Rate of Flow and Mechanics of Bubble Formation from Single Submerged Orifices

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A study has been made of the rate of flow and mechanics of bubble formation from single submerged orifices 1/64, 1/32, 1/16, and 1/8 in. in diameter installed in an 8-in. I.D. column operating in the air-water system. The coefficients of discharge obtained for sharp-edged orifices operating with this system indicate that the effective orifice discharge area for this type of operation is greater than that for an orifice of the same size and type operating at the same pressure ratio in the air-air system. The effective orifice discharge areas for a round-edged orifice operating in either the air-water or air-air systems appear to be identical at the same pressure ratio. The thick-plate orifice operating in the air-water system exhibits a constancy of discharge coefficient at ratios of the downstream to upstream pressures less than 0.33. Inasmuch as bubble formation occurring close to the downstream face of a sharp-edged orifice operating in the air-water system influences the effective orifice discharge area, liquid physical properties may be expected to be important in determining the rate of flow from this type of orifice for other gas-liquid systems.

In Part II photographic studies of bubble formation reveal that nonuniformity of bubble size is initiated by the onset of turbulence in the air stream flowing through the orifice. In the section of the laminar-flow range studied in this investigation ($200 < N_{Re} < 2{,}100$) the frequency of bubble formation is nearly constant with respect to Reynolds number. The bubble size is relatively uniform at a given Reynolds number and depends markedly upon orifice diameter. Stroboscopic examination reveals that as turbulence is fully developed for the air flow through the orifice, a counterclockwise spiraling, swirling motion of the air jet is initiated. In the turbulent-flow range the bubblesize-distribution data are fitted reasonably well by a logarithmic-normal-probability distribution. More data for bubble formation in other liquids (particularly liquids of low surface tension) are necessary before a general correlation for bubble size in gas-liquid systems can be developed.

I. Rate of Flow Studies

The introduction of a gas into a liquid through submerged orifices plays an important part in many gas-liquid contacting operations and processes. This investigation is concerned with bubble formation and behavior in the high-seal liquid-level systems encountered in the aeration of fermentation broths (*1* and *16*), gas reactions in liquids (*11*), foam flotation (*9*), and the air-lift pump (*6*). Previous workers (*7, 10, 14, 15, 21, 22,* and *24*) have studied bubble formation as a function of flow rate in low-seal liquid-level systems analogous to bubble-cap and sieve-tray columns. In the majority of these investigations the rate of gas flow is small and the pressure drop across the orifice pulsates rapidly. Very few data are available in the literature for the rate of gas flow through a single submerged orifice discharging into a liquid. Part I of this investigation was undertaken to obtain data concerning the rate of air flow into water through single, submerged, sharp-edged orifices operating in both the subcritical and supercritical regions. A study of the mechanics of bubble formation at high rates of gas flow is reported in Part II.

Pressure ratio is defined in this paper as the ratio of the pressure downstream from the orifice to that upstream from the orifice. To review the concept of the critical pressure ratio, one may consider the case of an ideal nozzle operating in a gas-gas system. As the downstream pressure is decreased while a constant upstream pressure is maintained, the weight rate of discharge of the gas increases to a maximum (*8* and *18*) as the pressure ratio decreases to the critical pressure ratio. At the critical pressure ratio the linear velocity at the throat of the nozzle is equal to the velocity of sound in the gas at the throat temperature. The rate of discharge from an ideal nozzle is constant at all pressure ratios less than the critical pressure ratio. In the supercritical region the pressure at the throat of the nozzle (i.e., axial critical pressure) cannot decrease to a value less than the product of the upstream pressure and the critical pressure ratio. The ratio of this minimum pressure to the upstream pressure is constant for any given fluid. Values of the critical pressure ratio calculated at 15°C. are 0.49 for monatomic gases, 0.53 for diatomic gases, and slightly higher for gases of greater atomic complexity.

