14. Higbie, Ralph, *Trans. Am. Inst. Chem. Engrs.*, **31**, 365 (1935).
15. Hobson, Merk, and George Thodos, *Chem. Eng. Progr.*, **47**, 370 (1951).
16. Johnson, A. I., and Chen-Jung Huang, *A.I.Ch.E. Journal*, **2**, 412 (1956).
17. Kramers, H., and P. J. Kreyger, *Chem. Eng. Sci.*, **6**, 42 (1956).
18. Leveque, J., *Ann. Mines*, **13**, 283 (1928).
19. Lin, C. S., R. W. Moulton, and G. L. Putnam, *Ind. Eng. Chem.*, **45**, 636 (1953).
20. Lynch, E. J., and C. R. Wilke, to be published, *A.I.Ch.E. Journal*.
21. Lynn, Scott, J. R. Straatemeier, and H. Kramers, *Chem. Eng. Sci.*, **4**, 58 (1955).
22. McCune, L. K., and R. H. Wilhelm, *Ind. Eng. Chem.*, **41**, 1124 (1949).
23. McHenry, K. W., and R. H. Wilhelm, *A.I.Ch.E. Journal*, **3**, 83 (1957).
24. Mixon, F. O., and J. J. Carberry, to be published, *Chem. Eng. Sci.*
25. Moison, R. L., and H. A. O'Hern, *Chem. Eng. Progr. Symposium Series No. 24*, **55**, 71 (1959).
26. Raimondi, Pietro, and H. L. Toor, *A.I.Ch.E. Journal*, **5**, 86 (1959)
27. Schlichting, Hermann, "Boundary Layer Theory," Pergamon Press, New York, (1955).
28. Thoenes, D., and H. Kramers, *Chem. Eng. Sci.*, **8**, 271 (1958).
29. Toor, H. L., and J. M. Marchello, *A.I.Ch.E. Journal*, **4**, 97 (1958).
30. Wilke, C. R., and O. A. Hougen, *Trans. Am. Inst. Chem. Engrs.*, **41**, 445 (1945).
31. Wilke, C. R., Remarks at St. Paul, Minn., A.I.Ch.E. Meeting (Sept., 1959).
32. Yagi, Sakae, and Noriaki Wakao, *A.I.Ch.E. Journal*, **5**, 79 (1959).

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Entrainment and Pressure Drop in Concurrent Gas - Liquid Flow: I. Air - Water in Horizontal Flow

MOYE WICKS, III, and A. E. DUKLER

University of Houston, Houston, Texas

Experimental equipment and data are reported for entrainment and energy loss in annular, two-phase flow of water and air. Measurements were made with a sample withdrawal technique in 1- and 3-in. horizontal tubes. A knowledge of entrainment is necessary to an understanding of various mass transfer, heat transfer, and separation problems in two-phase flow. A preliminary correlation is presented.

Research in two-phase gas-liquid flow has increased steadily over the past ten years. In addition to a long-standing need for a better theoretical understanding of this type of flow the demands of a group of important industrial problems have accelerated this work.

Several investigators (*8, 17*) have demonstrated that when two phases flow together in a tube the liquid and gas streams can assume several different shapes. At high gas rates a predominant pattern is annular flow with the liquid at the wall and the gas moving in the core. This type of flow is thought to be accompanied by a dispersion or entrainment of part of the liquid in the gas phase. Entrainment is of considerable importance to an understanding of mass transfer, heat transfer, separation processes, and energy loss. This paper reports the first phase of a program to study entrainment. Equipment designed for direct measurement of entrainment and entrainment distribution is described. Experimental data on the air-water system is presented and preliminary correlation is proposed.

PREVIOUS STUDIES

Experimental data on entrainment or entrainment-measuring techniques in moving gas streams are very limited in the literature. Several studies of drop distribution from nozzles, spray chambers, and rotating disks (*16*) can be found. However in each of these cases the amount of liquid dispersed can be predetermined by the experimenter and the problems restricted to a study of drop-size distribution, spray areas, etc. In two-phase flow the entrainment is generated by the action

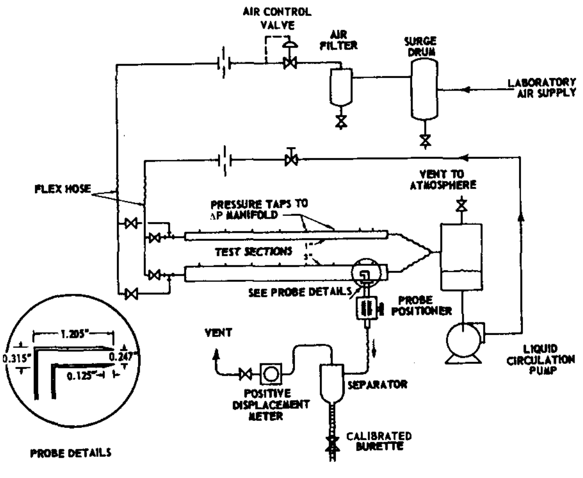

Fig. 1. Experimental equipment.

