Controlling Bubble Coalescence in a Fluidized-Bed Model Using Bubble Injection

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Gas–solids fluidized beds are characterized by the presence of gas voids or bubbles causing a mass-transfer resistance. Enhancing the mass transfer from the bubbles to the emulsion phase by reducing the bubble size can be advantageous for the chemical performance (like the conversion and selectivity) of the reactor. A model using a 2-D version of the dynamic bubble model of Clift and Grace (1970, 1971) where bubble trajectories are predicted based on an analytic expression for the flow field around a bubble was studied. Bubble coalescence can be reduced by injecting bubbles in certain patterns, which leads to a reduction of the average bubble size higher in the bed. A simple proportional feedback control method to force bubbles on a horizontal line made it possible to generate a bubble injection pattern automatically, leading to smaller bubbles than without the feedback control method. The principle of the controlled bubble injection could lead to improved gas distributor designs.

Introduction

Gas–solids fluidized beds are characterized by the existence of gas voids or bubbles. For typical fluidization conditions with Geldart B-type particles (see Kunii and Levenspiel, 1991), and not too high gas velocities, these bubbles are formed directly above the gas distributor at the bottom of the bed. In the region above, frequent coalescence of bubbles takes place, resulting in bubble growth. This process can continue to form large bubbles in the upper region of the bed. Large bubbles cause a limitation to mass transfer from the bubble gas to the solid particles, for example, catalyst or sorbent. This can have a negative effect on the chemical performance of the reactor, like the overall conversion or the selectivity of a reaction. For that reason it is desirable to reduce the bubble size. One possible way to achieve this is to use internals or baffles in the bed that cause breakup of the bubbles; see, for example, Papa and Zenz (1995). However, these internals may be sensitive to corrosion or erosion, and a method to reduce the bubble size without internals may be beneficial. In this article it is attempted to achieve this by injecting gas bubbles in a certain pattern above the distributor plate in a simplified dynamic model of a fluidized bed. The model is a mechanistic approach for predicting bubble flow patterns, as described by Clift and Grace (1970, 1971), Rafailidis et al. (1991), and Halow et al. (1998), where the trajectories of individual bubbles are calculated. The underlying assumption of these models is that each bubble present in the bed generates a certain flow field around it. This flow field affects the rising velocity of nearby bubbles. It was found that these models can give a quite reasonable description of the bubble interaction without requiring a huge computational effort. Hence, these models are suitable for investigating the effect of different bubble-injection patterns.

The next section describes the basics of the model used in this work, as it was developed by Clift and Grace (1970, 1971). In the third section it is shown how the model predicts bubble coalescence. Based on the insight obtained, the fourth section describes how bubble coalescence can be altered to reduce the bubble size by the injection of bubbles in certain patterns. Finally, the fifth section describes an extension of this technique to obtain an optimum bubble-injection pattern, by using a feedback control method.

Theory

The basics of the model as described by Clift and Grace (1970, 1971), is that the velocity of each bubble is equal to the rising velocity of an individual bubble in an infinite

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medium plus the emulsion phase velocity at the nose of the bubble. The emulsion phase velocity is assumed to be a linear combination of the velocities induced by all other bubbles. The velocity induced by one bubble is obtained from the flow pattern of the spherical Davidson bubble; see, for example, Kunii and Levenspiel (1991). All gas in excess of the minimum fluidization velocity flows through the bed as bubbles. In this article, it is chosen to study only a two-dimensional fluidized bed for simplicity. Clift and Grace show that these assumptions lead to the following equations for the vertical (u_i) and horizontal (v_i) components of the instantaneous velocity of the ith bubble:

$$u_i = u_{b\infty,i} + \sum_{j \neq i} l_{ij} u_j + \sum_{j \neq i} m_{ij} v_j, \tag{1}$$

and

$$v_i = \sum_{j \neq i} m_{ij} u_j - \sum_{j \neq i} l_{ij} v_j. \tag{2}$$

The rising velocity of an individual isolated bubble, $u_{b\infty,i}$, is proportional to the square root of the bubble radius R, $u_{b\infty,i} = 0.71\sqrt{g2R_i}$; see, for example, Kunii and Levenspiel (1991). The coefficients m_{ij} and l_{ij} follow from the assumed Davidson flow pattern around each individual bubble, with horizontal and vertical coordinates x and y:

$$l_{ij} = \frac{\left[(y_i - y_j + R_i)^2 - (x_i - x_j)^2\right] R_j^2}{\left[(y_i - y_j + R_i)^2 + (x_i - x_j)^2\right]^2}, \tag{3}$$

and

$$m_{ij} = \frac{2(y_i - y_j + R_i)(x_i - x_j) R_j^2}{\left[(y_i - y_j + R_i)^2 + (x_i - x_j)^2\right]^2}. \tag{4}$$

Figure 1 shows the flow pattern around a spherical Davidson bubble, computed from Eqs. 1 to 4. For N bubbles present in the bed, this gives $2N$ equations with $2N$ unknown velocities. Because these equations are linear in the velocities (but strongly nonlinear in the positions), they can be solved numerically very efficiently. The numerical method used in this work uses an LU decomposition to achieve the solution (see Press et al., 1995). The effect of the bed walls is taken into account by the method of images; see, for example, Milne-Thomson (1968). Mirror images of the bubbles are added outside the reactor walls during the simulation. When a bubble approaches that wall, it is repulsed by its mirror image. This prevents bubbles from moving through the wall. It is possible to rewrite the set of Eqs. 1 and 2 to incorporate the effect of these images without changing the number of unknown velocities to be solved, because the velocities of a bubble and its images are dependent. It is assumed that when bubbles touch, a new bubble is formed with the same total volume on the center point of gravity of the two original bubbles. This may cause a slight deviation from reality, because for some particle systems the total bubble volume increases

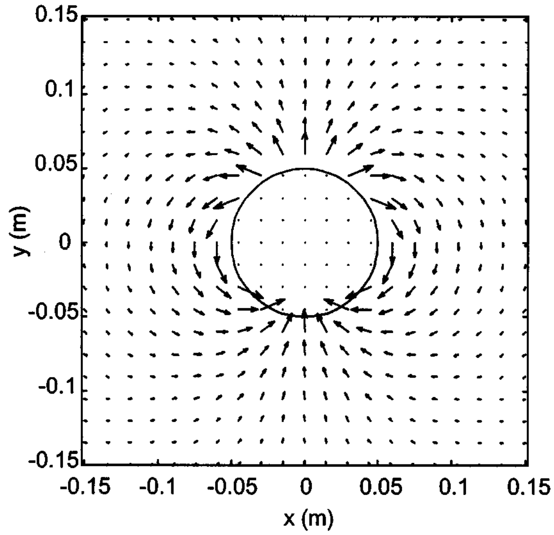

Figure 1. Flow pattern around a 2-D spherical bubble with a radius of 5 cm.

