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NOTATION

- e = emf developed by the strain gauge differential pressure transducer
- k = response coefficient of the transducer, defined in Equation (6)
- n = number of moles
- p = pressure
- R = gas constant
- T = absolute temperature
- V = system volume
- $\bar{V}$ = partial molal volume
- $\tilde{V}$ = molal volume of a pure substance
- z = compressibility factor, $p\tilde{V}/RT$

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Flow Characteristics of Horizontally Moving Stable Aqueous Foams

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An empirical study was made of the flow characteristics of a stable aqueous foam (based on dilute solutions of saponin) moving horizontally inside a duct. Characteristic foam data have been determined experimentally, namely, drainage, interfacial areas, and related dimensions such as lamella thickness and foam cell size, fractional liquid holdups, foam velocities, and extent of gas channeling through the foam. Simple correlatability of drainage, interfacial area, and fractional liquid holdup in terms of basic parameters such as the liquid flow rate entering the apparatus, and the longitudinal position in the duct has been demonstrated. The sometimes simple dependence on the geometry of the perforated gas-liquid contactor and on the physical properties of the foaming solutions (surface tension and bulk viscosity) has also been described.

In the application of moving foam systems to specific purposes such as the recently reported results on mass transfer (*16*), it is necessary to know what the factors governing the behavior of such foams are and in which way they operate.

Extensive and somewhat controversial findings were reported in the areas of foaming in general and behavior of stagnant foams in particular (*1, 4* to *7, 9* to *11, 14*). In one case mention has been made of a linear relationship between the velocity of a moving foam plug and the shear stress (*10*), but the data, as reported, were scarce and limited only to that particular relationship. By and large, however, the interest in moving foams is centered around the techniques of gas absorption, particle collection, and separation by foam fractionation. All these techniques are based on empirical treatments of vertical operation in columns of varied designs, and their literature has been rather extensively reviewed elsewhere (*15*). Recently, an attempt was made to derive a theoretical model describing interstitial drainage in a stagnant or moving vertical foam fractionation column and agreement with experimental data was reported (*8*).

The applicability of studies of vertical foam columns to the case of horizontal foam movement is, however, not apparent; direct investigations of horizontal foam flow will therefore be necessary to fully understand and define its mechanism.

The present empirical study describes the flow behavior of a foam that is made to move horizontally inside a duct completely filled by it. The foam is produced from a solution of 0.2% by weight (in most cases) of saponin* in deionized water and, as such, belongs to the category of slow draining, true polyhedral-bubble systems.

The characteristic factors studied are drainage flow rates, interfacial areas and average lamella (film) thicknesses, fractional gas and liquid holdups, and extent of gas channeling effects. These factors are reported as functions of the basic parameters: liquid flow rate entering the apparatus,† gas flow rate, position in the duct, geome-

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* Saponin is an extract of naturally occurring glucosides, nonionic in character, and known to produce very stable slow draining foams. The 0.2% concentration was found to be the minimum amount permitting good operation of the foam apparatus over a wide range of gas and liquid flow rates (*15*).

† It should be noted here that because of foam drainage, the horizontal liquid flow rate in the duct decreases in the downstream direction. The liquid flow rate entering the apparatus is, of course, the easiest to measure and control.

try of the foam generation device, and physical properties of the foaming solution.

It has been shown elsewhere (*16*) how the type and amount of information presented in the present work were sufficient to allow reasonable predictions of the rates of gas-liquid mass transfer attained in a moving foam.

APPARATUS AND PROCEDURE

The foam apparatus consisted of a plexiglass duct 6 in. by 6 in. cross section and 2 ft. in length (Figure 1). The dimensions of the duct were sufficiently large so that its shape would not affect the flow properties of the foam enclosed within. The foam was generated at the upstream end by contacting a stream of air with the saponin treated solution. The air passed through a perforated plate inclined at 60 deg. with respect to the horizontal and the solution discharged from a bath, over a weir, and flowed as a thin layer down the plate.†

In operation both streams were kept at 30°C., and the air was prehumidified to the saturation point at the same temperature. The duct was provided with bottom drain spouts at 6 in. intervals. Dams, ¼ in. high were situated immediately following any drain opening to enable the collection of liquid draining out of the foam from any desired test section of the duct.

