THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

AIR-BUBBLE GENERATOR

BY J.J. DONOGHUE

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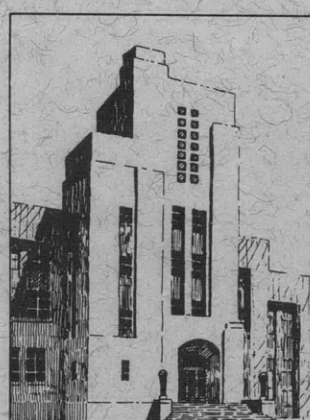

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PERSONNEL

The experimental work was performed by F. Bird and J.J. Donoghue. This report is the work of Mr. Donoghue.

AIR-BUBBLE GENERATORS

ABSTRACT

Methods of generating air bubbles in water are reviewed. The effects on the bubble size of such variables as surface tension and viscosity are discussed, with reference to the work of other investigators. Two generators are described for producing uniform and reproducible screens of air bubbles. In the first design moving a stream of water past the air orifices shears off bubbles of uniform size. In the second design, the release of a high pressure over a saturated solution of air in water generates very fine bubbles.

INTRODUCTION

In the course of an investigation of various underwater sound and explosion phenomena at the David W. Taylor Model Basin, two air-bubble generators were developed to suit the special requirements of the current test program. Although the production of air bubbles under water in a random distribution is quite simple, underwater sound measurements require that the size and concentration of the bubbles and the thickness of the bubble screen be reproducible for successive tests.

A search of the literature revealed various designs of bubble generators in use in industry and research, but none of them was suitable for the purpose in hand. The principles involved have been described by many investigators, but so far as is known they have not been applied in the manner here described.

Gas bubbles have many industrial uses, as set forth in Appendix 1. They may vary in size from those with diameters greater than 0.5 inch, such as are used to agitate the water above a dam to prevent freezing, to those with diameters less than 0.001 inch, as used in the emulsion process for producing hollow rayon threads. Intermediate sizes are used in ore-leaching and sewage-disposal plants, and in various manufacturing processes.

The generators for making these bubbles are of various types. They include simple orifices emitting air, special nozzles and shearing devices to control the bubble sizes, and several methods of producing extremely fine air bubbles, such as electrolysis, chemical reactions, and dissolution due to pressure reduction over gas-saturated water. Appendix 2 contains an outline classification of the known types of bubble generators.

In the first generators tested at the Taylor Model Basin, variables existed which were not easily controlled, and a design was sought which would eliminate their defects.

This report describes in detail two satisfactory bubble generators developed after a series of experiments, set forth at some length in Appendix 3 and based largely on the work of previous workers in this field. This appendix is a critical review of various typical methods of bubble generation and a summary of experiments conducted with some of them at the Taylor Model Basin.

