Influence from Particle Size Distributions on the CFD Simulations and Experiments of Bubbling Fluidized Beds

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Abstract

Industrial fluidized beds in common normally use powders with size distributions. The size and size distributions of particles used in the bed may lead to different bubble behaviours. Because of that it is important to study the influence on bubble behaviour from particle size distribution in fluidized beds.

In addition to that it is important to study the influence on the simulations of fluidized beds from particle size distributions. That is because, in modelling of fluidized beds a mean particle diameter is often used, and important information about flow behaviour can therefore be lost.

A series of experiments are performed in order to check the effect from particle size distribution on bubble behaviour. Several simulations also carried out in order to analyse the influence from the particle size distribution on the simulated results. The particle size distribution is accounted for by including multiple particle phases.

The computational and experimental results are analyzed separately and compared with each other with respect to the volume fraction changes along the bed with time, particle segregation and bubble frequency.

The simulations and experiments show that the particle size distributions significantly influence on the bubble behaviour and particle segregation.

Introduction

Fluidized beds are widely used in industrial operations. Good mixing and large contact area between phases, enhances chemical reactions, heat transfer and mass transfer. Industrial fluidized beds normally use powders with particle size distributions. The efficiency of fluidized beds depends on bubble behavior and bubble characteristics in the particle phase. The bubble characteristics are very important in the design of fluidized beds because they govern hydrodynamics and efficiency of the operation for which the bed is used [1]. The size and size distributions of particles used in the bed may lead to different bubble behaviors. Because of that it is important to study the influence of particle size distribution on bubble behavior in fluidized beds. Both simulations and experiments have a major role when it comes to the noted aspect. In simulations of fluidized beds a mean particle diameter is often used, and due to this important information about flow behavior can be lost.

Computational fluid dynamics is the key role of simulations and has been improved significantly during the last decades. Two different approaches are used in modelling of fluidized beds, the Euler-Lagrange and the Euler-Euler approaches. The Euler-Euler approach is most commonly used and is also used in this work. In the Euler-Euler model, all the phases are considered as a continuum. The Euler-Euler approach is useful and computationaly cost effective when the volume fractions of the phases are comparable, or when the body forces such as gravity act to separate phases, or when the interaction within and between the phases plays a significant role in determining the hydrodynamics of the system [2]. Halvorsen, B. [3] has used the Euler-Euler approach in the simulations of bubbling fluidized beds. Patil et al [4] and Patil et al [5] have used Euler-Euler approach with two different closure models. Those are the constant viscosity model and a model based on the kinetic theory of granular flow. Enwald et at [6] have presented a model using Euler-Euler approach as well as the application of the model in the simulations of bubbling and circulating fluidized beds. Huilin et al [7] has used both the Langrangian and the Eulerian approaches separately and the results have been compared to experimental data. Boemer et al [8] have developed a computer code to simulate the fluid dynamics of fluidized beds using Eularian approach. Arastoopour, H. [9] has used Eularian approach for the simulations he used to compare the predicted flow parameters with large scale experimental data of fluidized beds. Few studies have being carried out including particle size distributions in simulations. Among the few, Huilin et al [10] has used multi fluid Eulerian CFD model with closure relationships according to the kinetic theory of granular flow to study the motion of particles in a gas bubbling fluidized bed with the binary mixtures. Mathiesen et al. [11],[12],[13] presented both computational and experimental data from their work with circulating fluidized beds.

A lot of effort has been devoted to experimental studies of bubbles in a fluidized bed. For practical reasons the experimental studies have been performed on cold beds. Different measurement systems have been developed and used for studying bubble behavior in fluidized beds. Werther and Molerus [14] used a miniaturized capacitance probe for measuring parameters characterizing local state of fluidization in cylindrical beds. Gidaspow et al. [15],[16], Kuipers et al. [17], Halvorsen and Mathiesen [18],[19], Bokkers et al [20], Patil et al. [5] studied bubbles in two dimensional beds with a jet. Patil et al. [4] also studied bubbles in two dimensional beds with uniform air distribution. In these studies photographic techniques as movie camera or digital video camera were used to measure bubble sizes and bubble velocities and the experimental data have been used to validate CFD models.

