Studies on Entrainment

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After application of a biochemical technique, size distribution of liquid drops from air bubbles blown through water and a butanol and glycerine solution filled to a certain depth in a glass cylinder 9.6 cm. in diameter and 47 cm. in length was measured.

The initial vertical velocity of drops was estimated from the experimental results, with reference to its trajectory.

Entrainment is frequently encountered in such equipment as distillation columns and evaporators. The phenomenon generally causes low plate efficiencies in distillation and reduced purity and yield of products. The published papers on entrainment have advocated the provision of an appropriate space above the liquid surface or the use of a reasonable gas or vapor velocity in the space (*1, 2, 5*). These studies have been made under specific experimental conditions. For instance, in the study of entrainment in evaporators a small amount of sodium chloride solution is added to the boiling liquid and the chloride ion content of the condensate is determined in order to evaluate the over-all degree of entrainment (*2*).

Recently Newitt *et al.* (*6*) took high-speed photographs of air bubbles bursting at a water-air interface. Garner *et al.* (*3*) also measured the size and number of drops thus generated. Such studies were undertaken to clarify the mechanism of drop formation, an intrinsic feature of entrainment.

Since the phenomenon is very complicated, many facts remain to be disclosed experimentally and theoretically before entrainment can be prevented, therefore this experimental study on entrainment was made.

EQUIPMENT AND PROCEDURE

Figure 1*a* is a schematic diagram of the experimental apparatus. The inner diameter and height of the glass cylinder used in this experiment are 9.6 and 47 cm., respectively. Adjacent to its bottom, a brass pipe 1.0 cm. in diameter, with closed end, was inserted horizontally along a radius of the cylinder. Along the top line of the pipe nine orifices each 0.103 cm. in diameter were bored at 1.0-cm. intervals, and air from a compressor was blown through them. The rate of air flow was measured with an orifice flow meter.

Water, butanol, and glycerine solutions were used in this series of experiments. The glass cylinder was filled with each liquid to a certain depth above the pipe. Air bubbling was continued for several minutes; then liquid drops entrained in the space above the liquid were sampled, and the size distribution was determined by the following procedure.

First, a glass plate (7.7 by 2.6 by 0.1 cm.), after being cleansed with cleaning solution, distilled water, and alcohol, was placed at a certain height above the liquid surface, perpendicular to the air flow to catch the liquid drops.

Second, a cascade impactor, made of a tin plate, was used to trap droplets which are small enough to bypass the glass plate. The linear velocity of air at the entrance of the impactor was adjusted so as to be identical with the nominal linear velocity of air in the glass cylinder. The principal dimension of the impactor is also shown in Figure 1*a*.

A species of bacteria, *Serratia marcescens*, was suspended in each liquid (10^7 cells/cc. of the liquid). Impinged drops which contain the bacterial cells left on the glass ring-shaped stains formed by the cells aligned along their circumferences. The stains were then colored with methylene blue solution, and the size was easily determined with a microscope, as shown in Figure 1*b*.

It was ascertained that such a concentration of the bacterial suspension exerted little influence on the physical properties of the liquid, in particular on the density, viscosity, and surface tension.

It is possible that small droplets impinged on the glass plate will be vaporized immediately after the glass is taken outside for inspection and thus missed; however this possibility is minimized by the procedure outlined above.

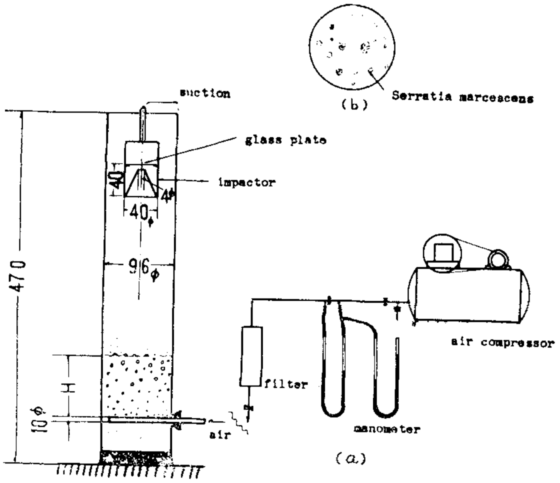

Fig. 1. Schematic diagram of experimental apparatus.