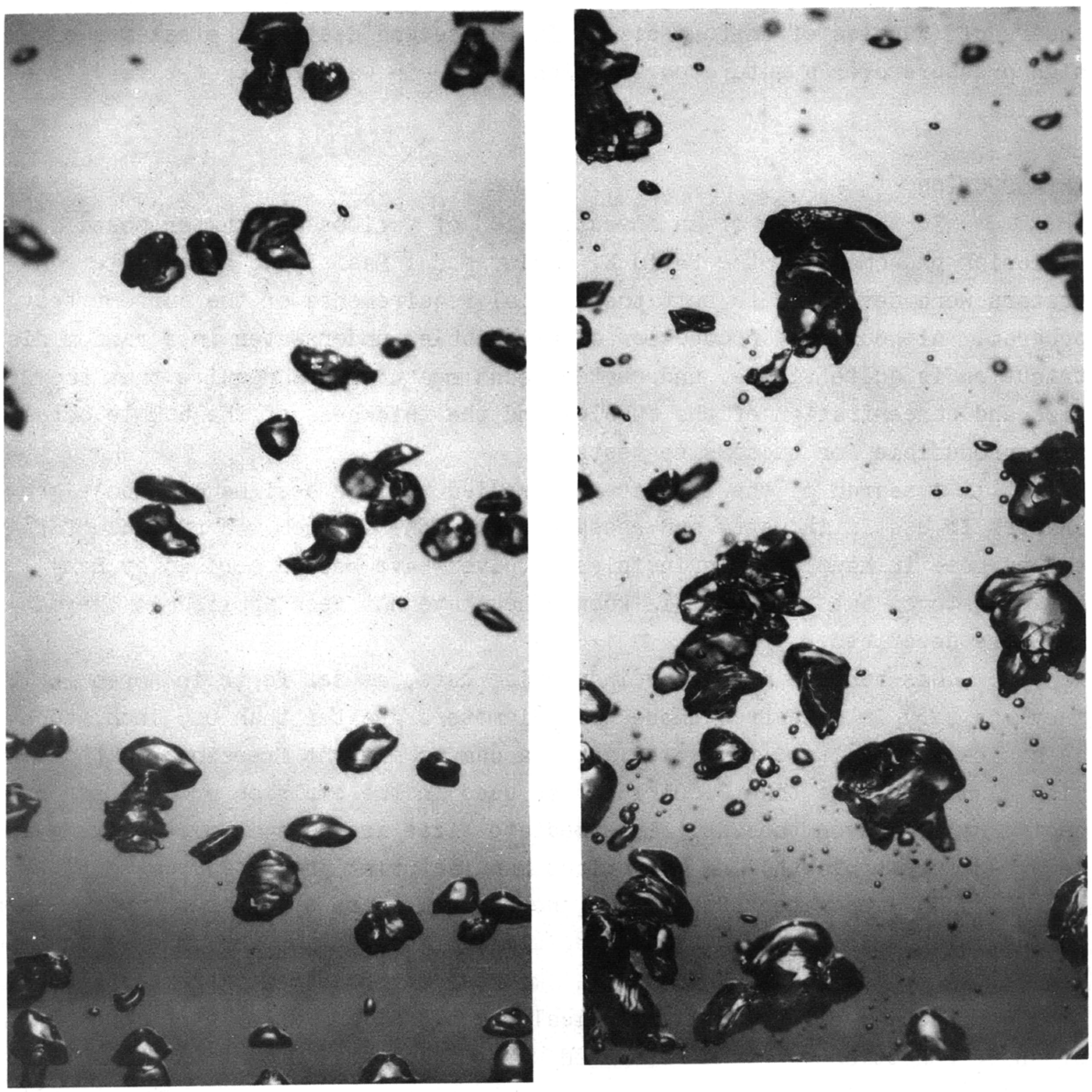

Figure 1a
The air flow is 0.016 cubic feet per minute per orifice and the water flow is zero.

Figure 1b
The air flow is 0.05 cubic feet per minute per orifice and the water flow is zero.

Figure 1 - Bubbles Generated by Forcing Air through Simple Orifices, 0.025 inch in diameter

The orifices are not visible. They are spaced three-quarters of an inch apart.

SHEAR-TYPE BUBBLE GENERATOR

The forces that act to remove the growing bubble from its attachment to an orifice determine its time of release, and therefore its size.

A bubble forming in still water breaks away from the orifice when its buoyancy overcomes the attractive forces. These forces vary greatly with the impurities in the water. For example, if the surface tension of the liquid that wets the orifice is decreased, the bubble formed is smaller, because the decrease in the holding force due to the surface tension has decreased the time of contact. Some variations in the sizes of air bubbles produced from a simple orifice under water are shown in Figure 1.

A dynamic method of shearing off the air bubble as it emerges from an orifice would decrease the variation in size resulting from variations in these forces. This is accomplished in a shear-type generator by moving water past the orifice.

Figure 2 shows the detail of one nozzle of the shear-type bubble generator designed at the Taylor Model Basin. The jet of water flowing past the air nozzle shears off air bubbles whose diameters are determined by the relative rates of flow of air and water. The positions of the nozzles for air and for water are fixed relative to each other so that the behavior of the nozzles does not change.

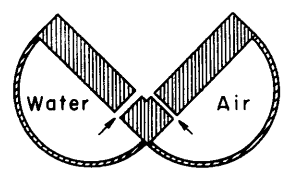

Figure 2 - A Section of One Nozzle of a Shear-Type Generator

The diameter of the air orifice is 0.025 inch and that of the water orifice is 0.055 inch.

The number and size of the bubbles may be varied within wide limits, by varying the relative rates of flow of air and water. The range of size may be shifted by changing the diameters of the air and water holes.

With no water flow, the bubble size is that produced by a simple air jet under water, as shown in Figure 1a. As the air flow is increased the size of the bubble is increased, as can be observed from Figure 1b, but not the number of bubbles per second (1) (2) (4) (5) (6).*

The photographs of Figure 3 show the variation in the size of the air bubbles produced with a constant air flow, as the water flow is increased.

As the water flow increases, with constant air flow, the size of the bubbles decreases and their number increases; compare Figures 1a, 3a, and 3b. At increased water flow rates the bubble diameters approach the diameter of the orifice. The water flow in the tests described was limited by the available pressure head.

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* Numbers in parentheses indicate references on page 8 of this report.