The arrows on the grid points indicate the dense phase velocity relative to the bubble. Calculated from Eqs. 1 to 4 by using a second bubble with zero radius on all of the grid positions.

after coalescence with approximately 15% for equally sized bubbles (see Rafailidis et al., 1991). Because this percentage is unknown to us for bubbles of different sizes, however, the volume increase is not used in the model. This can cause a small deviation from reality in the bubble radius after coalescence of up to 5%. When the center of a bubble crosses a fixed-bed height, it is removed from the simulation.

The entering gas flow is simulated as new bubbles that are created periodically above the distributor plate. In this study it is assumed that it is possible to generate bubbles of a certain size at different positions above the bottom of the bed. This is comparable to using standpipes as a gas distributor (see the fourth section). With such a gas distributor, the gas enters the bed through a number of vertical tubes. The timing of bubble injection at different positions serves as an actuator to control the overall bubble flow. For simplicity, these bubble injection points are placed not too close to the wall (typical distance to wall larger than 20% of the column diameter) such that in the lower region of the bed the wall effect can be neglected. This simplifies the interpretation of the results. Because of bubble injection and coalescence taking place, there is a constant shifting in the number of dynamic variables present. This makes the model an unusual type of differential equation. Therefore, it is solved with an Euler integration routine with step size Δt:

$$\begin{pmatrix} y_i \\ x_i \end{pmatrix}_{t+\Delta t} = \begin{pmatrix} y_i \\ x_i \end{pmatrix}_t + \begin{pmatrix} u_i \\ v_i \end{pmatrix} \Delta t. \tag{5}$$

The total gas flow into the bed fluctuates with bubble injections. The average total gas flow is equal to the time-averaged bubble flow plus the gas flow through the dense phase that rises with the minimum fluidization velocity. The mini-

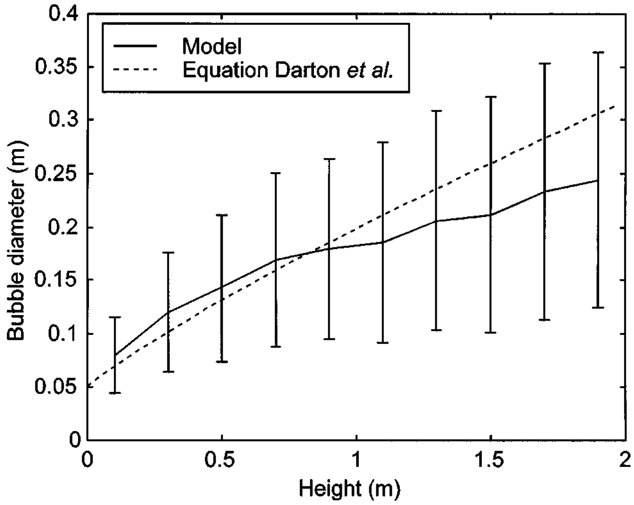

Figure 2. Mean bubble diameter vs. height in the bed for this model (solid line) and the model of Darton et al. (1977).

The bars around the mean values of the model indicate the standard deviation. The equation of Darton et al. falls well within the wide range of bubble sizes observed.

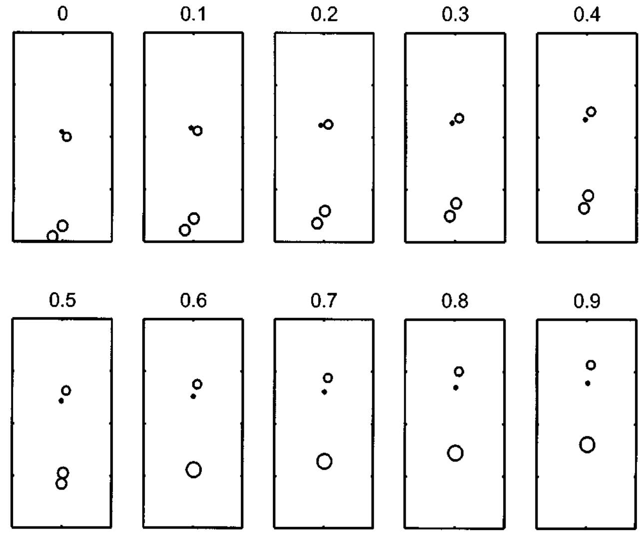

Figure 3. Bubble interaction for two pairs of bubbles.

The time is indicated in seconds at the top of the pictures. The size of the bed is 1×2 m (width×height). The equally sized bubbles in the lower bubble pair coalesce after 0.5 s. The bubbles in the upper bubble pair are not of equal size, and the smaller bubble is pushed away by the larger one. The rising velocity of the smaller bubble is too small and the distance to the large bubble too large to let them coalesce once the smaller bubble is below the larger bubble.

mum fluidization velocity does not influence the bubble dynamics in the model. It is obvious that many simplifications of the reality are present in this mechanistic model, and undoubtedly there may be systematic deviations from the reality. Clift and Grace (1970, 1971), however, showed that the model is well able to predict experimentally observed bubble interactions. Figure 2 shows another indication that the model is in correspondence with reality. It compares the bubble size predicted by the model with a bubble-size relationship for Geldart B particles from the literature (Darton et al., 1977). The wide range of bubble sizes found is not in contradiction with this literature relationship. Therefore, we consider this Clift and Grace model useful for developing a new control method for bubble injection that is able to suppress coalescence.

Coalescence Behavior

This paragraph explains how the interaction between two or three bubbles leads to coalescence. For this purpose, model simulations were carried out for a bed with only two pairs of bubbles present initially. During the rising process of the bubbles, no other gas is brought into the bed. The results are applied in the next paragraph where a continuous injection of bubbles is used.