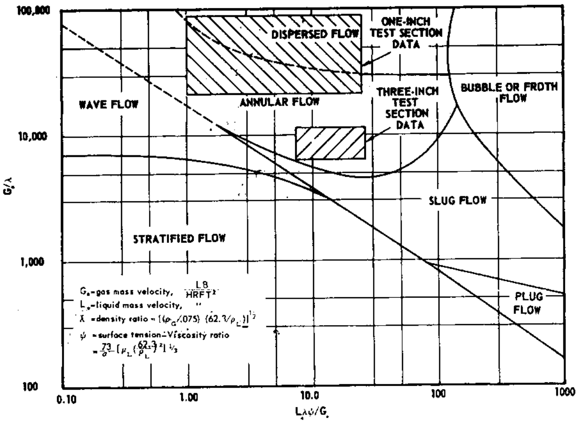

Fig. 2. Flow regimes.

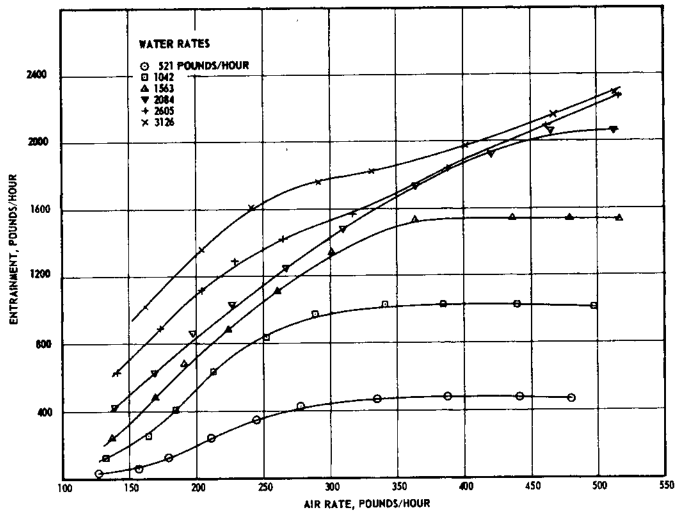

Fig. 3. Entrainment air on the tee, 1-in. tube.

of the gas on the liquid, and it is first necessary to determine how much liquid is entrained. The only source of reliable published data in the literature seems to be five points presented by Alves (2), four for air-water and one for an SAE-oil system. Entrainment data are also reported by Krasjakova (*12*). A study of these Russian data seems to indicate that the experiments were carried out in stratified flow, and flooding of the sampling tube took place. Less generally known are two studies at the University of Delaware; Fritzlen (*7*) and Budd (*4*) measured entrainment over limited conditions.

Closely associated studies are the work of Alexander and Coldren (*1*) who measured droplet deposition rate downstream from an atomizer spraying into a turbulent air stream and Longwell and Weiss (*15*) who measured distribution of fuel injected into high velocity air streams. In both of these cases all of the liquid was injected by some device into the gas phase and then allowed to distribute. Entrainment was close to 100%. Most recently Hanratty and Engen (*9*) report on the nature of waves formed by the flow of air across a water surface. Lane (*14*) and Hughes *et al.* (*11*) have suggested mechanisms whereby the gas moving across the surface may generate drops which are carried along in the gas phase.

EXPERIMENTAL APPARATUS

General

The system used in this study was air and water.

Figure 1 is a schematic diagram of the equipment used. After passing through control valves and calibrated metering devices the fluids entered the test section through a standard 1-in. screwed tee connection. The piping was arranged so that each phase could be injected at either the side or the run of the mixing tee.

Two-phase pressure drop can be strongly affected by mechanical vibrations transmitted to the test section (*13*). For this reason care was taken to insulate the system from such pulsations by the use of rubber-tubing connections up and downstream of the test sections. Rubber-cushioned machine bolts supported the test section at 3-ft. intervals.

A baffled 33-gal. galvanized barrel served as the water reservoir and separator. Air discharged to the atmosphere through a 3-in. gate valve on top of the barrel. Back pressure in the test section was controlled by this valve.

Table 1 shows pertinent dimensions for each test section.

