Study of Bubbling Performance in Relation to Distillation and Absorption

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One of the important factors affecting the efficiency of vapor-liquid contacting operations is the relationship between available interfacial area and contact time.

Because of the difficulties in measuring these quantities, little information has heretofore been made available on them. Previous studies have been confined to extreme over-simplifications of the turbulent type of contacting taking place in fractionation devices. The present investigation consisted of the determination of interfacial area and contact time for the formation of air bubbles submerged in water and aqueous solutions. The bubbles were produced at single vertical slots and rose through a flowing liquid. In order to complete the study on physical contacting, a companion study is concerned with vapor-liquid behavior in the froth and entrainment zones. The experimental technique in this study involved taking high-speed motion pictures of the bubbling action. Measurements of the area and volume of bubbles were made at intervals during the course of their growth, and values of total contact time and average interfacial area per unit volume of vapor are presented.

It was found that both the average interfacial area per unit volume of vapor a and the total contact time t_m were primarily affected by the head of flowing liquid on the slot. Below slot submergence of approximately 2.5 in. of liquid, interfacial area was shown to decrease with increasing slot submergence and increasing slot area. Above 2.5 in. of liquid, interfacial area was a function of skirt clearance, liquid viscosity, and surface tension.

Total contact time was found to increase with increasing slot submergence and to decrease with increasing vapor rate and skirt clearance.

Through the use of an integrated mass transfer–rate equation, the terms a and t_m can be used in conjunction with the appropriate mass transfer coefficient for predicting the point efficiencies on bubble-cap plates.

OBJECTIVES AND SIGNIFICANCE OF THE STUDY

One of the chief problems still confronting the designers of distillation and absorption columns is the accurate prediction of the degree of approach to equilibrium of the contact steps involved, better known as the *efficiency*. In the case of bubble-cap towers, plate efficiencies, as they are called, are expressed in one of the three following terms: (1) over-all plate efficiency, (2) Murphree plate efficiency, (3) point or local Murphree plate efficiency.

Murphree plate efficiency is an integrated average of local Murphree efficiencies at all points across a full plate. Over-all plate efficiency represents the average of efficiencies for all the plates in a column. The calculation of plate or over-all values from point efficiencies has been well discussed (*27*).

Correlations for over-all plate efficiency have been proposed (*2, 3, 9, 30*). Extensive plate-efficiency studies have been reported (*18, 19, 20, 32*). Walter and Sherwood (*43*) have developed a useful correlation for local efficiency with the aid of certain simplifying assumptions. Because local efficiency is the "building block" from which the plate and over-all values are obtained, it was felt that the factors affecting this term should be determined.

The purpose of the present study is to investigate the factors affecting local Murphree plate efficiency at single, vertical bubble-cap slots. The factors involved are operating conditions, mechanical design of the tray and bubble caps, and the physical properties of liquid and vapor of the system. A companion project (*19, 26*) is concerned with extending these results to the case of multiple slots, analogous to a "full tray" of a bubble-plate tower.

The instantaneous rate of transfer of a single component, present in concentration C, from a volume of vapor V_M to the liquid through which it is rising, can be represented by

$$K_{G_1}A(C - C^*)\,dt = -V_M\,dC \quad (1)$$

By integrating Equation (1) over the liquid layer through which the vapor bubble rises, one obtains

$$\ln(1 - E_{LM}) = -\int_0^{t_m} \frac{K_{G_1}A\,dt}{V_M} \quad (2)$$

The over-all mass transfer coefficient, K_{G_1}, can be assumed practically constant

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when the vapor is bubbled through the liquid (*2*, *3*). Thus

$$\ln (1 - E_{LM}) = -K_{G_1} \int_0^{t_m} \frac{A\, dt}{V_M}$$

$$= -K_{G_1} a t_m \quad (3)$$

For the purpose of the present studies, in which the investigation was divided into two parts of mass transfer phenomena at single and multiple slots, respectively, Equation (3) can be modified by the addition of a froth and entrainment term ($K_{G_2} a_2 t_{m_2}$) to

$$\ln (1 - E_{LM}) = -K_{G_1} a_1 t_{m_1} - K_{G_2} a_2 t_{m_2} \quad (4)$$

Employment of single slotted caps made the extent of the froth and entrainment zones in this study negligible. The experimental portion of this work then involved only the determination and correlation of the terms K_{G_1} and $a_1 t_{m_1}$. The terms a and t_m were evaluated by means of high-speed motion pictures of the action of air bubbling through water and aqueous solutions. Mass transfer coefficients were evaluated and correlated from actual point-efficiency data obtained from a distillation system composed of various concentrations of acetone and water (*14*). These results, together with those for the multiple slot case in which froth and entrainment regions are involved, will provide considerably more insight into the physical mechanisms underlying vapor-liquid contacting on a bubble tray.

REVIEW OF LITERATURE

A search of the literature of the past thirty years reveals that there is considerable disagreement over the pertinent variables affecting bubble formation and that no universally acceptable correlations exist. For purposes of comparison, the previous work can be conveniently classified under two main headings: (1) bubble formation at circular orifices in a horizontal plane (*13*, *28*, *31*, *39* to *42*) and (2) bubble formation at vertical slots (*1*, *2*, *3*, *5*, *8*, *17*, *18*, *19*, *23*, *34*, *39*, *40*, *41*). As only the latter topic is of specific interest in this work, a review of investigations of the former is omitted here.

In his semitheoretical treatment of local efficiency, Geddes (*17*) utilized both a modified form of the static formation equation to obtain bubble size and an empirical formula derived from O'Brien's and Gosline's (*29*) data to find the ascending velocity. His assumption was that the contact time of a bubble emerging from a slot into a turbulent liquid stream approaches that of an isolated bubble rising in a quiescent liquid column of the same static height. In addition to neglecting the growth period of the bubble, during which its area is continually changing, Geddes also assumed the bubbles to be spherical in shape.

Davidson (*8*) presented some results of experiments on bubble formation at both orifices and single slots. Empirically, bubble size calculated by Geddes's equation and multiplied by a factor of three checked with Davidson's data. Davidson's theory that the area for bubbling at the slot is a function only of surface tension and liquid density would seem to apply only when the bubbles are in mechanical equilibrium with their surroundings during formation.

The works of Carey et al. (*1*) and Rogers and Thiele (*34*) seem to have confirmed the fact that slot opening is a function of gas rate, liquid density, and slot dimensions. Cross and Ryder (*5*) have recently improved the Rogers and Thiele equations by including the effect of surface tension.

The study of bubble formation at vertical slots, however, has been reported by Spells and Bakowski (*39*). Using a high-speed motion picture camera, they investigated the behavior of air bubbles produced at single slots submerged in water and concluded that bubble size was a function of vapor rate, the effect being stronger during the formation of the bubbles at the slot. Submergence not only helped to determine the mode of formation, but also affected the size in the latter case.

Although Spells and Bakowski's paper is of considerable value in providing the first reliable data in a relatively virgin field, their conclusions are subject to some doubt. Specifically, the statement that neither slot characteristics nor liquid properties influenced bubble development was based on a preliminary study which was not supported by quantitative evidence. Previous results on both the slot and orifice studies indicated that such was not the case. The air-flow rates employed were far below those which would be of commercial interest.

The results of a second investigation of bubble formation at submerged slots have recently been published by Spells and Bakowski (*39*). This study consisted of high-speed motion pictures of the formation of air bubbles in water at multiple vertical slots. It was noted that a vapor rate high enough to open the slots fully was never reached in this work.

From the results and analyses of previous studies, it seems clear that more data are required before an intelligent correlation of the factors affecting bubble formation can be made. Qualitatively, at least, there is an indication that the characteristics of bubbles formed at vertical slots are less dependent upon the physical and mechanical variables of the system than are those of bubbles formed at horizontal orifices.

If the effect of the vapor solubility on bubble size can be assumed negligible because of the brief contact time, it appears that the gas rate, liquid rate, slot and cap design, liquid submergence, surface tension, and liquid viscosity are principal independent variables governing bubble formation at vertical slots. To a markedly smaller extent, liquid density and vapor properties may exert some effect (*2*, *3*).

Based on this review, a program was set up to study the effect of these variables on the interfacial area and the contact time involved in vapor-liquid contacting. Because a fundamental approach to the type and mechanisms of mass transfer in the bubble-formation region was deemed impractical if multiple slot bubbling took place, the investigation was confined to single-slot behavior.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Description of Equipment

The experimental apparatus employed for the determination of the bubbling-area–time relationship, $a\, t_m$, was designed with the aim of permitting as large a variation in the operating and mechanical factors as possible. Although only the bubbling phenomena at single slots were studied in this program, the equipment is such that adaptations for further work on multiple-slot arrangements may easily be made. The bubble tray and its accessories were patterned, in general, after those used by the C. F. Braun Company for their film on bubble-plate action.