In this work glass particles with different size distributions are used to study how particle size distributions influence bubble behavior in a 2-D fluidized bed with uniform air distribution.

Experiments and Simulations

A series of experiments is performed to study the influence of particle size distribution on bubble behavior and particle segregation in fluidized beds. A 2-D lab scale fluidized bed with a uniform air distribution is constructed, and a video camera is used to record the bubble behavior in the bed. The width, height and depth of the bed is 0.20 m, 0.80 m and 0.025 m respectively. The experimental data are used to validate computational CFD model. Several simulations are carried out in order to analyze the influence of the particle size distribution on the computational results. The commercial CFD code Fluent 6.3 is used for the simulations. A 2-D wire frame mesh with the same dimensions as the experimental set-up is used. A model combination finalized by Ariyarathna [21] is used in this study. The particle size distribution is accounted for by including multiple particle phases in the simulations.

Spherical glass particles with density 2485 $\mathrm{kg/m^3}$ and mean particle diameter of 488 μm are used in all the experiments and the corresponding simulations. The superficial gas velocity is 0.134 m/s and the initial bed height is 28 cm. In the experiments glass powders with mean particle diameter of 153 μm , 488 μm and 960 μm are used, and different compositions of the three powders are used to give mixtures with mean diameter of 488 μm . The compositions of the mixtures are given in Table 1.The simulations are performed with one, two,

Table 1: Mean particle diameters and the compositions used in the experiments

Experiment	Particle phase			Particle phase		
No:	1	2	3	1	2	3
	Mean diameter, [μm]			Composition, [%]		
1	488			100		
2	153	960		58.5	41.5	
3	153	488	960	29	50	21

three and four particle phases. The composition of the computational particle phases are presented in Table 2. Simulations 1 and 2 correspond to experiments 1 and 2 respectively. Simulations 3, 4 and 5 are performed with

Table 2: Mean particle diameters and the compositions used in the simulations

Simulation	Particle phase				Particle phase			
No:	1	2	3	4	1	2	3	4
	Mean diameter, [μm]				Composition, [%]			
1	488				100			
2	153	960			58.5	41.5		
3	153	625			29	71		
4	153	488	960		29	50	21	
5	153	425	578	960	29	30.5	10.5	21

two, three and four particle phases, and the simulations correspond to experiment 3.

Analysis of the Results

The results from the simulations and the experiments are analyzed with respect to the bubble behavior and the particle segregations. Picture frames from the movies are used to analyze the experimental results and the contours along with the data recorded by the monitors are used to analyze the simulated results.

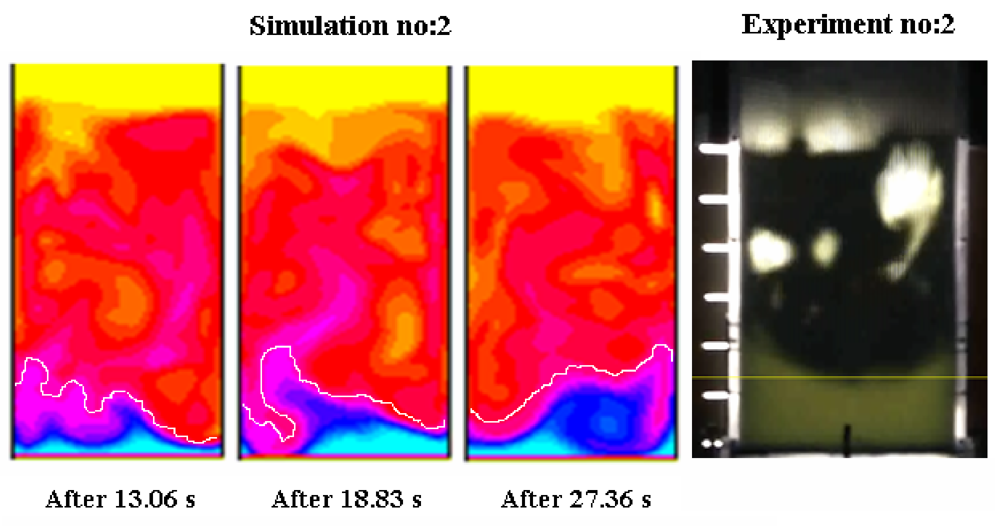

Figure 1: Representation of the particle segregation in simulation 2 and experiment 2