TABLE 1. DATA DESCRIBING TEST SECTIONS

Test section / Measurement	1-in. test section (type L copper water tube)	3-in. test section (type L copper water tube)
Outside diameter, in.	1.125	3.125
Wall thickness, in.	0.050 ± 0.004	0.090 ± 0.007
Inside diameter, in.	1.025 ± 0.008	2.945 ± 0.014
Total length, ft., in.	20′ 3¼″	20′ 6½″
Distance from entrance tee to entrainment, sampling hole, fee, in.	19′ 1⅛″	19′ 1⅜″
Distance from entrance tee to upstream pressure tap, ft., in.	6′ 4¼″	(No pressure-drop data obtained)
Distance from entrance tee to downstream tap, ft., in.	18′ 4¼″	(No pressure-drop data obtained)

Pressure Drop

When one measures two-phase pressure drop with a manometer, the lines between manometer and pressure tap must be full of one phase or the other. Preliminary experiments clearly demonstrated that the presence of two phases can cause errors in pressure drop as large as the value being measured. A purge of gas into the test section through the lead lines can be used to maintain this single-phase condition. The question arises whether this purge of itself affects the manometer reading when small differences are measured. This point was resolved by equalizing the pressure drop due to flow of purge gas in the two lead lines. The flow to each side was separately adjusted until two manometers measuring lead-line pressure drop showed the same reading. Additional details are available in reference *19*.

The technique just described was verified by excellent agreement obtained between calculated and experimentally measured pressure drop for single-phase air flow through the test section. Moreover neither pressure drop nor entrainment was measurably affected by the magnitude of the purge rate as long as it was less than 1% of the total gas rate to the test section.

Entrainment

A direct sample-withdrawal method was devised to measure entrainment. The liquid droplets and gas entered a 5/16-in. stainless steel probe with dimensions as shown in Figure 1. The probe mouth was located at the axis of the test section. Liquid and gas were separated in a small impingement separator with liquid dropping to a cali-

Table 2. Typical Data

Run no.	W_L lb./hr.	t_L °F.	μ_L lb.$_M$/ ft. hr.	W_G lb./hr.	t_G °F.	μ_G lb.$_M$/ ft. hr.	ρ_G lb.$_M$/ cu. ft.	$(Re)_G$ $x10^{-5}$	f_G	$\left(\frac{dP}{dL}\right)_{TP}$ lb.$_F$/ sq. ft./ft.	m $x10^3$ ft.	$(Re)_L{}'$	E lb.$_M$/hr.	X	R lb.$_M$cu. ft./ lb.$_F$hr.
2,106	521	85	1.92	244	95	0.0455	0.0900	0.809	0.0190	22.9	0.569	1,320	351	0.109	2.30
2,107	521	86	1.90	211	95	0.0455	0.0891	0.705	0.0204	19.3	0.880	2,180	243	0.125	2.40
2,108	521	87	1.88	179	95	0.0455	0.0882	0.604	0.0222	15.9	1.26	3,100	130	0.145	2.03
2,109	521	87	1.88	158	95	0.0455	0.0876	0.536	0.0233	13.5	1.50	3,500	60	0.161	1.31
2,110	521	87	1.88	127	95	0.0455	0.0865	0.435	0.0230	9.21	1.95	3,820	39	0.196	1.54
2,201	1,042	86	1.91	498	95	0.0455	0.1010	1.64	0.0158	67.1	0.122	203	1,016	0.105	1.98
2,202	1,042	85	1.92	439	95	0.0455	0.0991	1.44	0.0177	59.5	0.119	154	1,022	0.118	2.82
2,203	1,042	84	1.94	384	95	0.0455	0.0972	1.26	0.0199	52.1	0.118	112	1,028	0.133	4.03
2,204	1,042	84	1.94	340	95	0.0455	0.0957	1.12	0.0220	46.0	0.126	112	1,028	0.149	5.60
2,205	1,042	85	1.92	289	95	0.0455	0.0930	0.952	0.0251	39.1	0.254	558	970	0.174	8.25

brated burette and the gas vented to the atmosphere. A schematic drawing of this sampling arrangement is shown in Figure 1.

Liquid flow through the probe was determined by measuring the time to fill a calibrated burette. Knowing probe and pipe inside diameters one could calculate total entrainment by multiplying the mass velocity through the probe by the cross-sectional area of the pipe:

$$E = G' \, x \, A \qquad (1)$$

Equation (1) is actually a special case of the general equation

$$E = \int_0^{2\pi} \int_0^{r_0 - m} G(r, \theta) r dr d\theta \qquad (2)$$

which degenerates to (1) when G is independent of both r and θ and when the liquid film thickness is negligible compared with the pipe radius. To investigate this point entrainment was measured at various probe positions in both horizontal and vertical planes. Pertinent observations can be summed up as follows:

1. Variation of entrainment with probe position was greatest at low values of percentage total input liquid entrained.
2. Sensitivity to probe position decreased as completely dispersed flow was approached.
3. Even for the low percentage entrainment conditions sampling from the center of the pipe gave an averaged value for liquid loading.

Over the range of variables investigated the following factors were shown to have no significant effect on measured entrainment mass velocity when gas and liquid rates to the tube were held constant:

1. Gas flow through the probe from 9 1/2 to 1/3 of the mass velocity of gas in the test section.
2. Ratio of outside to inside probe diameter, from 1.40 to 1.02; probes of the following nominal size were tested 1/8, 3/16, 1/4, 5/16, 3/8, and 1/2, all stainless steel.
3. Length of probe along the tube axis; from 0.43 to 1.08 test-section diameters.