Pressure measurement connections were situated on the duct ceiling above each drain point. The downstream end of the duct had a foam disposal setup consisting of a timer-actuated, antifoam spraying nozzle. The complete experimental installation and details of the foam apparatus have been given elsewhere (*15, 16*).

The measuring technique consisted in bringing the system to steady operating conditions, and then recording gas and liquid flow rates entering the apparatus and drainage flow rates and pressure drops along the duct. The apparatus was divided into several sections from each of which drainage and other data were separately collected (see also Figure 1):

1. The foaming stage (fs), where the foam is generated. This was considered, mainly for mass transfer prediction purposes (*15, 16*), to be composed of three operationally distinct zones: the plate zone (p), where the foaming solution is contacted with gas; the bubble formation zone (b), arbitrarily defined as a slice of the foaming stage parallel to the plate and of a thickness equal to half the plate pitch (volume: 242 cc.); the foam zone (f), essentially identical in character to the foam column moving downstream in the duct (volume: 2,185 cc.)
2. The first foam stage (1f), corresponding roughly to the first half of the foam-filled duct (volume: 8,085 cc.).
3. The second foam stage (2f), corresponding roughly to the second half of the foam-filled duct (volume: 6,930 cc.).

Two different perforated plates were used to assess the effect of the plate zone geometry on the flow characteristics of the foam: with 126 circular holes, 1/16 in. in diameter (approx. 1% free area), with a length-to-diameter ratio of 1:1 and a triangular pitch of 0.56 in.; with 116 circular holes, ⅛ in. in diameter (approx. 3.7% free area) and the same pitch and length-to-diameter characteristics.

The following physical parameters were also varied:

1. Surface tension at constant bulk viscosity and specific gravity (achieved by varying the saponin content from 0.10% by weight, that is, 44.5 dynes/cm. surface tension to 0.75% by weight, which is 0.25% above the critical micelle concentration (14) and yields a surface tension of 36.6 dynes/cm.)
2. Bulk viscosity at constant surface tension and specific gravity (obtained by adding to a 0.2% saponin solution from 0.1 to 0.2% by weight Natrosol 250, giving a corresponding viscosity change from 1.8 to 5.5 centipoise as compared with 0.8 for pure water at 30°C.). Natrosol 250 is a nonionic hydroxyethylated cellulose manufactured by Hercules Powder Co.

Physical measurements: surface tensions were determined by the Du Nouy ring method (*2*), bulk viscosities by Ubbelohde viscometry, foaminess and foam stability by the Ross-Miles method (*3, 12, 13*), and specific gravity by hydrometry with temperature correction.

On separate runs the following foam characteristics were also determined: interfacial areas by photography, fractional liquid holdups by a technique based on an instantaneous stopping of the gas and liquid flow rates after steady operating conditions had been attained, and measurement of the amount of liquid collected from the killed foam section in each stage. A detailed description of the experimental procedure has been published (*15*).

RESULTS AND DISCUSSION

Many of the experimental data were obtained with dilute solutions of carbon dioxide and ammonia, since these were also used for mass transfer studies (*16*). The solutions were sufficiently dilute so as not to exhibit differences in foaming behavior.

The data were processed based on available literature data (9), which suggest the following relationship between the average thickness of a foam lamella δ', the characteristic size of the foam cell a', and the fractional liquid holdup $\mathcal{L}$:

$$\delta' = 0.796\, a'\, \mathcal{L}^{1.01} \qquad (1)$$

Since in polyhedric foams with thin lamellas, as in the present case, the interfacial area is given by

$$a = \frac{2\mathcal{L}}{\delta'} \qquad (2)$$

We obtain, from (1) and (2)

$$a = \frac{2.511}{a'\, \mathcal{L}^{0.01}} \qquad (3)$$

The average horizontal foam velocity in any given stage or section of the duct $\bar{v}_H$, followed from a knowledge of the density and molecular weight of the foaming solution (closely approximating water), ρ_L and M_W, respectively, the average horizontal volumetric flow rate in the same duct portion $\bar{\lambda}$, the fraction liquid holdup $\mathcal{L}$, and the cross-sectional duct area S:

$$\bar{v}_H = \frac{M_W}{\rho_L}\, \frac{\bar{\lambda}}{S\mathcal{L}} \qquad (4)$$