In the case of a sharp-edged orifice operating in a gas-gas system, the stream filaments of the orifice jet converge to a minimum section (*vena contracta*) downstream from the orifice and then diverge (*23*). The ratio of throat length to orifice diameter is 0.125 or less for a sharp-edged orifice and the cross section of the upstream edge of an orifice of this type is square (*2*). The upstream edge of a round-edged orifice is beveled to minimize the constriction of stream filaments at the throat of the orifice. In the supercritical region, as the pressure downstream from a sharp-edged orifice is decreased, the *vena contracta* moves toward the orifice and increases in diameter. Although the linear velocity at the *vena contracta* is constant at sonic velocity, since the *vena-contracta* diameter increases, the weight rate of discharge is also increased. Cox and Germano (*4*) have interpreted the data of Stanton (*23*) and Schiller (*20*)

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to show that a 12% maximum increase over flow at the critical pressure ratio is attained as the pressure downstream from a sharp-edged orifice is reduced while a constant pressure is maintained upstream from the orifice. Other investigators (*5, 12, 17, 19*) studying gas-gas systems in the supercritical region have noted similar increases over flow at the critical pressure ratio.

Grace and Lapple (*12*) present orifice discharge coefficients calculated from the critical-orifice-flow equation (*8*) for sharp-edged and round-edged orifices varying from 1/32 to ⅛ in. in diameter. Their work indicated that at a given pressure ratio the orifice discharge coefficient increases as the orifice diameter is decreased.

The behavior of a thick-plate orifice operating in a gas-gas system is somewhat similar to that noted above for a sharp-edged orifice. However, several important differences have been shown in previous work. Grace and Lapple (*12*) reported a data scatter as great as 30% for the flow of air through an orifice 1/32 in. in diameter with a ratio of throat length to diameter of unity. Reynolds (*19*) studied the flow of air through thick-plate orifices ranging from ⅛ to ½ in. in diameter in 1/16-in. increments. Although Reynolds reported his orifices as sharp edged, the ratio of throat length to diameter was greater than 0.125 in all cases. His results contradict those of Grace and Lapple, inasmuch as Reynolds' data are reproducible within ±2% throughout the entire range. In several runs with a ¼-in. orifice, varying the ratio of throat length to orifice diameter from 0.25 to 0.75 produced no change in the adiabatic coefficient of discharge. Reynolds found this coefficient to be substantially constant at pressure ratios less than 0.33. Blackshear (*3*) corroborated this result using a thick-plate orifice 0.04 in. in diameter with a ratio of throat length to orifice diameter of 0.25. The constancy of the orifice coefficient of discharge at pressure ratios less than 0.33 is also shown by the data of Grace and Lapple for a thick-plate orifice 1/16 in. in diameter with a ratio of throat length to diameter of unity.

In summary, studies of gas-gas systems have shown that a marked increase in the rate of discharge from a sharp-edged orifice occurs as the pressure ratio is decreased below the critical pressure ratio. This increase is less marked for flow through a round-edged orifice. For flow through a thick-plate orifice, the coefficient of discharge is relatively constant at pressure ratios less than 0.33. For orifices from 1/32 to ⅛ in. in diameter, at a constant pressure ratio, the discharge coefficient increases as the orifice diameter is decreased.

Compared with a gas-gas system, the mechanics of flow for a gas-liquid system are further complicated by bubble formation with resultant gas-liquid mixing occurring close to the downstream face of the orifice. Furthermore, one would expect liquid physical properties to be of some importance in determining the rate of discharge of gases from submerged orifices. In this study interest has been focused on determining the effect of orifice diameter and type on the rate of discharge from single submerged orifices operating in the air-water system only.

APPARATUS

A schematic flow diagram of the experimental equipment is presented in Figure 1. Air at pressures up to 115 lb./sq. in. abs. was supplied to the column by a reciprocating-piston compressor. The flow of air to the column was controlled by a ¾-in. Keckley pressure-regulating valve in series with a ¼-in. needle valve. All air lines were ½-in. black-iron pipe with the exception of a section of ¾-in. pipe from the compressor to the pressure-regulating valve. The orifice assembly tube was made from 2-in. stainless steel tubing. A 12-ft. section of ½-in. metallic hose was provided upstream from the orifice assembly tube to permit the introduction of air at either the bottom or the side of the column with a minimum of piping changes.

The experimental column, shown in detail in Figure 2, consisted of an 82-in. section of 8-in. standard black-iron pipe. Clear vision over the entire length of the column was provided by two sets of three Lucite windows located in parallel planes. The window frames were fabricated from ⅜-in. angle iron welded to the outside of the column. Rubber-sheet gaskets 1/16 in. thick were sealed to the angle-iron window frames with an adhesive cement. The Lucite windows were clamped into place over these rubber gaskets by steel frames fitted with sixteen ⅜-in. machine bolts per window.