These measurements suggested that the capture efficiency (the ratio of the actual droplet capture rate to that if there were no interference from the sampler) was essentially 100%. Dussourd and Shapiro (6) suggested this capture efficiency term and related it to the dimensions of the sampler. Using their relationships one can predict the capture efficiency to be 100% for this probe system.

EXPERIMENTAL DATA

This initial series of experiments was restricted to the system water-air at low pressures. Entrainment and pressure-drop data were taken in the 1-and 3-in. test sections over the following ranges of rates: 1-in. test section; water rate: 500 to 3,100 lb./hr., air rate: 100 to 500 lb./hr., 3-in. test section; water rate: 4,000 to 8,000 lb./hr., air rate: 300 to 550 lb./hr.

Data were obtained with two basic entrance sections for all rates: (*a*) water entering along the axis of the test section with air introduced at 90 deg. and (*b*) air entering along the axis of the test section with water introduced at 90 deg. In addition the effect of absolute pressure level over the limited range of 0 to 5 in. of mercury, gauge, was explored. Two hundred and twenty-five data points were obtained for the 1-in. section and forty-four points were taken in the 3-in. section. In addition a limited number of measurements were made to determine entrainment distributions in the flow cross-sectional area.

Some picture of the flow regimes covered here can be obtained by the use of the graphical form suggested by Baker (3). In Figure 2 the area covered by this work is shown blocked in for the 1- and 3-in. tube. It should be noted that over the region shown for the 1-in. tube entrainment varied from less than 5 to 100% of the liquid feed to the test section. The transition from annular to dispersed flow is gradual, and no distinct boundary can be defined.

Typical plots of the raw entrainment data for the 1-in. test section appear in Figures 3 and 4 for each entrance section. In both cases shown the static pressure at the sampling point was 5 in. of mercury gauge. Similar data for the 3-in. section

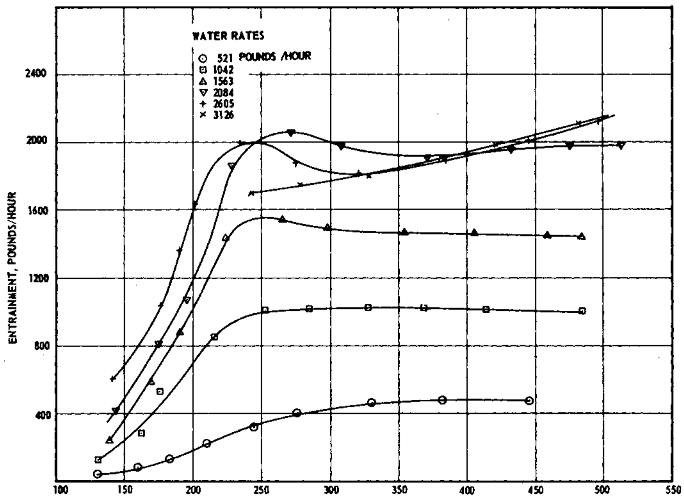

Fig. 4. Entrainment water on the tee, 1-in. tube.

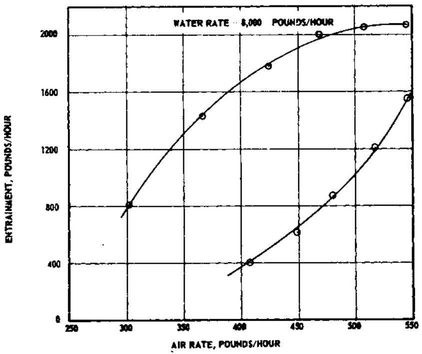

Fig. 5. Entrainment 3-in. tube, water on the tee.

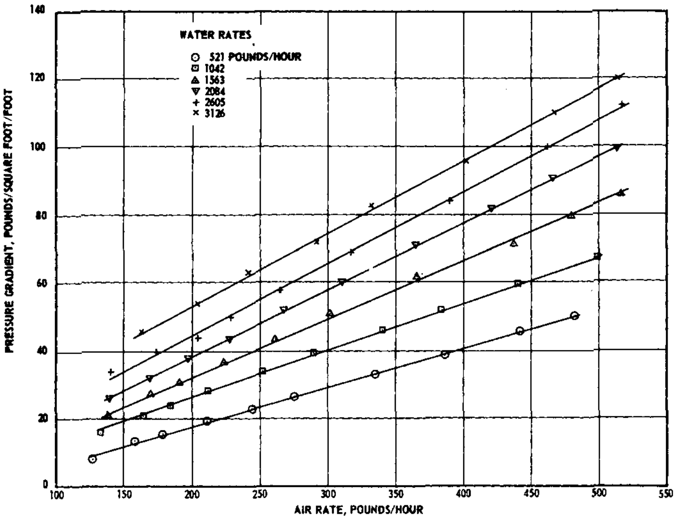

Fig. 6. Pressure drop 1-in. tube, air on the tee.

are presented in Figure 5, where the air pressure was 2.5 in. of mercury. Typical data are shown in Table 2. Complete data may be found in reference *19*. Pressure-drop data for the 1-in. test section corresponding to data in Figures 3 and 4 are presented in Figures 6 and 7. In the 3-in. test section pressure drop was very small, and accurate values could not be obtained.