A diagrammatic layout and photograph of the equipment are presented in Figures 1 and 2. The "column" is seen to consist of a single, rectangular, aluminum plate *A* topped by transparent walls and resting on an angle-iron base. The experimental plate was made removable so that different types of caps and cap arrangements might be tested. The walls *B* are constructed of methyl methacrylate (Lucite) joined at the edges by angle iron and held to the plate by angle-iron flanges. Below the plate is a copper surge tank *C*, through which the air enters and the back-trapped liquid leaves. The tank and plate are held by four angle-iron legs *E* with suitable supporting struts welded to them.

Air is supplied by a blower *F* and is metered before being discharged into the tank by an orifice plate *G*, placed in the galvanized-iron duct. Liquid is recycled by pump *H* from the holdup tank *I*, passed through an orifice meter *J* and introduced to the test plate. The space behind the inlet weir is packed with fine-mesh screen *D*, which serves to distribute the liquid flow to the plate. After flowing across the plate, the fluid is finally discharged through the downspout *K* and back into the holdup tank, where it remains long enough to be deaerated.

A pressure tap was soldered to the side of the surge tank with a lead passing to one end of a U-tube water manometer. Since the other end of the U tube was open to the atmosphere, plate pressure drop was obtained directly.

In order to effect a variation in the plate liquid height, Lucite outlet weirs of 1, 1½, and 3 in. were used. These weirs were

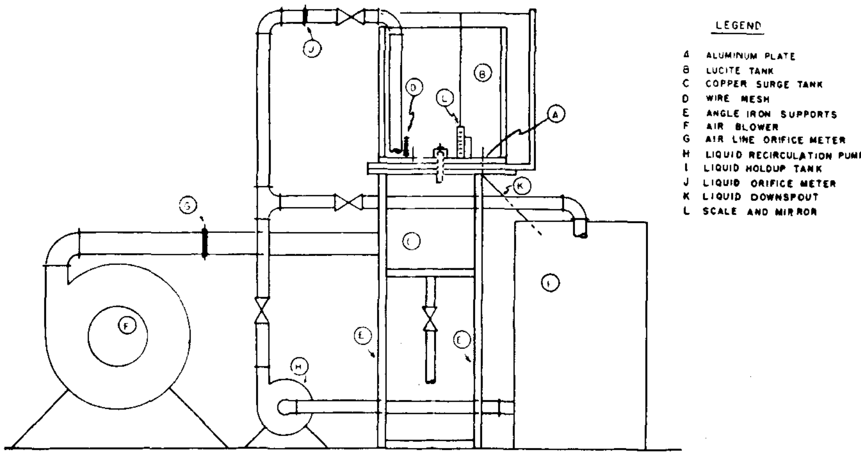

Fig. 1. Equipment for bubble-formation study.

bolted to the downstream end of the test plate.

Accessories

Two sizes of bubble caps were employed. The majority of the tests involved 1.5-in.-diam., 1/16-in. thick, spun-aluminum caps, 1.5 in. high. Various slot sizes were cut out by a milling machine. One set of runs was made by use of a commercial 3-in.-diam. cast-iron cap having a single 1¼- by ⅝-in. triangular slot exposed. The riser used in all runs consisted of a 4-in. length of 1-in. O.D. aluminum tubing threaded into the test plate and had a ⅜-in.-wide cross piece welded across its top. A machine screw, passing through holes in the cross piece and in the cap, served to attach the cap to the riser. An annular spool, having an inside diameter of 1 in., was fitted on top of the riser to reduce the annular flow area for the series of runs using the large cap. A plastic disk with an area 11/12 that of the riser was inserted into the riser for the small cap runs to equalize the riser and slot area. Although a comparison of several films of runs made with and without this riser constriction indicated that it had negligible effect on the results, all data reported here were obtained with the disk present. Drawings of the bubble caps and riser employed are given in Figure 12.

On the test plate itself, a mirror was placed at a suitable angle to the cap slot being photographed, so that two views of the emerging bubbles might be obtained. In addition, a scale was also included in the pictures, so that quantitative measurements were possible *L*.

In order to obtain a variation in viscosity, it was found desirable to elevate the temperature of the circulating water. For this purpose, a 5-kw. General Electric immersion heater was installed in the holdup drum for the series of runs listed under Results.

In another set of tests the effect of surface tension was determined. Surface tension was varied by the addition of a small amount of isoamyl alcohol to the circulating water. Concentrations of isoamyl alcohol were used up to a maximum of 2½%. In order satisfactorily to disengage the entrained vapor from this liquid, it was necessary to install a 2-ft. length of 10-in.-diam. galvanized-iron duct in the holdup drum. The duct acted to reduce turbulence and churning in the drum, thereby allowing runs to be made at surface tensions as low as 32 dynes/cm. Surface tensions were measured by means of a duNuoy tensiometer.

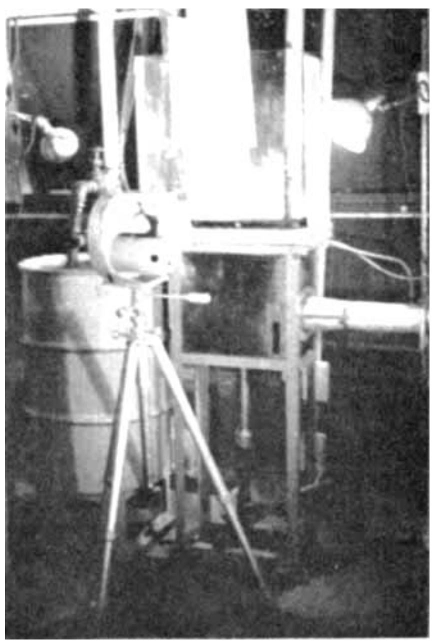

Fig. 2. Photograph of equipment for bubble-formation study.

For obtaining the data, a Wollensak Fastex 16-mm. high-speed motion picture camera was employed. At full voltage of 110 volts this machine has a top film speed of 7,000 frames/sec. Since maximum speed required in this work was 2,500 frames/sec., a Variac set at 70 volts was employed to obtain this speed. Illumination was provided by three RSP-2 photo spot lamps. The number and position of these lamps were determined by a trial-and-error method. The optimum conditions were found to consist of having one lamp behind and to the right of the subject and two in front, one on each side. Photographs of the equipment employed are shown in Figure 2.

EXPERIMENTAL PROCEDURE

The technique for obtaining data in this portion of the study was relatively simple. In a given run the mechanical features of weir height, cap and riser arrangement, and slot size were adjusted, and then the camera and lighting facilities arranged. Next the air blower and liquid-circulation pump were started and the air- and liquid-flow rates set at the desired values by means of damper and valve controls, respectively. The run, which consisted of taking the high-speed motion picture, was then made. At the film speed employed, the time required to expose 50 ft. of film was less than 1 sec. At the time of the film exposure, the following data were recorded: (1) air-flow rate, (2) liquid-flow rate, (3) air orifice temperature and pressure, (4) room temperature and pressure, (5) mechanical layout: (a) cap and slot and (b) weir height, (6) liquid employed—temperature and physical properties, (7) liquid height on plate, and (8) plate pressure drop.

Based both on the results of the literature review, which gave an indication of the factors possibly affecting bubble formation, and on the limits of the facilities available for the research, the variables and their ranges investigated were (1) vapor rate = superficial slot velocity, 15 to 50 ft./sec.; (2) liquid rate = 0.5 to 12.0 gal./(min./in.) of free plate width; (3) weir height = 1.0 to 3.0 in.; (4) slot submergence = 0.5 to 4.0 in.; (5) slot size = ⅛ to ½ to ⅝ by 1¼ in.; (6) cap size = 1½ to 3 in. diam.; (7) liquid surface tension = 30 to 72 dynes/cm.; (8) liquid viscosity = 0.4 to 1.0 centipoise. The results of the experiments involving these factors and the correlations developed are tabulated and explained in the sections on Results and Discussion of Results.

EXPERIMENTAL RESULTS AND DATA TREATMENT

A description of the procedure involved and the type of data obtained in this phase of the program has been given in the previous section. In order to understand and interpret the results obtained, it may be desirable to review the methods used in handling the data. The initial portion of this section is devoted to a discussion of these methods. Tabulations and plots of the actual results follow.

Data Treatment

The actual information on bubble size and contact time obtained from a frame-by-frame analysis of the films was a rather complex and time-consuming process. A preliminary study of several of the early films indicated that, although the bubbles followed a rather regular pattern of development insofar as shapes were concerned, the actual sizes varied considerably. In order to make quantitative measurements, it was nesessary to assign a particular geometric shape to each bubble in order to calculate its area and volume. It was found that as the bubble growth was initiated at the slot its shape closely approximated that of a paraboloid. When the bubble broke away from the slot, it assumed an ellipsoidal configuration. Because a mirror view of the bubbles was also included, it was not necessary to assume that the surfaces were figures of revolution. Indeed, later analysis showed that this assumption would have been considerably in error. Equations were derived expressing the surface area and volume of both an ellipsoid and a paraboloid as functions of the three principal diameters. Curves of area vs. diameter ratios were drawn up to facilitate computation. Copies of these curves were shown together with the derivation of the pertinent equations (*14*).

