APPARATUS FOR PRODUCING BUBBLES OF VERY SMALL, MICROSCOPIC SIZE

ABSTRACT: An apparatus is provided for producing bubbles of 5 to 10 micron size in a liquid by a sparger inside a pipe wherein the clearance between the sparger and the pipe is maintained in relation to the velocity of the liquid passing over the sparger such that the height of the laminar sublayer in the liquid is maintained less than 10 microns. The bubbles are produced by pressure perturbations in the turbulent layer above the laminar sublayer such that as gas issues from the sparger through the laminar sublayer the pressure perturbations will snap off the bubbles before they can grow larger than 10 microns in size. A narrow annular passageway is provided between the sparger and pipe. This annular passageway is provided with an increasing taper in the downstream direction of the liquid stream. The taper increase in flow cross section produces a corresponding pressure increase in the liquid stream in the direction of flow which is sufficient to compensate for the pressure drop due to friction losses. The liquid flow pressure over the surface of the sparger is maintained uniform. A stream lined tail cone portion is attached to the downstream end of the sparger. A convergence in the inner wall of the shell member in juxtaposition with the tail cone portion forms an exit passage of reduced cross section for the liquid stream. A handwheel is attached to the sparger for axially displacing the sparger relative to the shell member for adjusting the clearance space between the tail cone portion and the exit passage.
This invention is directed to means for producing large, homogeneous quantities of gas bubbles of microscopic size on the order of 5–10 microns in diameter. The invention finds particular utility in applications requiring the interchange of gases with liquids; for example, sewage treatment, water chlorination, petroleum processing, aeration, oxygenation, and other processes wherein a gas-phase material is to be dissolved or dispersed into a liquid medium medium.

The present invention utilizes the distinctive boundary layer characteristics of turbulent fluid-flow phenomena in order to achieve the consistent production and dispersion of large, homogeneous quantities microscopically sized bubbles (hereinafter sometimes referred to as microbubbles). The means of the present invention differs primarily from prior art techniques for the production of bubbles in that (1) dense clouds comprised exclusively of very large numbers of bubbles of microscopic size, on the order of 5–10 microns in diameter, are consistently produced and dispersed into the liquid medium without coalescence, and (2) after certain critical flow field conditions are attained, the production of the microbubbles according to the present invention proceeds virtually independently of increasing gas flow rate or fluid velocity. In order to better distinguish the manner in which the present invention differs from that of prior processes, the nature of some of the commonly used techniques for producing gas bubbles will be briefly reviewed.

In the airstone principle, which is an extension of the technique of blowing bubbles through a plurality of capillary tubes, the gas stream is forced through a porous surface having a large number of flow passages of very small diameter. The buoyant forces of the liquid medium above the airstone is utilized as the sole mechanism for detaching the bubbles from the surface. The size of the resultant bubbles, which is related to the flow rate of the gas stream, is not exceptionally small nor homogeneous, and it is rare for bubble sizes less than 1,000 microns in diameter to produced.

In order to improve the mechanism of bubble production by the airstone principle and to obtain bubbles of smaller size, it has been conventional to impart a flow of relatively low velocity to the fluid medium in order to detach the bubbles away from the gas outlets and into the liquid. In such a system the viscous forces of the fluid flow shear the bubbles off of their gas outlets at a preameter size, and the resultant bubble size is then a function of both the gas and liquid flow rates. However, as first recognized in the present invention, unless certain critical flow conditions are present in the fluid stream, homogeneous clouds of gas bubbles of microscopic size will not be consistently produced.

In the present invention, a turbulent boundary layer is established in a liquid flow passing over a suitable bubble-producing surface, which may be in the form of a porous plate, cylinder, or the like having a large number of flow passages of sufficiently small diameter to permit production at the interface of bubbles of micron size. The liquid flow is made sufficiently turbulent such that an intense velocity gradient is present near the surface of the gas phase, and the result of pressure perturbations around the bubble which are of the magnitude necessary to overcome the relatively high interface forces securing the bubble to the surface. Detachment of the bubbles from the surface then occurs as a result of forces applied normal to the surface as the bubble responds to the random but highly frequent pressure variations in the turbulent boundary layer. However, and most importantly, in order to ensure the creation of bubbles of the desired microscopic size, it is critical that the laminar sublayer of film, which exists in the boundary layer of the liquid flow between the turbulent stream and the bubble-producing surface, have a thickness which is approximately equal to, or less than, the diameter of the desired microbubbles to be produced.

