Bubble Driven Fluid Circulations

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Bubble driven fluid circulations are present in bubble columns, gas lifts, pool boiling, etc. Their mechanism is shown to be quite similar to the mechanism of natural convection but with much larger driving forces. These ciiculations aie stable in many baffled systems but unstable and rapidly changing in size, shape, and orientation in unbaffled systems. The effect of these circulations in bubble columns is to lower holdup and vapor residence time, thus decreasing the mass transfer efficiency of the column.

Bubble driven fluid circulations occur in fluid systems containing bubbles of gas entrained in or flowing through a fluid in a gravitational field. Examples of this type of flow are pool boiling and flow in downcomers, bubble columns, and any device which uses a gas sparger. Fluidized beds contain a form of these circulations; gas lifts and thermosyphon devices may be considered a form of them.

The circulation can occur with or without net superficial liquid motion, but it requires net upward (or counter gravity) motion of the gas. The work to drive the circulations is supplied by bouyant work of the gas as it rises through the liquid. In gas lifts part of the work of this rising gas is used to lift liquid to a higher elevation. In most other applications this work is dissipated as friction heating. The circulation generally consists of an upward flow region where liquid relatively rich in entrained bubbles (that is, with a high void fraction) moves upward and a compensating region where a liquid poor in bubbles moves downward.

In some cases this circulation is desirable, for example, gas lifts and thermosyphon devices. In the downcomers of distillation columns it speeds vapor disengagement. When gas-liquid contacting is the objective of the operation, this circulation is undesirable because it decreases the gas retention time and causes liquid backmixing and vapor bypassing, each of which decreases the mass transfer efficiency of the apparatus.

Several theories of the behavior of large masses of bubbles in a liquid have been published (*1* to *3*) in which it is assumed that in such a system the flow is uniform across any horizontal cross section. When these circulations are present, this is not the case, and these theories predict higher gas holdups and better mass transfer performances than are actually observed. At the other extreme it has been proposed (*4*) that large gas-bubble systems are one completely backmixed stage. Although this is probably true for systems in which the entire vessel participates in one circulation, it may not be true for those vessels in which there are many circulations, for example, long, thin vessels.

The effect of these circulations on gas holdup in a bubble column is illustrated on Figure 1. For the flow of a mass of bubbles through a liquid (moving or stagnant) the holdup is given by

$$\epsilon = \frac{u_s}{u_{\text{avg}}} \tag{1}$$

At very low flow rates there are very few bubbles, and each one rises at practically its terminal velocity in the liquid u_t. Therefore, for the stagnant liquid, u_{avg} in Equation (1) is practically equal to u_t; that is

$$\epsilon = \frac{u_s}{u_t} \tag{2}$$

Nicklin (*1*) has shown that for the flow of a mass of bubbles through a stagnant liquid, if each bubble moves at its terminal velocity relative to the fluid surrounding it, then

$$u_{\text{avg}} = u_t + u_s \tag{3}$$

or

$$\epsilon = \frac{u_s}{u_t + u_s} \tag{4}$$

If the bubbles exhibited hindered flow of the type shown by masses of solid particles settling through a liquid, then the velocities of the individual bubbles would be given by the correlations for hindered settling, for example that due to Richardson and Zaki (*6*):

$$u_{\text{avg}} = u_t\,(1-\epsilon)^n \tag{5}$$

This leads to

$$\epsilon(1-\epsilon)^n = \frac{u_s}{u_t} \tag{6}$$

Figure 1 shows Equations (2), (4), and (6) and compares them with a typical set of experimental data for gas holdup in a bubble column (*6*). The experimental data agrees reasonably well with Equations (2) and (4) at low superficial velocities but agrees very poorly at higher superficial velocities. At these higher superficial velocities,

