directly influences the cluster definition and cluster sizes and hence the number of detected clusters.

To select a suitable value of F and a suitable size for the analysis region these two parameters were varied in wide ranges and the number of clusters found in a typical image at bed bottom was calculated. The trade off between these parameters is shown in Figure 2. When the image is divided into smaller fractions or the value of F is reduced, the tresholding procedure splits the dense regions in a larger number of mainly small clusters. By visual ispection of the produced clusters, compared to the original image, the values for F and analysis region were finally chosen.

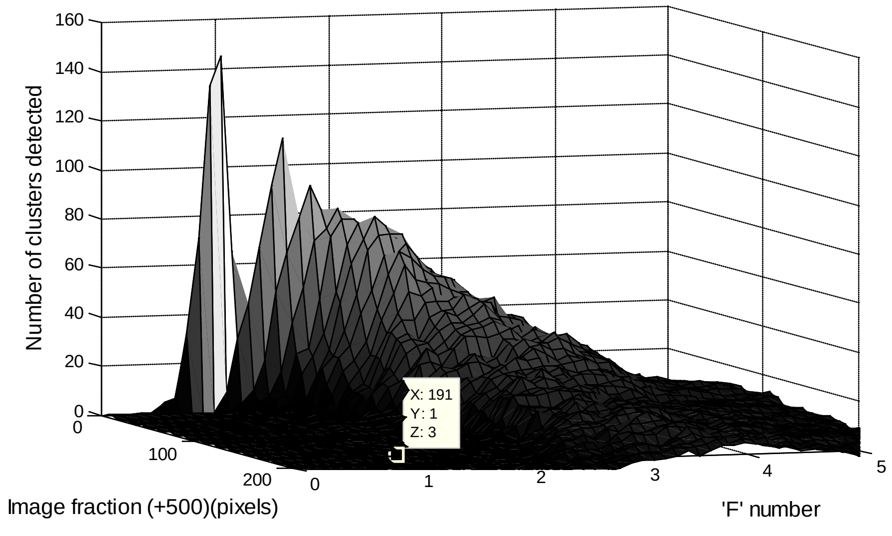


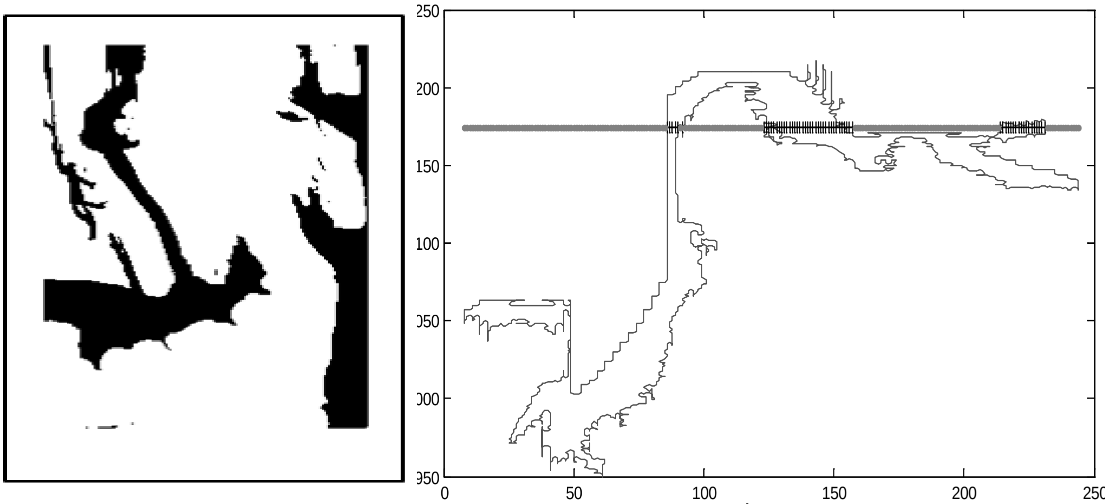
Figure 2. Trade off between image fraction and parameter F used for the analysis with the corresponding number of clusters obtained from the analysis.