It is characteristic of the present invention that, once suitable conditions have been established for the production of microbubbles by the attainment of a satisfactorily high flow velocity in the liquid stream, the flow rate of the introduced gas may be increased independently without affecting the size of the bubbles produced. Conversely, once the conditions of microbubble production are established, any increase in the velocity of the liquid flow similarly will not substantially affect the size or rate of production of microbubbles.

Control of the thickness of the laminar sublayer in the turbulent boundary layer of the fluid flow is the crucial parameter in determining the ultimate size of the produced bubbles. From empirical tests it has been determined that the thickness of this laminar sublayer should preferably be on the order of 0.9 of the diameter desired for the resultant gas bubbles. While the growing bubble remains entirely in this region of laminar flow, which exists between the surface of the bubble-producing gas outlets and the turbulent boundary layer of the fluid, it is subjected only to viscous shear stresses; however, once the hemispheric of the growing bubble enters into the region of the turbulent boundary layer, the bubble is then subject to the severe and irregular pressure variations, normal to the surface wall, which are characteristic of turbulent flow and produced by the transfer of fluid masses between adjacent layers. These pressure perturbations serve to snap off the bubble from its gas outlet before further growth permits it to protrude to any substantial depth into the turbulent boundary layer.

In an exemplary embodiment of the present invention, apparatus has been provided for accomplishing the desired microbubble production by utilizing the boundary layer phenomena described above. Means are provided in the apparatus for controlling the flow rate of liquid past the bubble-producing surface in order to establish the desired turbulent bubble boundary layer and for regulating the thickness of the associated laminar sublayer. Once the predetermined critical flow conditions are established, the apparatus will then produce and disseminate into the liquid stream dense, homogeneous clouds of very fine, microscopically sized gas bubbles.

It is therefore a principal objective of the present invention to provide apparatus for producing large, homogeneous quantities of extremely small, microscopically sized gas bubbles. It is another objective of the present invention to provide apparatus for improving the intermixing of gases with liquids.

It is a characteristic feature of the present invention that a turbulent fluid flow stream is utilized to produce gas bubbles of extremely small size on the order of 5–10 microns in diameter.

It is another distinctive feature of the present invention that the size of the resultant gas bubbles is on the same order of magnitude as the thickness of the laminar sublayer present in the boundary layer of the turbulent fluid flow.

It is an important advantage that the size of the microscopically small bubbles produced by the process of the present invention is independent of both the gas flow rate and the velocity of the fluid stream, as long as certain boundary layer conditions, conditions are maintained in the fluid flow.

The foregoing and other objectives, features, and advantages of the present invention will be more readily understood upon consideration of the following detailed description of the invention, taken in conjunction with the accompanying drawings.

FIG. 1 is a schematic diagram illustrating the boundary layer conditions present in the flow of a turbulent stream of liquid over a flat, smooth surface.

FIG. 2 is a schematic diagram, similar to FIG. 1, showing the progressive growth of bubbles from gas outlets in a porous plate.

FIG. 3 is a front sectional view, partially broken away, of an exemplary embodiment of apparatus for producing microbubbles in accordance with the present invention.

FIG. 4 is a cross-sectional view, taken along the lines 4-4 in FIG. 3.

FIG. 5 is a sectional view, taken along the lines 5-5 in FIG.
Referring now to FIG. 1, which will be useful for background purposes in understanding the fluid flow phenomenon in the present invention, there is shown a velocity profile diagram of the boundary layer conditions which are present in the flow of a turbulent stream over a flat, smooth plate or boundary wall 10. As is presented by the curve 12, the velocity of the fluid at points along a vertical section of the flow is zero at the surface of the boundary wall 10 and increases asymptotically to a constant value v in the laminar region 16 outside the turbulent boundary layer 11.

The fluid in the region 13 of the boundary layer immediately adjacent to the boundary wall 10 moves very slowly in parallel layers, and there is no transfer of fluid masses between adjacent layers in the flow. In this region 13, known as the laminar sublayer or film, the fluid flow is laminar in nature, its velocity gradient follows a linear relationship with increasing distance from the boundary wall 10, and the pressure differential is small and uniform within this sublayer.