Air entered through the orifice assembly tube located at either the bottom or the side of the column. Suitable packing glands were provided to permit the location of the orifice at any point desired. For the runs made with a side entry, the orifice assembly tube was pointed down at an angle of 15 degrees from the horizontal.

Three metering instruments were used to determine the rate of air flow in most of the experimental runs. A range of air-flow rates from 0.0400 to 11.0 std. cu. ft./min. was covered. A rotameter was located upstream from the orifice to meter the flow of air to the column. From 0.0400 to 0.500 std. cu. ft./min. the rate of air flow from the column was measured by several wet-test meters of suitable capacity. From 0.500 to 2.00 std. cu. ft./min. this flow rate was measured by a specially calibrated standard rotameter and a wet-test meter of suitable capacity in series. Another specially calibrated standard rotameter was used to measure flow rates in the remainder of the experimental range.

In order to obtain accurate rates of air flow as a function of pressure ratio, pressures and temperatures were measured at several points in the flow system. The pressure was measured immediately downstream from the pressure-regulating valves, at the orifice-assembly tube, at the top of the experimental column, at the inlet and exit of the specially calibrated standard rotameter, and at the wet-test meter. Temperatures were measured at the orifice-assembly tube, at the top of the column, and at the wet-test meter. Pressures less than 32 lb./sq. in. abs. at all points upstream from the orifice were measured with mercury manometers. Pressures greater than 32 lb./sq. in. abs. were measured with Bourdon gauges calibrated with a dead-weight gauge tester at frequent intervals during the experimental work. In most cases pressures downstream from the orifice were measured by use of water manometers. However, for air-flow rates greater than 2.00 std. cu. ft./min. pressures downstream from the orifice were measured by use of mercury manometers. Temperatures were measured by dial thermometers calibrated in degrees centigrade.

The investigation included four different orifice diameters, 1/64, 1/32, 1/16, and ⅛ in. The actual dimensions of the orifices and the velocity of approach factors are summarized in Table 1. The throat-length-to-diameter ratio of the sharp-edged orifices was less than 0.125 in all cases. The round-edged orifice 1/16 in. in diameter was machined with an included bevel angle of 90 deg. on the upstream edge. Two thick-plate orifices, ⅛ in. in diameter, were machined with throat-length-to-diameter ratios of 0.891 and 0.816. The machining of all orifices was observed with a low-powered optical microscope to ensure a minimum of variation in diameter and throat length. The upstream edge of each orifice was lapped by means of fine jeweler's rouge. Before use, the actual dimensions of each orifice were obtained with a sliding-stage microscope equipped with a microtessar lens, reticule micrometer, and a matching substage condensing lens. Each diameter was measured five times and the maximum variation encountered was ±0.0002 in. for the 1/64-in. orifice and ±0.0004 in. for the ⅛-in. orifice. The orifices were reexamined at intervals during the experimental work and no change in orifice diameter was detected.

A view of the orifice-assembly tube is shown in Figure 3. The tube inside diameter

Table 1. Orifice Dimensions

Series	Nominal diameter, in.	Actual diameter, in. D_o	Velocity of approach factor β	Orifice throat length, L_o	L_o/D_o
B	1/64	0.0165	0.00900	.....	< 0.125
C	1/32	0.0323	0.0176	.....	< 0.125
D	1/16	0.0635	0.0346	.....	< 0.125
D-R	1/16	0.0641	0.0350	.....	.....
A	1/8	0.1261	0.06879	.....	< 0.125
AT-11	1/8	0.1235	0.0674	0.110	0.891
AT-12	1/8	0.1311	0.0715	0.107	0.816

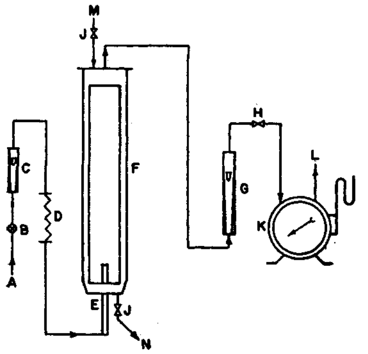

Fig. 1. Schematic flow diagram of equipment.

is 1.833 in. The velocity of approach factor varied from 0.00900 for the 1/64-in. orifice to 0.06879 for the ⅛-in. sharp-edged orifice. An undisturbed length equivalent to sixteen tube diameters was provided upstream from the orifice.

