CHAPTER 171

GUIDELINES FOR THE DESIGN OF AIR BUBBLE SYSTEMS

By

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ABSTRACT

Based on a literature review of theoretical and experimental work on air-bubble systems, guidelines for the ideal design of submerged distributors discharging air into water are presented.

A comprehensive study of gas-liquid dispersions was carried out to find out the effect of physical properties, distributor arrangement, and the air flow rate, on the flow pattern within the jet. This review revealed that the distributor arrangement largely influences the characteristics of the dispersion within the zone of flow establishment. Also, upon analyzing the experimental results of air-water systems, it was found that the zone of flow establishment extends to greater distances of the water depth than that in the case of one-phase turbulent plumes. Furthermore, the experimental results showed that the efficiency of air bubble plumes can be increased by the proper design of the distributor.

Recommendations for the distributor design are given, which include, diameter of orifices and their spacings, pressure drop across orifices, number of manifolds, and the maximum air flow rate.

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INTRODUCTION

Air-bubble systems have been used extensively for a variety of purposes, such as pneumatic breakwaters, prevention of ice formation, as barriers against salt water intrusion in rivers and locks, as barriers to reduce silt intrusion into estuaries, for stopping the spreading of oil spills on the water surface, for reduction of under water explosion waves, and for agitation, mixing, cooling, in process industries.

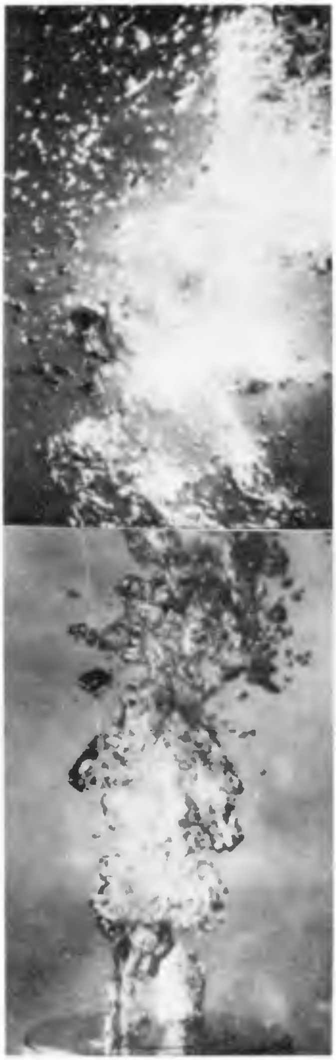
Based on the results of both small and large scale tests, and prototype tests, applied for use as pneumatic breakwaters, there has been a controversy for the past 30 years among investigators of the effect of the air distribution system on the efficiency of bubble systems. In addition, despite the wide range of practical applications, no theory has been developed to give a satisfactory description of the hydrodynamics of air-bubble systems. However, with a better understanding of the physical mechanism of this kind of plumes, there is some hope that the behavior of the air-bubble systems may be analyzed sufficiently well for design purposes.

Therefore, the fundamentals of disintegration of gas jets into liquids, and the subsequent upward motion have received consideration in the present work. This together with analyzing the previous theoretical and experimental work, provide us with some guidelines for the proper design of these bubble systems and necessary information to improve the present theoretical models.

DISINTEGRATION OF GAS JETS INTO LIQUIDS

In the range of air flow rates employed in most of the practical applications, the air issuing from a nozzle or an orifice quickly expands according to the sudden pressure drop across the nozzle, and eventually breaks up due to the instability of the jet. In other words, the continuous air stream disintegrates into series of closely spaced large irregular bubbles after it has travelled some distance from the air source. These irregular bubbles finally disintegrate into smaller ones and begin to rise through the water column. Normally, coalescence of bubbles occurs between bubbles of different sizes, and bubbles, during their rise, might coalesce depending upon their size distribution. Fig. 1 shows the disintegration of an air jet into water of depth 4.5 ft.