DISCUSSION OF DATA

The entrainment and pressure-drop data show consistent trends at all gas and liquid rates. The general trends are: both entrainment and pressure drop increase with water rate for a given air mass rate; both quantities increase with air mass rate for a given water rate; both entrainment and pressure drop decrease with increased total system pressure.

The influence of entrance section can be seen from Figure 8. With air on the run of the entrance tee the entrainment is higher (except at essentially completely dispersed flow) and the pressure drop is lower. Hinze (*10*) has suggested that the critical Weber number has different values depending on the manner in which the liquid mass is exposed to acceleration sources. He suggests a value of 13 for a sudden shock exposure to a fast moving gas stream and a value of 22 for gradual acceleration. It appears likely that water entering on the side of the inlet tee would behave as if it were suddenly exposed to sudden shock. On the other hand when air entered on the side into a liquid stream already filling the pipe cross section, the accelerations would be more gradual. These two entrance sections could be expected to correspond to two different critical Weber numbers. By the definition of the Weber number

$$We = \frac{\rho_A (U_A - U_W)^2 D}{\sigma_W \; g_c} \qquad (3)$$

the maximum stable drop size can be expected to be smaller for the air on the run entrance section. In accordance with the Mugele-Evans (*18*) drop size

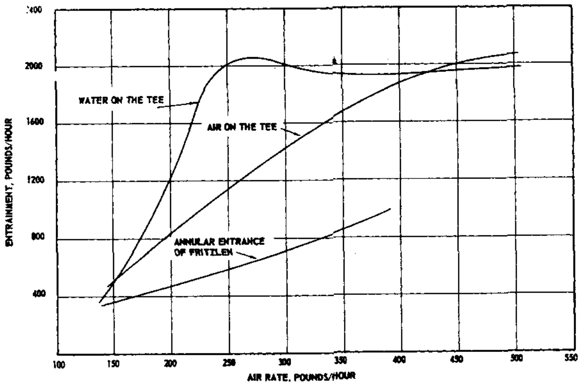

Fig. 8. Effect of entrance-section shear on entrainment.

distribution theory the drop size over the entire range will be smaller. Redeposition of drops created at the entrance can be expected to be lower and therefore the measured entrainment larger, as shown in Figure 8.

A comparison of pressure drops is not nearly as clear-cut. The conditions of Figure 9 demonstrate that the two phase pressure drop is lower when entrainment is higher at equivalent phase flow rates. This seems to be generally true at the lower liquid rates and suggests that it requires less energy to transport a given amount of liquid in the gas phase rather than as a thin film adjacent to the wall. However at high liquid rates this difference seems to disappear. Further careful studies of this trend are in progress.

Further information on the effect of entrance section on entrainment appears in Figure 8 where the data of Fritzlen (*7*) are compared with those of this study for the two entrance sections. Fritzlen's entrance section was a very gradual annular entrance which contacted the two phases with minimum interaction. Figure 8 shows that as the degree of shock due to entrance section design increases, the entrainment increases. This trend is in accord with expectations, since drop size decreases as the critical Weber number decreases. Calvert and Williams (*5*) report data which also seem to support these findings. Their data for upward

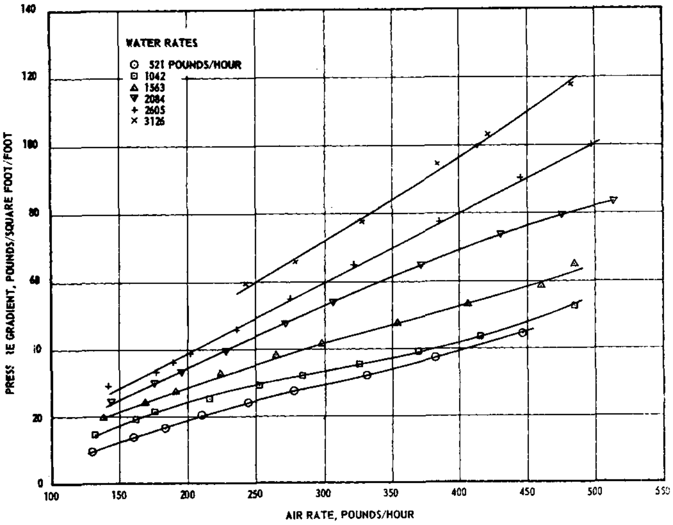

Fig. 7. Pressure drop 1-in. tube, water on the tee.