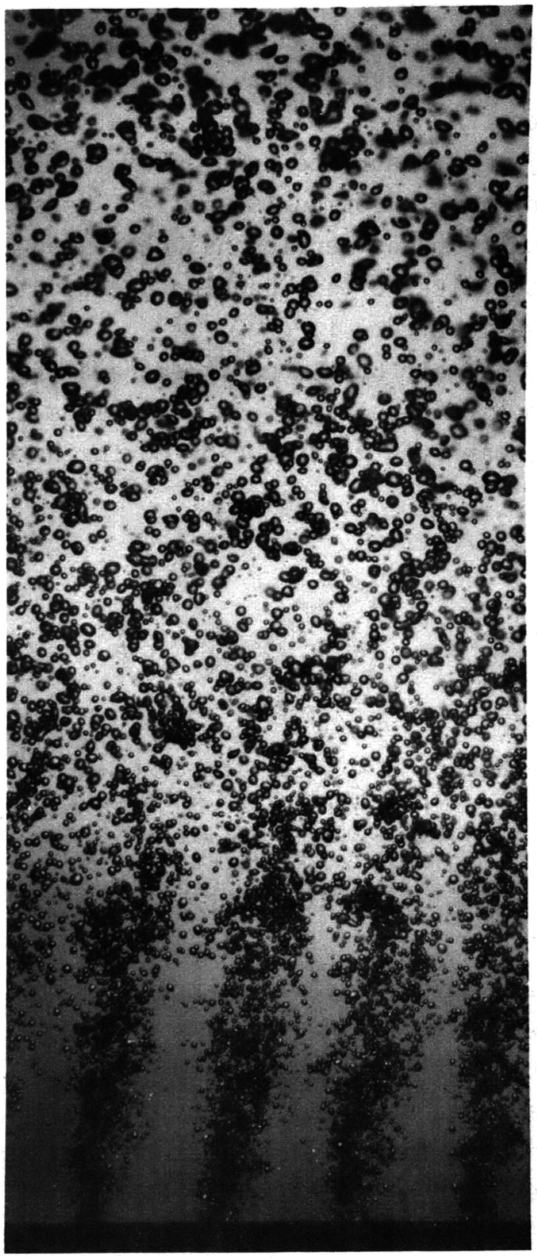

Figure 3a
The air flow is 0.016 cubic feet per minute per orifice and the water flow is 0.1 gallon per minute per orifice.

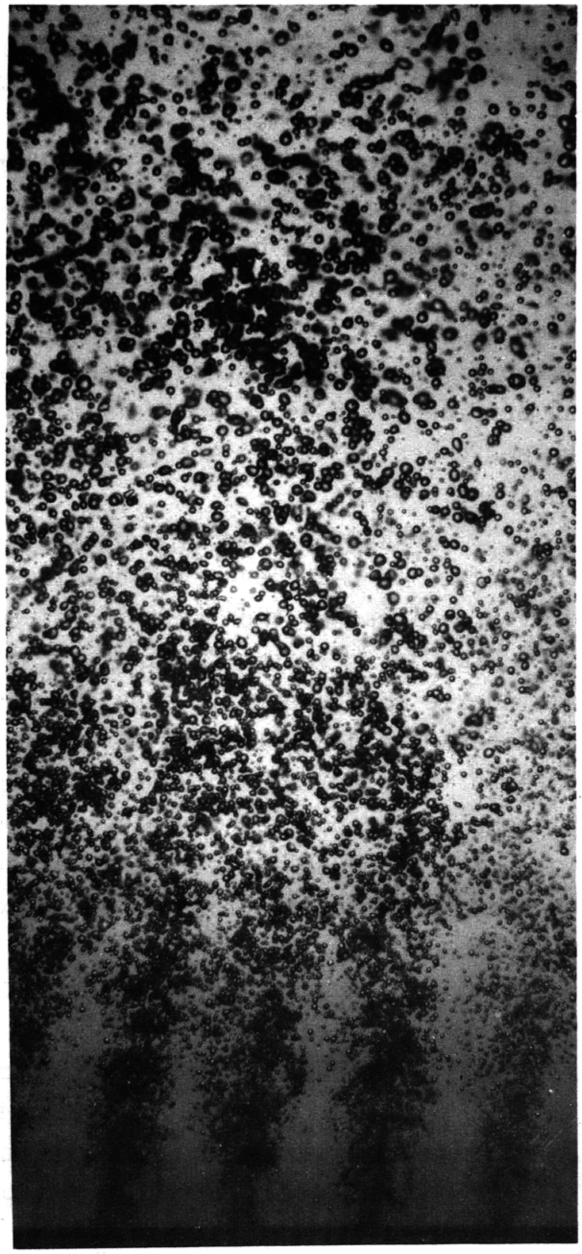

Figure 3b
The air flow is 0.016 cubic feet per minute per orifice and the water flow is 0.3 gallon per minute per orifice.

Figure 3 - Air Bubbles Generated by the Shear-Type Bubble Generator of Figure 2.

The orifices and the rate of flow of the air are the same as for Figure 1a. The water orifices are directed upward.