However, at a certain distance a away from the boundary wall 10, a transition is made into the turbulent region 14 where there is a relatively high velocity flow with a continuous intermix of fluid masses and transfer of momentum between adjacent layers. While, in this region 14, the fluid mass as a whole moves downstream, there is a generally steady average velocity, there are sharply fluctuating velocity components occurring in all directions. The flow pattern is unsteady, full of eddies, and apparently without any mathematically expressible regularity. These irregular and abrupt velocity fluctuations produce corresponding severe pressure variations within the turbulent region 14 of the fluid flow.

It should be recognized that the transition or interface 15 between the laminar sublayer 13 and the turbulent region 14 of the boundary layer is not in actuality a sharply defined edge, as indicated in the diagram; however, for purposes of simplifying the explanation of the invention the assumption will be made that the transition from laminar to turbulent flow is made abruptly at the edge 15. Using a generally accepted approach in the art, i.e., the Karman-Prandtl equation for the velocity distribution in turbulent flow near smooth boundaries, the transition line 15 may be nominally defined by the intersection of two curves: a straight line curve representing the essentially linear nature of the velocity gradient in the laminar sublayer 13, and a logarithmic curve representing the more complex relationship between flow velocity and distance from the boundary wall in the turbulent region 14. (For a detailed description of the flow phenomena occurring in a turbulent boundary layer, as well as the mathematical treatment thereof, reference may be made to any one of a number of standard treatises in the field of fluid dynamics, such as, for example, Honn, Elementary Mechanics of Fluids (Second Edition), Chapter VII, Wiley and Sons, New York, 1950.) Thus, as a generalization, it may be considered that flow in the fluid stream on the near side of the transition line 15 at distances of a or less away from the boundary wall 10 is laminar; while, on the other side of the line, the flow at distances greater than a is essentially turbulent in nature.

In FIG. 2 the fluid flow, schematically represented in FIG. 1, is now shown as passing over a porous plate or boundary wall 10 10' provided with a number of minute openings 20. These openings 20 act as outlets for a gas stream supplied under pressure to the underside of the porous plate 10'.

As gas emerges from each of the outlets 20 and is introduced to the fluid streams, growing bubbles such as B1 are formed on the upper surface of the porous plate 10'. During the time that the growth of the gas bubble B1 is relatively small and contained within the laminar sublayer 13 which exists in the region immediately adjacent the surface of the plate 10', the bubble will be subjected to only moderate shear and buoyant forces tending to detach it away from its outlet 20. If, for example, the fluid flow is comprised of water or other suitable liquid, the adhesive forces of surface tension produced at the gas-liquid interface of the bubble will be more than sufficient to prevent its detachment during this time.

However, once the hemisphere of the growing bubble protrudes beyond the relatively tranquil flow of the laminar sublayer 13 and into the turbulent boundary layer, the bubble, shown at B2, is then subjected to extremely strong detachment forces which are normal to the surface 10' and produced by the severe pressure fluctuations present in this latter region. These forces, which are of much greater intensity than those encountered while the growth of the bubble was confined entirely to the laminar sublayer 13, pluck off the bubble, now shown as B3, from its outlet 20 and thrust it into the flowing fluid stream before any significant amount of further growth is permitted to occur. Thus, the completed bubble B3 attains, at the instant of detachment from the surface 10', a size dimension d which is on the same order of magnitude as the thickness a of the laminar film 13. Since the laminar film in a turbulent boundary layer is very thin and on the order of only a few microns in thickness, the size of the detached bubble B3 is similarly quite small, typically being in the range of 5 to 10 microns in diameter.

As the thickness a of the laminar sublayer 13 remains constant with time and does not vary significantly along the direction of turbulent flow over the boundary wall 10', all of the completed bubbles B3 formed by the above-described process will have sizes resulting in the production of a homogeneous cloud of microscopically sized gas bubbles. Furthermore, since the thickness a of the laminar sublayer 13 decreases only slightly with increasing flow velocity in the turbulent boundary layer 11, any change in the velocity of the fluid stream will not substantially affect the size or rate of production of the resulting microbubbles. As long as turbulent flow conditions are maintained, the process permits a ready determination to be made as to whether the proper flow conditions have been established in a system for the production of microbubbles according to the principles of the present invention.