A model simulation was carried out, with two pairs of bubbles at an initial condition without other bubbles in the bed. This is illustrated in Figure 3. The size of the vessel was taken as 1×2 m (width×height), and the exact initial positions and radii of the bubbles are listed in Table 1. The distance between the two bubble pairs is approximately one meter, which means the interaction between the pairs is negligible. The lower bubble pair of equally sized bubbles shows a typical coalescence process. The upper bubble rises almost straight upward with a relatively constant velocity. The lower bubble follows the leading bubble, and accelerates toward the lowest point of the upper bubble when it comes closer. This is observed for almost all coalescences; one bubble moves below a leading bubble, and then its rising velocity increases until co-

Table 1. Initial Bubble Positions that Were Used to Illustrate Bubble Coalescence as Predicted by the Model

Figure	Bubble nr *i*.	x_i (m)	y_i (m)	R_i (m)
3, 4	1	0.0	0.15	0.05
	2	−0.1	0.05	0.05
	3	0.04	1.0	0.04
	4	−0.01	1.05	0.015
5, 6a	1	−0.1	0.05	0.04
	2	0.0	0.10	0.04
	3	0.1	0.06	0.04
6, 7b	1	−0.1	0.10	0.04
	2	0.0	0.05	0.04
	3	0.1	0.11	0.04
11a	1	−0.2	0.15	0.05
	2	−0.066	0.05	0.05
	3	0.066	0.05	0.05
	4	0.2	0.15	0.05
11b	1	−0.2	0.05	0.05
	2	−0.066	0.15	0.05
	3	0.066	0.15	0.05
	4	0.2	0.05	0.05
12a, b, c	1	−0.30	0.05	0.05
	2	−0.10	0.05	0.05
	3	0.10	0.05	0.05
	4	0.30	0.05	0.05

Note: $x = 0$ corresponds to the center line of the bed.

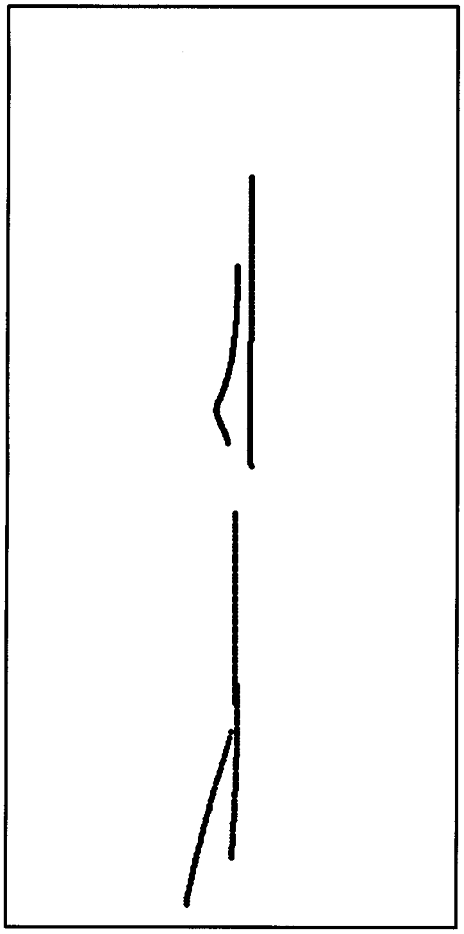

Figure 4. Bubble trajectories in the 1 × 2-m bed from the simulation in Figure 3.

alescence occurs. The bubble pair in the middle of the bed shows different behavior. The small bubble is pushed away by the larger bubble and moves around it. When it comes below the upper bubble, its rising velocity does not increase enough to catch up with the leading bubble. The initial positions of the smaller and larger bubbles at time $t = 0$ were chosen to demonstrate how the solids flow around the larger bubble has an effect on nearby bubbles. If the initial position of the smaller bubble would have been chosen slightly more to the right (~ 1 cm), the more vertical alignment would have caused coalescence. Coalescence would also have occurred when the small bubble was larger, or in reality with large Geldart B- or D-type particles, which are characterized by a large gas exchange between bubbles, because the gas flows directly through the dense phase.

Figure 4 is a different representation of Figure 3. It shows trajectories of the bubble centers from time $t = 0$ to 1 s. It is obvious that the leading bubble of the lower bubble pair rises in an almost straight line, while the chasing bubble moves sideward. The small bubble of the upper bubble pair is pushed sideways during the passage of the larger bubble.

A more detailed study about how coalescence occurs, starting from certain initial positions of equally sized bubbles, is given by Clift and Grace (1971). We can learn from this simulation how to reduce the the bubble size by reducing the number of coalescences: bubbles should not be allowed to come close to each other, with one bubble tracing a leading bubble. This reduces the probability of early coalescence. Using controlled bubble injection, the gas feed can be injected such that the new bubbles do not start close to the bottom of leading bubbles.

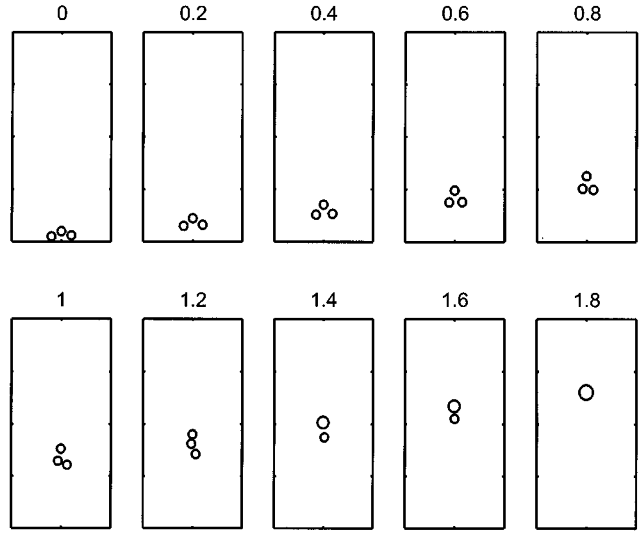

Figure 5. Three bubbles in an initially upward triangular pattern leading to rapid coalescence.

The bed is 1 × 2 m and the time is indicated in seconds on the top of each picture.