Because of the small depth of field in the photographs, the great increase in small air bubbles is not readily apparent. The fine bubbles produce a greater depth of bubbles than the larger ones, and many are out of focus when the screen is photographed. The contrast is very marked on visual observation.

Figure 4a
The air flow is 0.05 cubic feet per minute per orifice and the water flow is 0.1 gallon per minute per orifice.

Figure 4b
The air flow is 0.083 cubic feet per minute per orifice and the water flow is 0.1 gallon per minute per orifice.

Figure 4 - Air Bubbles Generated by the Shear-Type Bubble Generator of Figure 2

If a larger air flow is used, and the water flow is gradually increased, a similar progressive change in size and number of air bubbles occurs - compare Figures 1b, 4a, and 4b - except that now the air concentration is higher. The bubble size for a given water flow will now be larger, in part because the air pressure inside the bubble at the time of separation is greater; this results in greater expansion.

Some difficulty was experienced in attaining a uniform flow of air from some of the first of these bubble generators, consisting of from 30 to 40 orifices of the type illustrated in Figure 2.

After a number of trials, it was found that there is a critical location of the air orifice when uniformity is to be maintained at low rates of air flow. For the diameters indicated in Figure 2, the near edge of the air orifice must be 0.01 to 0.005 inch from the inside corner of the angle. At this distance a slight negative pressure is developed by the flow of water past the air orifice. At distances greater than about 0.03 inch, a positive pressure appears over the air orifice that increases with the rate of water flow. The position of the water orifice is not critical. A uniform spacing between the near edge of the orifice and the inside corner of the angle of 0.01 to 0.03 inch was satisfactory.

A similar effect was noted by C.G. Maier (6), who found that the back pressure on the air orifice reached a temporary minimum as the liquid flow increased.

DISSOLUTION-TYPE BUBBLE GENERATOR

Extremely fine air bubbles were generated by dissolution methods. To create an air-bubble screen under water a solution of air in water was delivered from a high-pressure tank to a number of small openings in the supply tube, distributed over the area where the bubble screen was to be produced.* The resulting bubbles were so fine that they were practically motionless in the water. Hence, in order to define the boundary of the bubble screen, a retaining wall of cellophane or paper was placed around the solution outlets.

The apparatus used at the Taylor Model Basin delivered the solution under pressure from a supply tank to the desired place through a number of small openings, as indicated diagrammatically in Figure 5.

Initially the supply tank contained a known volume of water, actually about 5 gallons. The tank was only half filled, to minimize the change in delivery pressure as it emptied. The tank was then connected to a source of compressed air and the pressure of the air inside raised to the desired value. The tank was disconnected and the mixture was violently agitated until the pressure within remained constant. From the known solubility of air in water, the volume of air dissolved could be determined from the pressure and temperature inside the tank.

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* The solubility of air in water is about 2 per cent per atmosphere by volume.

Then the tank was inverted and connected to the delivery line; see Figure 5. This line ended in a series of small holes which distributed the solution from the supply tank over the required area in the water tank. Small openings in the relatively large delivery line were necessary to insure a small pressure drop in the delivery line, otherwise, dissolution and the formation of large air bubbles would occur in the delivery line itself.

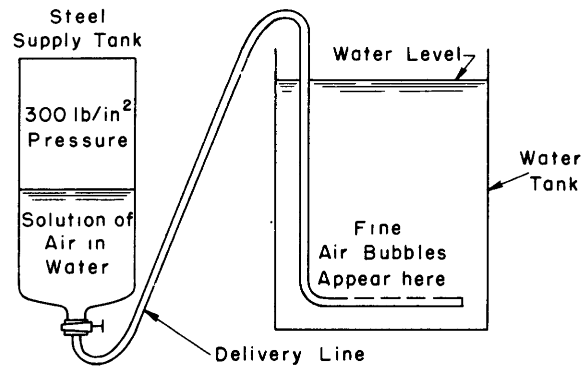

Figure 5 - Schematic Sketch of Dissolution-Type Generator

CONCLUSIONS AND RECOMMENDATIONS

By far the greater part of the volume of air passing through the shear-type generator forms bubbles of nearly uniform diameter. It is estimated from visual observations of the generator in action, that upward of 90 per cent of the air is in this uniform range of bubble size. This figure may be reduced somewhat when the smaller sizes are being generated, because a few large bubbles will carry a relatively large volume of air.

Further research on the nozzles of the shear-type generator is indicated if the stray bubbles are to be completely eliminated.

The bubble screen is reproducible when air- and water-flow settings are the same. This reproducibility is a practical impossibility with simple orifices, as indicated in Appendix 2.

The shear-type generator now in use at the Taylor Model Basin was designed to produce bubbles in the range of size illustrated. If the range of size is to be changed, the relative size of the air and water orifices must be correspondingly modified.