FIGS. 3-5 illustrate an exemplary embodiment of an apparatus which has been constructed for producing microbubbles in accordance with the present invention.

The apparatus 30 comprises a cylindrical spargor portion 35 having a porous surface 35' with an average pore diameter of 5 to 10 microns—a pore size which is slightly less than the size of the resulting microbubbles to be produced. The sparger 35 is mounted inside an outer shell member 34, the clearance between which is tapered inward toward the left-hand end of the apparatus for reasons that will hereinafter be explained. Of course, either the inner wall of the shell 34, as shown in FIG. 3, or the outer surface 35' of the sparger 35, may be configured to have the required taper. For construction and mounting purposes, the shell member 34 is in two parts flanged together at 26 with connecting bolts 26a and sealing gasket 26b. A set of longitudinally extending guide vanes 45, attached to the inner wall of the shell member 34 by fasteners 45a, maintain the sparger 35 in a coaxial relationship inside the shell member with a small tapered passageway 49 therebetween whose cross section, as shown in FIG. 4, is in the form of a segmented annular ring.

With fluid and gas flows both proceeding from left to right in the diagram of FIG. 3, the left-hand, or upstream, end of the sparger 35 is joined through a connector 47 to a gas inlet pipe 53. The left-hand end of the shell member 34 is connected to joint 38 threaded with a handwheel assembly 41, 42, 43 which enables the sparger 35 to be adjustably positioned along the
axial shell. Also at the upstream end of the apparatus, a fluid inlet pipe 32 is connected at right angles through joint 38 to the shell member 34.

At the right-hand, or downstream, end of the apparatus the sparger 35 is terminated in a hydrodynamically streamlined tail cone portion 36, and the shell member 34 converges at 34a into a discharge line connector 37. Thus, by longitudinal displacement of the sparger 35 through operation of the handwheel 42, the size of the fluid passage 51 between the tail cone 36 and the converging walls 34a of the shell member may be adjusted, similar to a valve, to provide a flow control point downstream of the sparger 35 of for reasons which will be shortly explained.

As shown in FIG. 3, it the fluid flow from the inlet pipe 32 (represented by the solid arrows 31), after it enters the apparatus at joint 38 and makes a right-angled turn, then passes into the narrow annular passageway 49 which surrounds the body of the sparger cylinder 35. Due to this severe constriction in the cross-sectional area of the fluid flow as it travels through the annular passageway 49, boundary turbulent shear flow will be produced in the fluid stream (assuming the fluid entering at inlet pipe 32 is of a suitable velocity).

As the turbulent flow proceeds through the narrow annular passageway 49, as shown in FIG. 3 (represented by the dashed arrows 40) at the boundary wall presented by the porous surface 35' of the sparger. The combined fluid-gas flow stream (represented by the dotted-dashed arrows 50) then emerges at the downstream end of the apparatus 30 passing through the clearance space 51 around the tail cone portion 36 of the sparger and thereafter into the discharge line connector 37 from which it is exhausted.

The purpose of providing a taper in the annular passageway 49 is to maintain the flow pressure constant along the length of the cylindrical body of the sparger 35. If the fluid-gas differential pressure in the fluid passing over the porous surface 35' of the sparger body is not kept uniform, there will be the possibility that the gas will be injected into the fluid flow at too great velocity at some points, or that, due to excessive fluid pressure, fluid will seep into the porous sparger at other points.

When the gas flow 40 inside the hollow sparger body is at essentially a constant pressure throughout it is therefore necessary to maintain constant as well the fluid pressure on the outside of the sparger, in order that a uniform fluid-gas pressure distribution exist along the length of the interface boundary surface 35'.

In order to counteract the pressure drop in the fluid flow caused by friction as the fluid travels along the length of the sparger body, the cross-sectional area of the fluid flow is gradually increased in the downstream direction by means of the taper so that the consequent decrease in fluid velocity, due to the enlarging cross section, produces a pressure increase which just compensates for the pressure decrease due to friction losses. (The amount of the taper which must be provided in the passageway 49 to achieve the desired degree of compensation can be readily calculated by known fluid dynamics techniques, taking into account the parameters of the flow system.)