In a particular run it was found that five to six axial measurements of a bubble at various stages in the course of its development were sufficient to define its "growth curve." From the 50 ft. of film exposed in a run it was usually possible to make measurements on five or six bubbles. In all runs the results of all bubbles were averaged. Each set of measurements included the following data (*14*): (1) frame number after start of bubble (e.g., when bubble first emerges, frame number is zero); (2) axial measurements of height, width, and depth; (3) shape—whether paraboloidal or ellipsoidal. The diametrical measurements were taken with a centimeter scale. In order to convert these dimensions into "true" values, a scale factor referring the centimeter scale to the scale photographed was calculated.

As all the pictures were taken at the same applied voltage to the camera, the speed at corresponding frames after the start of the film was the same. Thus generalized film-speed curves were derived, so that contact times might be easily obtained. These curves with a parameter of initial cumulative frame number related time elapsed from frame zero to any frame studied. Data for these curves were obtained by means of a time trace from a flashing neon light (60 cycles/sec.) in the film margin. Details of the camera speed curve were given (*14*). Contact-time data for a particular bubble were obtained by marking the frame in which the bubble started as frame zero so that the number of frames from the start of the film to any point might be measured, and by then going to the generalized camera speed curves to read off time values corresponding to the frame numbers recorded with the bubble-size data. The total time was that required for the bubble to disappear into the froth.

In the calculation of the interfacial area A, the pertinent diameter ratios were first obtained and A was then obtained directly from the previously mentioned computational curves. Maximum bubble volume V_M was next calculated from the measured diameters. The ratio A/V_M was plotted against contact time, t, for several of the early runs, and it was noted that these "growth" curves had a characteristic S shape.

Daniel (*6*) showed that these curves could be rectified by plotting

$$\ln \frac{A/V_M}{(A/V_M)_{max} - (A/V_M)} \text{ vs. } t$$

where $(A/V_M)_{max}$ is the asymptotic value reached by the ratio (A/V_M). By this procedure the following mathematical expression, relating A/V_M to t, was evolved:

$$A/V_M = \frac{(A/V_M)_{max}e^{j+bt}}{1 + e^{j+bt}} \quad (5)$$

where j and b are the intercept and slope, respectively, of the rectified curve.

The area at_m could then be obtained as

$$at_m = \int_0^{t_m} (A/V_M)\, dt$$

$$= \frac{(A/V_M)_{max}}{b} \ln \frac{(1 + e^{j+bt_m})}{(1 + e^j)} \quad (6)$$

When Equation (6) was applied, the following facts soon became apparent.

$$e^j \text{ is a very small value, approximately } e^{-5} \quad (7)$$

and so

$1 + e^j$ is approximately equal to 1

and as

e^{j+bt_m} is approximately equal to e^{12}

$1 + e^{j+bt_m}$ is essentially equal to e^{j+bt_m}

It was then found that Equation (6) could be simplified to the following term to within an accuracy of less than 1%:

$$at_m = \int_0^{t_m} (A/V_M)\, dt$$

$$= (A/V_M)_{max}(t_m + j/b) \quad (8)$$

In summary, the treatment of the data consisted of the following steps:

1. Calculation of bubble area A and maximum bubble volume V_M by means of the computational plots relating these terms to bubble-diameter ratios.
2. Calculation of bubble-contact time t and maximum time t_m.
3. Evaluation of "bubble-growth" equation (A/V_M) as a function of t, found by plotting
$$\ln \left(\frac{(A/V_M)}{(A/V_M)_{max} - (A/V_M)}\right) \text{ vs. } t$$
4. Calculation of at_m by means of equation: $at_m = (A/V_M)_{max}\ (t_m + j/b)$.
5. Calculation of a as $a = at_m/t_m$.

Description of Results

The results of this investigation, calculated as described in the previous paragraphs,* are presented in Figures 3 through 9. In the graphical presentation both interfacial area per unit volume of vapor a and total contact time t_m were plotted against static slot submergence s. The latter term was defined as the weir height minus slot height plus weir crest. For each of the plots one other independent variable has been employed as a parameter in order to show its effect. Where effects of the parameter were noted, the data have been cross plotted to illustrate the magnitude of the effects.

Effect of Liquid Rate and Weir Height

No direct relationships for either interfacial area or contact time with liquid rate or weir height were obtained. However, it was soon found that a third factor, dependent on these two, did correlate the former terms effectively. This intermediate factor is the static slot submergence. Because it exerted the major effect on the mechanism of bubble formation, static slot submergence was employed as the abscissa for most of the subsequent plots.

Effect of Air Rate

With the results tabulated*, Figure 3, interfacial area per unit volume of vapor vs. slot submergence, and Figure 4, total contact time vs. slot submergence, were constructed by means of the various air rates tested. Superficial slot velocities of 15 to 50 ft./sec. were used in the test work. The shape of the curve given in Figure 3 was unchanged by changes in any of the other variables studied. No significant effect of air rate on a, the interfacial area, can be detected from these runs.

The results depicted in Figure 3 were obtained from runs made with zero skirt clearance. To confirm these results, additional tests involving the variation of vapor rate were conducted by means of a 0.25-in. skirt clearance. Results of this set of experiments are presented in Figure 3A. These data also indicate that vapor rate has no effect on interfacial area.

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*Tabular material has been deposited as document 5110 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D.C., and may be obtained for $1.25 for photoprints or 35-mm. microfilm.

Figure 4 is typical of the contact-time-slot-submergence relationships found in the remainder of the work. The data indicate that air rate does exert some effect on contact time.

Since the effect of vapor rate on contact time is small, additional data from some of the later runs in which slot velocity was varied are shown in Figure 4A. The same small effect of vapor rate is shown in this curve.

A cross plot of the data on slot velocity is given in Figure 4B. It is interesting to note that contact time decreases with vapor rate and goes through a minimum at a slot velocity of approximately 30 ft./sec. The change in contact time between air rates of 30 and 50 ft./sec. is small at the higher slot submergences. It was observed that the slot became wide open at air rates of between 20 and 30 ft./sec., depending mainly on the static head of liquid above the slot. It seems quite possible, therefore, that the effect of air rate on total contact time is reduced after the slot becomes fully open.

Effect of Skirt Clearance

The summary of results applicable to these determinations is given elsewhere.* Figure 5 shows the relationship between interfacial area and slot submergence for various values of skirt clearance. It is somewhat surprising to note that the data for shirt clearance of 0 and 0.5 in. fall on the same curve, while the results at a clearance of 0.25 in. are substantially higher. This point will be discussed under Results. Figure 5A is a cross plot of interfacial area vs. skirt clearance for submergences greater than 0.25 in. and shows the magnitude of the effect directly.

The contact time t_m is shown as a function of slot submergence and skirt clearance in Figure 6. As it had been shown that vapor rate has an effect on contact time, only those runs in which slot velocity = 30 ft./sec. were employed in this figure, which shows that there is a small but significant effect of skirt clearance on t_m.

Attempts to obtain data at values higher than 0.5 in. in the present study were unsuccessful owing to the action of vapor bubbling underneath the cap. It is more likely that this sort of bubble leakage occurs in the commercial towers operating at high vapor rate. However, extraneous bubbles formed in this manner were found to obscure the bubbles passing through the slot, thereby preventing measurement of the latter. In addition, it was felt that clearances of greater than 0.5 in. would be quite out of proportion to the 1.5-in.-diam. caps used.

Effect of Slot Area

Figure 7 contains plots of interfacial area vs. slot submergence for various slot sizes. The curves show that for slot

*See footnote on page 19.

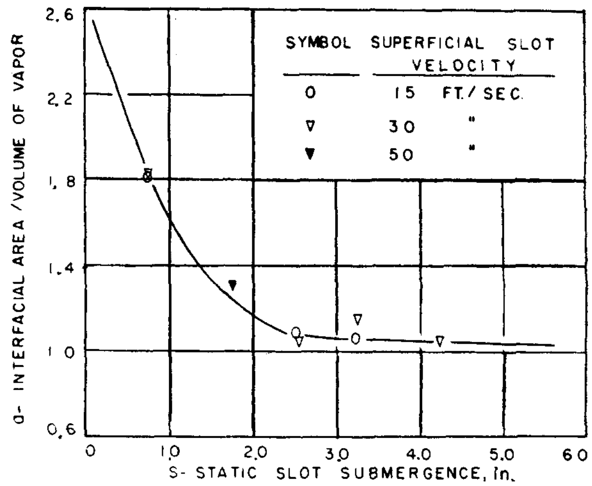

Fig. 3. Effect of vapor rate on interfacial area.