The dissolution method has not been followed up with the idea of varying the size of bubbles produced. However, it is known from experiments made, especially on carbonated water, that the physical properties of the solution as well as the presence of nuclei affect the size of the gas bubble produced when the pressure over the liquid is reduced (7) (12) (17) (18) (19). Hence it may be possible by varying the physical properties of the solution to control the size of the air bubbles produced by the release of pressure.

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APPENDIX 1

INDUSTRIAL USES OF GAS BUBBLES IN LIQUIDS

The designs of gas bubble generators used in industry are as many and varied as their uses.

To prevent freezing, air bubbles are used to agitate the water above dams supplying hydroelectric installations. Submerged orifices about 1/8 inch in diameter are fed by blowers. The large, irregular bubbles bring the deeper warmer water to the surface.

Some types of sewage disposal plants, operating on the activated sludge system, use porous materials on the tank bottoms to circulate small air bubbles through the sewage. The method depends on the presence of oxygen in solution in the sludge.

Aspirator types of aerators, operating on a variant of the shear method, are used when the need for fine gas bubbles compensates for the higher production cost. Several small bubbles have a greater surface area than a single large one of the same total volume, hence gas is absorbed more rapidly from the small bubbles. These aerators are used in water purifying processes, small sewage disposal plants, and certain manufacturing processes such as ore leaching, beer manufacture, hydrogenation of edible oils, and the oxidation of linseed oil.

Dissolution methods are used for generating extremely small air bubbles, less than 0.005 inch in diameter. These bubbles have been used in the manufacture of the highest quality paper. They are used for the flotation of the finest fibers, which would otherwise be lost.

Minute gas bubbles, generated by chemical reaction, have been used in the manufacture of hollow rayon threads from liquid rayon-air emulsions.

R. Auerbach has made a comprehensive study of the thermodynamics and production of disperse gases for commercial uses, where the maximum efficiency of gas absorption is desired (22) (23).

APPENDIX 2

A CLASSIFICATION OF BUBBLE GENERATORS

I. SUBMERGED ORIFICES EMITTING AIR

- A. Simple orifice
- B. Multiple orifices from porous materials
    1. Pierced rubber sheets
    2. Leather
    3. Fabrics
    4. Ceramic bodies
        - a. Unglazed bricks
        - b. Alundum, specially made
    5. Porous bronze bearing material (Oilite)
- C. Nozzle or shear type
    1. Bubbles emerging from a fine orifice in the side of a channel are removed at uniform size by the rapid flow of water past the orifice
        - a. in the expanding throat of a venturi tube carrying water
        - b. at a channel between two cylinders
        - c. in a single nozzle - 2 adjacent orifices at right angles
    2. A simple orifice may be vibrated under water, perpendicular to the direction of air flow, to give an effect similar to C1

II. DISSOLUTION TYPE

- A. Gas held in solution in water by high pressure is dissolved in a reservoir of water; the water generates many minute bubbles when the pressure is released
    1. Carbon dioxide
    2. Air
- B. Continuous Dissolution type

III. ELECTROLYSIS OF WATER, CHEMICAL REACTIONS, ETC.

APPENDIX 3

THE PRELIMINARY INVESTIGATION OF AIR BUBBLE GENERATORS AT THE TAYLOR MODEL BASIN

Many preliminary experiments were performed with a number of bubble generators. These generators were found unsatisfactory for reasons to be described. Numerous references are cited to illustrate the variables that had to be controlled to produce the desired bubble screen.

SIMPLE ORIFICE

The simplest type of bubble generator is the submerged orifice; see Figure 6. It was found unsuitable for the following reasons:

1. The minimum diameter of the bubble emerging from a circular orifice under water is approximately ten times the diameter of the orifice (6).

2. If the material in which the orifice occurs is not wetted by the solution the bubble size may be further increased (6).

3. At extremely low rates of flow there is some departure from this relationship (1) (6), but this is of no practical consequence because of the relatively high rate of air flow used for generating a high concentration of air bubbles.

4. As the rate of evolution of the gas is increased the size of the bubble increases, but not the number of bubbles per second (1) (2) (4) (5) (6). Moreover, the emerging bubbles coalesce if the distance between orifices is less than 10 times the bubble diameter obtaining at the lowest rate of flow. The orifice spacing must be greater for higher rates of flow if coalescence is to be avoided (1) (2) (3) (6).