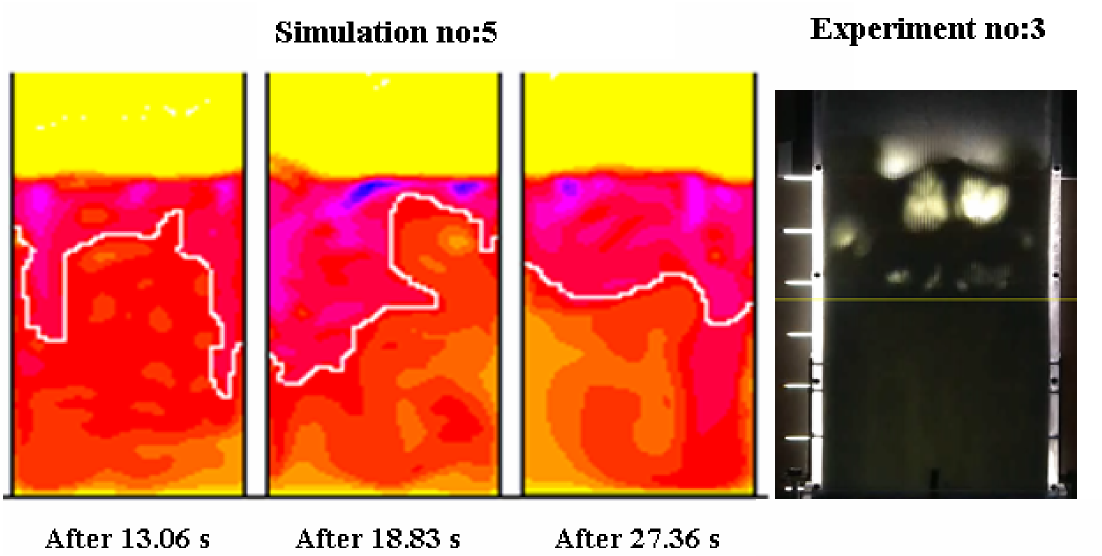

Figure 2: Representation of the particle segregation in simulation 5 and experiment 3

Particle Segregation

Experiment 1 is performed with a powder with a particle diameter range of 400-600 μm. The corresponding simulation is carried out with one particle phase. No bubbles are observed in the experiment and the simulation. The superficial gas velocity, 0.134 m/s, is well below the theoretical minimum fluidization velocity for particles with diameter 488 μm, and bubble formation is therefore not expected.

The simulations 1, 3, 4 and 5 were analyzed with respect to particle segregation and bubble appearance in an earlier study by Jayarathna et al. [22]. The computational results were compared to experimental data performed by Wu et al. [23]. The comparison of the results showed that the deviation between simulations and experiments decrease significantly with increasing number of particle phases in the simulations.

Experiment 2 is performed with a mixture of the powders with mean diameter of 153 μm and 960 μm, and the mixture includes a wide range of particle sizes. The experiment corresponds to simulation 2 which is carried out with two particle phases. The comparison between experimental and computational results is shown in Figure 1. Both the experiment and simulation predict a very clear segregation of particles. The segregation influence on flow behavior and this effect can only be predicted by using multiple particle phases in the simulations.