The average gas velocity in the duct u_H is based on the open cross-sectional area $S\mathcal{H}$, where $\mathcal{H}$ represents the fractional gas holdup; it can be approximated by the superficial velocity term u based on the entire duct area:

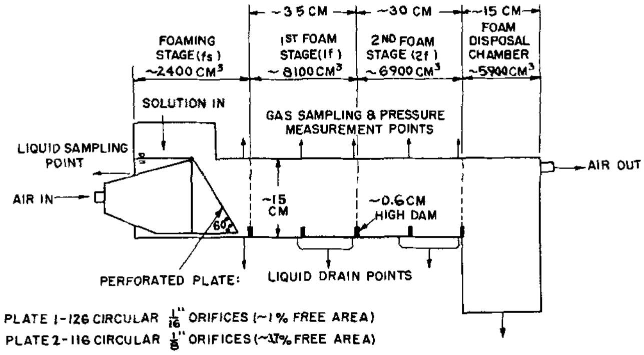

Fig. 1. Schematic representation of foam apparatus showing the division by stages.

† With this arrangement the only pressure drop loss occurred at the perforated plate. No measurable pressure drop could be detected, owing to the moving foam column, over the entire practical range of gas and liquid flow rates. The pressure drops through the plate are minor (max. 4 to 5 cm. water) because the apparatus must operate at low gas flow rates (in our case, up to 30 cm./sec.) for efficient foam operation.

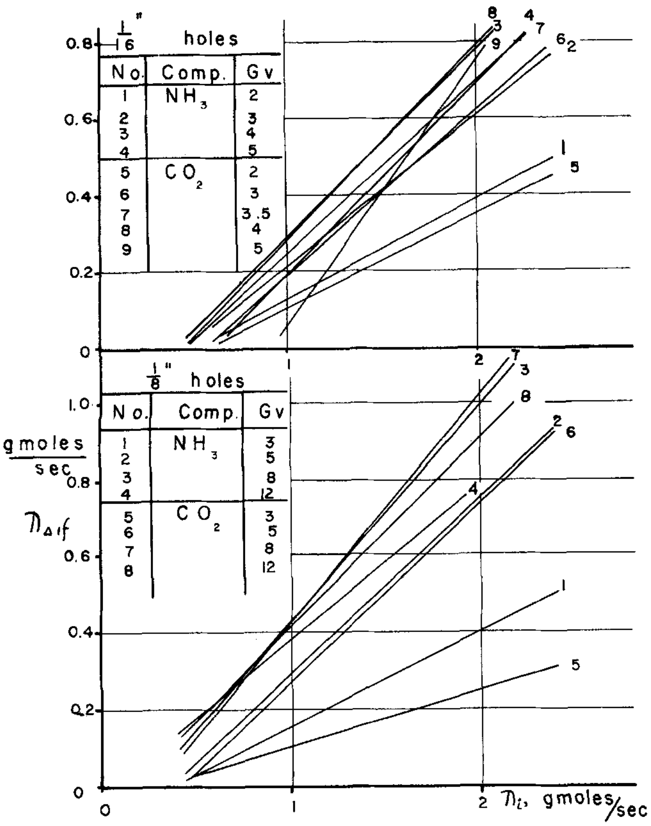

Fig. 2. Drainage flow rates vs. the liquid flow rate into the apparatus; Parameter: G_v; first foam stage.

$$u_H = \frac{G'}{SH} = \frac{G'}{S(1-\mathcal{E})} \approx u = \frac{G'}{S} \tag{5}$$