EXPERIMENTAL PROCEDURE

At the beginning of each data series the pressure upstream from the orifice was set at approximately 20 lb./sq. in. abs. The column was filled with liquid to a depth of 50 in. above the orifice in all experimental runs. By placing the orifice-assembly tube under pressure before the introduction of liquid to the column, the back-flow of liquid into the orifice-assembly tube was prevented. The level of the orifice was held at 12 in. above the bottom of the column in all the experimental runs. For the limited amount of data obtained with side entry, the orifice-assembly tube projected into the column a distance of approximately 2 in., as measured on the center line of the tube.

In operation the pressure-regulating valve was used for coarse adjustments in the air rate of flow, and fine adjustments were made with the needle valve. The air entered the column through the orifice, bubbled through the liquid, passed through the flow meters downstream from the column, and was discharged to the atmosphere. The globe valve located downstream from the column was adjusted to minimize pressure fluctuations. The absence of fluctuations in the readings of the manometers and flow meters was accepted as a criterion for equilibrium. Sufficient time was allowed for the liquid to become saturated with air before any readings were recorded.

RESULTS

Orifice discharge coefficients have been calculated for the rate of flow data of this

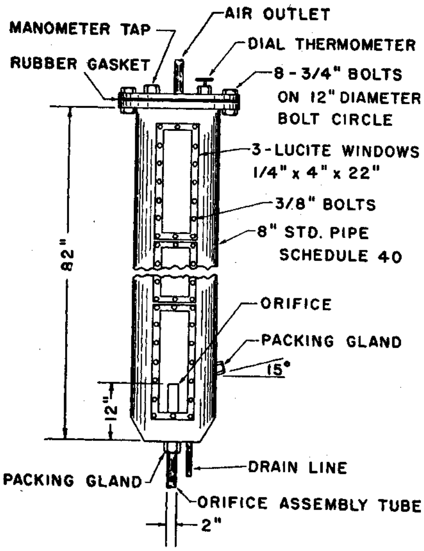

Fig. 2. Details of column design.

study by use of the critical orifice-flow equation:

$$C_n = \frac{w}{A_o P_1 \sqrt{\dfrac{g_c k M_W}{R T_1}\left(\dfrac{2}{k+1}\right)^{\frac{k+1}{k-1}}}} \qquad (1)$$

The coefficient C_n is the ratio of the discharge obtained from an orifice to that from an ideal nozzle operating at pressure ratios less than 0.53. The coefficient C_n may also be regarded as the ratio of the effective orifice discharge area to the actual orifice cross-sectional area. Pressure ratio is the ratio of the pressure downstream from the orifice (taken as equivalent to the static head of the liquid plus the pressure at the top of the column) divided by the pressure upstream from the orifice.

In Figure 4 the orifice discharge coefficient is plotted vs. pressure ratio for the 1/64- through ⅛-in. sharp-edged orifices. Within the accuracy of the data, the results for the 1/64- and 1/32-in. orifices fall on one curve and those for the 1/16- and ⅛-in. orifices fall on another. There is a considerable increase in C_n as the pressure ratio decreases even in the supercritical flow region. Approximately a 12% maximum increase in the coefficient of discharge over that at the critical pressure ratio occurs for the 1/64- and 1/32-in. orifices and a 14% maximum increase occurs for the 1/16- and ⅛-in. sharp-edged orifices. The data fit the curves with an average deviation of approximately ±1.5%. The effect of orifice diameter on the coefficient of discharge is similar to that obtained by Grace and Lapple (*12*). The data show approximately a 6% increase in the coefficient of discharge for the 1/64- and 1/32-in. orifices compared with the 1/16- and ⅛-in. orifices. In the course of the experimental work, to obtain clearer vision of the bubble formation occurring at the orifice, the included angle of the bevel on the downstream face of each