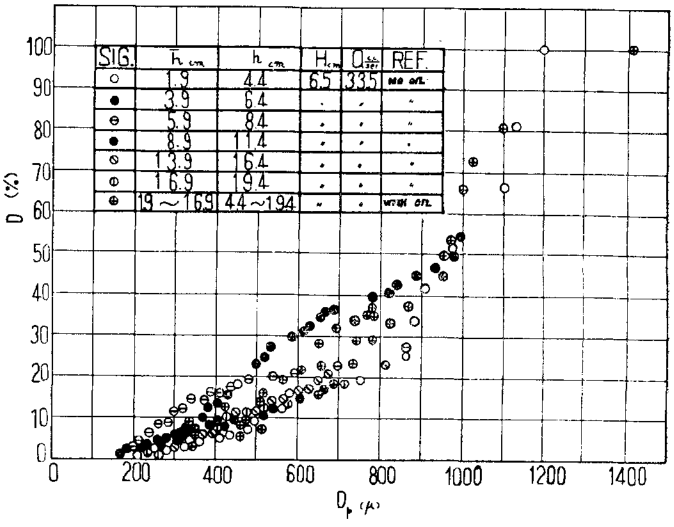

Fig. 2. Comparison between cumulative volume curves obtained by the use of glass plates with and without oil; $v' = 0.46$ cm./sec.

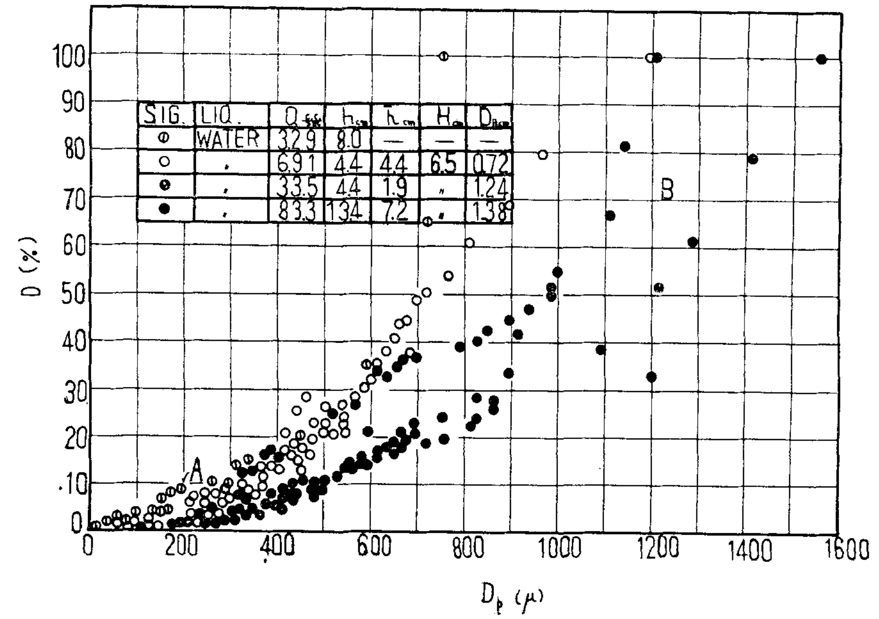

Fig. 3. Effect of air flow rate on cumulative volume curves of liquid drops. ***A*** **refers to the data (*1*).** $v' = 0.86$ **to 10.37 cm./sec. (Q = 6.91 to 83.3 cc./sec.).**

Under each experimental condition, which will be referred to later, the height of sampling was changed, and the diameters of the stains were then determined, except when the drops were apparently split owing to impingement.

The diameters thus determined are thought to be very different from those of drops just before they impinge, because of the contact angle between the liquid and the glass plate. Therefore the diameters of drops before the impingement were estimated by the following calibration.

Liquid drops from a glass capillary were dropped onto a glass plate and the volumetric mean diameter was calculated on the basis of the measurement of the total number and the mass of these drops. On the other hand, the diameters of the stains were determined as explained previously and the volumetric mean was calculated. Thus the correction factor, defined by the ratio of the former diameter to the latter, was found to be 0.5 ± 0.1 in the range of $D_p' = 3{,}000$ to 500μ. It was assumed that such a calibration also holds true for the case of D_p' less than 500μ.

Furthermore, to ascertain the reliability of the calibration, a glass plate coated with a mixture of grease and gas oil was suspended inside the cylinder to catch the entrained drops.