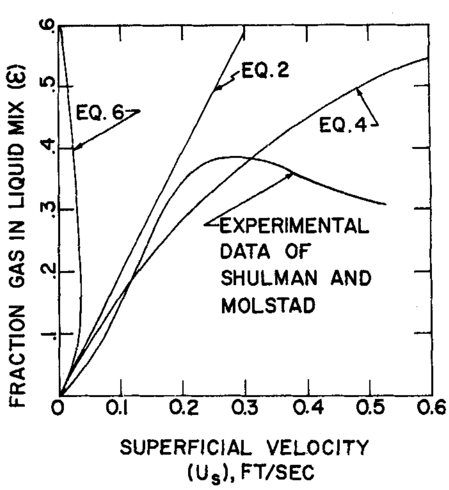

Fig. 1. Comparison of experimental bubble holdup data, and the predictions of various equations. Calculations were made with u_t = 0.5 ft./sec. and n = 4 assumed.

the principal mode of gas transport is bulk motion of the gas-liquid system rather than motion of the bubbles relative to the liquid. Hence, the bubbles move through the system much faster than Equations (2), (3), or (5) predict and have much lower retention time and less holdup then they would if such circulations were not present. For additional experimental curves like the one shown in Figure 1, see references (*3*), and (*7* to *12*.)

This picture of the effect of fluid circulation is complicated by coalescence. Large bubbles are observed to form owing to coalescence (*8*) at the higher gas-flow rates at which fluid circulations exist, and these rise very rapidly through the fluid. The high velocity of these bubbles is associated both with their increased velocity relative to the fluid surrounding them [which increases roughly as the square root of the bubble diameter (*13*)] and also with the motion of the fluid surrounding them, which they cause to move rapidly upward.

THE CIRCULATION MECHANISM

In all these circulations there is a density difference driving force as illustrated in Figure 2. Here a flow is shown in a baffled system. A gas is introduced by a sparger to the right of the baffle. If there were no motion, then there would exist a pressure difference under the baffle equal to

$$\Delta P = g\, h_b\, \Delta\rho \qquad (7)$$

Here $\Delta\rho$ is the difference in density between the clear liquid on the left of the baffle and the bubble-liquid mixture on the right. This pressure difference causes a flow under the baffle and thus drives the circulation. From this explanation it is clear that this type of flow is quite similar in mechanism to natural convection; the principal difference is the greatly increased density-difference driving force. In natural convection in liquids such density differences seldom exceed 1% of the density of the liquid. In natural convection in gases they sometimes reach 10% of the gas density. In bubble driven fluid circulations the density difference is normally 20 to 50% of the liquid density.

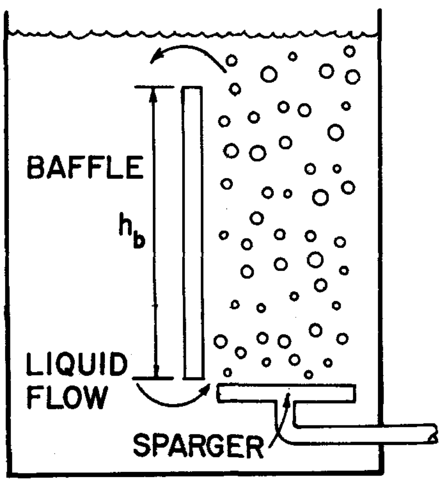

Fig. 2. Illustration of density-difference driving force in a system with nonuniform bubble distribution.

The analogy with natural convection is not complete, however. In natural convection systems the mixing of the streams of different densities (as by turbulence) destroys the driving force by producing a stream of intermediate density. By the second law we know that this fluid cannot regroup itself spontaneously into hotter and colder parts. However, if a bubble rich and a bubble poor stream are mixed (as by turbulence) to produce one of intermediate bubble content, this can regroup (by buoyancy) to reform bubble rich and bubble poor streams. Thus, mixing does not permanently destroy the driving forces of bubble driven circulations as it does in natural convection.

UNBAFFLED CIRCULATIONS

When there is no baffle in the system, the vertical height of the circulation in a bubble column is very small for a low viscosity fluid like water and much larger for a viscous fluid like glycerine. The flow starts to one side above the sparger, swings strongly to that side of the column, and then swings back over the center of the column. Figure 3 shows such an unbaffled circulation above a sparger plate in a bubble column. The flow issues from eight holes placed symmetrically about the axis of the column (as shown in Figure 4) and swings upward to the left. The small round bubble in the clear liquid at the right is moving downward with the stream.