The flow pattern of one-phase turbulent jets can be divided into distinct zones. The boundary between the zones of flow establishment and established flow, can be defined



After Abdel-Aal (1)

Fig. (1). Dynamic Behavior of The Air-Water Jet in the terms of the variation in the velocity and concentration. The extent of the ZFE either for the velocity or for the concentration is just few times the width of the slot.

In the case of a two-phase jet it is rather difficult to determine such boundaries between the different zones of the air-bubble flow. Generally the lateral spreading of the bubbly flow is less than that of the plume. With respect to the air stream, the flow can be divided into the following zones.

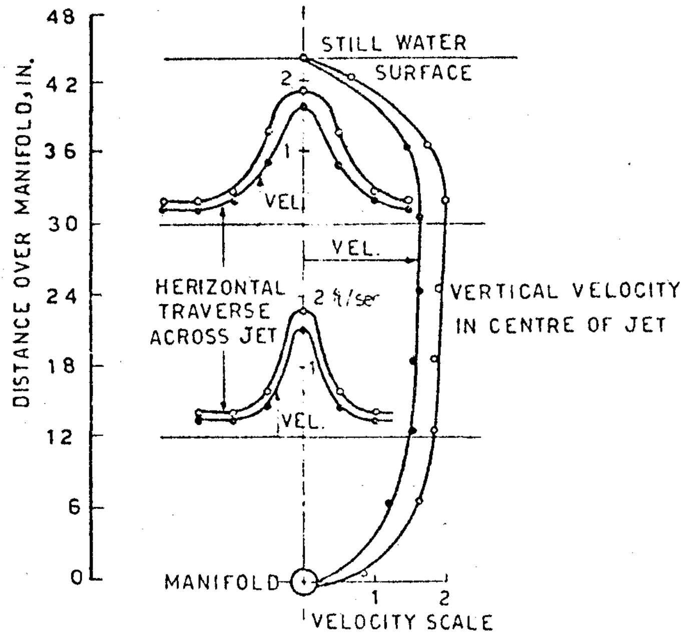
(a) Zone of Flow Establishment (ZFE): This zone can be subdivided:

i) the initial zone where the air stream is still stable at the end of this zone, the air disintegrates into closely spaced large bubbles.
ii) the transition zone, where the irregular large bubbles break up into discrete bubbles of various sizes.

and (b) Zone of Established Flow (ZEF): Regarding the gross behavior of the jet, all the previous experimental studies reveal that the center-line velocity reaches an almost constant value, and the velocity profiles become similar, with respect to a virtual source, at some distance above the air source. This defines the region of the jet, where the flow becomes fully developed. In this region, the air-water stream will rise with a velocity which depends on the bubble size distribution and concentration. All the previous experimental work indicates that this distance is comparable to the submergence of the air source which distinguishes this kind of jets from one-phase turbulent jets. Figure 2 shows a typical velocity traverses in a rising air-water jet.

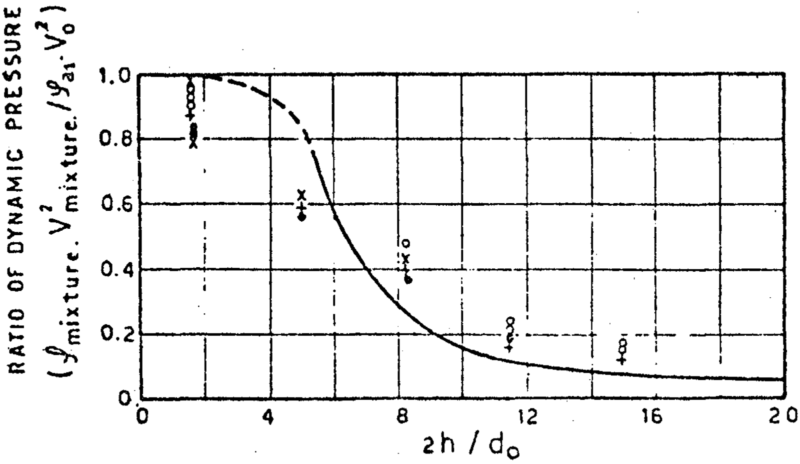
In this kind of turbulent jet, most of the kinetic energy of the air leaving the manifold is rapidly dissipated in the turbulent shearing of the liquid and generation of new surface area (1). Therefore, it is a good assumption to consider that only the potential energy of the bubbles, which is converted to the kinetic energy of the water jet. This is evident, as is shown in Fig. 3. The momentum flux increases due to the buoyancy terms which grow logrithmically with distance above the air source (12 and 13).