In Figure 2, the particle segregation in experiment 3 and simulation 5 is compared. The thickness of the layer of small particles on the top of the bed is about the same in the simulation as in the experiments. In the

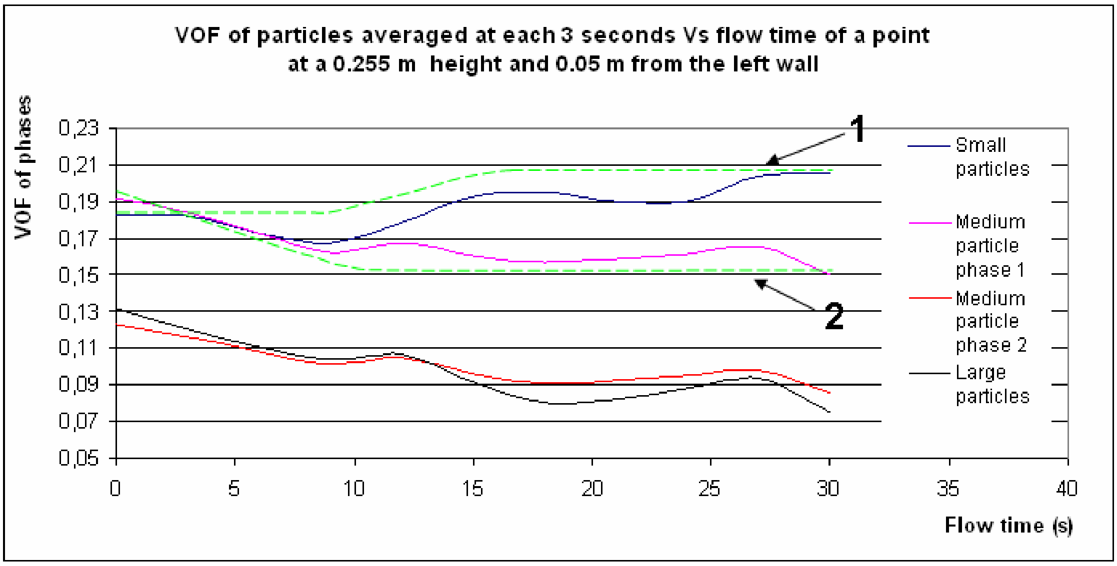

Figure 3: Particle segregation as a function of time at a selected point in the particle bed of the simulation 5.

experiment the boundary between small and large particle layer can be assumed to be at the same level as the bubbles appear. The simulation 5 is performed with 3 particle phases.

Segregation as a function of time

Figure 3 shows the segregation of particles as a function of time observed in simulation 5. The analysis is performed at position 0.05 m from the wall and height 0.255 m in the bed. The simulation is performed with 4 particle phases, small particles, medium particles 1, medium particles 2 and large particles. The particle diameters for the phases are given in Table 2. In the figure the volume fraction of the different phases are averaged over 3 seconds, and the values are given from time 0 to time 30 s. It can be seen that the tendency is that the fraction of small particles increases with time, the medium 1 particles decreases slightly, and the medium 2 and the large particles decreases significantly with time at the current position. The dashed lines marked with 1 and 2 are presenting the segregation tendencies of the small and medium particles 1.

Bubble velocity

Bubble velocity (rise velocity) of the simulations and the experiments are compared using an averaged velocity values. Rise velocities is useful to study the dynamics in the particle bed and also to compare the prediction of the simulations with the reference experiments to evaluate how close the simulations are to the experiments.

Rise velocities of the bubbles in the simulations are calculated using contours of VOF of the gas phase that shows some of the bubbles raised in the particle bed at each simulation. For the experiments, movie frames were used. To calculate the rise velocity, one or more bubbles are selected and the change of the position of the bubble with time is measured. Bubble position variation of two selected bubbles with time from the simulation 5 is presented in Figure 4. Those two bubbles have 0.25 $\mathrm{m\,s^{-1}}$ and 0.33 $\mathrm{m\,s^{-1}}$ respectively as their average rise velocities. The calculated averaged velocities are presented in Table 3.

Table 3: Averaged velocities.