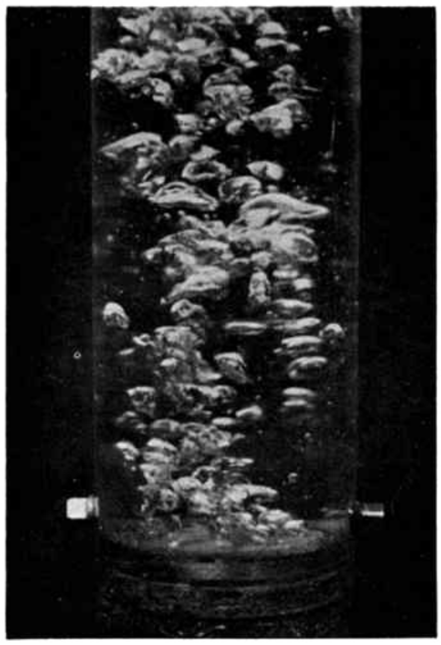

Fig. 3. Unbaffled circulation above a sparger.

This photo and all others in this paper were taken at 1/1,000 sec. with air flowing into distilled water. The air flow rate for all corresponds to an average velocity of 280 ft./sec. through the holes in the sparger and a superficial velocity of 0.05 ft./sec. in the column.

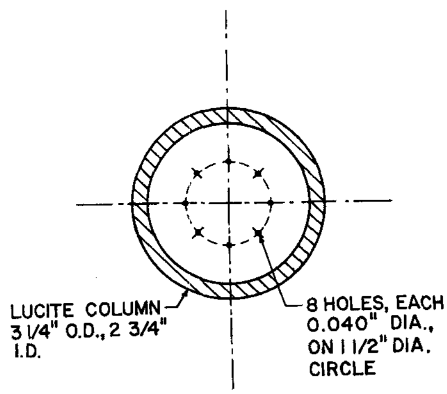

Fig. 4. Plan view of column used in Figures 3, 7, 8, 9, and 10.

This circulation can be explained and a simple mathematical model for it found by assuming that around the circulation path the friction pressure drop per unit length is constant, that the liquid velocity is constant, and that the density of the gas is negligible compared with the density of the liquid. Then, as shown in Figure 5, the pressure changes for the individual parts of the path are

$$P_2 = P_1 - h\rho_{\text{liquid}}\,(1-\epsilon)\,g + h\left(\frac{dP}{dL}\right)_{\text{friction}} \tag{8}$$

$$P_3 = P_2 + w\left(\frac{dP}{dL}\right)_{\text{friction}} \tag{9}$$

$$P_4 = P_3 + h\rho_{\text{liquid}}\,g + h\left(\frac{dP}{dL}\right)_{\text{friction}} \tag{10}$$

$$P_1 = P_4 + w\left(\frac{dP}{dL}\right)_{\text{friction}} \tag{11}$$

When these four equations are added, the pressure terms cancel; then the resulting equation can be solved for h:

$$h = \frac{w}{\dfrac{\rho_L g \epsilon}{2\left(-\dfrac{dP}{dL}\right)_{fr}} - 1} \tag{12}$$

The fluid flows around the circulation because the flow from 4 to 1 and the flow from 2 to 3 are both from higher to lower pressure. These pressure differences are caused by the difference in density between the rising liquid-gas flow from 1 to 2 and the sinking clear-liquid system from 3 to 4.

Equation (12), although based on a very simplified model, shows correctly that as the width of the system is increased, the height of an unbaffled circulation increases proportionately, and that as the friction pressure drop per foot increases (as by increasing the viscosity), the height of the free circulation goes up. The behavior as the gas flow rate is decreased to zero is not clearly shown because both ϵ and $(-\,dP/dL)_{\text{friction}}$ approach zero, making the first term in the denominator indeterminate. However, it appears that this first term approaches 1 at low flow rates because as the gas flow rate becomes negligible, the height of the circulation becomes infinite (that is, it disappears).

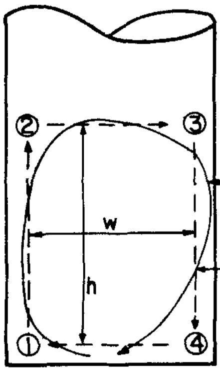

Fig. 5. Circulation path used for computational model.