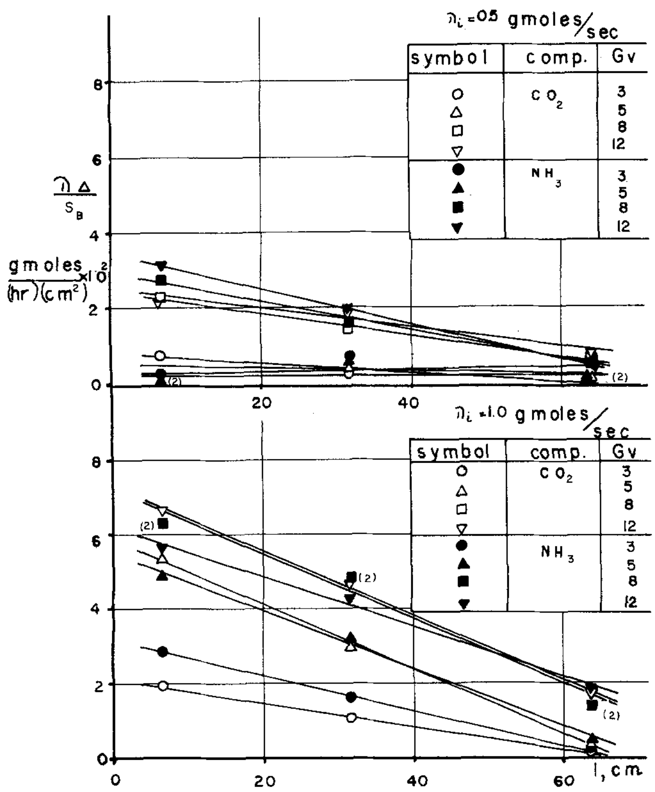

Fig. 3. Drainage per unit bottom area vs. the longitudinal position in the duct for a given liquid flow rate into the apparatus; Parameter: G_v; ⅛ in. perforations.

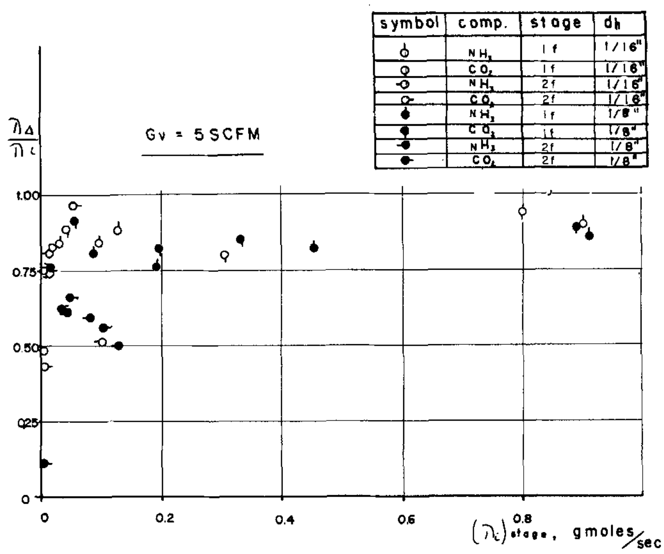

Fig. 4. Fractional drain out vs. the liquid flow rate entering any stage

where G', the volumetric gas flow rate in cubic centimeters per second, has been measured in terms of G_v (standard cubic feet per minute) and calculated from the relationship

$$G' = 1{,}218.8\,\frac{G_v T}{P} \tag{6}$$

The gas channeling through the moving foam column was defined in terms of the dimensionless channeling ratio

$$\text{C.R.} = \frac{\overline{v}_H}{u_H} \tag{7}$$

(Note that for the case of zero channeling $\overline{v}_H = u_H$.) This criterion had a practical application in predictive calculations of mass transfer (*16*).

Drainage Flow Rates

Data reported in the literature for stagnant foams (for example p. 101 in reference *4*) cover time intervals orders of magnitude higher than for moving foams.* Only a qualitative comparison with flowing foam data is warranted under these circumstances; it indicates that liquid drainage proceeds at considerably faster rates in flowing foams that in stagnant foams. Other differences are observed when flowing foam drainage data obtained from the foaming stage are compared with flowing foam drainage data from the various foam stages.