Most of the conventional theoretical treatments of one-phase turbulent jets and plumes have considered only the main region of the jet, on the assumption that the extension of the zone of flow establishment is very small compared to the submergence of the jet. The integral technique, used in these treatments has been applied recently, by Cederwall and Ditmars (8), to study the gross behavior of air-bubble plumes over the whole depth of the air-source submergence. The predictions of their model do not represent well the



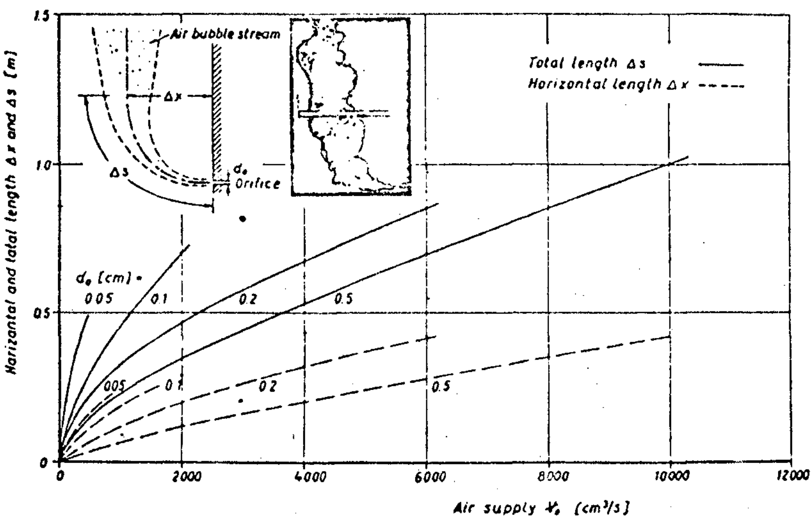
After Charlton (9)

FIG. (2) VELOCITY TRAVERSES IN THE RISING JET SHOWING THE EFFECT OF BUBBLE SIZE AT AN EQUAL AIR-FLOW OF 0.036 FT^2/SEC



After Abramovich (3)

FIG. (3) THE VARIATION IN DYNAMIC PRESSURE ALONG THE AXIS OF A JET GENERATED BY THE DISCHARGE OF AIR IN WATER.



After Kobus (13)

Fig. (4) Extent of Initial Region

actual behavior of the plume. However, a more satisfactory model necessitates a full knowledge of the complex details of the flow conditions in the zone of flow establishment to provide a proper mathematical formualtion.

ZONE OF FLOW ESTABLISHMENT

Figure 4 shows the experimental results of Kobus (13) regarding the extent of the zone of flow establishment. It seems from this figure that the length of this zone is proportional to both the air flow rate per orifice and the pressure drop across the orifices. This would suggest that such correlation from these results could be applied to the case of multiple orifice pipe if the individual jets do not merge before disintegration. This could exist if the spacing between orifices is equal to the mean jet diameter at the point of disintegration.

Silberman (21) derived an equation which gives the mean jet diameter, J, by the end of the initial zone which he verified experimentally.

$$J = \left(\frac{q_1}{0.81\ \pi^2 g}\right)^{1/5} \qquad \text{in ft} \ .... \ (1)$$

where q_1 = the volumetric air flow rate measured at the pressure and temperature in the liquid at the orifice ft^3/sec.

g = the acceleration of gravity ft/sec^2.