Effects of air flow rate, liquid surface tension, liquid viscosity, and liquid depth on the size distribution of the entrained drops were studied. Concomitantly photographs of air bubbles at the liquid surface were taken, and the volumetric mean diameters (on the assumption that they were spherical) were computed. Since it was seen that the air bubbles at the liquid surface were rather uniformly distributed, the apprehension of nonuniformity of generation of air bubbles through the nine orifices seems unbounded.

This series of experiments was conducted at room temperature (20° to 25°C.), the surface tension and viscosity of the liquid being determined by the use of the platinum-wire method and the Ostwald viscometer, respectively.

EXPERIMENTAL RESULTS*

It was found that the cascade impactor was effective only when the sampling location was far from the bubbling surface. Conversely, near the surface the existence of larger drops made the determination of small droplets difficult.

When it was noted that the vaporization of liquid drops seemed unlikely in the space inside the glass cylinder, the cumulative volume curves relating to each sampling location were superimposed on the curve that was obtained at the lowest sampling height, as shown in Figure 2. It is also noted from Figure 2, which represents an average of the size distribution of drops collected at $h = 4.4$ cm., that the aforementioned calibration of diameters of liquid drops is reasonable, because the data thus calibrated agree well with those which are considered to be free from the deformation of drops.

In the same manner the experimental results relating to other conditions are summarized in Figures 3 to 6. Most of these cumulative curves have a sampling location of $h = 4.4$ cm. In these figures the volumetric mean diameter of bubbles at the liquid surface is also shown.

Though the height of sampling is not always the same in these figures, these curves indicate the size distribution of drops near the bubbling liquid surface. It is seen that the cumulative volume of small droplets less than about 100 μ is negligible. It is also seen that the physical properties of the liquid and the operating conditions exert a rather marked influence on each curve of the size distribution.

DISCUSSION OF EXPERIMENTAL RESULTS

Since these drops are collected predominantly by inertia, it is necessary to estimate the collection efficiency. The

*Tabular material has been deposited as document 6049 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.

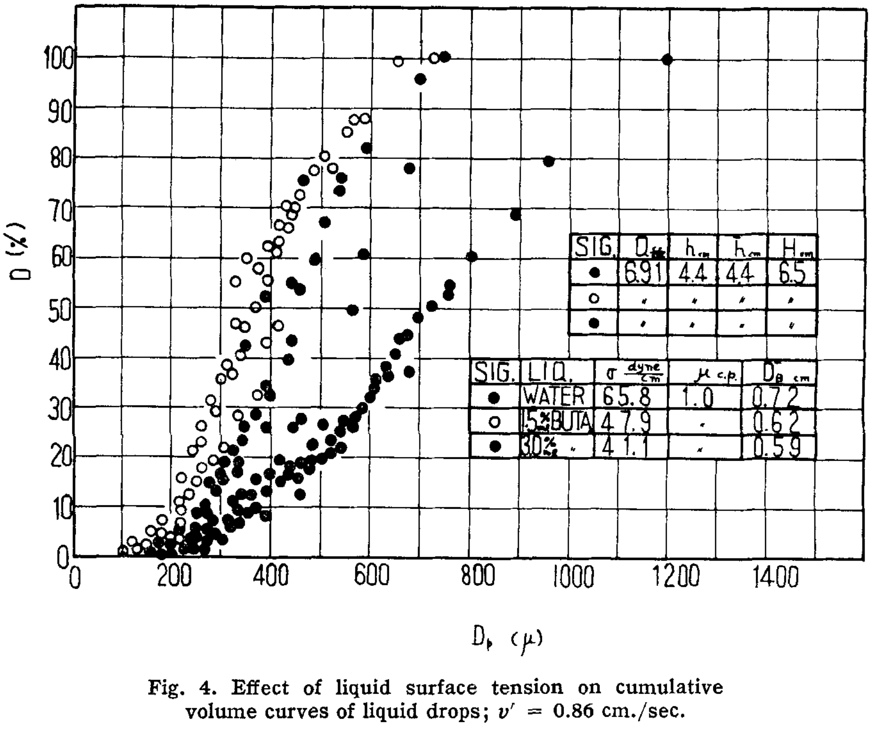

Fig. 4. Effect of liquid surface tension on cumulative volume curves of liquid drops; $v' = 0.86$ **cm./sec.**

result of this estimation with the equation presented by Ranz *et al.* (*8*) used showed that η for the droplet, for example of 10 μ collected by the cascade impactor, was about 100%. The estimation of η for larger drops collected without the impactor is difficult because the velocity of impingement of these drops is unknown. However with an assumption that the velocity is of the order of the nominal linear velocity of air above the liquid, η for the drop of 100 μ was estimated to be of the order of 50% in the experimental range of air flow rates. Therefore as far as the distribution expressed by the cumulative volume percentage is concerned, the effect of η on the distribution curve seems to be negligible.