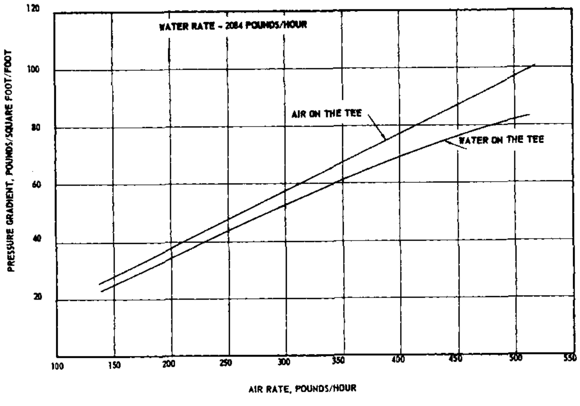

Fig. 9. Entrance-section effect on pressure drop.

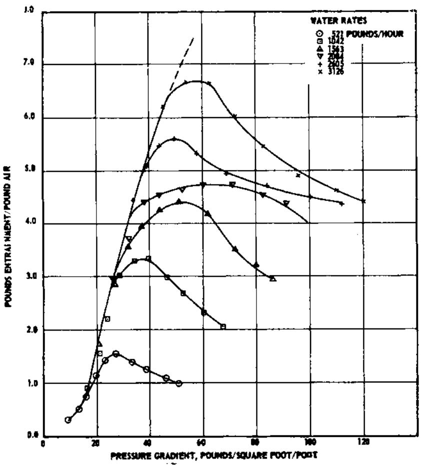

Fig. 10. Entrainment concentration, air on the tee.

concurrent two-phase flow appear to show a distinctly higher two phase pressure drop for a gradual annular entrance than for tee and ell entrances.

Figures 10 and 11 present entrainment in concentration units as a function of pressure drop. The curves for each water rate originate from a single curve at the lower gas rates. By careful observations it was found that this curve, common to all liquid rates, seemed to characterize a change in the flow pattern. As gas rate was increased and individual liquid rate lines emerged, severe manometer fluctuation seemed to be damped and a more nearly steady state flow achieved. It is suggested that this may represent the upper limit of the slug flow region, where the frequency of the slugs becomes effectively infinite and the amplitude approaches zero.

PRELIMINARY CORRELATION

Several approaches to entrainment theory have been examined, based on a study of the forces acting at the interface. As yet this method has not produced usable results. The complexity of the resulting relationships require additional experiments to define the entrainment distribution and its variation with fluid properties and channel dimensions in order to assist in arriving at suitable simplifying assumptions. Further experimental work along these lines is now in progress. However it has been possible to arrive at a semitheoretical basis for explaining the gross entrainment. This method is based on the assumption that the similarities in the mechanisms for mass and momentum transfer which have been shown to exist in single-phase flow also apply in two-phase flow. The eddies moving between the interface and the gas stream transport the liquid between the bulk liquid phase and the drop form in the gas. It thus seems likely that those external factors which determine the scale, velocity, and other characteristics of the eddy motion would influence, in a similar manner, the entrainment. Although the complete picture for energy loss and momentum transfer in two-phase flow is yet to be evolved, a preliminary relationship of entrainment can be arrived at in the following manner.

Martinelli defines ϕ as

$$\phi^2_G = \frac{\left(\frac{dP}{dL}\right)_{TP}}{\left(\frac{dP}{dL}\right)_G} \tag{4}$$

The pressure gradient is directly proportional to the rate of momentum transfer per unit area in the direction normal to flow. Thus ϕ^2_G becomes the ratio of the rates of momentum transfer in single and two-phase flow.

Define an analogous quantity ϕ'_G such that it represents the ratio of the rate of mass transfer per unit area in two-phase flow to the mass transfer rate in a unit area for single-phase flow. Now, Martinelli has correlated the term ϕ_G with a parameter X defined by Equation (5):

$$X = \left[\frac{\left(\frac{dP}{dL}\right)_L}{\left(\frac{dP}{dL}\right)_G}\right]^{1/2} \tag{5}$$

It is assumed that this same variable X can be used to correlate the quantity ϕ'_G, defined by Equation (6):

$$\phi'^2_G = \frac{M_{TP}}{M_G} \tag{6}$$

It is necessary to obtain expressions for M_{TP} and M_G.