ZONE OF ESTABLISHED FLOW

All the previous theoretical work such as that of Kurihara (14), Charlton (9), Ismail (12), Cederwall and Ditmars (8), have revealed that the potential energy of bubbles is more effectively used for generating an air-water jet by minimizing the relative velocity between the two-phases. In the following, the fundamentals of the bubble-liquid interaction are presented in order to reveal the effect of the various factors such as the physical properties, distributor design, and gas flow rate on the relative velocity of the air stream. The review can be generally classified into two parts. The first is concerned with the disintegration of the air jet while the second deals with the motion of the bubble stream.

Bubble Formation

Leibson et al (15), and Abdel-Aal (1) described in detail the complex breakup of the air-jet in the turbulent region. The turbulent region, where most of the applications of air-bubble systems exist is when the orifice Reynolds number, R_{eo}, exceeds 2100.

The experimental results of Leibson et al, for the case of single orifices, are shown in Fig. 5. This figure shows that as turbulence becomes fully developed (i.e., $2,100 < R_{eo} < 10,000$) the effect of orifice size and Reynolds number on the bubble diameter could be expressed as:

$$d_b = 0.18\ d_0^{1/2}\ R_{eo}^{1/3} \quad \text{in inches} \quad .... \qquad (2)$$

where d_0 is the orifice diameter in inches. This correlation falls closely to the experimental results of Davidson (10) for the same flow conditions. The results also indicate that there is no noticeable effect of orifice diameter d_0 on the bubble size, d_{bvs}, in the fully turbulent region. The bubble size d_{bvs} is defined as the diameter of a bubble whose ratio of volume to surface is equivalent to that of the bubble size distribution. For the air-water system, Leibson et al obtained the following experimental equation which fits the data for orifice Reynolds number greater than 10,000:

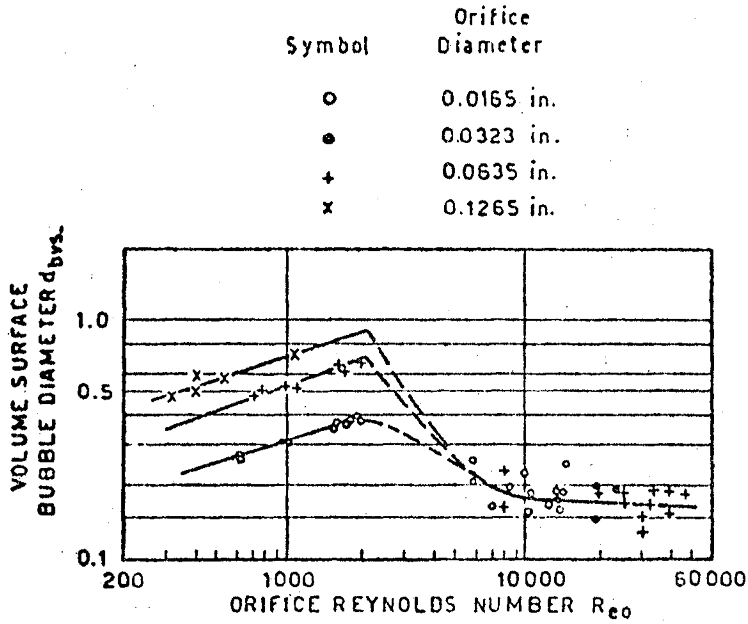
$$d_{bvs} = 0.28\ (R_{eo})^{-0.05} \quad \text{in inches} \quad ... \qquad (3)$$

It is important to notice that these results give the bubble size just after jet disintegration. Therefore by increasing the air flow rate within the turbulent region, the bubble size is expected to increase by the end of the transition zone, due to the coalescence of bubbles caused by their increasing proximity (7).