In operation, with an illustrative set of flow parameters, the required turbulent flow conditions for the production of microbubbles according to the present process may be established in the apparatus by the adjustment of the sparger cylinder 35 for optimum pressure and flow rate characteristics in the following manner: A high fluid flow rate 31, on the order of 100 gallons per minute or greater, is established through the apparatus 30 with the sparger cylinder 35 located in the maximum upstream position (i.e., to the left as shown in FIG. 3). By means of the adjustment provided by the handwheel 42, the sparger 35 is then slowly moved in the downstream direction (i.e., toward the right in FIG. 3), moving the tail cone 36 closer to the converging walls 34a. The constriction of the fluid flow in the tail cone region 51 will, in much the same manner as a valve, cause the flow of fluid 31 passing over the surface 35' of the sparger body to decrease, while the pressure head slowly builds up.

The placement of the low control point, which is provided by the valve action in the tail cone region 51, at a location downstream of the sparger body 35 is an important feature of the sparger design. If a flow constriction, having a smaller cross-sectional area than the minimum clearance area in the tapered annular passageway 49, is not provided downstream of the sparger body, then a differential pressure drop will occur in the fluid flow somewhere along the surface 35' of the sparger. This differential pressure drop will, under certain circumstances, move rapidly back and forth along the sparger surface 35' and will completely disrupt the formation of microbubbles according to the disclosed process. By movement of the sparger along the axis to control the area of constriction in the tail cone region 51, and thereby causing the required pressure drop at a point downstream of the sparger body 35, a constant pressure along the entire surface 35' of the sparger body may be easily maintained.

As the pressure head in the fluid flow begins to increase sharply due to the constricted flow at the tail cone region 51, reaching 75 p.s.i. or so, the gas stream is then induced into the center of the porous sparger 35, via the inlet line 33, at a flow rate of 10 to 15 volumetric cubic feet per minute. With the position of the sparger thus adjusted to produce a turbulent boundary layer over the surface of the cylinder, the bubbles of gas forming at the surface pores 35' or of the sparger 30 will be detached and swept into the fluid as soon as they project beyond the laminar sublayer of the flow, thus producing microbubbles in accordance with the process disclosed earlier. The gas flow 40 may thereafter be increased to any desired rate without affecting the production of microbubbles, the flow rate of gas being limited only by the crowding of attached bubbles during their formation on the porous surface 35' of the sparger 35.

The narrow tapered passageway over the sparger body, together with the valve action provided by the axial adjustment of the sparger which establishes a flow control point for pressure head control downstream of the sparger body, enables the production of gas bubbles of microscopic size in the sparger apparatus 30 without the need for any external adjustment of the liquid or gas flow rates. The only limiting condition on the operation of the apparatus is that the fluid flow rate must exceed a certain minimum value corresponding to the establishment of the necessary fluctuating turbulent flow field over the porous cylindrical body 35' of the sparger so that microbubbles will be produced.

The terms and expressions which have been employed here are used as terms of description and not of limitation, and there is no intention, in the use of such terms and expressions, of excluding equivalents of the features shown and described, or portions thereof, it being recognized that various modifications are possible within the scope of the invention claimed.

I claim:

1. An apparatus for producing large homogeneous quantities of gas bubbles of microscopic size of 10 microns or less in diameter, comprising:
   a. a bubble-producing surface having a plurality of gas outlets of smaller diameter than that desired of said resultant bubbles;
   b. a surface opposing said bubble-producing surface and forming therewith a passageway for liquid flow;
   c. means for passing a liquid flow therethrough at positive pressure;
   d. means for adjusting the velocity of said liquid flow in relation to said passageway to establish a turbulent boundary layer therein, said boundary layer being comprised of a turbulent region having severe and irregular velocity fluctuations therein and a laminar sublayer having a regular linear velocity gradient, said sublayer being situated beneath said turbulent region and adjacent said bubble-producing surface and having a thickness comparable to the diameter desired of said resultant bubbles, said sur-
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faces diverging in the direction of said flow to compensate for friction losses in said flow to maintain fluid pressure on said bubble-producing surface constant over its length; and

e. means for supplying a gas stream to the outlets on said bubble-producing surface, whereby gas bubbles forming on said surface are detached therefrom and carried into said liquid flow when the size of said forming bubbles begins to exceed the thickness of said laminar sublayer and to project into said turbulent region.