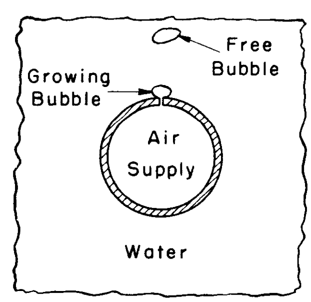

Figure 6 - The Simple Orifice

For uniform air flow from a number of simple orifices, all the openings must be under the same hydrostatic pressure; a small change in the relative submergence of a series of orifices will cause cessation of flow from the deeper orifices and an increased flow from the higher orifices, due to the small excess of air pressure over the hydrostatic pressure at the opening.

Only extremely small orifices generate small bubbles, but it would be practically impossible to keep such orifices clear. However, porous materials have many small orifices which do not become easily blocked on the inlet side because of the interconnecting pores within the material. Therefore a number of porous materials were tried, as described in the following.

MULTIPLE ORIFICES FROM POROUS MATERIALS

A rubber diaphragm about 1/16 inch thick, pierced with a number of small drill holes, was found unsatisfactory as a bubble generator. It has all of the disadvantages of a simple orifice. In addition, the orifice size increases with the pressure, which produces an additional increase in the bubble size (6).

A strip of leather, sealed over an orifice which was connected to a source of air and immersed in water, was found to emit fine air bubbles, but not of uniform size or in a reproducible manner.

Ceramic bodies are somewhat more reproducible but great care must be taken in their fabrication. Of a number of ceramic materials tried only specially fabricated Alundum* was uniform. It was observed that when first immersed in the water the Alundum produced a large range of bubble sizes. After water had penetrated deeply into the material the maximum bubble size was considerably reduced. This was probably due to a change in the effect of the interfacial forces at the surface of the Alundum. These effects are discussed later.

Oilite, a porous bronze bearing material, was also used to provide numerous orifices. Bubbles of greater uniformity than those from Alundum were reproduced in successive tests.

Whereas each of the materials tested was an improvement over those preceding, none approached the desired range of uniformity in the diameter of the bubble produced. This is to be expected because the pore size in these permeable materials is not uniform. The excess pressure required to cause emission of a gas into the supernatant fluid is an inverse function of the diameter of the pore. Hence the larger pores will pass gas when the smaller ones do not, or the larger pores will emit gas at a greater rate and hence the bubble produced will be larger.

DETERMINANTS OF BUBBLE SIZE

The factors that determine the size of an air bubble formed in water by forcing air through a permeable surface may be summarized as follows:

Changes in the diameter of the orifice and the rate of flow of the gas, and the proximity of other orifices produce effects which have already been explained with reference to published experimental work.

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* Alundum, a fused aluminum oxide, is a product of the Norton Refractories Company.

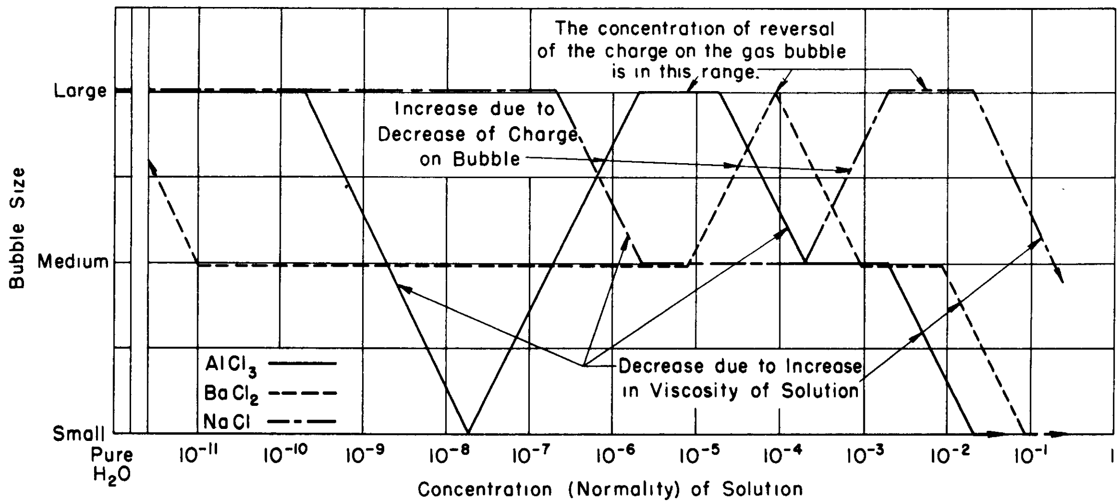


Figure 7 - The Effect of Added Salts on the Size of Air Bubbles Emitted by Small Orifices under Water

The data were taken from Schnurmann's 1929 paper (2). The graph was made at the Taylor Model Basin.

The interfacial forces in the liquid-solid boundaries at the orifice have a very pronounced effect on the size of the bubble formed (2).

For example, the bubble diameter changes markedly when small amounts of inorganic salts are added to the water; Figure 7 illustrates the effect of several salts. This effect is due to a change in the electrostatic charge on the bubble (2) (9). This charge resides on the interfacial surface layer which forms the gas-liquid boundary, illustrated in Figure 8.