Figures 5, 6, and 7 illustrate the idea. Three equally sized bubbles are positioned in a triangular pattern at the beginning of the simulation. In Figure 5, an upward triangular pat-

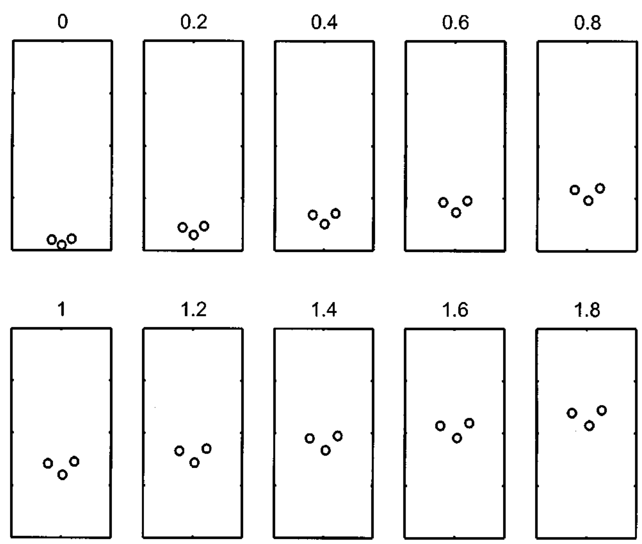

Figure 6. Three bubbles in an initially downward triangular pattern.

The lower, middle bubble is both attracted by the left- and right-leading bubbles, causing it to remain in the center. Time indicated in seconds on top of pictures.

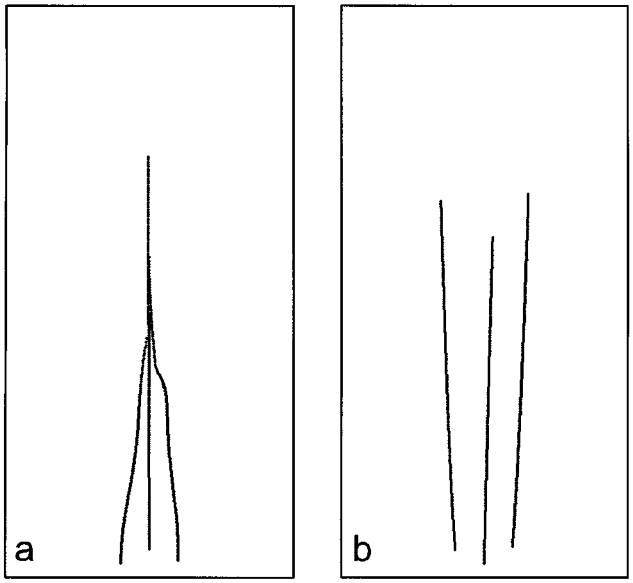

Figure 7. Trajectories of bubbles starting from: (a) upward triangular pattern leading to coalescence; (b) downward triangular pattern not leading to coalescence.

The time span is 2 s.

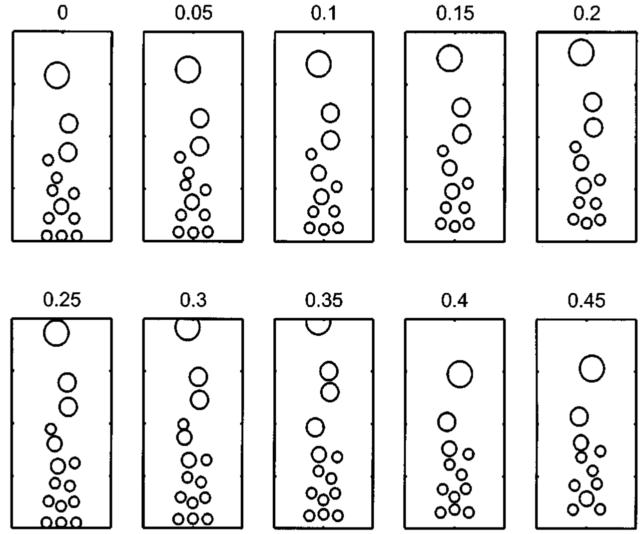

Figure 8. Snapshots of model simulation with three 5-cm bubbles injected simultaneously with a period of 0.25 s.

The time is indicated in seconds at the top of the pictures.

tern of bubbles leads to fast coalescence of all bubbles. As shown in Figure 6, a downward triangular pattern of bubbles does not lead to coalescence. Figure 7 shows the bubble trajectories of Figures 5 and 6. The explanation of the different bubble interaction is that in the upward triangular pattern the leading bubble "pulls" both chasing bubbles into it, while this is impossible in the downward triangular pattern. Both leading bubbles pull on the chasing bubble, but the resulting effect is that the lower bubble stays in the middle. Note that in Figure 6 the bubbles are not in a completely symmetrical pattern. Therefore, the forces on the center bubble are not completely balanced, and eventually coalescence will occur (at about 5 m). The "balancing" does not need to be perfect for the control method to work, as long as it is better than the completely unbalanced situation that occurs if bubbles are formed at random times and positions near the distributor.

Phenomena that occur for isolated bubble groups, like these triangular patterns, can be used in the situation of continuous gas flow where bubbles are formed periodically at certain injection points. The is illustrated in the next section.

The choice for the bed size and bubble size is rather arbitrary. Results similar to the ones just described can also be obtained with other choices. For the rest of this article, we will keep using the same dimensions (1×2-m bed size, 5-cm bubbles). This is also an arbitrary choice that allows us to illustrate the principle of how the bubble behavior can be changed.

Continuous Injection of Bubble Patterns

In the first subsection of this section, the continuous injection of bubbles in a triangular pattern using three injection points is studied. In the second subsection, bubble patterns with four injection points are studied.

Three injection points

At each injection point, bubbles are injected with a period of 0.25 s (that is, 4 bubbles per injection point per second). One of the injection points is located at the vertical center line of the 1×2-m bed and the other two at 15 cm to the left and right of this center line, respectively. All are located at 5-cm height above the bottom of the bed. At the beginning of the injection period, two bubbles, each with a radius of 5 cm, are injected at the two outer injection points. At the center injection point a 5-cm bubble is injected after a certain delay time between 0 and 0.25 s. This specific injection frequency and the bubble size chosen correspond to a mean excess gas velocity of 9.4 cm/s.