For the case of multiple orifices, the mean bubble size after jet disintegration is given by Calderband (7) for turbulent conditions ($R_{eo} > 2,100$) as

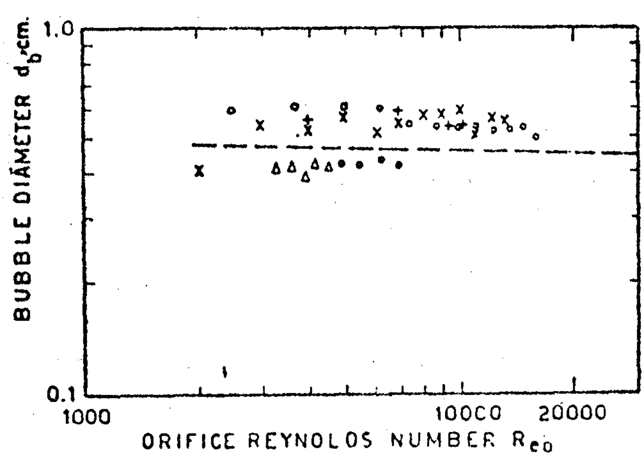
$$d_b = 0.713\ (R_{eo})^{-0.05} \quad \text{in inches} \quad ... \qquad (4)$$

This equation is comparable with Leibson's equation for single orifices in the fully developed turbulent regime. These results agree with the findings of Rennie and Evans (20), which are shown on Fig. (6).



After Leibson(15)

FIG. (5) BOTTOM-ENTRANCE FLOW MEAN BUBBLE DIAMETER VERSUS ORIFICE REYNOLDS NUMBER.



After Rennie and Evans (20)

FIG. (6) BUBBLE DIAMETER AGAINST ORIFICE REYNOLDS NUMBER.

In addition to the previous mentioned effect of high gas flow rates on the proximity of bubble, which could be shown in the experimental results of Silberman (Fig. 7), there is another factor affecting coalescence. Normally coalescence of bubbles occurs between bubbles of different sizes. At low gas rates and intensities of turbulence the ranges of bubble sizes normally encountered is not very great. By increasing the gas flow rate or the pressure drop across orifices, turbulence will increase and the size distribution will spread, thus increasing the rate of coalescence. Therefore, in situations where it is desired to attain maximum interfacial area, it is advantageous not to exceed the orifice Reynolds number greater than 10,000.

In this respect Silberman (21) derived an equation by which the size of the largest bubble formed from jets may be predicted and he confirmed it by experiments: the mean bubble diameter is given by

$$d_{b\ell} = 1.41 \left(\frac{q_1^2}{g}\right)^{1/5} \quad \text{in ft. ...} \qquad (5)$$

where q_1 is the volumetric air flow rate evaluated at the orifice in ft^3/sec., and g is the acceleration of gravity.

The above equation still holds for the case of multiple orifices as long as the individual jets do not merge before disintegration. It is worthwhile to show the effect of distributing the same air flow rate over many orifices on the mean bubble size. This effect is shown when comparing the bubble sizes in Fig. 7-b and Fig. 8 where the size in the latter figure is smaller due to the decrease of the air flow rate per orifice.

In case where porous pipes are used, the size of bubbles produced depends upon both the size of the pores and the pressure drop across them. For every type of porous pipes, the manufacturer suggests a working limit for gas flow rate (18), after which serious coalescence will occur. Table 1 gives this limiting gas flow rate for various types of porous pipes.

Bubble Motion

In the zone of established flow the rise of bubble swarms is more complicated than the case of single bubbles. This is caused by the interaction of bubbles among themselves. However the motion of single bubbles in stagnant water still provides an instructive conceptual picture of the motion of bubble streams (11).

a)  b) 

Q = 0.0058 cts Q = 0.151 cts

c)  d) 

Q = 0.0410 cts Q = 0.1525 cts

Fig. (7). Effect of Air Flow Rate on Bubble Size in the Transition Zone

Photographs after Silberman (21)

Fig. (8). Jets from 9, 1/32-in. Circular Orifices
Total Discharge = 0.0108cfs

TABLE (1): Characteristics of Porous Septa

Grade	Avg % porosity	Avg pore diam.	Air-permeability data		
			Diaphragm thick in.	Pressure differential, in. water	Air flow cu.ft/(sq.ft)(min.)
			Al and um porous alumina		
P 236	34	240	1	2	40
P 216	..	720	1	2	110
			National porous carbon		
25	48	120	1	2	13
			Filtors porous silica		
Coarse	34.5	250	1.5	2	31 - 59
Extra	36.5	300	1.5	2	60 - 100
			Porous plastics		
Kel-F	...	15	0.125	138	13
			Micro Metallic porous stainless steel		
D	50	65	0.125	1.38	60
C	55	165	0.125	27.7	990

After Perry [18]

Therefore the fundamentals of bubble-liquid motion in stagnant water have been collected together on Fig. 8, which shows the various factors affecting the related aspects of bubble motion (12).