The rate of mass transfer between the liquid surface and the bulk gas is the sum of the mass of gas and liquid which is transported as the eddies change position. Under most conditions

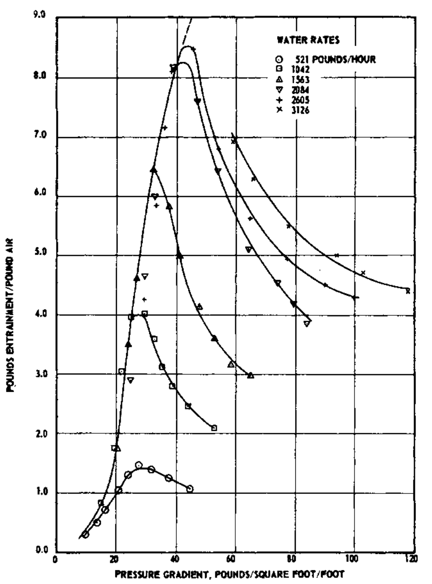

Fig. 11. Entrainment concentration water on the tee.

the liquid gas density ratio is large. For any significant degree of entrainment the mass of liquid involved is large compared with the vapor. M_{TP}, then, is uniquely related to the liquid movement. Entrainment can be pictured as a process in dynamic equilibrium. If a concentration of entrained material is defined as C_E, the rate of mass transfer can be written in the simplified expression

$$M_{TP} = kC_E \tag{7}$$

When one defines E as the mass rate of flow of entrained liquid and Q_G as the volumetric flow of gas

$$C_E = \frac{E}{Q_G} \tag{8}$$

$$M_{TP} = \frac{kE}{Q_G} \tag{9}$$

Although no quantitative picture of the factors influencing k can be given now, it is possible to examine this qualitatively. The rate of shearing from the liquid surface will depend on the pro-

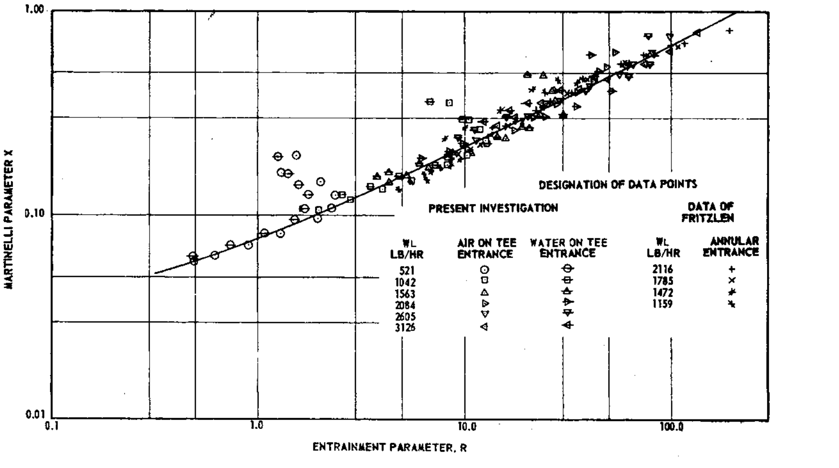

Fig. 12. Entrainment correlation.

file of that surface, the forces acting there, and the size of the liquid droplets formed when they enter the gas phase. Therefore k should depend on the external rates, the properties of the liquid, and the channel dimensions; in addition k should depend on the critical Weber number which determines the maximum drop size and drop-size distribution. Until additional data are developed, the following relationship is suggested:

$$k \sim Q_L We_c \qquad (10)$$

Thus

$$M_{TP} \sim \frac{Q_L}{Q_G} We_c E \qquad (11)$$

The rate of mass transfer for single-phase flow represents the rate of movement of eddies in the direction normal to flow. Once again it is assumed that this is proportional to the rate of momentum transfer or to the pressure gradient calculated for single-phase flow:

$$M_G = K\left(\frac{dP}{dL}\right)_G \qquad (12)$$

When one combines (11) and (12) into the definition of ϕ'_G, Equation (6) gives

$$\phi'^2_G = \frac{Q_L/Q_G\, We_c E}{K(dP/dL)_G} \qquad (13)$$

When one sets

$$R = \frac{Q_L/Q_G\, We_c E}{\left(\frac{dP}{dL}\right)_G} \qquad (14)$$

and assumes that the Martinelli parameter X will correlate ϕ'_G as it did ϕ_G, then X should also correlate the entrainment group R. Figure 12 shows all of the data of this study and the data of Fritzlen plotted on this basis. In accordance with entrance section discussions above, different critical Weber numbers could be expected for the two entrance sections used in this study and for the entrance section of Fritzlen. Based on the suggestions of Hinze a value of We_c of 22 was assumed to apply to Fritzlens equipment, with values of 13 and 16 assigned to the two entrance sections of this study. Except for some points in each series which drift away from the line, the data appear to agree within about 25% of the best curve. Experimental work, now in progress, should assist in improving this correlation.

SUMMARY

Experimental apparatus is described for the study of entrainment of liquid into a fast moving gas stream. Experimental data are presented over a wide range of air and water rates in a 1-in. tube and over a more limited range in a 3-in. tube. The influence of entrance-section design on pressure drop and entrainment is demonstrated. A preliminary correlation is presented relating an entrainment variable to the single phase pressure drops. Work is continuing with studies of entrainment distribution and property effects as well as new theoretical approaches.