The principal limitation of this model is that it assumes that the liquid continues to circulate around the same closed loop while the gas enters at the bottom and leaves at the top. This is a fair description of the behavior near a fixed sparger at the bottom of a vessel, so the predictions of this model are reasonable for the first circulation which exists above such a sparger. However, at the top of this first circulation (Figure 6), some of the liquid continues to move with the gas which is leaving the circulation. Because this liquid leaves the area of the first circulation, other liquid must flow in somewhere to replace it. For the simple model shown, there is no place for this fluid to come in, so it can only come in by disrupting the simple flow assumed above and by diverting the horizontally flowing gas-liquid stream aside to make room for itself. This disruption makes the circulation change its size and orientation in a random fashion.

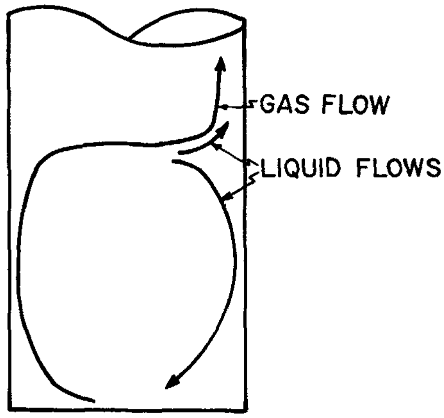

Fig. 6. Escape of liquid from circulation, which disturbs circulation.

If such a circulation exists in some region in the middle of a bubble column, then it will be disturbed not only by this inflow of liquid from above but also by exchange of liquid with the circulating region below it. As a result of these two disturbing influences the regions of bubble columns well away from the sparger are full of wildly chaotic circulations which change size, place, and orientation rapidly.

BAFFLED CIRCULATORY FLOWS

Although the random oscillating circulations described above are the most industrially significant case of a bubble driven circulatory flow, the phenomena involved are much easier to observe and to study if baffles are introduced into the system. Insertion of a vertical baffle can make the circulation stable both in direction and orientation. (Such a flow is considered stable if minor fluctuations die out and do not change the overall flow pattern.)

Such flows will be stable if the velocity of the liquid flow under the baffle is large enough to cause those bubbles formed on the downflow side to flow under the baffle and not to rise against the downflowing liquid. This liquid velocity is obviously a function of gas velocity, geometry of the baffle-sparger system, and bubble size. It is not necessary for all the bubbles formed on the downflow side to flow under the baffle; some small percentage can flow upward, counter to the flow, without destroying the flow stability. Normally, these must grow by coalescence to much larger than average size in order to be able to move counter to the flow.

Figure 7 shows a stable circulatory flow around a flat, vertical, 10 in.-long Lucite baffle. The air enters the water from eight symmetrically placed holes and from all flows under the baffle, rising on its left side. The small, round bubbles on the right side are flowing downward with the downflowing liquid; a few of them may be seen flowing under the baffle. These small bubbles are drawn into the liquid flowing over the top of the baffle. The baffle here appears to be cocked slightly to the right; despite this slight asymmetry, the flow will circulate in either direction around this baffle, its direction being determined by some random event when the flow is started.

Figure 8 shows a stable up-the-center flow in a cylindrical geometry. The cylinder is 12 in. long with a 0.875 in. I.D. and a 1.00 in. O.D. It is supported from above by a rigid rod of 0.375 in. O.D. In Figure 8 all the bubbles are formed at orifices further from the center of the column than the outside diameter of the cylindrical riser. Nonetheless, they are dragged by the fluid into the center and all flow up the center. The small bubbles seen in the annular space are flowing downward; they were sucked into the downward flow in the annulus from above.