These aspects include the shape of the bubble, its rise path, the drag exerted by the liquid on it, and its rise velocity.

The effect of turbulence on the relative bubble velocity of rise is not yet well defined. The only available data (5) is shown in Fig. 9. This figure shows that for a bubble size larger than 0.3 cm the relative velocity remains relatively constant at approximately 25 to 27 cm/sec., until an equivalent diameter of about 0.9 cm is reached beyond which the slip velocity slightly increases.

DISCUSSION

In the various applications of air-bubble systems there are two descriptions of efficiency which can be applied to an air-water jet. For mixing purposes, the interest is the mass transport capacity of the system, and the efficiency is represented by the ratio of total entrained water to the air flow rate. For pneumatic breakwaters, the criteria of the wave stopping power is the energy of the surface current, and the efficiency is measured by the ratio of the kinetic energy of the surface current to the potential energy available in the air jet leaving the manifold.

The air-bubble systems have proved to be a very efficient means of entrainment water. Table 2 lists entrainment ratios for a wide-world experimental work. On the other hand pneumatic breakwaters have been demonstrated by model tests and full scale tests in U.S.A., England, Japan, and Germany, to be only feasible to attenuate seas of length/water depth up to 5 and periods up to 5 sec. (12). For swell the Japanese experience suggests using parallel multiple air distributors, spaced four times their submergence, when there is an adequate air supply, which imposes limitations for using air-bubble systems to attenuate swell (14).