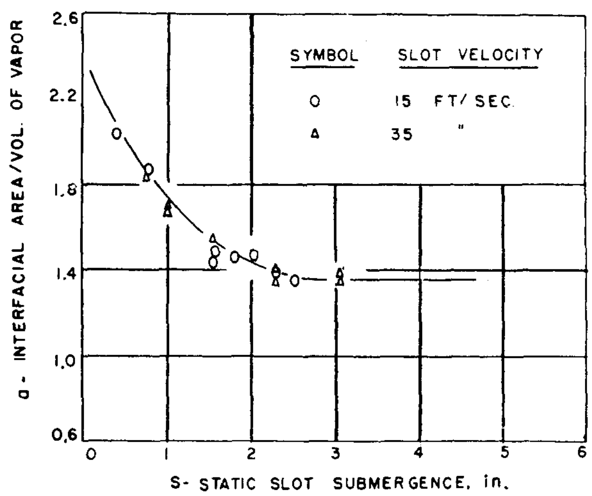

Fig. 3a. Effect of vapor rate on interfacial area.

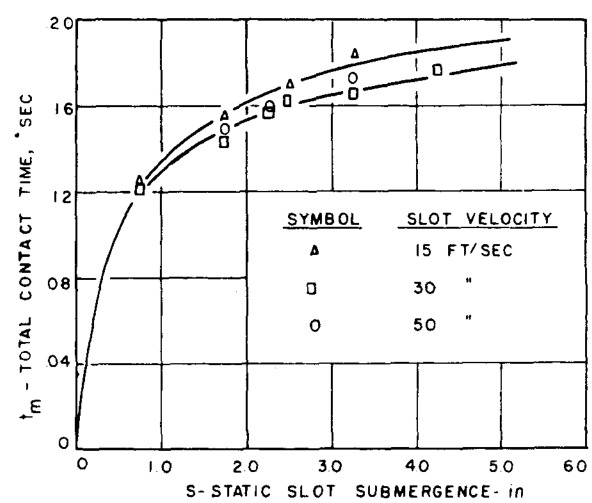

Fig. 4. Effect of vapor rate on contact time.

submergence lower than approximately 2.5-in. interfacial area is reduced by an increase in slot area. These results indicate that there is no effect of slot area on contact time.

Effect of Surface Tension

Results of runs in which surface tension was varied from 72, 60, 45 to 32 dynes/cm. are given elsewhere.* At slot submergences greater than 2.0 in. there appears to be an effect of surface tension on interfacial area, with the interfacial area being lowered by a reduction of surface tension. The data

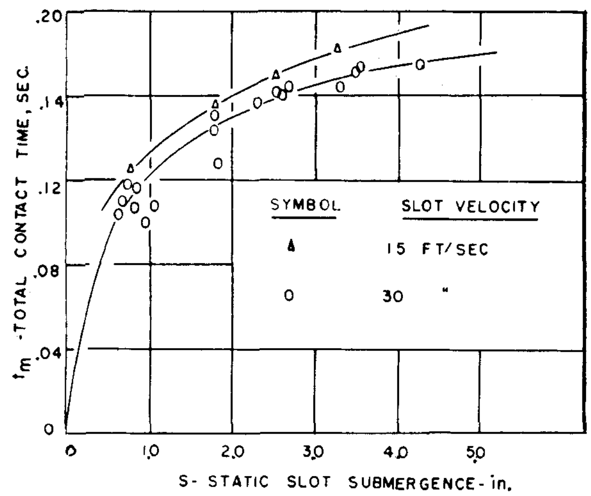

Fig. 4a. Effect of vapor rate on contact time.

for slot submergences greater than 2.5 in. indicate the negligible effect of surface tension upon time of contact and interfacial area.

Effect of Viscosity

During the investigation, the viscosity values were varied, ranging from 0.95 to 0.66 and 0.40 centipoise. The relationship between interfacial area and liquid viscosity is shown directly in Figure 8 for slot submergences greater than 2.5 in. The data indicate that lowering the viscosity results in a reduction of interfacial area. Because viscosity was varied by raising the temperature of the circulating water, slight reductions in surface tension due to the higher temperatures were unavoidable. The change in surface tension is of insufficient magnitude to affect interfacial area. The change in interfacial area can be attributed only to viscosity. Figure 9 shows clearly that the contact time is not affected by liquid viscosity.

Since the results of the mass transfer study in the next section indicated that the bubble-formation region is of considerable importance in vapor-liquid

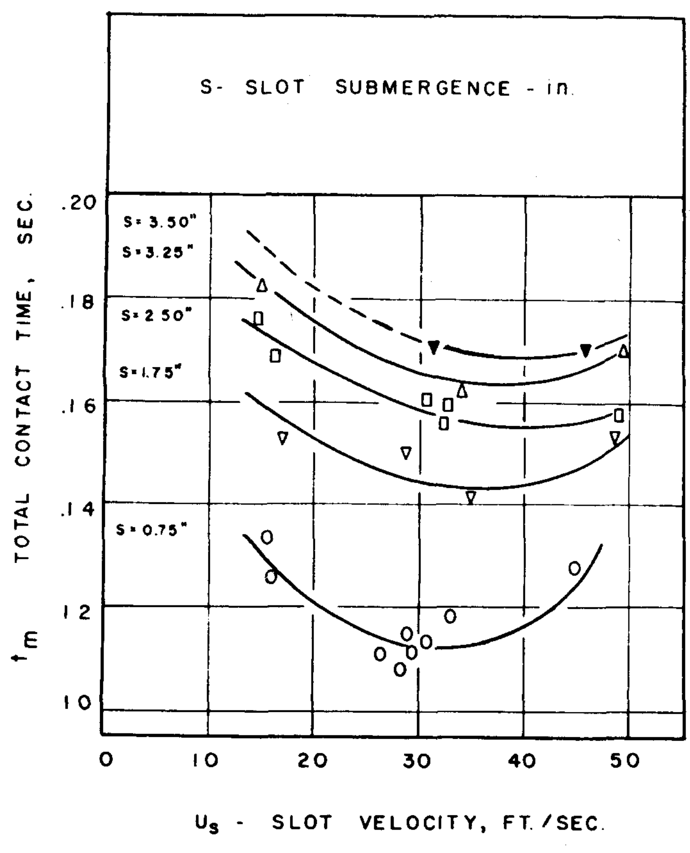

Fig. 4b. Total contact time vs. superficial slot velocity for various slot submergencies.

contacting, an attempt at correlating these results in the form of useful design equations is described on the following pages.

Correlation of Bubble-formation Results

The tables and plots of the previous section illustrate the effects of the different variables tested on interfacial area and on contact time. Insofar as the attempt to provide a basis for future studies on commercial-sized equipment is concerned, this information demonstrates the variables to be considered. An attempt has also been made to include all these findings in a single correlation in a

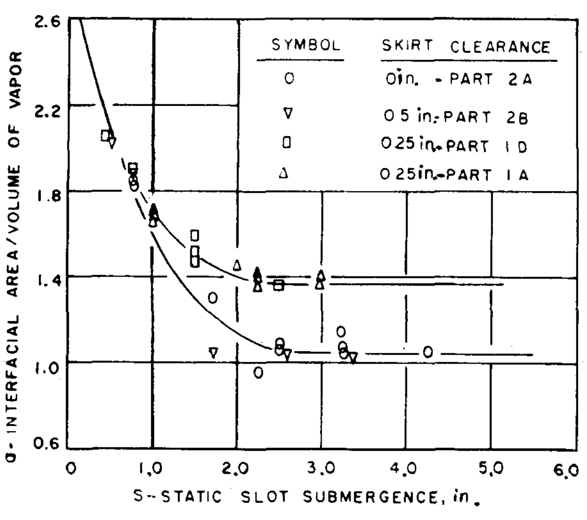

Fig. 5. Effect of skirt clearance on interfacial area.

*See footnote on page 19.

manner suitable for use by design engineers.

Interfacial Area per Unit Volume of Vapor a

It has been shown that two modes of formation are possible, depending upon slot submergence. Reference to the curves of interfacial area vs. slot submergence Figures 3 to 9 show that the horizontal portions of the curves consistently start in the range of slot submergence, 2.25 to 2.75 in. For correlation purposes, an average value of 2.5 in. has been taken as the point at which interfacial area becomes independent of slot submergence. For values of static slot submergence less than 2.5 in., the variables shown to influence a were slot submergence and slot area. Equations found to characterize this relationship are of the form

$$\frac{1}{a - a_0} = K_1 s - c \qquad (8)$$

where a_0, K_1, and c are functions of slot area. A tabulation of the values of these constants for the slot areas considered is presented in Table 1. The constants are related to slot area, A_s, by the equations

$$a_0 = 5.88 A_s^{0.30} \qquad (9)$$

$$K_1 = 985 A_s + 0.20 \qquad (10)$$

$$c = 332 A_s - 0.40 \qquad (11)$$

The final equation for interfacial area is

$$\frac{1}{a - 5.88 A_s^{0.30}} = A_s(985s - 332) + 0.20s + 0.40 \qquad (12)$$

For values of slot submergence greater than 2.5 in., interfacial area has been shown to be a function of skirt clearance, liquid viscosity, surface tension, and, to a small extent perhaps, liquid density (*2*, *3*). Expressing this relationship symbolically gives

$$a = (h, \mu, \sigma, \rho) \qquad (13)$$

where h = skirt clearance.