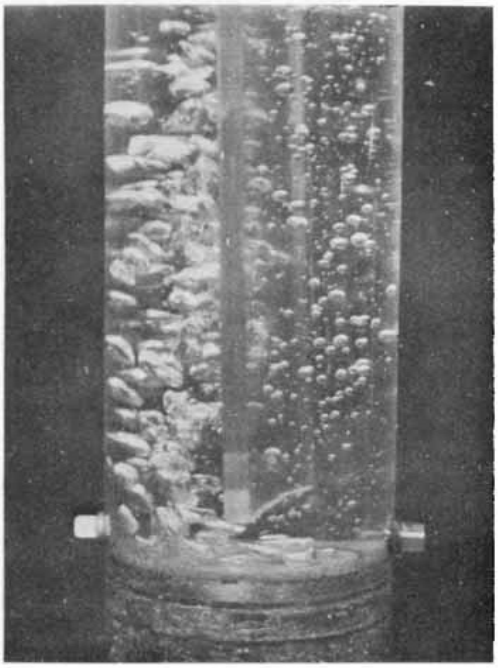

Fig. 7. Stable circulation in a symmetrical baffled system.

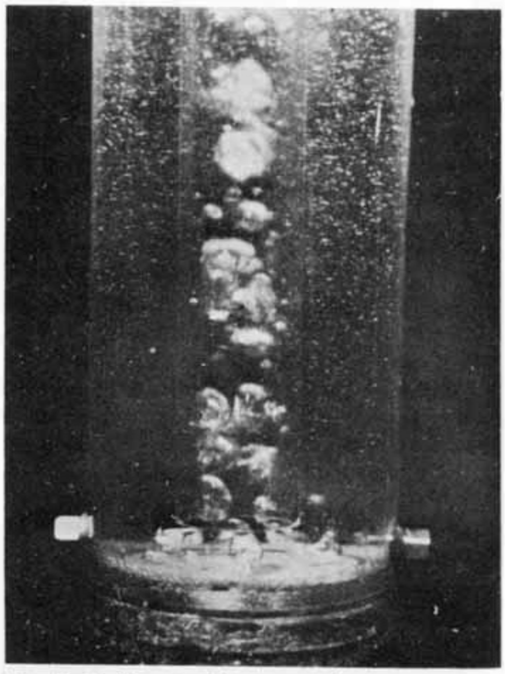

Fig. 8. Stable circulatory up-the-center flow in a cylindrical-annular geometry.

If the circulatory flow in some baffled system is stable, then the noncirculatory flow in the same system is unstable. For example, for the system shown in Figure 7, if the liquid level (expanded owing to the presence of bubbles) is lower than the top of the baffle, then the bubbles rising from the sparger will rise about equally on both sides of the sparger. If the liquid level is raised to be above the top of the baffle, then the flow will rapidly take up the circulatory flow mode. Which direction it takes is a chance occurrence (which can be influenced by manually tilting the column to one side or the other). Once the circulation begins, it will continue indefinitely in the same sense unless the external conditions are changed.

CYLINDRICAL GEOMETRY

If one inserts a cylindrical baffle open at both ends into such a flow, he divides the flow into cylindrical and annular regions instead of dividing it into two identical regions as the plane baffle does. In this geometry the flow can be up the annulus or up the center. Both of these modes are observable in equipment with a fixed geometry at a fixed flow rate.

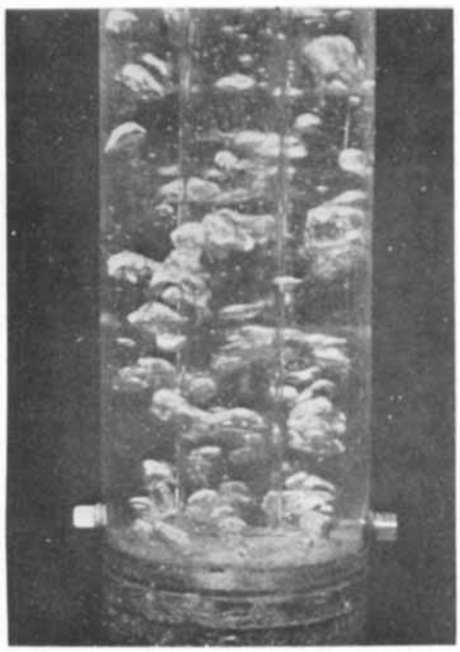

Fig. 9. Down-the-center circulatory flow in a cylindrical-annular geometry.