In Figure 3, with the increase of Q, rather large drops are likely to become predominant, though each curve does not correspond to the same height of sampling because of foaming. This tendency agrees qualitatively with the experimental results of Akselyrod (*1*) and Garner (*3*), an exact comparison between them is difficult.

The volumetric mean diameter of bubbles in Figure 3 is plotted against Q in Figure 7 (*a*). The relationship is approximately expressed by

$$\bar{D}_B \propto Q^{1/3} \qquad (1)$$

Equation (1) is similar to an empirical correlation presented by Leibson *et al.* (*4*). It is seen from Figure 4 that the decrease in σ tends to decrease the number of large drops. $\bar{D}_B$ in Figure 4 is plotted against σ in Figure 7 (*b*). The correlation is approximately expressed by

$$\bar{D}_B \propto \sigma^{1/3} \qquad (2)$$

As is shown in Figure 5 it is difficult to change the viscosity exclusively without affecting the surface tension in the case of glycerine solution. When one refers to Equation (2), $\bar{D}_B\sigma^{-1/3}$ vs. μ is plotted in Figure 7 (*c*). The effect of μ on $\bar{D}_B$ is not clear. Accordingly the change of the size distribution in Figure 5 is caused primarily by the change of the surface tension, and therefore the effect of viscosity μ on the drop size is not evident.

The experimental relationship between H and $\bar{D}_B$ is shown in Figure 7 (*d*). The effect of H on $\bar{D}_B$ is not very clear. Most of the curves in Figure 6 also indicate that the increase of $\bar{D}_B$ is accompanied by the predominance of larger drops. In the case of H = 0.6 cm., specially large drops are seen; direct splashing of liquid by the air flow might have been the cause, since in most cases effect of these various factors might be equivalent to that of the bubble diameter on the size distribution.

Next the initial vertical velocity of drops will be considered. In this consideration small droplets, the terminal settling velocity of which is less than each nominal linear velocity of air in the space above the liquid, were excluded.

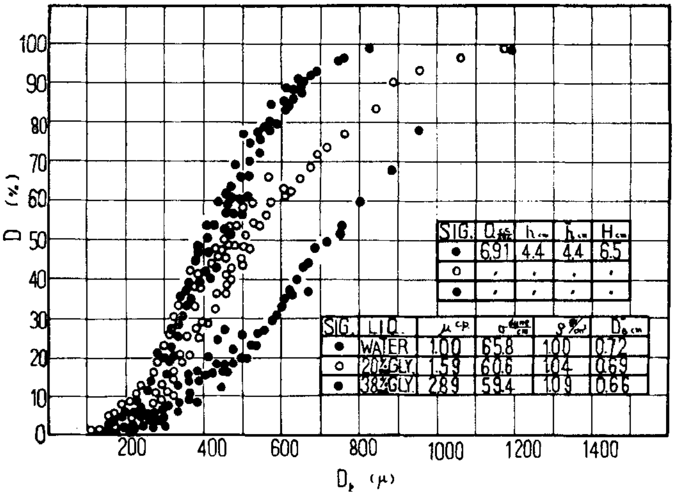

Fig. 5. Effect of liquid viscosity on cumulative volume curves of liquid drops; v' = 0.86 cm./sec.

First the volumetric mean diameter of the drops collected at the highest sampling location $h = h_1$ made in each experiment was calculated. Second $\bar{D}_{p2}$ of the drops at $h = h_2$, excluding those less than $\bar{D}_{p1}$, was determined. In the same manner $\bar{D}_{p3}$, $\bar{D}_{p4}$, and so on, corresponding to $h = h_3$, h_4, respectively, was thus determined ($h_1 > h_2 > h_3 > h_4$). It was postulated that the distance the drop of $\bar{D}_{p2}$ could reach was within the range from h_2 to h_1, while that of $\bar{D}_{p3}$ was from h_3 to h_2. In this calculation the surface of the foaming layer, if any, was chosen as the datum of the distance.