ACKNOWLEDGMENT

The authors are sincerely grateful to the National Science Foundation whose financial sponsorship of the project was indispensable. The helpful suggestions of F. L. Worley, Jr., M. A. Pike, Jr., and B. W. Burke were of great assistance in the construction of the experimental equipment.

NOTATION

A = test section cross-sectional area, sq. ft.
C_E = concentration of entrained liquid, $lb._M$/cu. ft.
D = drop diameter, ft.
$\left(\frac{dP}{dL}\right)_G$ = pressure gradient which would exist if gas flowed alone, $lb._F$/sq. ft./ft.
$\left(\frac{dP}{dL}\right)_L$ = pressure gradient which would exist if liquid flowed alone, $lb._F$/sq. ft./ft.
$\left(\frac{dP}{dL}\right)_{TP}$ = pressure gradient in two-phase flow, $lb._F$/sq. ft./ft.
E = measured liquid entrainment calculated by Equation (1), $lb._M$/hr.
G = entrainment mass velocity at any point in the pipe cross-sectional area, $lb._M$/hr. sq. ft.
G' = entrainment mass velocity through the sampling probe measured at the pipe center line, $lb._M$/hr. sq. ft.
g_c = 32.17 $lb._M$ ft./$lb._F$sec.^{2}
K = proportionality constant in Equation (12)
k = rate constant in Equation (7)
M_G = rate of mass transfer per unit area in the gas phase normal to the net flow direction during single phase gas flow, $lb._M$/hr. sq. ft.
M_{TP} = rate of mass transfer of liquid per unit area in the gas phase normal to the net flow direction during two-phase flow, $lb._M$/hr. sq. ft.
m = liquid film thickness, ft.
P = static pressure
Q_G = volumetric flow rate of gas, cu. ft./hr.
Q_L = volumetric flow rate of liquid, cu. ft./hr.
R = entrainment correlation parameter defined by Equation (14), $lb._M$ cu. ft./$lb._F$ hr.
r = internal radial distance, ft.
r_o = inside test section radius, ft.
U_A = entering air velocity, ft./sec.
U_W = entering water velocity, ft./sec.
We = Weber number defined by Equation (3)
We_c = critical Weber number

Greek Letters

θ = angle between two radius vectors, radians
π = 3.14159
ρ_A = air density, $lb._M$/cu. ft.
σ_W = interfacial tension, $lb._F$/ft.
ϕ = Martinelli momentum transfer parameter defined by Equation (4)
ϕ'_G = two-phase mass transfer parameter defined by Equation (6)
χ = Martinelli momentum transfer parameter defined by Equation (5)

LITERATURE CITED

1. Alexander, L. G., and C. L. Coldren, *Ind. Eng. Chem.*, **43**, 1324 (1951).
2. Alves, G. E., *Chem. Eng. Progr.*, **50**, 449 (1954).
3. Baker, O., *Oil Gas J.*, 185 (July 26, 1954).
4. Budd, J. T., III, B.Ch.E. thesis, Univ. Del., Newark (1950).
5. Calvert, Seymour, and Brymer Williams, *A.I.Ch.E. Journal*, **1**, 78 (1955).
6. Dussourd, J. L., and A. H. Shapiro, "A Deceleration Probe for Measuring Stagnation Pressure and Velocity of a Particle-Laden Gas Stream," Heat Transfer and Fluid Mechanics Inst., Univ. Calif., Los Angeles (June 23-25, 1955).
7. Fritzlen, A. F., M.Ch.E. thesis, Univ. Del., Newark (1951).
8. Gazely, C., "Co-current Gas-Liquid Flow—III, Interfacial Shear and Stability," Heat Transfer and Fluid Mechanics Inst., Univ. Calif., Berkeley (1949).
9. Hanratty, T. J., and J. M. Engen, *A.I.Ch.E. Journal*, **3**, 299 (1957).
10. Hinze, J. O., *ibid.*, **1**, 289 (1955).
11. Hughes, R. R., H. D. Evans, and C. V. Sternling, *Chem. Eng. Progr.*, **49**, 78 (1953).
12. Krasjakova, L. U., *J. Tech. Phys.* (*U.S.S.R.*), **22**, No. 4, 654 to 699 (1952).
13. Laird, A. D. K., *Trans. Am. Soc. Mech. Engrs.*, **76**, 1005 (1954).
14. Lane, W. R., *Ind. Eng. Chem.*, **43**, 1312 (1951).
15. Longwell, J. P., and M. A. Weiss, *ibid.*, **45**, 667 (1953).
16. Marshall, W. R., *Chem. Eng. Progr. Monograph Ser. No. 2*, **50** (1954).
17. Martinelli, R. C., and R. W. Lockhart, *Chem. Eng. Progr.*, **45**, 39 (1949).
18. Mugele, R. A., and H. D. Evans, *Ind. Eng. Chem.*, **43**, 1317 (1951).
19. Wicks, Moye, III, M.Ch.E. thesis, Univ. Houston, Houston, Texas (1958).

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