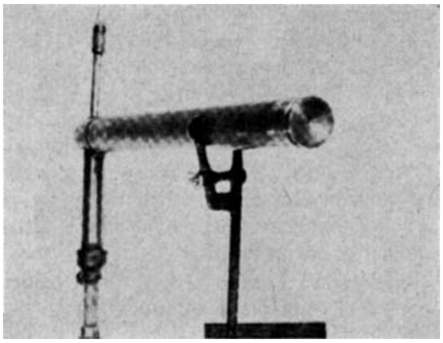

Fig. 3. View of the orifice-assembly tube.

orifice was changed from 90 to approximately 160 deg. with no effect on the experimental results. A single point at the critical pressure ratio reported by Pattle (*16*) for bubble formation from a nozzle 0.0394 in. in diameter is shown in Figure 4 to be in close agreement with the present work.

The air-air–system data in the literature were obtained in most cases with the diameter of the tube upstream equal to that downstream from the orifice. In this study the orifice was mounted in the end of a 2-in. stainless steel tube which is placed inside an 8-in. column. It has been shown by Datta, Napier, and Newitt (*6*) that the principal effect of column diameter in the air-water system is the wall effect which results for bubble formation in equipment with a large ratio of orifice diameter to column diameter. The column diameter was not varied in this investigation; however, it is felt that for small values of the ratio of orifice diameter to column diameter the effect of column diameter may be neglected. The range of values for this ratio in the air-air–system data from the literature is from 0.03 to 0.12. In this paper the corresponding range for the air-water system is from 0.002 to 0.012.

In Figure 5 the data for the ⅛- and 1/16-in. submerged sharp-edged orifices discharging air into water are compared with the data in the literature for sharp-edged and round-edged orifices operating in an air-air system. In the subcritical region the data for the flow of air into water approximate the data in the literature for the air-air system. As the pressure ratio is decreased, however, the curve approaches that of Grace and Lapple (*12*) for a ⅛-in. round-edged orifice. Similar behavior is exhibited by the data for the 1/32- and 1/64-in. orifices, as shown in Figure 6. On the basis of the data obtained, the effective orifice discharge area for a sharp-edged orifice operating in the air-water system must be greater than that for an orifice of the same size and type operating at the same pressure ratio in the air-air system. This behavior may be attributed to the tendency of the bubble formation which occurs close to the downstream face of the orifice for the air-water system to inhibit the development of the *vena contracta* ob-

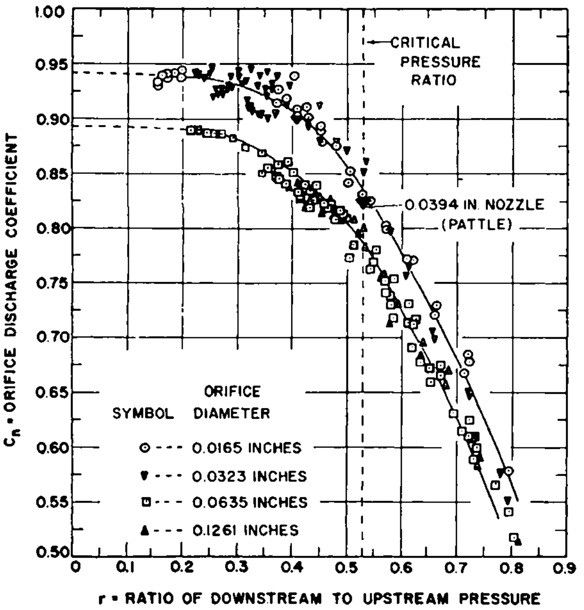

Fig. 4. Sharp-edged orifices.

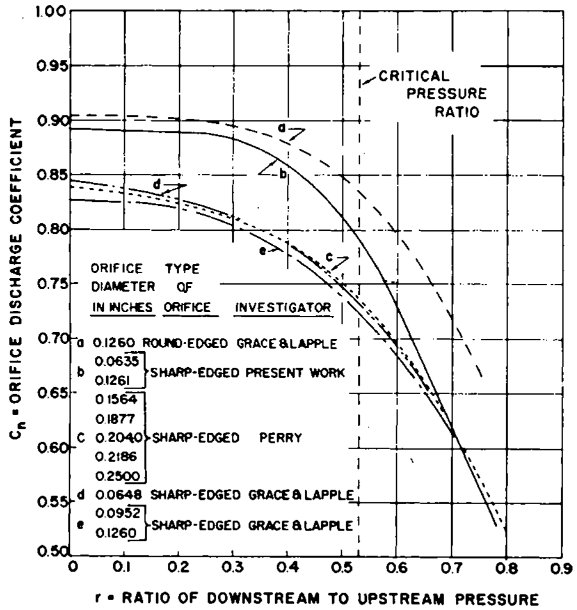

Fig. 5. Comparison with previous work.