The foaming stage certainly belongs to a category apart, mainly because of the relatively large contributions of the nonfoamed liquid portions (from the plate zone) to the total measured drainage flow rates (plate + bubble + foam zones). The first and second foam stages yield true foam drainage data, but most of the transformations in liquid holdup along the duct, due to drainage, occur in the first foam stage. This first stage also happens to be more active for purposes of mass transfer for instance (*16*). The second stage consists of lamellae that have apparently been thinned down to a state of inactivity characterized by structural weakness and low liquid content (as well as low mass transfer rates).

The experimental drainage data can be approximated by a linear relationship in terms of the liquid flow rate entering the foam apparatus; this holds true for the entire range of liquid flow rates permitting foam formation and horizontal movement:

* The longest residence time encountered in the present work is of the order of 2 min.

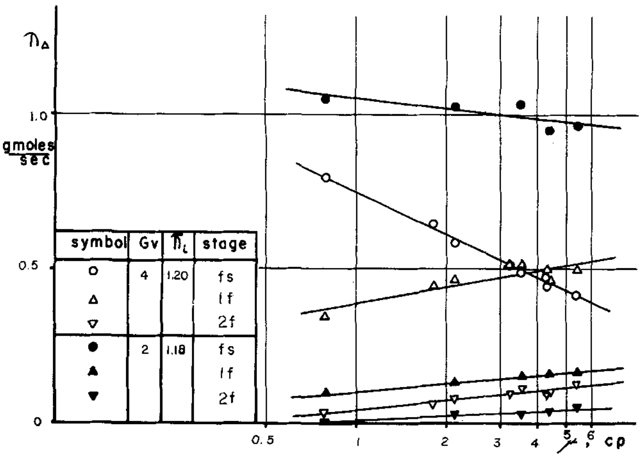

Fig. 5. Drainage flow rates vs. bulk viscosity; Parameter: G_v; 1/16 in. perforations.

$$\lambda_\Delta = A\,\lambda_i + B \tag{8}$$

Equation (9) is graphically represented in Figure 2, for the first foam stage (for sake of clarity, the numerous experimental points have not been marked on the figure).

An examination of the various slopes in the figure reveals that there is no uniform trend in terms of the gas flow parameter. Indeed, a cross plotting of the data, as drainage vs. gas flow rates, would yield curves sometimes exhibiting distinct maxima.

On the other hand, the possibility of obtaining linear relationships of cumulative drainage data for the various portions of a moving foam column, as a function of the incoming liquid flow rate, has considerable practical significance. It is this incoming liquid flow rate which can readily be measured and controlled in any flowing foam device. As one might expect, attempts to compare and interpret this foam drainage behavior based on data and

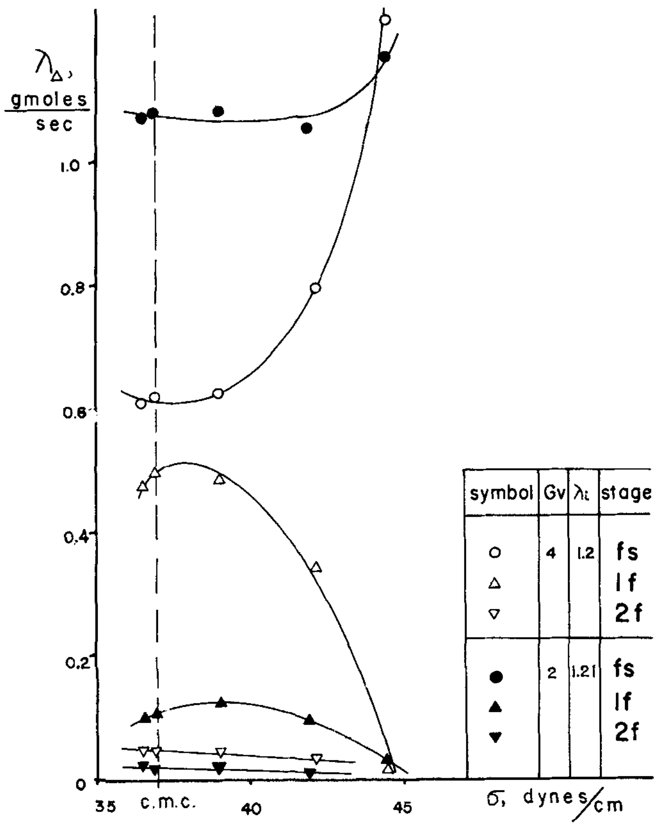

Fig. 6. Drainage flow rates vs. surface tension; Parameter: G_v; 1/16 in. perforations.