Dimensional analysis reveals that the appropriate grouping of the variables in Equation (13) is

$$a = \frac{1}{h} F'\left[\frac{h\sigma\rho}{\mu^2 g_c}\right] \qquad (14)$$

where F' represents a mathematical function.

Because skirt clearances of zero were employed for many of the tests, h must be redefined in order to prevent Equation (14) from degenerating. If h_c is taken as the maximum height of the slot measured from the tray floor, it maintains its directional significance on the term a, as it includes skirt clearance and has the advantage of not taking on a null value. Equation (14) then becomes

$$a h_c' = F\left[\frac{h_c'\sigma\rho}{\mu^2 g_c}\right] \qquad (15)$$

Values of the group $(h_c'\sigma\rho)/\mu^2 g_c$ have been calculated for the various conditions employed in this study.* Interfacial areas for slot submergences greater than 2.5 in. may be predicted from the correlation curve, Figure 10.

Total Contact Time t_m

The variables shown to exert an influence on contact time were slot submergence, vapor rate, and skirt clearance. It was found that the contact-time data given on the previous pages could be rectified by plotting them against the dimensionless ratio s/h_c on logarithmic coordinate paper. A family of essentially parallel lines was obtained which followed the equation

$$t_m = d(s/h_c)^{0.27} \qquad (16)$$

where h_c is skirt clearance + slot height, in., and d is a function of slot velocity, u_s, and of h_c'. The appropriate grouping is, by dimensional analysis,

$$d = f(h_c'/u_s) \qquad (17)$$

A tabulation of the values of d calculated for various conditions of h_c'/u_s is given elsewhere.* A graphical relationship allowing the constant to be easily evaluated is presented in Figure 11.

In order to test the reliability of these equations, measured values of the product at_m were compared with values calculated by the foregoing techniques. The comparison is presented in Table 2. It will be noted that an average deviation between the measured and calculated values of 7.2% was obtained.

Error Analysis

This section deals with a discussion of the types and magnitudes of the errors introduced into the results of this study and their effects on the precision of the final correlation.

Interfacial Area

The characterization of the growing bubbles as either ellipsoids or paraboloids in order to calculate interfacial areas was discussed in a previous section. This hypothesis is considerably more realistic than the assumption of bubble sphericity used in earlier studies (*2*, *3*, *17*). The bubbles, however, were not always geometrically regular and it was necessary to neglect any additional surfaces formed by the irregularities. While these additional areas could not be accurately evaluated, they were estimated to be less than 10% of the measured values in the majority of runs. It is significant that the errors introduced by neglecting these areas were of a more or less systematic nature, and so the results reported are consistent within themselves. An exception to this was noted in the tests made at reduced surface tension. In this case a certain amount of foaming at the bubble-liquid interface was observed; the actual values of interfacial area under these conditions therefore probably are higher than Figure 11 indicates.

While the diametrical bubble measurements were being made, it was found that a reproducibility of about 1 mm. in the scale reading was possible. Since the values of average interfacial area are most strongly affected by errors in the determination of bubble area when the bubbles have become large, this does not result in a serious error. In the latter phase of the bubble growth period, bubble diameter in an average case will be about 4 cm. The probable error in interfacial area, therefore, for a single bubble becomes about 2.5%, as measurement errors result in the same directional changes in both numerator and denominator of A/V_M. Measuring a number of bubbles in each run negated the effects of error measurement of this type.

The chief cause of error in the reported values of interfacial area is thought to be the fact that the bubbles themselves were not reproducible. During a given run the six to ten bubbles photographed showed frequently a large variation among their sizes. As successive diametrical measurements showed that each bubble followed a regular growth pattern, it was considered more advantageous to minimize the number of measurements on each bubble studied during a run. The emphasis was therefore placed on considering as many bubbles as possible. Except where poor photographing conditions prevailed, it was usually possible to average the values obtained from four to eight bubbles per film.

An example of the reproducibility of a series of runs is shown in the 0.25-in. skirt-clearance tests of Figure 5. Two sequences of runs were made at identical conditions to check the reproducibility of the technique. As can be seen, the two sets of data show excellent agreement. It can be concluded that the effects observed are significant and are not the result of random fluctuations.

Contact Time

The error analysis of contact-time values reported is somewhat easier to perform. This term was taken as the interval between the time a bubble first showed itself from under the slot and the time it disappeared into the froth region. Errors in this quantity arose from two sources: (a) finding the specific frames showing the appearance and disappearance of a bubble and (b) calculating the average film speed between the two points.

*See footnote on page 19.

Contact time was calculated by dividing the counted number of frames by the average film speed. In general, the initial and final frames of a sequence were readily located to within five frames at either point. If there was any question, the film was run slowly through the projector, backward and forward, at the approximate start or finish in order to locate the precise frame.

Film speed was evaluated from a time trace in the film margin resulting from a flashing (60 cycles/sec.) neon light in the camera. Based on the results of a number of films, a generalized curve was drawn up (*14*) and used to obtain film speed. Speed was thus calculated as

$$S = 120N \text{ (frames/sec.)}$$

where

N = number of frames between neon-lighted frames
S = film speed, frames/sec.

The number of frames n was evaluated to the nearest plus or minus one-half frame on each side.

The equation for contact time is

$$t_m = \frac{n}{120N} \tag{18}$$

where

n = number of frames between the start and finish of a bubble.

For a single bubble, the probable error in contact time for an average case of n = 240 and N = 18 is (*14*)

$$\frac{\text{p.e. } (t_m)}{t_m} = 0.8453\sqrt{\frac{2}{\pi}\left[\frac{s^2(n)}{n^2} + \frac{s^2(N)}{N^2}\right]}$$

$$= 0.67\sqrt{\frac{(10)^2}{(240)} + \frac{(1)^2}{(18)}}$$

$$= 4.6\% \tag{19}$$

The derivation of Equation (19) is given elsewhere (*14*).

Since an average of six bubbles per run was employed, the effect of this measured error is reduced less than 2% on the average reported.

As in the case of interfacial area, the lack of reproducibility is felt to be the major source of inaccuracy in the reported t_m values. The average standard deviation in t_m for the 6B runs is 0.013. For a typical value of t_m = 0.13 sec., averaged over six bubble measurements, a 90% confidence interval of 0.13 ± 0.010 is obtained. This is equivalent, on a percentage basis, to saying that it is 90% certain that the true value lies within a range of ±7.7% of the measured value of t_m.

DISCUSSION OF RESULTS

The results of this study as presented in the previous section indicate that static

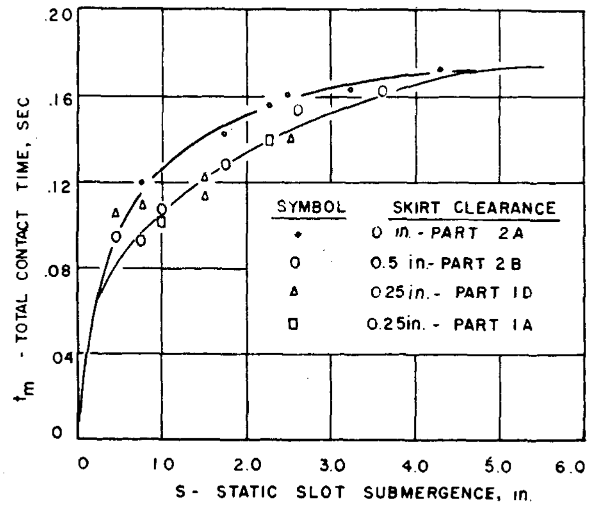

Fig. 6. Effect of skirt clearance on contact time.

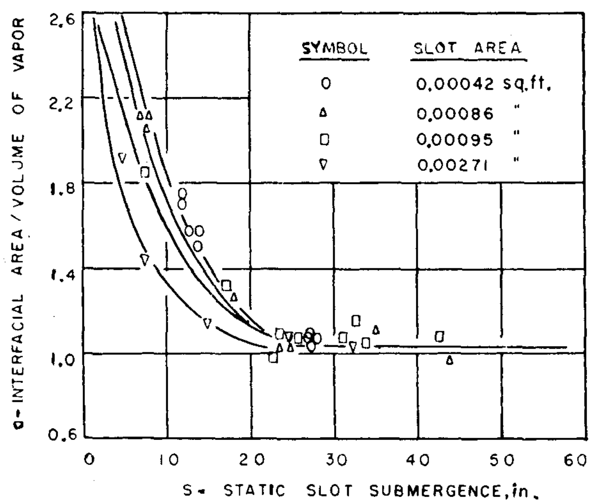

Fig. 7. Effect of slot area on interfacial area.