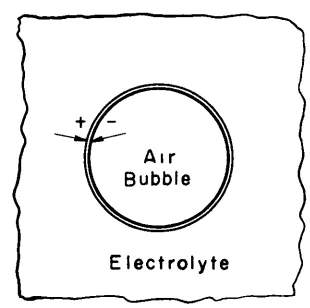


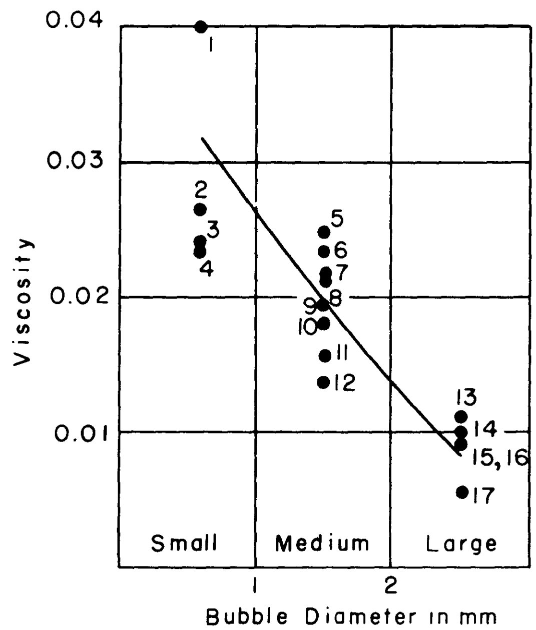
Figure 8 - The Boundary Layer of a Gas Bubble in a Liquid

The sketch illustrates the region referred to as the boundary layer, and a possible charge distribution at the layer.

Increasing the viscosity of the supernatant fluid also decreases the size of the bubble (2) (3); see Figure 9.

Decreasing the surface tension decreases the size of the bubble formed (1) (13); this effect was confirmed at the Taylor Model Basin. A few grams of Santomerse C, a wetting agent which reduces the surface tension, were added to a 200-gallon tank of water containing a porous-solid type bubble generator. The average size of the bubbles was noticeably reduced. However, the surface tension is one of the minor factors determining the size of the gas bubble (3) (14) (15).

Another factor affecting the size of the bubbles is the so-called "induction time." This is the minimum time of contact necessary for a bubble



Point	Liquid	Solution per cent	Temperature degrees C
1	Isobutyl Alcohol		20
2	Propyl Alcohol	60	25
3	Acetic Acid	78	25
4	Ethyl Alcohol	45	25
5	Propyl Alcohol	74	25
6	Ethyl Alcohol	33	25
7	Ethyl Alcohol	67	25
8	Propyl Alcohol	25	25
9	Propyl Alcohol	100	25
10	Ethyl Alcohol	90	25
11	Methyl Alcohol	40	25
12	Methyl Alcohol	20	25
13	Ethyl Alcohol	100	25
14	Methyl Alcohol	80	25
15	Isobutyl Alcohol		80
16	Water		25
17	Methyl Alcohol	100	25

Figure 9 - The Effect of the Viscosity of the Liquid on the Size of the Air Bubbles Emitted by Small Orifices in the Liquid

This graph was taken from Schnurmann's 1937 paper (3).

to adhere to a solid surface under water (16). It is a phenomenon of great importance in ore flotation processes, where a small induction time is desirable. The size of the bubble formed at an orifice decreases if the induction time is increased, because the area of contact of the bubble at any instant is then diminished, so that the attracting force is decreased. For example, Schnurmann (2) found that the addition of a small amount of lactic acid will decrease the size of bubbles formed at a porous surface. Lactic acid has a long induction time (2) (3).

THE SHEAR METHOD

Since all the above described forces are acting on a bubble while it is in a nearly static condition, a dynamic method of shearing off the air bubble as it emerges from the orifice would decrease the variation in size resulting from the effects described. This may be accomplished by moving water past the orifices. A number of investigators have done this (6) (8) (10) (20) (21) (22).

One application of the shear method now in commercial use in sewage disposal and water purification plants is the venturi tube aspirator type aerator (10). It is shown diagrammatically in Figure 10. Air inlets are placed in the downstream side of the constricted portion of the tube. In the tests described (10) by Professor Babbitt, as much as 16 per cent of air was entrained in the form of fine air bubbles. This method was not tried because

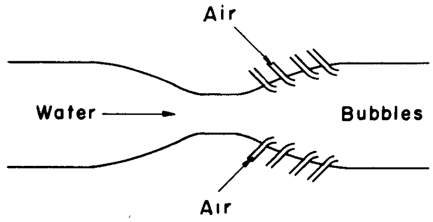


Figure 10 - Sketch illustrating the Venturi Tube Aspirator Type Aerator

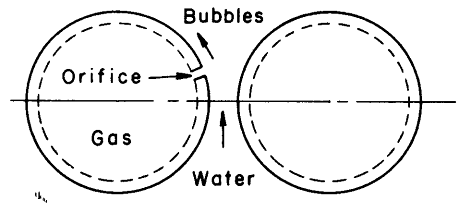


Figure 11 - Diagram of Grid-Type Shear Bubbler

Taken from Maier's paper (6).

it obviously lacked the necessary uniform concentration of air bubbles over a considerable rectangular area.