On the other hand the equation of motion of a spherical drop which is assumed, for simplicity, to be ejected vertically from the liquid-air interface is as follows:

$$\frac{dv}{d\theta} = -g\left(\frac{\rho - \rho'}{\rho}\right) \mp \left(\frac{3\rho'}{4\rho D_p}\right)\cdot C\cdot(v - v')^2 \qquad (3)$$

where $\mp$ corresponds to the case $v \geqq v'$ and $v \leqq v'$, respectively. When

$$g\left(\frac{\rho - \rho'}{\rho}\right) = a,$$

$$\frac{dv}{d\theta} = \frac{dv}{ds}\cdot\frac{ds}{d\theta} = \frac{dv}{ds}\cdot v$$

$$\frac{3\rho'}{4\rho D_p} = b$$

Equation (3) is simplified as follows:

$$v\,dv/ds = -a \mp b\cdot C\cdot(v - v')^2$$

Then the distance S the drop reaches is expressed by Equation (4):

$$S = \int_{v_0}^{v'} \frac{v\,dv}{-a - b\cdot C\cdot(v - v')^2} + \int_{v'}^{0} \frac{v\,dv}{-a + b\cdot C\cdot(v - v')^2}$$
$$= \int_{N_{Re_0}}^{0} \frac{(kN_{Re} + v')k}{-a - b\cdot C\cdot k^2\cdot N_{Re}^2}\,dN_{Re} + \int_{0}^{N_{Re'}} \frac{(kN_{Re} + v')k}{-a + b\cdot C\cdot k^2\cdot N_{Re}^2}\,dN_{Re} \qquad (4)$$

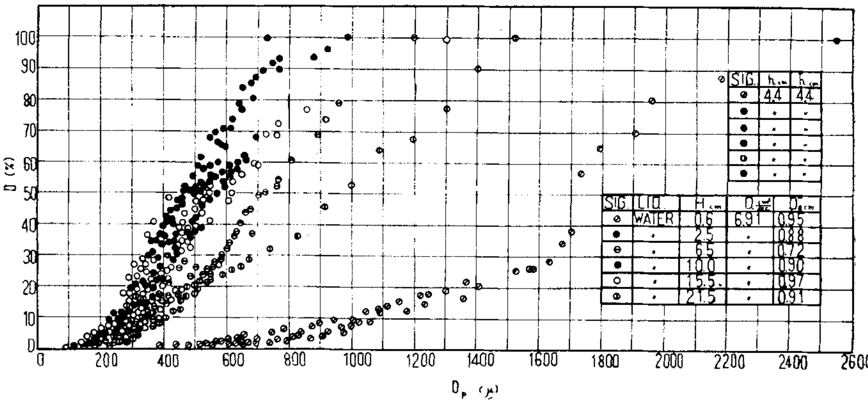

Fig. 6. Effect of orifice submergence on cumulative volume curves of liquid drops; v' = 0.86 cm./sec.

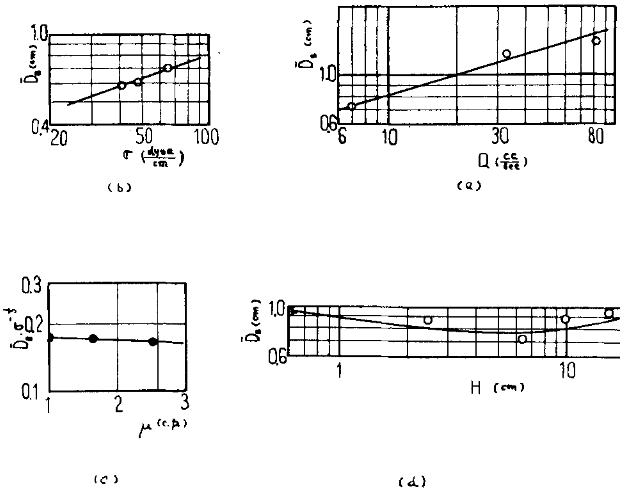

Fig. 7. Relations between bubble diameters and various factors.

where

$$N_{Re} = \frac{D_p(v - v')\rho'}{\mu'} = \frac{v - v'}{k};$$

$$k = \frac{\mu'}{D_p \rho'}; \qquad v_0 - v' = kN_{Re0}$$

$$- v' = kN_{Re'}$$

Relating to each nominal velocity of air above the interface, one could calculate in advance the trajectories of the drop under various initial velocities. In these calculations the drag coefficient was taken from the published data (*7*). When one referred to these diagrams of trajectories and the data of distance the drop could reach, the initial vertical velocity was estimated.