2. The apparatus set forth in claim 1 further including means for maintaining uniform the liquid-gas pressure differential at said bubble-producing surface by compensating for frictional losses in said liquid flow thereover.

3. The apparatus set forth in claim 1 further including means for controllably constricting said liquid flow at a position immediately downstream of said bubble-producing surface, thereby to prevent the creation of a differential pressure drop in said fluid flow at a location on said surface.

4. The apparatus set forth in claim 1, further including means for providing a flow control point in said liquid flow at a location downstream of said bubble-producing surface, comprising:

a. an end portion on said bubble-producing surface;
b. a convergence in said opposing surface in juxtaposition with said end portion to form an exit passage of reduced area for said liquid flow; and
c. means for displacing said bubble-producing surface along a line parallel to said liquid flow relative to said opposing surface for adjusting the size of the clearance space between said end portion and said exit passage.

5. An apparatus for producing large homogeneous quantities of gas bubbles of microscopic size of 10 microns or less in diameter, comprising:

a. a hollow sparger having a porous, cylindrical surface with an average pore diameter of 5 to 10 microns in diameter;
b. a cylindrical shell member coaxial with said sparger and having an inner wall greater size;
c. the arrangement of said sparger surface and the inner wall of said shell member forming an annular, narrow passageway therebetween;
d. means for supplying a pressurized stream of gas to the inside of said sparger for dispersion to the outside through the surface pores thereof; and
e. means for directing a liquid stream into said passageway at a pressure of at least 75 p.s.i. to establish a turbulent boundary layer over the surface of said sparger, wherein said annular passageway is provided with an increasing taper in the downstream direction of said liquid stream, the tapered increase in flow cross section producing a corresponding pressure increase in said liquid stream in the direction of flow which is sufficient to compensate for the pressure drop due to friction losses, whereby the liquid flow pressure over the surface of said sparger is maintained uniform.

6. An apparatus for producing large homogeneous quantities of gas bubbles of microscopic size of 10 microns or less in diameter comprising:

a. a hollow sparger having a porous, cylindrical surface with an average pore diameter of 5 to 10 microns in diameter;
b. a cylindrical shell member coaxial with said sparger and having an inner wall of greater size;
c. the arrangement of said sparger surface and the inner wall of said shell member forming an annular, narrow passageway therebetween;
d. means for supplying a pressurized stream of gas to the inside of said sparger for dispersion to the outside through the surface pores thereof; and
e. means for directing a liquid stream into said passageway at a pressure of at least 75 p.s.i. to establish a turbulent boundary layer over the surface of said sparger, and
f. means for providing a flow control point in said liquid stream at a location downstream of said sparger surface, said means comprising, a streamlined tail cone portion attached to the downstream end of said sparger, a convergence in the inner wall of said shell member in juxtaposition with said tail cone portion to form an exit passage of reduce cross section for said liquid stream, and means for axially displacing said sparger relative to said shell member for adjusting the size of the clearance space between said tail cone portion and said exit passage.

7. An apparatus for producing large homogeneous quantities of gas bubbles of microscopic size 10 microns or less in diameter, comprising:

a. a hollow sparger having a porous, cylindrical surface with an average pore diameter of 5 to 10 microns in diameter;
b. a cylindrical shell member coaxial with said sparger and having an inner wall of greater size;
c. the arrangement of said sparger surface and the inner wall of said shell member forming a generally annular, narrow passageway therebetween;
d. means for supplying a pressurized stream of gas to the inside of said sparger for dispersion to the outside through the surface pores thereof; and
e. means for directing a liquid stream into said passageway at a pressure of at least 75 p.s.i. to establish a turbulent boundary layer over the surface of said sparger; and
f. means for providing a flow control point in said liquid stream at a location downstream of said sparger surface, said means comprising:

i. an end portion on said sparger;
ii. a convergence in the inner wall of said shell member in juxtaposition with said end portion to form an exit passage of reduce cross section for said liquid stream; and
iii. means for axially displacing said sparger relative to said shell member for adjusting the size of the clearance space between said end portion and said exit passage.