Simulation	Averaged rise velocity, m/s			Experiment	Averaged rise velocity, m/s		
No:	Bubble1	Bubble2	Bubble3	No:	Bubble1	Bubble2	Bubble3
1	No bubbles			1	No bubbles		
2	0.35	0.39	0.41	2	0.21	0.42	0.59
3	0.29	0.22		3	0.31	0.47	0.41
4	0.39	0.46	0.26				
5	0.25	0.33					

Since the simulation 3, 4 and 5 represents the particle distribution in the experiment 3 but with different number of particle phase, velocity values found in those are compared with the respective experiment. Results from the simulation 2 is compared with the experiment 2. The comparison showed that all the bubbles that

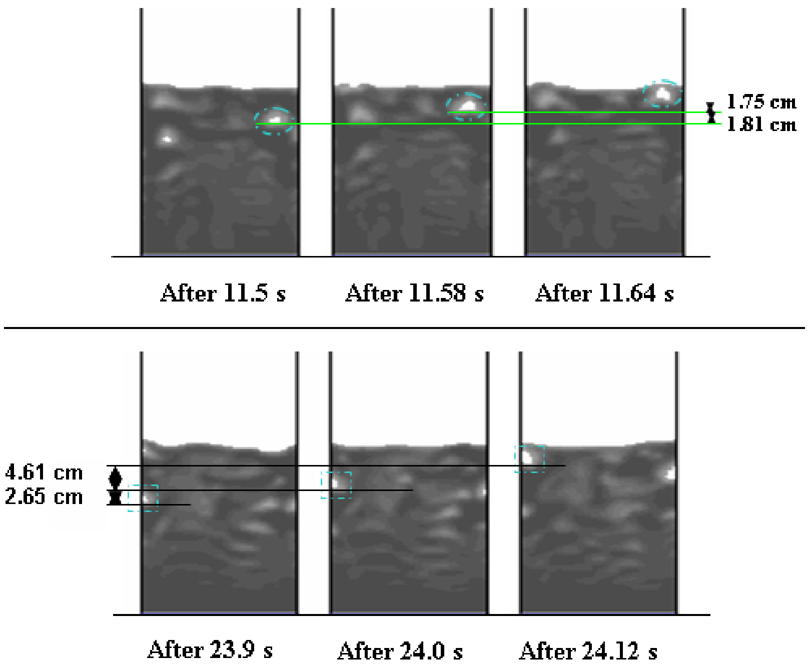

Figure 4: Change of the position of the bubbles with time in the particle bed of the simulation 5.

are analyzed have velocities values which are very much different from each other. In addition, it was clearly noticeable that the bubbles are growing larger with time and speeds up as the bubbles grow. Since the bubble dimensions are not analyzed during this study, it is not possible to give a conclusion regarding the bubble velocities. But, when the rise velocities are compared with the emulsion gas velocity, it is clear that all of the analyzed bubbles are fast moving bubbles.

Bubble Appearance

Bubble appearance in the bed is also analyzed both in the simulations and the experiments. The lowest position of bubble appearance should depend on particle segregation present in the bed. Figure 5 shows the lowest position for bubble appearance in the particle bed in the simulation 2 and 5 and in the experiment 2 and 3. Comparison of the details in the picture shows that the simulation 2 have similar predictions to the experiment 2 while the simulation 5 have predicted the results similar to the experiment 3.

By including multiple particle phases in the simulations, the particle size distribution present in the experiments are accounted for in the simulation, and the flow behavior can be predicted without loosing important information.

Bubble frequency

The assumption of solid free bubbles is an oversimplification of what actually happens in the particle bed [24]. To accept some particles inside the bubbles, a volume fraction of gas of 0.7 is selected as the criterion for a bubble. Bubble frequencies are calculated for all the five simulations, and it is found that the bubble frequency is lowest close to the walls and along the central axis of the bed. It is observed that the bubble frequency increases with increasing height in the bed. Figure 6 shows the bubble frequency as a function of radial position at two heights in the bed. The figure represents the results from simulation 4 which is performed with three particle phases.

Similar observations are done with the experiments 2 and 3. Figure 7 provides evidence for the above statement.