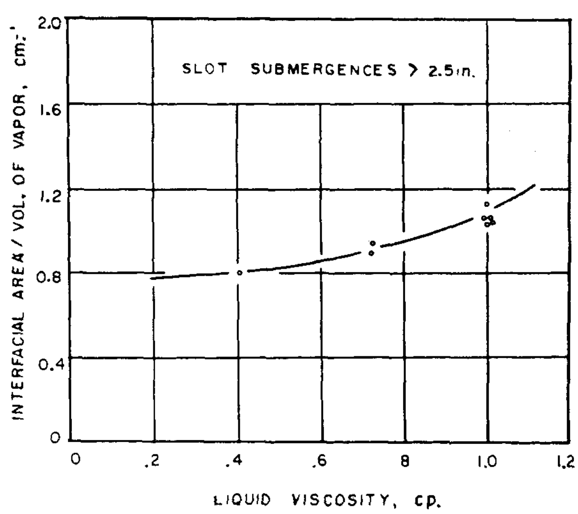

Fig. 8. Effect of liquid viscosity on interfacial area.

slot submergence had the greatest effect of all the variables tested on both the average interfacial area for mass transfer and the time of contact between the rising vapor and the liquid. Other variables showing smaller but nonetheless significant effect on one or both of these terms were vapor rate, slot area, skirt clearance, liquid viscosity, and surface tension. An attempt to explain these results and to compare them with the results of previous studies is given in the following paragraphs.

Effect of Slot Submergence

A study of several of the films showed that apparently two mechanisms of formation were possible, depending on the slot submergence. At low slot submergence the growth period was fairly short and the bubbles reached the liquid surface while they were still relatively small. It is interesting to note that even at low submergences there was no significant jetting action and vapor flow was in the form of discrete bubbles. Thus a bubble emerging from the slot continued to grow until its top reached the liquid surface. As slot submergence was increased up to approximately 2 in., the bubble size also increased.

At higher slot submergences the mode of formation changed and a second growth period occurred after a bubble broke away from the slot. In this case a thin channel connected the bubble and the slot, and so the bubble continued to expand until the channel became unstable and broke. Because of the channel, larger bubbles were formed at the higher submergences with a subsequent reduction in area per unit volume of gas. Continued increase in slot submergence above a value of about 3 in., however, resulted in no change in the average time required for the channel to collapse; i.e., bubble size then ceased to be a function of slot submergence.

The effect of slot submergence on contact time may be explained in the following manner. At slot submergences approaching zero, an emerging bubble is very small in size and leaves the slot almost instantaneously. As submergence is increased, a resistance is placed in the bubble path which it must overcome in order to escape. Therefore the bubble not only must expand energy to move against this resistance, but must also grow larger at the same time. More surface for the frictional drag of the water is thus provided. At high submergences bubbles have a chance to break away from the slot and rise, at constant size, through the liquid. A linear relationship between contact time and slot submergence should then exist, corresponding to a period of free rise. At the higher submergences the contact time can therefore be considered to consist of two periods: (1) a period of formation where velocity is low because energy must be expended to create new surface and (2) a period of free rise. The higher the submergence, the more dominant will be the latter period. The relationship between contact time and interfacial area will approximate linearity.

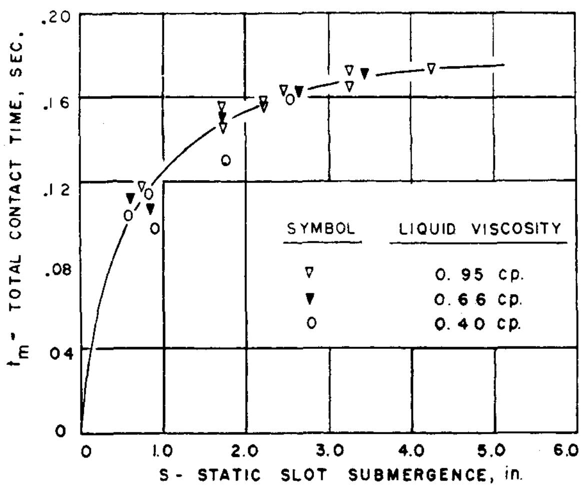

Fig. 9. Effect of liquid viscosity on contact time.

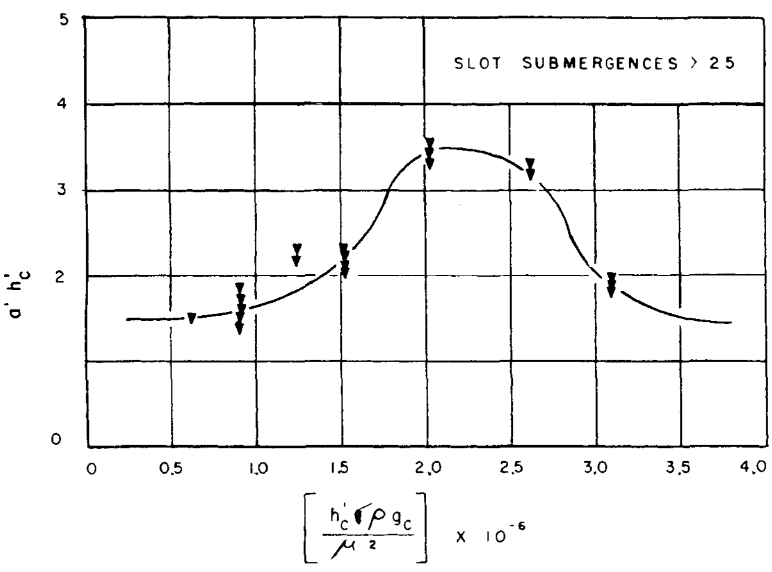

Fig. 10. Determination of interfacial area.

Effect of Air Rate

The data in Figure 3 show that air rate has no significant effect on the interfacial area. At first glance this result appears to contradict some of the earlier studies in which vapor rate was shown to influence final bubble size (*8, 29, 39, 41*). Spells and Bakowski (*40*) reported that the combination of vapor rate and slot submergence completely characterized the mode of formation and the final bubble size. Their findings on the effect of slot submergence and their explanation of formation mechanism are in complete agreement with the results presented here. Data showing the effect of air rate on bubble volume for both studies have been plotted in Figure 13. Although the range of air rates and the test equipment employed differed substantially, the results show fairly good agreement. In Figure 13 the present results show that final bubble size is influenced by air rate at the lower air rates. This conclusion is in qualitative agreement with the findings of other investigators (*8, 29*) but appears contradictory in view of the lack of effect on *a*, the interfacial area.

West et al. (*44*) reported values of effective surface area per unit volume of gas in the foam region above perforated plates. With the data of the previous investigators (*18*) they made a similar calculation for bubble-cap plates. No direct measurements of interfacial area were made in either case and the values given were indirectly arrived at by the use of Higbie's (*20*) equation for unsteady state diffusion. Although considerable error may be involved in this technique (*44*), West et al. conclude that the directional effects were substantially correct. Although Higbie's constants could not be checked for the particular systems and apparatus employed, the errors were felt to be systematic. Considerable scattering of the perforated-plate data on a plot of interfacial area vs. gas velocity is evident, and no significant effect of gas velocity is noticeable. The bubble-cap data (*18*) when plotted in a similar manner are considerably more consistent. In the latter case it appears that two regions are possible: (1) at low gas-flow rates, interfacial area a is slightly decreased by an increase in gas velocity, and (2) at moderate and high flow rates, a is unaffected by changes in gas velocity.

The small effect of air rate on interfacial area shown by the analysis of the previous data (*18*) is felt to be an excellent confirmation of the findings reported in this study.

However, still to be accounted for is the somewhat paradoxical conclusion that air rate in the low range exerts an effect on final bubble size and does not appreciably influence the average interfacial area per unit volume a. Two reasons can be advanced to account for this result. The mathematical expression for a derived by dividing Equation (8) by t_m is

$$a = at_m/t_m$$

$$= (A/V_M)_{max}(1 + j/bt_m) \quad (20)$$

The interfacial area a is proportional to the ratio $(A/V_M)_{max}$. It is approximately inversely proportional to the cube root of V_M, and for a sphere the proportionality is exact. Thus large increases in V_M result in very much smaller changes in $(A/V_M)_{max}$, and small changes in V_M could easily be lost in the process of evaluating the more insensitive interfacial area a. It was shown that, as air rate was increased to 30 ft./sec., total contact time was found to decrease (Figure 7). The small decreases in $(A/V_M)_{max}$ resulting from an increase in air rate are consequently offset by the decrease in t_m, insofar as the determination of a is concerned.

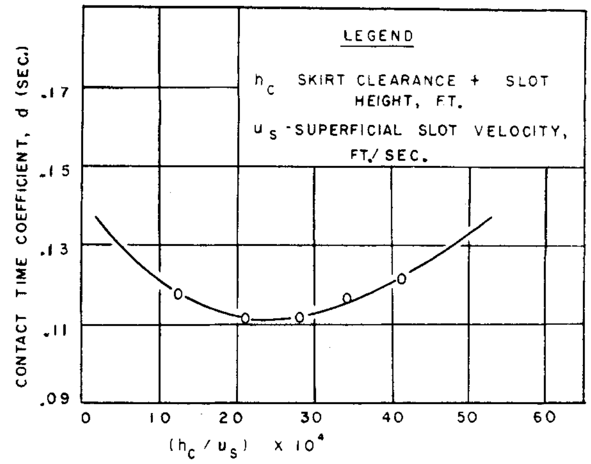

Fig. 11. Correlation of contact-time coefficient *d*.