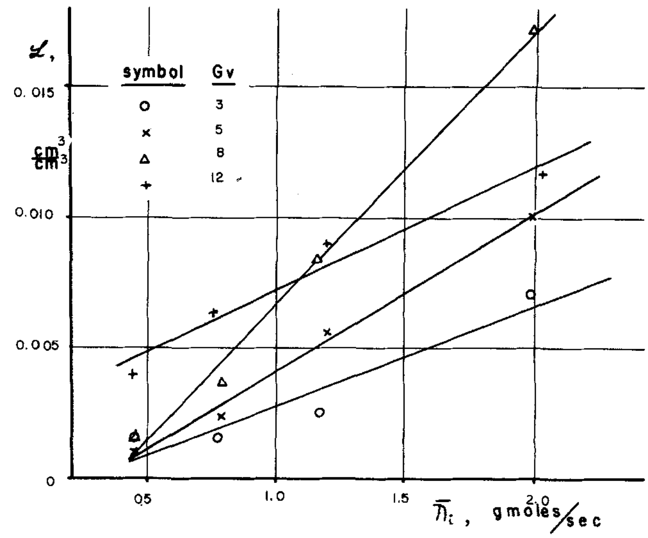

Fig. 7. Fractional liquid holdup vs. liquid flow rate into the apparatus; Parameter: G_v; ⅛ in. perforations; first foam stage.

theories available in the literature did not yield practical results.

Figure 3 exhibits the linear relationship of flow drainage data referred to the unit area of duct bottom (that is, the plane normal to the direction of flow) when the independent variable is taken as the longitudinal position in the duct. Here, the gas flow rate has been taken as a parameter, although the same holds true also if the data are regrouped with the liquid flow rate as the parameter.

As expected, different drainage rates were measured for different perforated plate (plate zone) geometries. This occurs also in the case of the foaming stage (probably due to the relative influence of the bubble and foam zones) at equal gas velocities through the plate perforations. However, if the drainage data are normalized as

$$\left(\frac{\lambda_\Delta}{\lambda_i}\right) = \text{fractional drain out}$$

the results appear to be relatively invariant with plate geometry. This is illustrated in Figure 4.*

Investigations of the effect of solution viscosity on the drainage flow rate revealed the following relationship:

$$\left(\frac{\lambda_\Delta}{\lambda_i}\right) \text{ or } \lambda_\Delta = A \log \mu + B \tag{9}$$

Figure 5 represents this exponential relationship in terms of λ_Δ vs. μ.

When surface tension was considered as the independent variable, no simple relationship was found. This is illustrated in Figure 6.

In both instances, the difference in behavior between the foaming stage and the foam stages is indicated by the change in slope sign.

Fractional Liquid Holdups, Interfacial Areas

These two important properties of a flowing foam are amenable to similar simple correlations in terms of the entering liquid flow rate (Figures 7 and 8) and longitudinal position in the duct, yielding combined equations of the form

$$\mathcal{L} = I l_{1,\ldots,n}\,\bar{\lambda}_i + J\,\bar{\lambda}_i + I' l_{1,\ldots,n} + J' \tag{10}$$

for the fractional liquid holdup, and

* The fractional drain out has been shown to be one of the necessary criteria in the estimation and prediction of diffusional phenomena occurring in flowing foams (*14, 15*).