The whole image includes 690 pixels, which on the above plot is shown as 190 (690-500). After analysis of the results obtained with different image fractions, the whole image was taken as the image fraction in this analysis.

Cluster identification and determination of the length scale

The threshold was applied on the original images and the cluster boundaries became distinct as shown in Figure 3a. The individual clusters were then represented as polygons, as shown in Figure 2b.

The length scales of clusters were calculated by measuring the cluster width and height at 20 heights at each of the bed positions in Figure 1. First, along a particular bed height, the number of all the intersecting cluster sections was calculated. The intersecting cluster sections can be branches of a single cluster, as shown in Figure 3b, or all separate clusters. The cluster width, or more specifically cluster branch width, was calculated by calculating the number of points inside the polygon at a particular vertical coordinate.



a. b.

Figure 3. a. A binary image after applying the threshold according to the above mentioned criteria. b. A cluster separated and converted to a polygon from which the widths of the cluster branches at a specified height were determined.

The selection of ‘F’ number is important as the cluster definition depends on it as can be seen in figure 4.

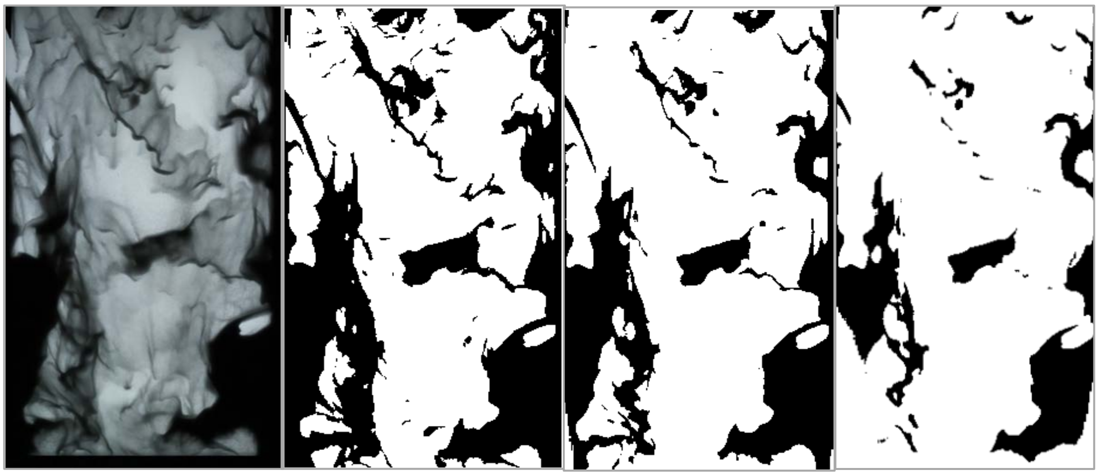


Figure 4. Defining clusters in an image with ‘F’ number 1, 1.5 and 2.

Figure 4 illustrates the challenge in defining and separating the clusters from the background. At the ‘F’ number 1 the clusters are well defined but the unwanted small cluster branches are also visible. If the ‘F’ number is increased to 1.5 or 2, the small branches are removed to some extent but also significant clusters are getting affected. Considering the tradeoff between cluster definition and getting suitable results the value of F equal to 1 was chosen.

RESULTS

The cluster branch widths are calculated for 20 bed heights in each extracted video image. The cluster branch widths and their respective numbers along the heights were recorded. From these numbers of clusters with different widths, cumulative cluster size distributions at specific heights were calculated and plotted. Figures 5 to 9 show the cluster branch widths with the corresponding cumulative percentages of the total cluster area for the bed heights of 0.423 m, 0.64 m, 0.84 m, 1.22 m and 1.43 m, respectively.