Figure 8 shows typical bubble behavior for a zero-delay time where a complex coalescence pattern leads to large bubbles in the upper region in the bed. Figure 9a shows the bubble trajectories of this simulation. It illustrates that there is periodic coalescence behavior where at only two horizontal positions bubbles leave at the top of the bed. When the center bubble is injected with a delay time of 0.05 s after the outer bubbles, the bubble trajectories change to those in Figure 9b. Bubbles from one injection point do not coalesce anymore with bubbles from other injection points, because three bubble paths are formed that repulse each other. Figure 9c belongs to the case where the middle bubble is injected 0.15 s after the outer bubbles. In this situation only the bubble behavior in the lower part of the bed is periodic, but above approximately one quarter of the total bed height, the bubble behavior becomes deterministically chaotic. Figure 9d shows the bubble paths when bubbles of the same size are injected randomly at the same injection points and with the same mean gas flow. A uniform probability distribution is used for this

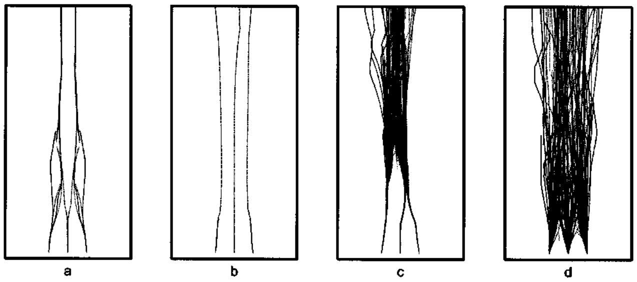

Figure 9. Bubble paths obtained from model simulations with three 5-cm bubbles injected with a period of 0.25 s in various ways at the bottom of the bed.

(a) All three bubbles injected simultaneously; (b) the two outer bubbles are injected simultaneously, the center bubble has a delay of 0.05 s; (c) as (b), but with a delay of 0.15 s; (d) corresponds to the random injection of equally sized bubbles. In (a) and (b), periodic behavior occurs, while in (c) the dynamics are only periodically below approximately one quarter of the bed height. Above that distance the bubbles behave chaotically. Part (d) is neither periodic nor chaotic because of the random bubble injection.

simulation, which means that on average the same number of bubbles is injected at each point. It can be seen that random bubble injection causes bubbles to attract each other more quickly. This will eventually lead to larger bubbles higher in the bed. To quantify the change in bubble size, the mean radius of the bubbles leaving the bed was determined for the different bubble-injection patterns. The results are shown in Figure 10, which is calculated from simulations with approximately ten thousand bubbles formed per simulation. The mean radii of the exiting bubbles differ significantly (from 12.3 cm to 6.7 cm) for the various bubble-injection patterns. Random injection of the bubbles leads to a mean bubble radius of 9.4 cm, which is larger than the best triangular pattern, but smaller than periodic simultaneous patterns of three bubbles.

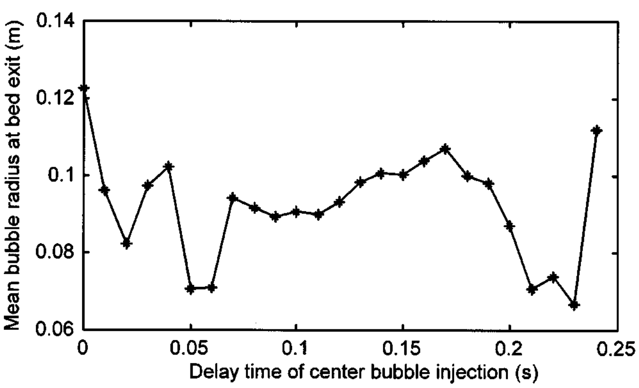

Figure 10. Mean radius of bubbles leaving the bed as a function of the delay time in which the center bubble is injected after injection of the two outer bubbles.

Compare with Figure 9. Injecting the three bubbles simultaneously (that is, zero delay time) gives the largest diameter of bubbles leaving the bed (12.3 cm). Note that the (random) error in the estimate of the mean bubble radius is small (95% probability interval < 0.001 m) because it is averaged from thousands of bubbles leaving the bed.

From these simulations it can be concluded that the mean bubble radius at the exit is sensitive to the way of bubble injection. For certain delay times, much smaller bubbles occur because at those delay times bubble patterns develop near the bottom with a smaller tendency to coalesce. The principle is the same as in the case where only three bubbles were present at one time in the bed. The interaction with bubbles above increases the complexity, though, and means that there is no simple relationship between the delay time and the bubble size (see Figure 10). The nonsmooth behavior of Figure 10 is not unexpected. In recent years the perception has increased that fluidized beds show chaotic behavior. For chaotic systems it is well known that sudden changes in a variable can occur when a parameter is changed. For instance, if one considers a bifurication diagram, then small changes in a parameter lead to a large change in dynamic behavior.

The question rises if this is also valid for a different number of injection points. A larger number of injection points at which smaller bubbles are formed is of special interest for obtaining many small bubbles in the bed. This issue is, however, extremely complex and corresponds to predicting time-averaged properties of a high-dimensional spatiotemporal system that can show both periodic and chaotic behavior, possibly with multiple attractors present. As an illustration, Figures 9b and 9c show an asymmetric response to a symmetric input, which suggests that at least two, and possibly more, steady-state behaviors exist. For example, a mirror image of this behavior also must exist that is symmetrical around the bed's vertical center line.

In the next subsection, simulations will be shown where one extra bubble injection point is included.

Four injection points

The idea for an injection pattern with four injection points was based on the bubble trajectories shown in Figure 11. See Table 1 for the exact initial positions of the bubbles. It was expected that two leading bubbles on the outside (Figure 11a) would move further away from the center line than two leading bubbles on the inside (Figure 11b). If bubbles move away from the center line of the bed, the concentration of bubbles will be lower near that center line. For continuous bubble injection, this will reduce the frequency of bubble coalescence, which then leads to smaller bubbles.

Bubble-injection patterns based on four equally spaced injection points (-30, -10, 10, and 30 cm from the center line, all at 5 cm from the bottom of the bed) were simulated. Bubbles were formed with an initial radius of 5 cm. The injection period was 0.20 s, and the average excess-gas velocity was 15.7 cm/s. To limit the possible number of bubble patterns, only symmetric patterns were tested, with the two outer bubbles formed simultaneously, and the two inner bubbles formed simultaneously after a delay time. The largest and smallest mean radii of bubbles leaving the bed are obtained when the two center bubbles are injected 0.07 and 0.15 s, respectively, after the two outer bubbles.