Figure 9 shows a down-the-center flow with the same geometry and flow rate shown in Figure 8. The flow in the annulus is chaotic with circulations imposed on the overall vertical flow; this can be observed by the distorted shapes of the bubbles in the annulus. On the other hand the bubbles which are flowing down the center are smooth and have the spherical cap shape described by Davies and Taylor (*14*) for large bubbles not influenced by surrounding walls. One of these is seen in the center about one-fourth of the way up the picture.

In small diameter equipment the up-the-center mode is more stable over most of the flow velocity regime because of the formation of large bubbles in the center. When the flow is down the center, bubbles are sucked in and flow downward. Occasionally they coalesce, forming a large bubble. This bubble takes on a bullet shape and remains almost motionless in the tube, held in place by the balance between its buoyant force and the drag of the fluid flowing around it. Frequently, such a bubble grows large enough practically to fill the tube, thus stopping the flow. When the flow is stopped, it then reverses and flows the other way, thus initiating up-the-center flow. Figure 10 shows such a bubble in the process of converting the flow from down-the-center mode to the up-the-center mode. The bubble is of the type reported by Davies and Taylor (*14*) for the emptying of vertical tubes and is located about half way up the photograph. Since there is no corresponding type of large bubble formed in the annulus when the flow is down the annulus, this phenomenon can switch the flow from up the annulus to up the center but not the reverse; hence, the greater stability of the up-the-center mode.

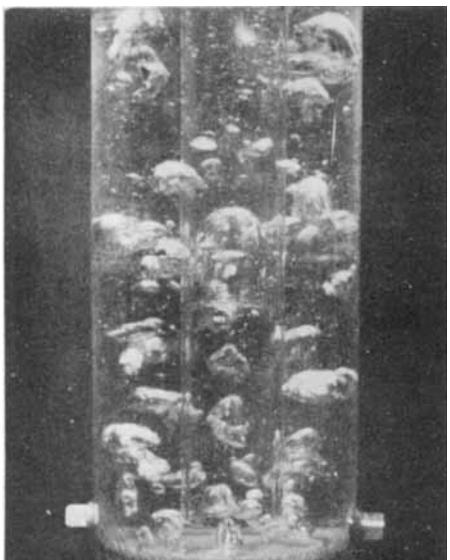

Fig. 10. Down-the-center circulatory flow converting to up-the-center circulatory flow in a cylindrical-annular geometry.

MIDCOLUMN CIRCULATIONS

The types of flow shown with baffles in Figures 7, 8, and 9 are all observable in an unbaffled bubble column with masses of gases rising through a liquid. However, these are not stable; in the absence of a baffle they switch quickly from one mode to the other. From the experimental data shown in Figure 1, it is apparent that at low flow rates, where circulations are not present, the average rise velocity of the bubbles is about 0.5 to 0.6 ft./sec. At the higher flow rates, where the principal mode of transport is by fluid circulations, the average fluid velocity is proportional to the gas superficial velocity, the proportionality constant being about 3.

CONCLUSIONS

1. Bubble driven fluid circulations are caused by the density differences between regions richer and poorer in bubbles.
2. These circulations are easily demonstrated; they are quite stable in baffled systems and take on interesting forms in different geometries.
3. In unbaffled systems these circulations are unstable and change size, shape, and orientation chaotically. These chaotic circulations provide the principal mode of vertical bubble transport in bubble columns over a wide range of operating conditions.

ACKNOWLEDGMENT

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NOTATION

g = acceleration of gravity, ft./sec.^{2}
h = height of a circulation, ft.
h_b = height of a baffle, ft.
L = length in the flow direction, ft.
n = exponent in Equation (5), normally about 4
P = pressure, lb.$_f$/sq.ft.
u = velocity, ft./sec.
u_{avg} = average velocity of a swarm of bubbles, measured relative to the fixed container, ft./sec.
u_s = superficial velocity of gas flow = volumetric flow rate of gas/cross-sectional area of column, ft./sec.
u_t = terminal velocity of rise for a single bubble in an infinite quiescent liquid, ft./sec.
w = width of circulation, ft.
ϵ = volume fraction of gas-liquid mixture occupied by gas
ρ_L = liquid density, lb.$_m$/cu.ft.

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