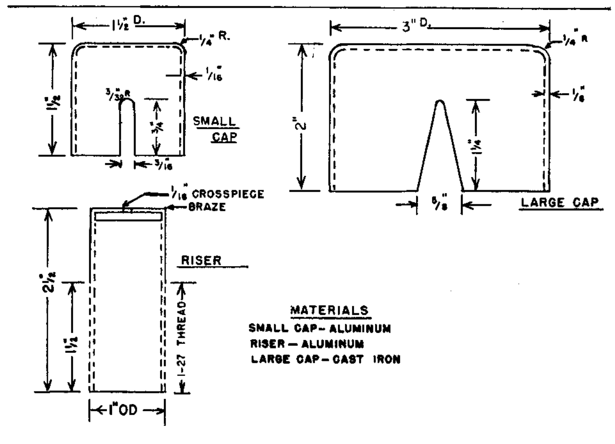

Fig. 12. Details of caps and riser, bubble-formation study.

Effect of Slot Area

At low submergences slot area was shown to exert a considerable influence on the size of the bubbles produced and consequently on their average surface area. Above submergences of about 3 in., slot area ceased to affect interfacial area. The result may be explained as follows. At low slot submergences the average bubble size will be determined largely by the manner in which it is formed, as there is no secondary growth period and no period of free rise. Thus a stream of gas emanating from a large nozzle would be expected to be dispersed into large bubbles, with a resultant low value of interfacial area. As slot submergence is increased, however, the period of secondary channel feeding starts. In this region both the final size and the average size depend largely on what happens to the bubble after it has emerged from the slot. Slot size would therefore be expected to play a markedly smaller role in the over-all contacting process. Experimentally it was found that at low slot submergences increasing slot size resulted in a decrease in interfacial area equivalent to an increase in bubble size. On the other hand, bubble size was virtually unaffected by slot area at higher submergences.

The lack of effect of slot size on contact time again indicates that the period of free rise is appreciable only at the higher slot submergences. During free rise, bubble velocity is a function of its size. Since the bubble size is constant at higher submergences, velocity and contact time are therefore not functions of slot size.

Effect of Skirt Clearance

The effect of skirt clearance on interfacial area shown in Figure 5 was rather anomalous. At 0- and at ½-in. clearances the data fell approximately on the same curve, indicating no significant variation. However, a substantially higher curve was obtained at a skirt clearance of 0.25 in. In order to substantiate this result, as well as to check on the reproducibility of the technique, a second series of tests was made at the latter clearance. As Figure 5 clearly shows, the data lined up perfectly with those of the first tests. In Figure 6 it can be seen that an increase in skirt clearance at constant slot submergences causes a reduction in contact time, but the irregular effects noted in the case of interfacial area at the slot submergence of 0.25 in. were not

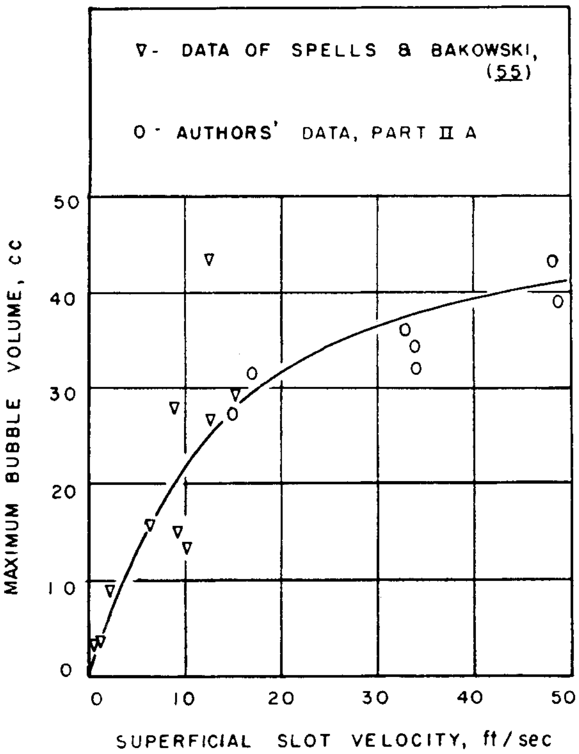

Fig. 13. Maximum bubble volume vs. superficial slot velocity.

detected. Smolin, Goldberg, and Welsh (*26*) in their study on froth heights and densities used the same cap and riser design that was used in this study and also observed significantly different tray hydraulic properties at this skirt clearance.

It is reasonable to presume that the cause of this strange behavior at 0.25-in. skirt clearance is related to the effect of the flowing liquid on bubble formation. At zero clearance all liquid streams contacting the emerging bubble can be assumed to possess approximately the same velocity. When the cap is raised above the tray floor, however, an additional liquid stream flowing under the cap contacts the vapor. At low skirt clearance of about ¼ in. the liquid passing under the cap apparently reaches a fairly high velocity. An additional drag force is thereby exerted on the emerging bubble, pulling it away from the slot before it has the opportunity to reach full size. This mechanism also explains the reduction in contact time, since the bubbles which have been removed from the slot earlier also reach the liquid surface earlier.

At half-inch skirt clearances the constriction is much larger. The velocity of the liquid stream contacting the base of a growing bubble is therefore not so great. Substantially smaller effects on the resultant bubble size would be postulated for this condition.

The large increase in interfacial area found at skirt clearance of 0.25 in. indicates that further study is warranted. It is probable that in a given case the optimum skirt clearance for high interfacial area is a function of the geometry of the cap and tray design.

Effect of Surface Tension

The values of interfacial area are affected by surface tension only at the higher values of slot submergence. In this region the average values of A/V_M are independent of submergence. This finding is in sharp contrast to that noted in the case of the slot size tests. In this case the effects were of importance at low liquid heights. The influence of surface tension, therefore, must be related to the period of secondary bubble growth, a region not existing at low submergences. In effect, what must happen is that a lowering of surface tension allows the channel to become somewhat larger, which consequently enables it to feed more vapor into the connected bubble. By this means, bubble size is increased and the ratio A/V_M decreased.

Measurements in this phase of the study were complicated by the amount of froth that existed in the liquid. This was partially due to the creation of additional surface area by a slight decomposition of the rising bubbles, thus introducing some error into the calculation of interfacial area. Most of the froth was carried over from the holdup drum due to poor vapor-disengaging characteristics of the liquid. It was only because of the installation of a 3-ft.-long, 8-in.-diam. galvanized duct, through which the downcomer liquid had to pass in a tortuous path, that it was possible to make runs at surface tensions of 45 and 32 dynes/cm. Without this duct the flowing liquid became almost opaque from the entrained vapor. Even with the duct in place it was necessary to maintain low liquid flow rates in order to obtain satisfactory photographic conditions. Variation in slot submergence for these runs was obtained largely by the use of different weir heights.

There was no significant variation in contact time with static surface tension measured, although more than usual scattering of the data points occurred. The latter phenomenon appears to be due chiefly to the difficulty in interpreting the films of these tests. The heavy froth carryover made measurements both of size and time somewhat unreliable. In cases of low surface tension the application of the correlations here alone to predict point efficiency is not recommended because of the possible effects of the froth layer. It is hoped that the combination of these results with those obtained in the companion study on froth characteristics by Smolin (*38*) will prove valuable.

Effects of Liquid Viscosity

A small effect of liquid viscosity on average interfacial area, a did exist, with lower values of a resulting from viscosity decrease. The relations are similar to those obtained in the surface-tension tests and again indicate that the major influence of viscosity is felt during the channel-feeding period. Apparently vapor escapes into the bubble at a faster rate as viscosity is decreased.

The literature shows considerable disagreement over the effect of viscosity on bubble size. Schnurmann (*35*) investigated the size of gas bubbles produced in a variety of liquids, including alcohols, acids, sugar solution, and certain electrolytes. He found that bubble size was independent of the method of bubble production but tended to vary inversely with liquid viscosity. Datta, Napier, and Hewitt (*7*), on the other hand, investigated the formation of gas bubbles at circular orifices and noted that a hundredfold increase in viscosity resulted in only a 10% reduction in bubble volume. Their study involved aqueous glycerine solutions of various concentrations.

The other indication of the effect of viscosity on the size of bubbles formed at bubble-cap slots was obtained from the work of Keyes and Byman (*23*). These authors reported that an increase in bubble-cap plate efficiency was found when liquid viscosity was raised. The higher efficiency was attributed to a reduced bubble size.

It is significant to note that all investigators have found that bubble size is reduced by an increase in liquid viscosity. The disagreement is on the magnitude of the effect. While the results of the present study tend to

TABLE 1.

TABULATION OF CONSTANTS IN INTERFACIAL-AREA EQUATION (SLOT SUBMERGENCE < 2.5 in.)