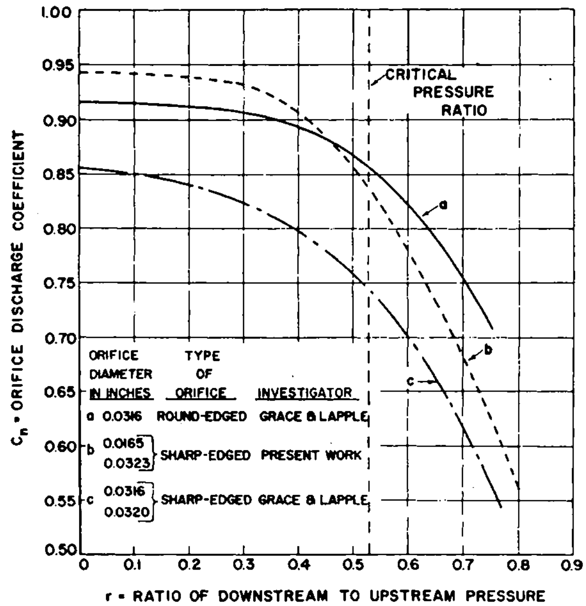

Fig. 6. Comparison with previous work.

served for the air-air system. Attempts to verify this premise by making longitudinal pressure traverses downstream from the orifice with a specially constructed pressure probe were unsuccessful. In every case visual evidence was obtained that the presence of the probe disturbed the bubble formation. However, the pressure-probe measurements did indicate that at pressure ratios less than the critical pressure ratio the bubbles formed at the orifice possess an excess internal pressure compared with the pressure equivalent to the static head of the liquid at this point.

In Figure 7 the coefficients of discharge calculated from the data for the 1/16-in. submerged round-edged orifice are compared with data in the literature for a 1/32- and a 1/8-in. round-edged orifice operating in the air-air system. Close agreement is shown for the discharge coefficients for the round-edged orifice operating in the two systems. For a round-edged orifice operating in the air-air system the *vena contracta* is located at the throat of the orifice. Consequently, one might expect that for a round-edged orifice operating in the air-water system, bubble formation would have little or no effect on the effective orifice-discharge area.

Coefficients of discharge for two 1/8-in.-thick–plate orifices with ratios of throat length to diameter of 0.816 and 0.891, respectively, are shown in Figure 8. These data are reproducible within $\pm 1.5\%$. In the supercritical region the curve is located approximately 8% above that given by Grace and Lapple (*12*) for a 1/16-in.-thick–plate orifice operating in the air-air system. As discussed in the introduction, the coefficient of discharge for a thick-plate orifice operating in the air-air system is relatively constant for values of the pressure ratio less than 0.33. For a 1/8-in. submerged thick-plate orifice discharging air into water there is only a 3% increase in the coefficient of discharge over that at the critical pressure ratio. Thus the coefficient of discharge for a submerged thick-plate orifice operating in the air-water system exhibits constancy similar to that shown by the coefficient for an ideal nozzle operating in the supercritical region.

SUMMARY

The coefficients of discharge obtained for sharp-edged orifices operating in the air-water system indicate that the effective orifice-discharge area for this type of operation is greater than that for an orifice of the same size operating at the same pressure ratio in the air-air system. The effective orifice-discharge areas for a round-edged orifice operating in either the air-water or air-air systems appear to be identical at the same pressure ratio. The thick-plate orifice operating in the air-water system exhibits a constancy of discharge coefficient at pressure ratios less