Conclusions

Experiments and simulations are carried out on a 2-D bubbling fluidized bed with uniform air distribution. The aim of the work is to study the influence of particle size distribution on flow behavior in a fluidized bed. The

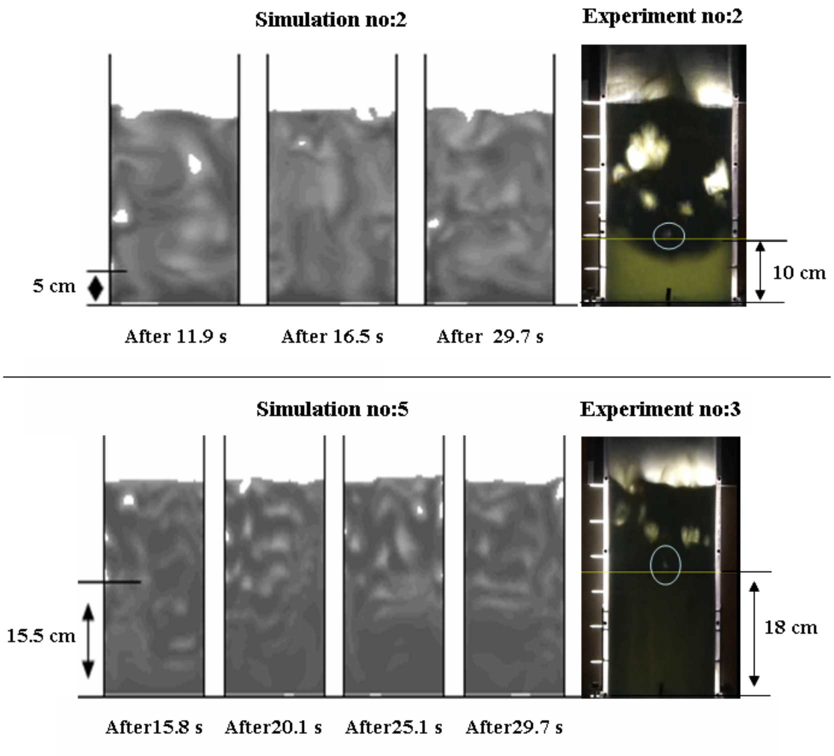

Figure 5: Lowest position for bubble appearance in the particle bed of the simulations 2, 5 and experiments 2, 3.

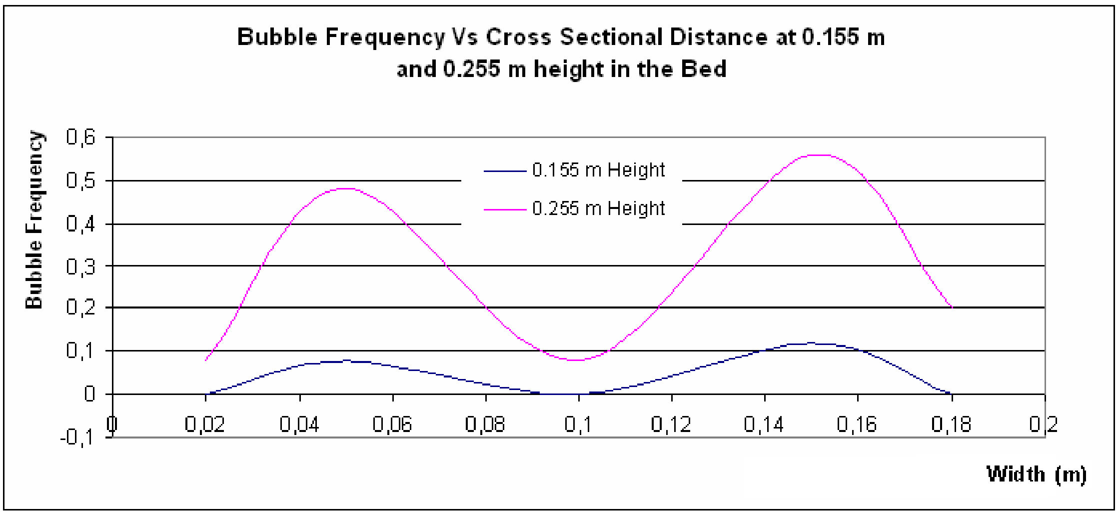

Figure 6: Bubble frequency in two selected levels in the particle bed of the simulation 4.