Figure. 5 Bed height 0.423 m

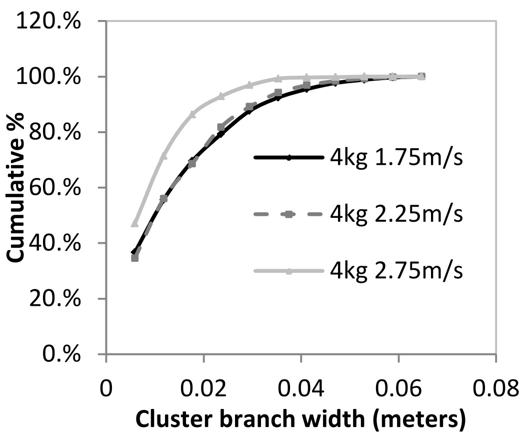
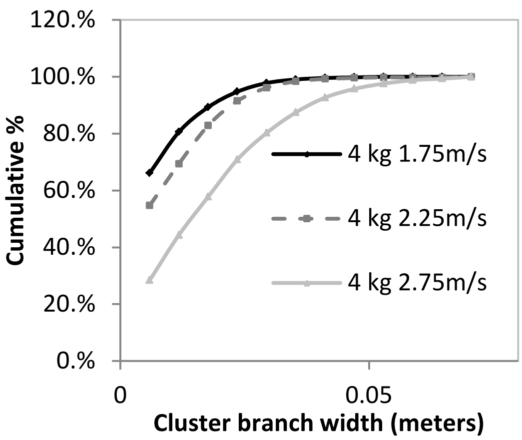


Figure. 6. Bed height 0.64 m



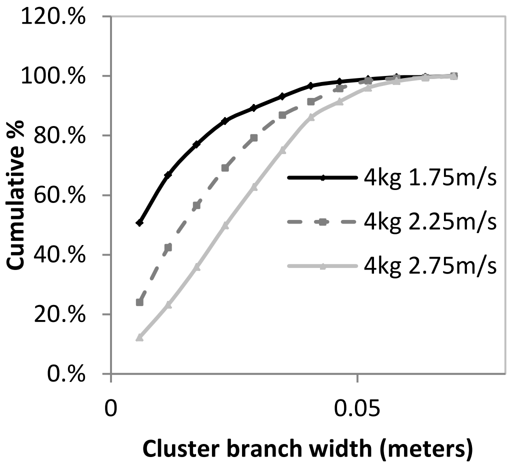


Figure. 7. Bed height 0.84 m

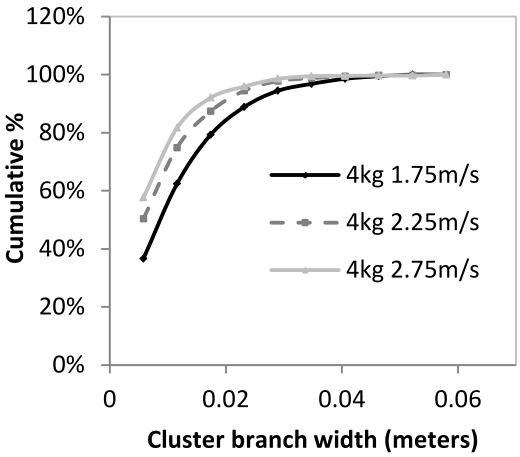


Figure. 8. Bed height 1.22 m

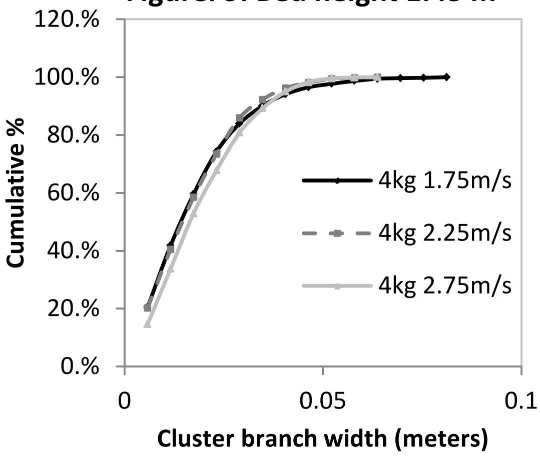


Figure. 9. Bed height 1.43 m

Figure 5 to 9. Cluster branch widths with the corresponding cumulative percentages of the total cluster area at heights 0.423 m, 0.64 m, 0.84 m, 1.22 m and 1.43 m, respectively.