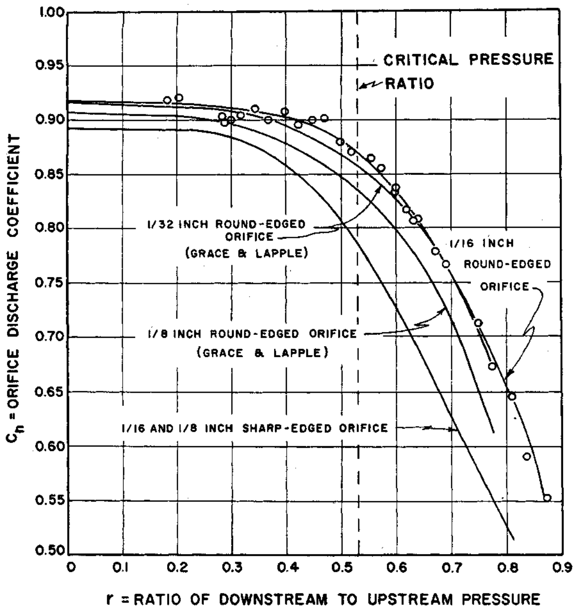

Fig. 7. Round-edged orifice.

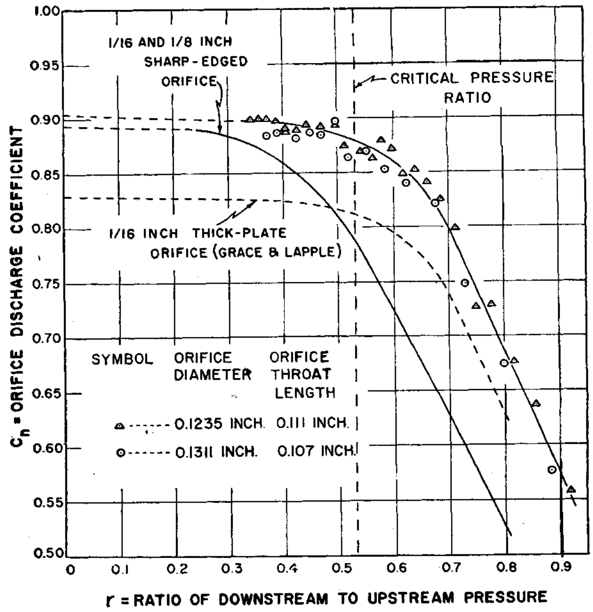

Fig. 8. Thick-plate orifice.

than 0.33. Inasmuch as bubble formation occurring close to the downstream face of a sharp-edged orifice operating in the air-water system influences the effective orifice discharge area, liquid physical properties may be expected to be important in determining the rate of flow from this type of orifice for other gas-liquid systems. Before a generalized correlation can be developed for the flow of gases into liquids through single submerged orifices further data must be obtained for systems containing liquids other than water.

NOTATION

		Dimension
A_o	= orifice cross-sectional area	L^2
C_n	= orifice coefficient of discharge	
D_o	= orifice diameter	L
g_c	= conversion factor = 32.17 (lb./lb. force)(ft./sec.²)	$ML/F\theta^2$
k	= ratio of specific heat at constant pressure to specific heat at constant volume	
L_o	= orifice throat length	
M_W	= molecular weight, lb./lb. mole	
P_1	= absolute pressure upstream from the orifice	F/L^2
P_2	= absolute pressure downstream from the orifice	F/L^2
q	= volumetric rate of air flow at standard conditions, 32°F. and 14.7 lb. force/sq. in.	L^3/θ
R	= gas constant	LF/MT
r	= ratio of absolute pressure downstream from the orifice to the absolute pressure upstream from the orifice	
T_1	= absolute temperature upstream from the orifice	T
T_3	= temperature of the air flowing from the experimental column	T
w	= mass flow rate	M/θ
β	= ratio of orifice diameter to orifice-assembly-tube diameter	
ρ_1	= gas density upstream from the orifice	M/L^3

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II. Mechanics of Bubble Formation

Very little information is available concerning bubble formation and behavior at the high rates of gas flow reported in Part 1. The purpose of this paper is to develop an understanding of the mechanics of formation and detachment of bubbles from single, submerged orifices operating at relatively high rates of air flow in a high-seal liquid-level system. Studies of these phenomena by use of orifices, nozzles, capillaries, and porous plates operating at low rates of gas flow have been made by many investigators (*5, 8, 9, 15, 28*) and were thoroughly reviewed by Jackson (*16*).

PREVIOUS WORK

Studies of bubble formation reported in the literature show that as the rate of gas flow through the orifice is increased, three regions of bubble formation are obtained. At very low rates of gas flow (below the