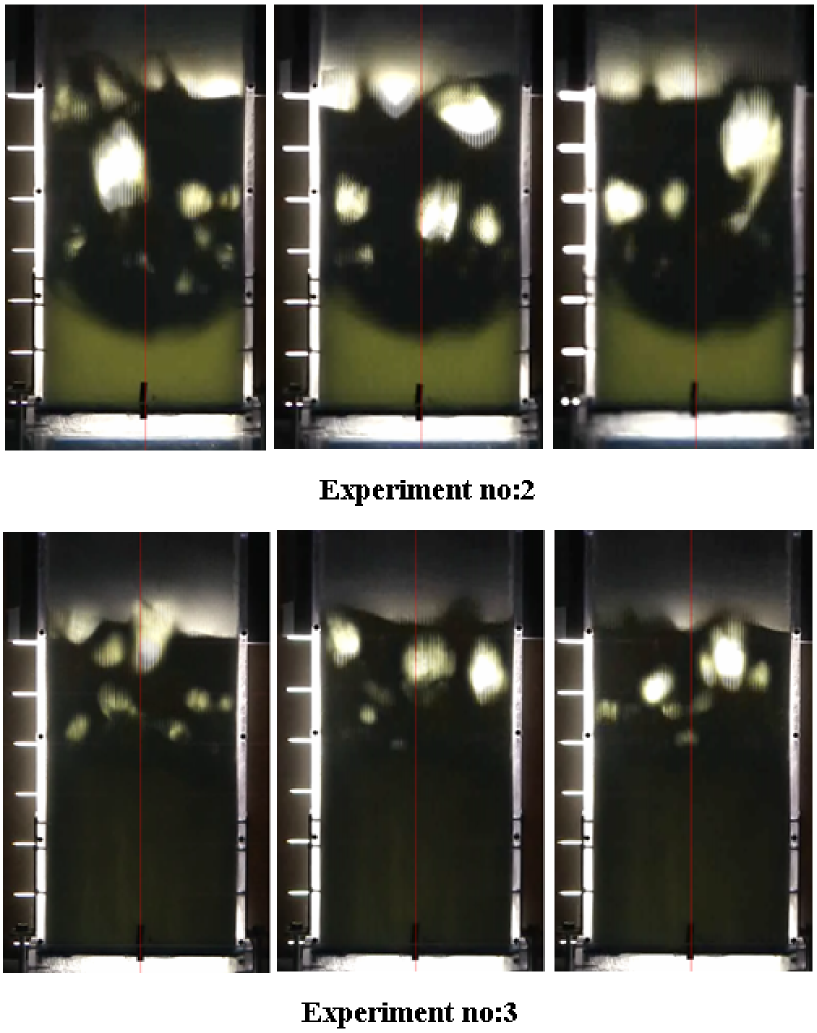

Figure 7: Bubble appeatence in the particle bed of the experiment 2 and 3.

comercial CFD software Fluent 6.3 is used in the computational study.

Three experiments are performed with glass particles with the same mean particle diameter but different particle size distribution. The mean diameter is 488 μm and the superficial gas velocity is 0.134 m/s. The superficial velocity is well below the theoretical minimum fluidization velocity for particles with diameter 488 μm. The results from the experiments show that when particle mixtures with a wide range of particle sizes are used, the particles will segregate, and bubbles will appear although the superficial velocity is below the calculated minimum fluidization velocity. Segregation influences significantly on the flow behavior and the position of bubble appearance in the bed. It is therefore important to account for the particle size distribution in the simulations in order to get an acceptable prediction of flow behavior in fluidized beds.

Simulations are performed with the same conditions as used in the experiments, and in order to study the effect of particle size distribution, multiple particle phases are included. The simulations are performed with one, two, three and four particle phases, and the results are compared to each other and to the experimental data. It was found that the simulations with the highest number of particle phases give a good agreement with experiments. The results of the simulations show the same tendency of particle segregation as is found in the experiments. Segregation of particles as a function of time is analyzed in one selected position in the bed. The analysis shows that the larger particles tend to settle close to the bottom of the bed whereas the smaller particles tend to accumulate in the upper part of the particle bed with time.

The results from the simulations and experiments support to conclude that the particle size distribution has a significant effect on the flow behavior in fluidized beds, and that this has to be accounted for in the simulations. The analysis proved that the validity of the simulated results depends on the accuracy of representing the particle size distribution.

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