Discussion of the results and length scales

From the above results it can be seen that at the lowermost bed portion at the height 0.423 meters (Figure 5) the clusters are mostly above 0.011 m of width. They are typically in the range of 0.011 m to 0.06 m. The smaller clusters of the order of 0.005 m and below consume 34% of the total cluster area at velocity 1.75 m/s, as the cumulative plot shows. It also shows that, as the velocity increases, the clusters of widths of the order of 0.005 m and below occupy a larger fraction of the cluster area but still the clusters of widths 0.011 m and above dominate the total cluster area.

At the height of 0.64 m (Figure 6) and at the lowest velocity of 1.75 m/s the clusters of the order of 0.005 m and below occupy almost 66% of the total cluster area. But as the velocity goes up to 2.25 m/s this percentage becomes 54% and at 2.75 m/s it becomes 28%. At the velocity of 2.75 m/s clusters of widths 0.011 m and above occupy almost 56% of the total cluster area.

At the height of 0.84 m (Figure 7), which is in the middle portion of the riser, the effect of velocity on the clusters is pronounced. At the lowest velocity of 1.75 m/s the percentage of clusters of the order of 0.005 m and below is 50% and it goes down to 12% at the highest velocity of 2.75 m/s. In comparison the occurrence of clusters of width 0.011 m and above goes up from 34% to 77% for the above increase in velocity.

Going up the bed the scenario changes with the velocity increase as can be seen at 1.22 m height in Figure 8. At 1.75m/s the fine clusters of the order of 0.005 m and below occupy 64% of the total cluster area and at 2.75 m/s their share becomes 43%. The clusters of width 0.011 m and above occupy 38% and 20% for the respective velocities.

At the highest elevation studied, i.e. at 1.43 m height (Figure 9), the effect of the increasing velocity is not that visible. For all the velocities 1.75 m/s to 2.75 m/s clusters of width 0.005 m to 0.011 m share 20% of the total cluster area. At this height the clusters having widths of 0.011 m and above occupy 60% of the cluster area at 1.75 m/s and 67% at 2.75 m/s. So it is visible that cluster widths are increasing with the increase in velocity but not significantly.

In conclusion to the above results it is to be said that the clusters of the order of 0.005 m and below are common for all the velocities and all the portions of the bed.

Implications for CFD modeling

Very narrow strands occur practically everywhere in the riser, and the fraction of the total cluster volume covered by the narrowest clusters is significant. Filtering out length scales below 0.005 m would result in a significant loss of information. Cluster widths in the range below 5 mm are common and need to be resolved by the computational mesh. Thus mesh spacing of the order of 1-2 mm is indicated.

Drag laws for filtered equations can also include the cluster size as a parameter. In some models, the particle diameter is replaced by a cluster diameter (McKeen & Pugsley (7)). The fairly popular filtered drag model EMMS (energy minimization multi-scale) (Lu et al (8)) is based on the division of the suspension in dense and dilute regions. It uses the cluster size or a heterogeneity index as a parameter and computes them from empirical equations. The data retrieved from the experiments in the present work could be used to test the accuracy of the correlations for cluster size. The particle size used here is typical of CFB boilers. Still, extension of the experiments to different particle sizes and process conditions is required in order to further extrapolate the results to the wide field of conditions encountered in fluidized beds. Applicability of the results to 3D cases needs to be evaluated in the future.

CONCLUSIONS

In the present study, the length scales of the variations in solids volume fraction in a 2D CFB riser were analyzed from a number of experiments carried out with Geldart B particles. Large length scales are typical for the bottom region above which more narrow dense clusters are common. The narrowest clusters are of the order of a few mm. A large fraction of solids seem to travel in clusters in the width range 0.005 mm which means that a mesh spacing of about 1-2 mm should be used not to lose significant details of the flow field. The study was conducted with a particle size typical of CFB combustors. Extension of the results to other particle sizes and 3D cases needs to be considered in the future.

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NOTATION

F parameter for determining cluster separation
δ Gray scale value
σ_δ Standard deviation of gray scale values

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