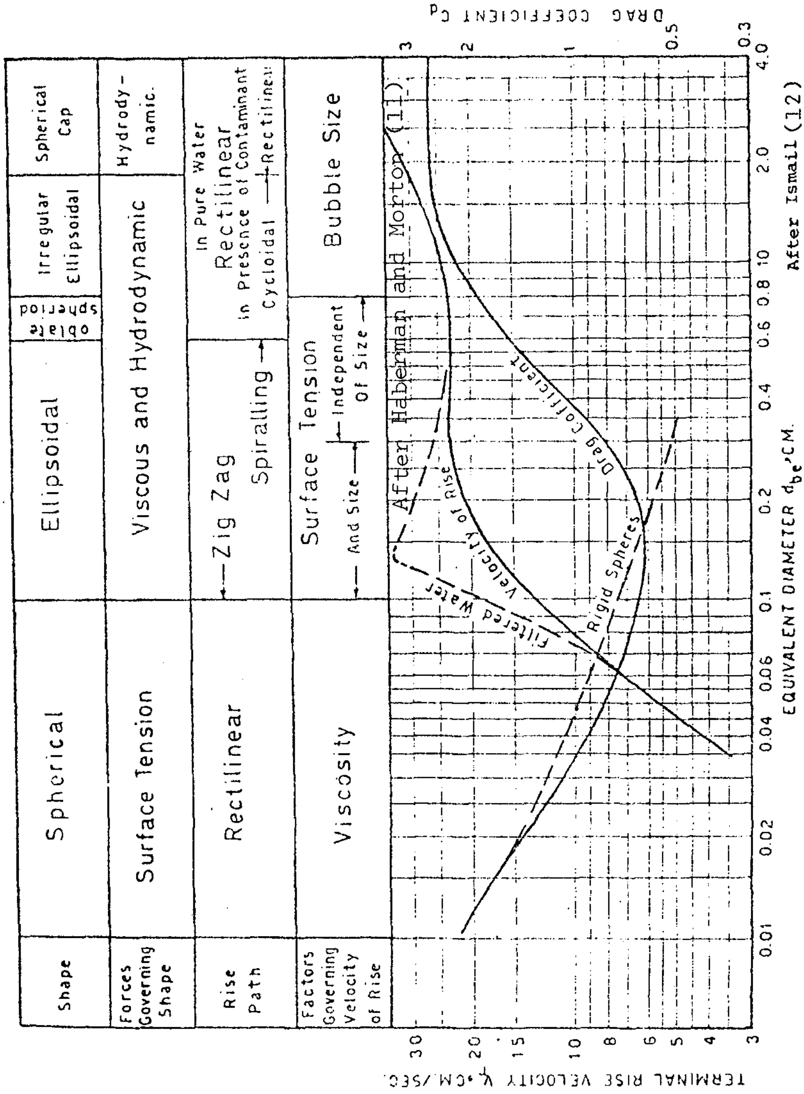
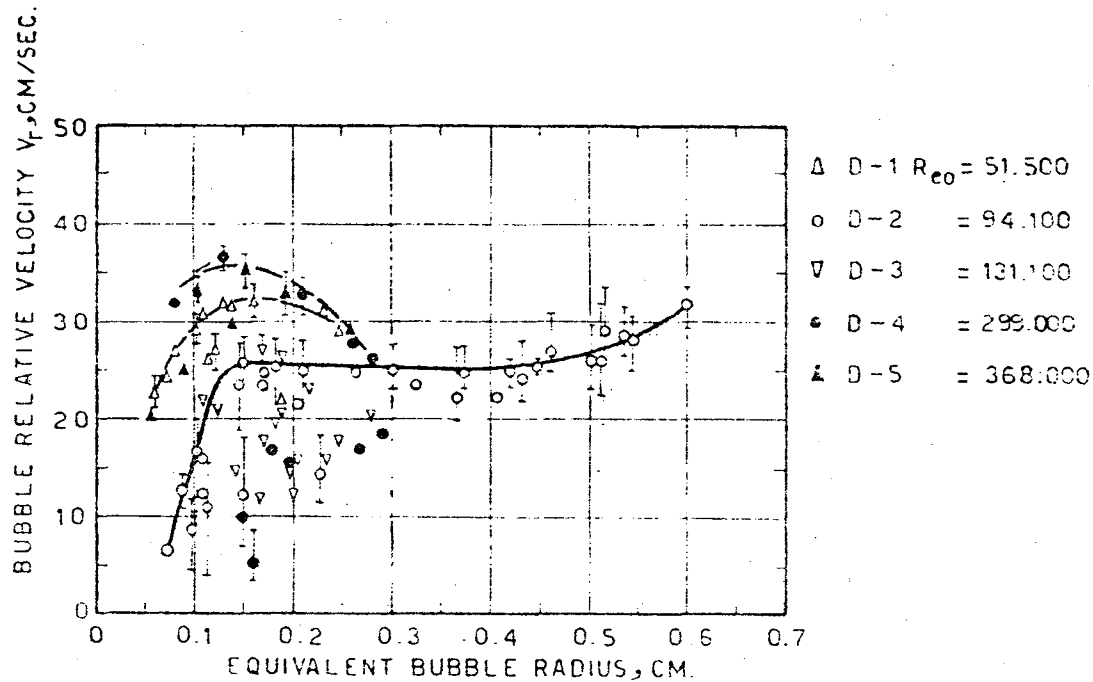


FIG. (9) FUNDAMENTALS OF BUBBLE - FLUID INTERACTION



After Baker and Chao (5)

FIG. (10) VARIATION OF BUBBLE RLATIVE VELOCITY WITH EQUIVALENT RADIUS DEMINERALIZED WATER.