Snapshots of the corresponding bubble flows are given in Figures 12a and 12b. The bubble pattern in Figure 12a leads to the formation of one array of large bubbles leaving the bed

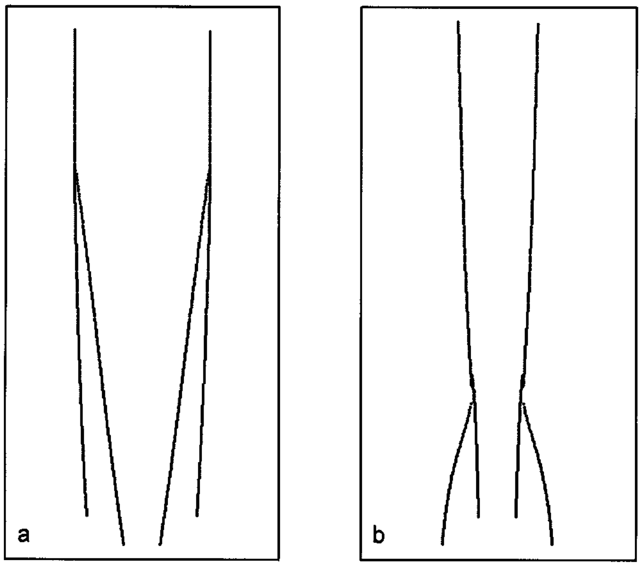

Figure 11. Bubble injection patterns with four injection points.

(a) Bubble trajectories where two leading bubbles are on the outside; (b) bubble trajectories where two leading bubbles are on the inside. Note that continuous injection of the bubbles in pattern (b) would lead to bubbles closer to each other higher in the bed, which could lead to more frequent coalescence and eventually to a larger bubble size.

in the center. Figure 12b shows a more desirable flow pattern, where three lines of bubbles are formed that are separated far enough such that coalescence between bubbles of these lines does not occur. Note that in this case coalescence at low height near the vertical center line is advantagesous for a smaller bubble size in the rest of the bed.

Figure 12c shows a snapshot of model simulation, with randomly injected bubbles of 5 cm at the same injection points as in Figures 12a and 12b. Figure 12d shows a situation comparable to a porous-plate gas distributor, where smaller bubbles (2.2 cm) are formed randomly on a line. The injection period was 0.01 s. The same average gas velocities are used for all cases illustrated in Figures 12a to 12d. Table 2 lists the mean bubble radii and illustrates that injection of smaller bubbles at the distributor plate does not necessarily lead to smaller bubbles higher in the bed. Note that the difference between number- and volume-averaged bubble diameter is relatively small because the bubble-size distribution is relatively narrow.

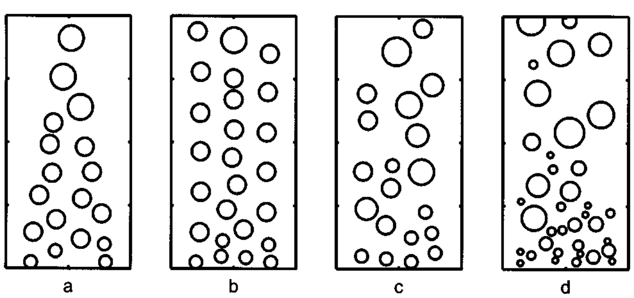

Figure 12. Different bubble flows arising from different bubble injections for an excess gas velocity of 15.7 cm/s.

In (a), (b), and (c), four injection points are present (see Table 1), while in (d) a porous plate is simulated. (a) Injecting the center bubbles with a delay of 0.07 s gives a bubble flow leading to strong coalescence, while (b) with a delay of 0.15 s the bubble coalescence is suppressed by forming three vertical bubble arrays. (c) Random injection using four injection points results in a mean bubble size at the bed exit that is in between those of (a) and (b).

Table 2. Mean Radii (R) of Bubbles Leaving the Bed (cf. Figure 12)

Bubble Injection Method				
No. of Inj. Points	Delay of Bubble Inj.	Figure	No. Avg. Radius (m)	Vol. Avg. Radius (m)
4	0.07 s	12a	0.1220	0.1237
4	0.15 s	12b	0.0805	0.0816
4	Random	12c	0.1034	0.1073
"Porous plate"	Random	12d	0.0899	0.0971

Note: The random injection method comparable to a porous-plate distributor (cf. Figure 12d) results sometimes in very small bubbles leaving the bed. Therefore, the volume-averaged bubble radii (2nd moment about origin for two-dimensional bed) are also given. See Table 1 for the positions of the injection points.

These results also show that it is possible to influence the mean bubble size by altering the way bubbles are injected at the gas distributor, although not as much as for three injection points (see the preceding subsection). It is beyond the scope of this article to predict what possibilities exist for reducing the bubble size for a larger number of injection points. This is a separate research topic, because the number of possible injection patterns greatly increases with the number of injection points. The point of this example with four injection patterns is to show that results and behavior as obtained with three injection patterns are not an extremely rare case that will cease to exist for a different number of injection points.

To estimate the effect that a reduction in bubble size will have on mass transfer from bubble to emulsion phase, we can use a relationship for mass transfer present in the literature. Kunii and Levenspiel (1991) approximate a gas-interchange coefficient for Geldart B type of particles. These typical give large bubbles, as is also the case in the model simulations. They show that the gas-interchange coefficient K_{be} is proportional to one over the bubble radius:

$$K_{be} \approx 4.5\left(\frac{u_{mf}}{2R}\right). \qquad (6)$$

This illustrates that a significant effect on the mass transfer can be expected as a result of the reductions obtained in the average bubble size. We will not attempt to translate this increase in mass transfer to a change in conversion or selectivity, by extending the model with a chemical reaction taking place. This would require an arbitrary choice for reaction kinetics. Therefore, the sensitivity of conversion and selectivity to the change in mass transfer would also get an arbitrary character. Instead, we refer to the work of Kaart et al. (1999). They show that a modest reduction in the mean bubble size can indeed significantly improve the conversion and selectivity of a chemical reaction.