Part*	Slot size, in.	a_0	K_1	c	A_s, sq. ft.
3B	½ × ⅛	0.52	0.60	−0.20	0.000422
3C	½ × ⅛	0.52	0.60	−0.20	0.000422
3D	½ × ⅛	0.52	0.60	−0.20	0.000422
2A	¾ × ⅛	0.71	1.15	−0.25	0.00095
3A	¾ × ⅛	0.58	0.99	−0.10	0.00086
5A	1¼ × ⅝	0.85	2.89	−0.50	0.00271

General equation

$$\frac{1}{a - 588A_s^{0.30}} = A_s(985s - 332) + 0.20s + 0.40$$

*Refer to the original data in reference 14.

TABLE 2.

COMPARISON OF PREDICTED AND MEASURED VALUES OF at_m

Run	Predicted	Measured	% Error	Run	Predicted	Measured	% Error
1A6	0.172	0.175	1.7	3A5	0.166	0.170	2.4
1A18	0.161	0.155	3.7	3A6	0.173	0.166	4.2
1A25	0.204	0.230	12.5	3A7	0.170	0.182	6.6
1A36	0.234	0.194	17.0				
1A37	0.189	0.175	7.4	3B1	0.228	0.231	1.3
1A38	0.173	0.153	11.5	3B2	0.238	0.208	14.5
				3B4	0.195	0.224	12.9
1D1	0.218	0.216	0.9	3B5	0.211	0.188	12.2
1D2	0.187	0.206	9.2	3B6	0.202	0.190	6.3
1D4	0.167	0.178	6.2				
1D4A	0.167	0.169	1.2	4A1	0.250	0.278	10.0
1D4B	0.246	0.243	1.2	4A2	0.170	0.163	4.3
				4A4	0.177	0.165	7.3
2A1	0.215	0.226	4.9	4A5	0.165	0.180	8.3
2A2	0.211	0.219	3.6	4A7	0.166	0.176	5.7
2A6	0.174	0.150	16.0				
2A10	0.211	0.190	11.0	4B4	0.140	0.152	8.5
2A11	0.194	0.186	4.3	4B5	0.127	0.129	1.6
2A12	0.202	0.180	12.2	4B6	0.133	0.139	2.9
2A13	0.192	0.180	4.4	4B8	0.140	0.120	16.7
2A14	0.180	0.171	5.3	4B9	0.147	0.133	10.5
2B1	0.206	0.188	9.5	5A1	0.191	0.203	5.9
2B2	0.183	0.172	6.4	5A2	0.165	0.154	7.1
				5A3	0.159	0.151	5.3
				5A5	0.163	0.155	5.2

Average error = 7.2

An average error of 7.2% in at_m is equivalent to an error of 2.5% in the calculated point efficiency.

confirm those of Schnurmann (*25*) and Keyes and Byman (*23*), all three investigations dealt with a relatively turbulent contacting operation. Since Datta et al. (*7*) employed a fairly quiescent bubbling zone, the difference in the magnitude of the effects of viscosity may be due to the presence of turbulence caused by a flowing liquid.

The lack of effect of liquid viscosity on contact time shown in Figure 9 is at first glance surprising. For free-rise conditions, Stokes's Law would predict that decreasing viscosity should result in an increase in velocity or a decrease in contact time. Because of the liquid turbulence, however, large deviations from Stokes's Law are to be expected. Available evidence from the other tests, especially the small effect of vapor rate on contact time, indicates that free rise does take place. A more complicated mathematical expression than Stokes's Law will be required to characterize this motion.

CONCLUSIONS

As part of a program to investigate the factors affecting point efficiency in distillation, a study was made of the formation of air bubbles at single bubble-cap slots immersed in aqueous solutions. An analysis of high-speed motion pictures of the bubbling action enabled both the average interfacial area for mass transfer and the total contact time to be determined under a variety of conditions. Vabiables tested included vapor rate, liquid rate, weir height, static slot submergence, slot size, liquid viscosity, and surface tension. The principal effects of these variables and the derived correlation for predicting interfacial area and contact time are summarized in the following sections.

1. The static slot submergency, or liquid seal on the slot, was found to exert a great effect on both interfacial area and contact time. With respect to interfacial area, the existence of two zones was established.

a. At slot submergences lower than approximately 2.5 in. interfacial area was found to decrease with slot submergence, according to the equation

$$\frac{1}{a - a_0} = K_1 s - c \qquad (8)$$

b. At slot submergences above 2.5 in. interfacial area was unaffected by variations in slot submergence.

Total contact time of a bubble was found to increase with slot submergence, according to the equation

$$t_m = d\left(\frac{s}{h_c}\right)^{0.27} \qquad (16)$$

where d is a function of slot velocity and skirt clearance plus slot height.

2. Slot size was the only other variable shown to affect interfacial area in the low slot-submergence region. The constants in Equation (11) were found to correlate with slot area.

3. In the high slot-submergence region (above 2.5 in.) interfacial area was found to be influenced by liquid viscosity, surface tension, and skirt clearance. Interfacial area was lowered by reductions in surface tension and liquid viscosity. Skirt clearances of from 0 to 0.5 in. were tested. Interfacial area was found to reach a maximum at a clearance of 0.25 in.

4. In addition to slot submergence, other variables found to affect total contact time were skirt clearance and vapor rate. Increase in both of the terms resulted in a decreased time of contact between vapor and liquid. An attempt is made to explain these results in the light of previous investigations.

5. Correlations for predicting interfacial area as a function of the variables studied were developed and took the form:

a. Interfacial area per unit volume of vapor:

(1) Slot submergences less than 2.5 in. of liquid:

$$\frac{1}{a - 5.88A_s^{0.30}} = A_s(985s - 332) + 0.20s + 0.40 \qquad (12)$$

2. Slot submergences greater than 2.5 in. of liquid:

$$ah_c' = F\left[\frac{h_c'\sigma\rho}{\mu^2 g_c}\right] \qquad (15)$$

where the functional relationship F is graphically represented by Figure 10.

b. Total contact time:

$$t_m = d(s/h_c)^{0.27} \qquad (16)$$

where d is determined from Figure 11 to be a function of h_c'/u_s.

c. Point efficiency, E_{LM}, is related to interfacial area and contact time through the equation

$$\ln(1 - E_{LM}) = -0.00848 K_G a t_m \quad (3)$$

ACKNOWLEDGMENT

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NOTATION

a = average interfacial area per unit volume of vapor, ft.$^{-1}$

a_0 = function of slot area = $5.88A_s$ = 0.30

A = interfacial area for mass transfer, sq. ft.

A_s = area per slot, sq. ft.

b = slope of rectified bubble-growth curve

C = concentration of component in vapor, lb. moles/cu. ft.

C^* = concentration of component in vapor in equilibrium with liquid, lb. moles/cu. ft.

c = function of slot area = $332A_s$ − 0.40

d = function of (h'_c/u_s), sec.

E_{LM} = Murphree point efficiency

F', F = Representation of mathematical function

g_c = consistency factor, (lb. mass)(ft.)/(lb. force)(sec.^{2})

h = skirt clearance, ft.

h_c = skirt clearance = slot height, in.

h'_c = skirt clearance + slot height, ft.

j = intercept of rectified bubble-growth curve

KG = over-all mass transfer coefficient, $\dfrac{\text{lb. moles}}{(\text{hr./sq. ft.})(\text{lb. moles/cu. ft.})}$

kG = vapor-film mass transfer coefficient, $\dfrac{\text{lb. moles}}{(\text{hr./sq. ft.})(\text{lb. moles/cu. ft.})}$

k_L = liquid-film mass transfer coefficient, $\dfrac{\text{lb. moles}}{(\text{hr./sq. ft.})(\text{lb. moles/cu. ft.})}$

L = liquid flow rate, ga./(min.)(in.) of free-plate width, free plate width defined as plate width minus bubble-cap diameter

m = slope of vapor-liquid–equilibrium curve, dC_V/dC_L

M = molecular weight

N = number of bubbles measured per run

n = number of frames between neon-lighted frames

P = pressure, lb./sq. ft.

p.e. = probable error of the mean of a series of measurements

r = bubble radius, ft.

R = gas-law constant, $\dfrac{\text{lb./ft.}}{(\text{lb. mole})(°\text{R.})}$

S = film speed, frames per sec.

s = static slot submergence, in.

t = contact time, hr.

T = temperature, °C.

u_s = slot velocity, ft./sec.

V = vapor velocity, cu. ft./sec.

V_c = superficial column velocity, ft./sec.

V_M = instantaneous volume of vapor bubble, cu. ft.

V_s = continuous-phase velocity–bubble velocity

W_h = weir height, in.

y = vapor composition, mole fraction

y^* = vapor composition in equilibrium with liquid

Z = length of bubble travel, liquid head on plate minus one-half slot height

μ = viscosity, lb./(ft.)(sec.) or centipoises

ρ = density, lb./cu. ft.

ρ' = molar density, lb. moles/cu. ft.

σ = surface tension, lb. force/ft.

Subscripts

L = liquid

V = vapor

1 = bubbling zone

2 = froth and entrainment zone

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