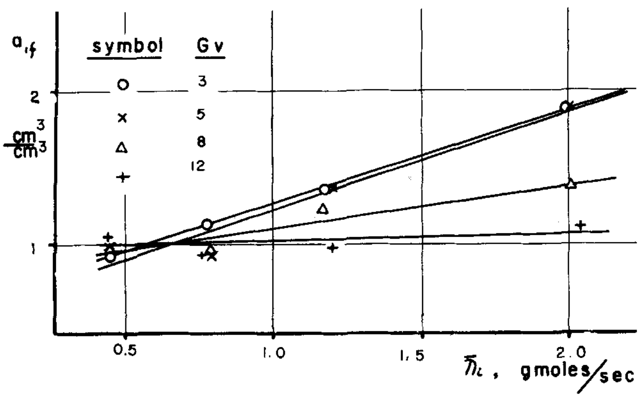

Fig. 8. Interfacial area vs. liquid flow rate into the apparatus; Parameter: G_v; 1/8 in. perforations; first foam stage.

$$a = J l_{1,\ldots,n}^{\,I}\, \bar{\lambda}_i + J' \exp\,(I' l_{1,\ldots,n}) \qquad (11)$$

for the interfacial area. For the case of drainage flow rates, these relationships are valid over the entire operating range of the moving foam.

Miscellaneous Foam Flow Data

Extensive tabulation of all of the above-mentioned data, including also other factors (lamella thickness, gas channeling ratio, average foam velocities, average foam cell size), as well as statistical coefficients, have been published (*15*).

CONCLUSIONS

Basic data characterizing stable aqueous foams in horizontal motion (drainage, interfacial area, fractional liquid holdup) are amenable to simple relationships, many of them linear, although a clear distinction has to be made between the region near the foam source (say, a perforated gas-liquid contactor) and the flowing foam column proper. The latter, too, changes its character as it advances along a given duct from an active, liquid-rich, fast draining type to an inactive, liquid-poor, slow draining type. These two types of operation have to be considered separately for a meaningful interpretation of experimental data.

Relationships can be obtained in terms of liquid flow rates entering the apparatus and longitudinal position in the duct. Gas flow rate, when taken as an independent variable, does not lead to similar simple descriptions of foam flow properties.

The draining characteristics of a moving stable aqueous foam appear to be geometry dependent (in terms of the gas-liquid contactor perforations) except when normalized as dimensionless fractional drain outs: λ_Δ/λ_i. They also depend on the physical properties of the foaming solution, namely, bulk viscosity and surface tension. Only the viscosity dependence is amenable to a simple mathematical interpretation.

ACKNOWLEDGMENT

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NOTATION

A = coefficient (slope) in various correlations
a = interfacial area, sq.cm./cc.
a' = average characteristic dimension of foam cell, cm.
B = coefficient (intercept) in various correlations
$C.R.$ = channeling ratio, defined by Equation (7)
c.m.c. = critical micelle concentration
d_h = diameter of plate perforation, in.
G' = gas flow rate, cc./sec.
G_v = gas flow rate, std. cu.ft./min.
I, J = slope and intercept, respectively, in correlations involving A as dependent variable
I', J' = slope and intercept, respectively, in correlations involving B as dependent variable
l = length of given foam stage or section, cm.
$l_{1,\ldots,n}$ = longitudinal coordinate, cm.
M_W = molecular weight of water
P = absolute ambient pressure, mm. Hg
S = cross-sectional duct area perpendicular to direction of flow, sq.cm.
S_B = cross-sectional area parallel to duct bottom, sq.cm.
T = absolute temperature, °K.
u = gas velocity (superficial, based on S), cm./sec.
v = liquid velocity or foam velocity, cm./sec.
$\mathcal{H}$ = fractional gas holdup, cc./cc.
$\mathcal{L}$ = fractional liquid holdup, cc./cc.

Greek Letters

δ' = thickness of foam lamella, cm.
λ = liquid flow rate, g.-moles/sec.
σ = surface tension, dynes/cm.
ρ_L = density of liquid, g./cc.
μ = viscosity, centipoise

Subscripts

$1f$ = first foam stage
$2f$ = second foam stage
fs = foaming stage
H = horizontal
i = incoming to the apparatus or to any given stage, if so mentioned
$\mathcal{H}$ = based on the gas fractional holdup
Δ = draining

Superscript

— = average

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