Maier's apparatus (6) involved the use of two parallel cylinders to guide the water past a series of air orifices in one of the cylinders, as shown in the diagrams of Figures 11 and 12.

This design was not tried because of mechanical difficulties which will not be considered here. Also, the present shear-type design uses less water for the same volume of bubbles.

Another method of generating air bubbles equivalent to the methods just described is to vibrate the air orifices under water (23). This was not tried.

Any channeling or mechanical mixing of the bubble mixture combines the bubbles; hence attempts to increase the uniformity of distribution of the bubbles from the last two generators described would increase their size. The

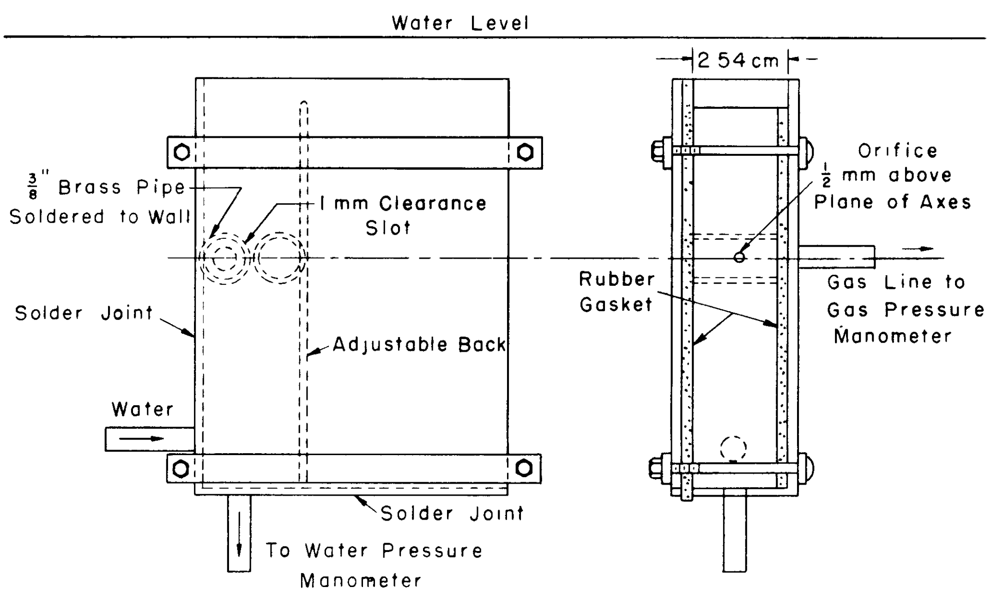


Figure 12 - Experimental Shear Bubbler, Grid Type

Taken from Maier's paper (6).

bubbles must be allowed to rise freely if their uniformity of size is to be maintained.

An effort to overcome all these uncertainties in reproducing a bubble screen led to the development of the design described and shown in Figure 2 of the report proper.

DISSOLUTION METHODS

The production of uniformly minute air bubbles may be accomplished by another method in which gas is driven into solution in the water by high pressure. When the pressure is released many minute bubbles appear. This method was described and illustrated in Figure 5 of the report. It was tried with both carbon dioxide and air. Carbon dioxide could be used only in a limited volume of water because the gas would redissolve unless the water were made acid.

No attempt was made to measure the diameter of the air bubbles produced in the solution, but it was noticed that the water turned milk white owing to the small size of the bubbles.

This method has not been followed up with the idea of varying size of bubbles produced. However, it is known from experiments made, especially on carbonated water, that the physical properties of the liquid as well as the presence of nuclei affect the size of the gas bubble produced when the pressure over the liquid drops (7) (12) (17) (18) (19). Hence it may be possible to control the size of the air bubbles produced by the release of pressure over a solution of gas in water.

These minute bubbles may be generated continuously by feeding a proportioned mixture of air and water through a high-pressure pump (11). The resulting solution may be discharged at any desired point.

ELECTROLYSIS OF WATER AND CHEMICAL REACTIONS

Electrolytic and chemical reaction methods of generating gas bubbles have been mentioned in the literature (12) but these methods are not feasible for relatively large air volumes.