Figure 8 summarizes the result of the same procedure of estimation. It is noted from Figure 8 that v_0 seems to depend on $\bar{D}_p$, and the effect of the aforediscussed factors on v_0 is not evident.

Although the probable error accompanying such estimations is of the order of 10%, the trajectories of drops, in practice, are considered to be far from those which are calculated from the simple assumptions described above. Therefore only the order of magnitude of v_0 is to be noted from Figure 8. The published data of v_0 (*1*), the procedure of estimation being about the same as in this paper, agree well with those of this series of experiments.

CONCLUSIONS

1. After the application of a biochemical technique, the effects of the physical properties of liquid, including those of some operating conditions on the size distribution of drops, were experimentally studied. Rather marked effects of these factors on the drop size were noted.

2. In most cases the drop-size distribution seem to be closely related to the bubble diameter bursting at the interface.

3. The initial vertical velocity of drops was estimated. As far as larger drops are concerned, such information will furnish a clue to determining the height of space above the foaming layer necessary to minimize entrainment.

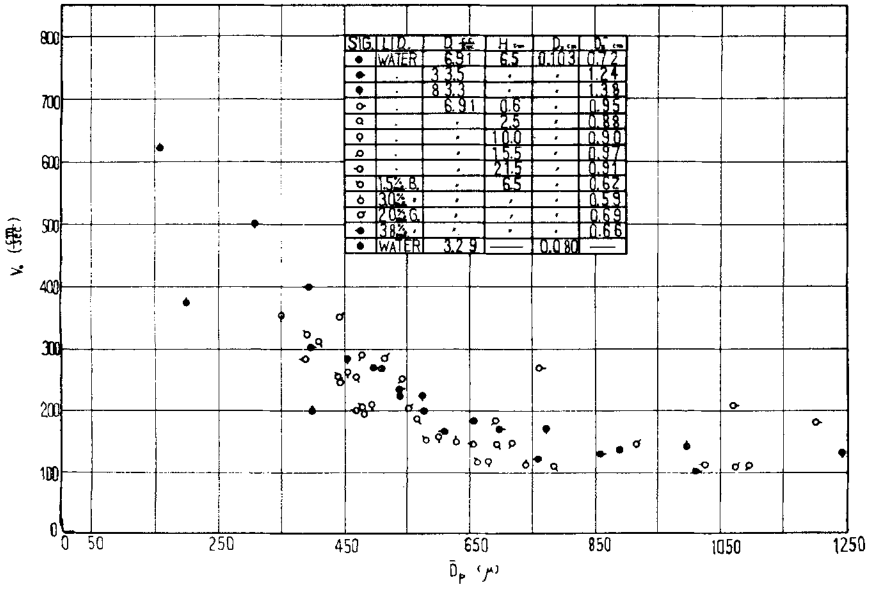

Fig. 8. Initial vertical velocity of liquid drops. Data of D_0 = 0.080 (cm.) are concerned with reference *1*.

NOTATION

C = drag coefficient
D = cumulative volume, %
D_0 = orifice diameter, cm.
$\bar{D}_B$ = volumetric mean diameter of bubbles, cm.
D_p = diameter of liquid drop, cm., μ
$\bar{D}_p$ = volumetric mean diameter of liquid drops, μ
D'_p = diameter of a stain of liquid drop collected on a glass plate, μ
g = accerelation due to gravity, cm./sec.^{2}
h = height of sampling above the liquid surface at standstill, cm.
$\bar{h}$ = height of sampling above the surface of the foaming layer, cm.
H = liquid depth (orifice submergence), cm.
N_{Re} = Reynolds number of liquid drop, $[D_p(v - v')\rho'/\mu']$
Q = flow rate of air through an orifice (total flow rate divided by the number of orifices), cc./sec.
s = distance
S = distance a drop can reach, cm.
v = vertical velocity of liquid drop, cm./sec.
v' = vertical velocity of air flow, cm./sec.
v_0 = initial vertical velocity of liquid drop, cm./sec.

Greek Letters

η = collection efficiency
θ = time
ρ, ρ' = densities of liquid and air, respectively, g./cc.
μ, μ' = viscosities of liquid and air, respectively, g./cm.-sec.
σ = surface tension of liquid, dyne/cm.

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