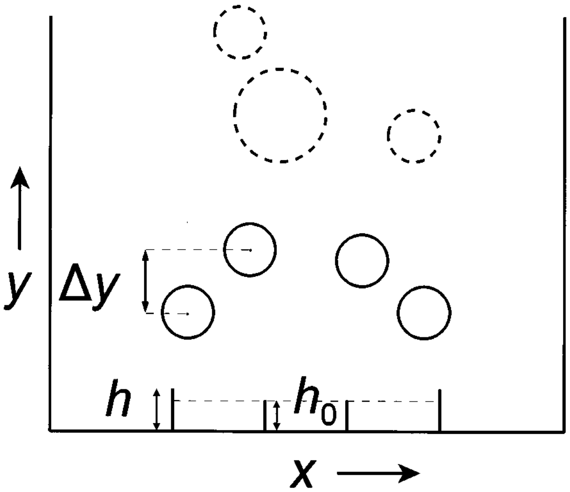

Figure 13. Explanation of the feedback control method.

Bubbles are injected at four positions at the bottom of the bed. This is indicated by the short vertical lines, comparable to standpipes. The two inner injection points have a constant height, h_0. The height, h, of the outer bubble injection points is controlled using the difference between the heights of the two lower, most left bubbles, Δy. Ideally, the two bubbles will be injected such that Δy becomes zero, reducing the probability of early coalescence. The positions of the dashed bubbles above the four lower bubbles are not measured, but they do affect the velocities of the lower bubbles.

Creating Bubble Patterns by Feedback Control

It is unknown how to predict the effect of an initial bubble injection pattern on the bubble flow pattern or on the mean bubble size. The only way available seems to be to carry out simulations and then observe what happens. However, testing many different delay times in a pattern, as was illustrated in Figure 10, requires many simulations. Use of this approach to an experimental system might also lead to a long experimentation time. For this reason, an attempt was made to generate a bubble-injection pattern more or less automatically, using feedback control.

The positions of the lowest bubbles in the bed are measured as an input to the controller. Figure 13 explains the idea graphically for four bubble-injection points. Before injecting new bubbles at the bottom, the vertical position of the most left, lower bubble is compared to that of its neighbor bubble immediately to the right. It is desired that the vertical difference, Δy, be small, preferably zero, because that means that both bubbles are on a horizontal line. This means that there is no highest or leading bubble that will draw a chasing bubble toward it, reducing the likelihood of early coalescence. With a proportional controller one can aim to reduce Δy by changing the vertical position, h, of the two outer bubble injection points:

$$h = h_0 + K\Delta y, \tag{7}$$

where K is the controller proportional gain, and h_0 the injection height for zero difference between the vertical bubble positions ($\Delta y = 0$). Although this moving up and down of the outer injection points might seem very different from varying a delay time, as used so far in this article, it is very much the same. A short delay (Δt) of one bubble before injection causes the other bubbles to be a few centimeters higher at the moment of injection (vertical displacement $\Delta h \approx u\Delta t$, with u the bubble rise velocity). This is comparable to injecting all the bubbles of the pattern at the same time, but with some bubbles a few centimeters higher. Therefore, equal results will be obtained when a delay time of injection is controlled properly instead of a height of injection.

Obviously, using a delay time is advantageous from an experimental point of view. In that case, the outer injection points do not need to be moved upwards and downwards. Nevertheless, the reason for controlling the injection height in the simulations was related to the choice of a fixed integration time step. Controlling the exact time of injection would require a variable step size and would only lead to slower calculations. To further illustrate the feasibility of using a controlled injection time instead of height, we refer to the work of Kaart et al. (1999). They present a control method for the injection time of a one-dimensional version of the model type used in this work.

Note that the difference in bubble position, Δy, is taken from two bubbles on the left half of the bed. No information about bubbles on the right is used, because the bubble injection is symmetrical. Therefore, no large deviations from a symmetric bubble distribution will exist for the lowest bubbles.

Simulations with the feedback controller were carried out for the same situations presented earlier with three and four injection points (see Figures 8 and 12). The vertical positions of the two outer injection points were used as adjustable parameters within a limited range of 5–25 cm, which is comparable to a time delay for injection at a fixed point between -0.14 and 0.14 s. The center bubble(s) was (were) injected in the center of this range, at 15-cm height. This is an increase of 10 cm compared to the bubble injection without feedback presented earlier. Therefore, the bed height was also increased by 10 cm to keep the same distance that bubbles need to travel to reach the bed surface.

The value of the proportional gain was found to have little effect on the bubble size when it was chosen between 0.2 and 2. It was found that feedback control automatically resulted in a bubble-injection pattern resembling the best pattern found earlier by simulating injection patterns with many delays. The mean bubble size at the exit of the bed was also the same. Development of this favorable bubble flow was found for both three and four injection points. The reason is that the controller tries to bring bubbles onto a horizontal line. Therefore, the occurrence of leading and chasing bubbles is counteracted such that coalescence reduces. Figure 14 shows the control action vs. time for the case of four injection points. After a short transient time of 2 s, a kind of period-two behavior starts to dominate the system dynamics, with small noisy deviations that somehow have an origin in the complex deterministic dynamics. The changes in injection height of the two outer bubbles are approximately 0.5 and 4.5 cm compared to the uncontrolled bubbles that were injected at a fixed height of 15 cm. This is comparable to time delays of 0.01 and 0.06 s. A typical snapshot of the bubble pattern is shown in Figure 15. This is almost identical to the best bubble pattern that was obtained in Figure 12b, and illustrates that the

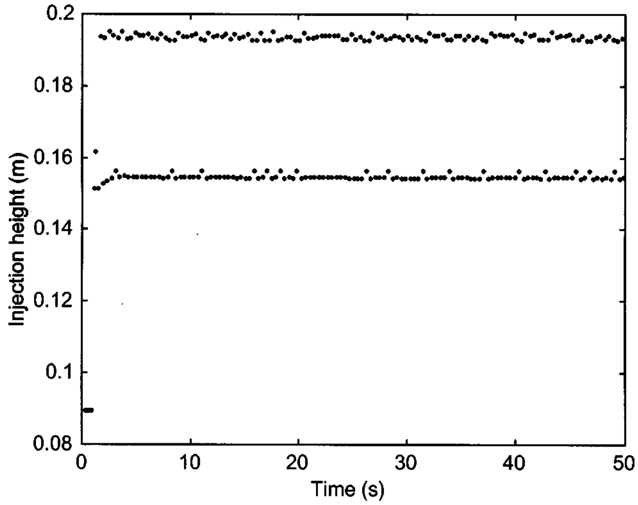

Figure 14. Injection height of the two outer bubbles as applied by the controller.