Table (2)

Entrainment Ratios of Air-Bubble Systems

Investigator	Water Depth	Air Discharge	Entrainment Efficiency
Baines and Hamilton (1959)	5.5 ft	1 ft^3/min	123
Bulson (6) 1961	25.5	0.18 ft^3/sec/ft	75
Bulson	34 ft	0.05 ft^3/sec/ft	132
Kobus (13)		3000 cm^3/sec/m	65
Kobus 1968	4.0 ms	6200 " "	85
Kobus		10000 " "	125
Kurihara (14) 1958	8.3 ms	13 lit/sec/m	50
Kurihara	162 ms	20 lit/sec/m	110

In order to reduce the power requirements of operating pneumatic breakwaters, researchers all over the world have investigated the effect of the distributor arrangements on the efficiency of the system. However, there has been a controversy for the last 30 years among the researchers upon this effect.

Bulson (6) reported that when the same quantity of air passed through a variety of orifice diameter and spacings, there was no significant difference in the velocity profile across the jet. Also, he found that results for a single manifold were not noticeably different from those when two or more adjacent manifolds were delivering the same total quantity of air. When using porous pipe as air distributor he found no significant difference in the resulting surface current velocity.

Kurihara (14) attributed the high efficiency obtained in the Japanese experiments to having a very fine dispersion. The air distribution system used in their experiments either in the full scale tests or model tests was distinguished by having a large number of holes. Both a single pipe and a ladder type of pipe were used. The latter was used to attenuate shallow water waves.

On the contrary, the experiments of the U.S. Army (25) showed that a single discharge manifold produces greater efficiency than do multiple manifolds separated by some distance.

The experimental results of Kobus (13) did not show any effects of the distributor arrangements on the jet-pattern.

In fact Bulson's data do not agree with his conclusions. His data are extrapolated to calculate the values of entrainment and energy efficiencies. This led to the conclusion that there is a positive effect of the distributor arrangements on the efficiency of air-bubble jet, even the range of variation in the arrangements was small. Bulson* agreed about the results of analyzing his data. The reason behind the lower performance he obtained than that of the Japanese experiments is due that the air flow rate per orifice is very large, which resulted in the formation of large air slugs. Also the pressure drop across orifices was very high, which had an adverse effect on the efficiency. This excessive pressure drop is the reason for the low velocity performance in the experimental work of Kobus (13).

On the other hand, decreasing the pressure drop across the orifices resulted in a high efficiency as the experimental results of both Kurihara and the U.S. Army showed.

Regarding the disappointing results which Bulson obtained, when using porous pipes, the type of porous pipe used in his experiments was not the proper one for discharging the high air flow rate employed in his experiments.

For those investigators who used multiple manifolds in order to attain a higher efficiency, the low efficiency obtained in some of their experiments had resulted from the improper design of the spacing between manifolds. This led to a low concentration of the air bubbles within the plume.

CONCLUSIONS

It is concluded that in order to obtain the best efficiency of an air bubble sytem: for a given air flow rate

*Special correspondence with P. S. Bulson, M.E.E., Christchurch, England, 1971.

i) The air flow rate should be distributed over a large number of orifices. This number is determined by calculating the air flow rate per orifice based on the designed maximum bubble size in the dispersion.

ii) The diameter of the orifices should be designed in a way that the orifice Reynolds number is in the fully turbulent region (10000), also the pressure in the manifold should be just sufficient to cause the air to be released.

iii) The minimum spacing between orifices should be equal to the mean jet diameter at the point of air disintegration, to allow disintegration before merging of the individual jets without serious coalescence.

iv) If the above conditions cannot be satisfied by using one manifold, different manifolds could be used. The spacing between them should be designed by model tests in order to achieve an optimum value of air concentration.

v) Porous pipes are preferable provided that we are working within their maximum air flow rate. The maximum limit of using them can reach up to 990 $ft^3/ft^2/min$ which makes the porous pipes utilizable for practical applications.

ACKNOWLEDGMENTS

This paper extends work which was done in 1971 at the Civil Engr. Dept., Alexandria Univ. Egypt. The author is greatly indebted to Professor H. Hammad and Professor I. Ebeido for their interest and continual guidance throughout that work. The valuable discussions of Professor A. El-Taweel, Chemical Engr. Dept., at that time made possible the completion of that work.

I would like to thank Professor R. L. Wiegel, Hydraulic Div., Univ. of Calif., Berkeley, for his critical review and comments on this paper.

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