Compare with Figure 13. The two inner bubbles are injected into the bed at a fixed height of 15 cm. At each injection point, 5 bubbles per second with a 5-cm radius are generated. After a transient time of 2 s, a period-two behavior develops with small deviations on it. Even after several minutes, the system does not develop true periodic behavior.

feedback method is able to generate the best injection pattern automatically.

Conclusions and Discussion

Using a two-dimensional version of the Clift and Grace bubble model, it was shown that it is possible to use the initial bubble-injection pattern as a tool to influence bubble coalescence and to reduce the average bubble size. This can be expected to increase the mass transfer between the bubble and emulsion phase, which is beneficial in the case that conversion or selectivity are affected by mass-transfer limitations; see, for example, Kaart et al. (1999) or Kunii and Levenspiel (1991).

It is without doubt that the model is an oversimplification of the physical reality, and therefore experimental validation will be necessary. Related to this simplification, we need to stress the following. All results presented in this article did not require much effort to optimize, for instance, positions of injection points, initial bubble sizes, or the injection frequency. It was not found that small changes in, for instance, the bubble size would cause the cessation of the observed behavior. Reductions in the average bubble size were still obtained. This indicates a sort of robustness of the method. The question arises as to what extent the bubble size can be reduced when optimizing the control method. At this point, the answer to this question is unknown. To our knowledge, there is no theory available that allows prediction of the bubble size directly from a specific, predefined injection pattern applied to the system. Currently, simulations are required to give a reasonable answer to the question of what the bubble size distribution will be. One approach could be to generate the injection patterns using an optimization algorithm that

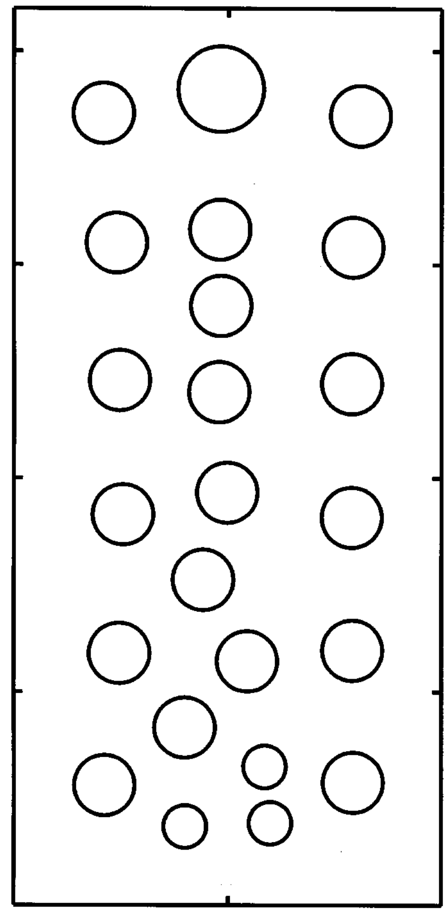

Figure 15. Typical distribution of bubbles during the feedback-controlled bubble generation at four injection points.

Compare with Figure 12b.

aims to minimize the average bubble size over a certain time span. This is comparable to what is known in control engineering as "optimal control." However, the development of a well functioning optimal controller is an extensive study in its own.

The results are also characterized by a robustness to model errors. This means that if the model is simulated with a systematic deviation, a reduction in bubble size is still obtained. Two different types of systematic deviations were simulated in the model. The first was a change (of 30%) in the rising velocity of an isolated bubble. The second was a change (of 30%) in the coefficient, l_{ij}, describing bubble interaction. Both changes indicate that as long as the nature of the dynamics is the same, the bubble size can be reduced by controlled injection. This robustness gives confidence that it may be possible to take advantage of the mechanism in an experimental system.

Experimental evidence that at least binary bubble interaction can be described reasonably well by the model is already given by Clift and Grace (1971). Further experimental validation for multiple bubbles is still necessary. Especially questions related to the breakup of bubbles and bubble injection

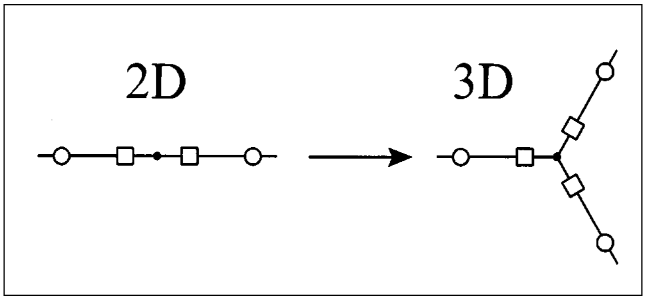

Figure 16. Illustration of how to come to a design for a 3-D bubble-injection pattern using rotational symmetry.

The view represents the look from above on the distributor plate. A symmetric bubble injection is used for the two-dimensional case, where bubbles are injected simultaneously through the two injection points indicated by circles and also simultaneously through those indicated by squares. Using rotational symmetry, a situation can be obtained where the bubble interaction will be very similar to the two-dimensional situation.

need to be answered, because these are not (well) described in the model.

Eventually, the idea of controlling bubble coalescence may lead to improved gas-distributor designs. Injection points above the bottom of the bed can be realized by vertical tubes (preferably all of equal length) entering at the bottom of the bed, which gives a standpipe distributor. A limited number of groups of such injection points can be controlled by one flow valve per group. This will achieve simultaneous bubble injection at multiple injection points, as was also assumed for most of the simulations in this study. At this point, only two-dimensional bubble dynamics were considered, but the step to a three-dimensional bed must be made. It is believed that two-dimensional bubble patterns can be understood well and might be helpful in making a three-dimensional injection pattern by, for instance, making use of symmetry in the design. Figure 16 shows a simple example of this, where rotational symmetry is used to modify the example of four injection points in the two-dimensional situation to a three-dimensional case. The principle should remain the same, of the method that should be aimed for. This is to avoid the vertical lining up of bubbles by bringing them into the same horizontal plane.

Acknowledgments

This work was supported in part by the Research Stimulus Fund of Delft University of Technology, in part by the Netherlands Foundation for Chemical Research (SON) with financial aid from the Netherlands Technology Foundation (STW), and in part by Aspentech, Akzo Nobel, and DSM, all of which are gratefully acknowledged.

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Manuscript received June 24, 1999, and revision received July 24, 2000.