High intensity ultrasonic vibrations are known to be efficient at destabilizing stationary foams. In this paper, the effect of the application of ultrasonic vibrations generated by an ultrasonic bath has been studied on the drainage of static foam. The vibrations are found to enhance the drainage rate of the foam and the model could be extended to correlate these drainage rates. This model can also be used to predict the variation in the foam cell size and shape factor during drainage. The effect of type of sparger and column diameter on the drainage rate has been studied. The rate of foam collapse depends on the foam cell size, which in turn depends on the sparger used for foam generation. The foam drainage and collapse rates were found to increase with the decrease in the column diameter.

**IPC Code:** B01D 19/02, B01J 19/10

**Keywords:** Ultrasonic vibrations, static foam

Foams are undesirable in many processing applications including bioprocessing. Fermentation media often contain some surface-active substances or many times such substances are generated as by products of fermentation, which reduce surface tension and lead to the formation of persistent foam. It is necessary to control excessive foam formation in fermenters. Conventionally, foam is controlled by chemical, mechanical or thermal methods. In many applications the effectiveness or nuisance due to the foam is related to its stability. Common method of characterizing stability is to measure the flow of liquid from the foam structure as a function of time as well as by measuring the rate of foam collapse.

A number of experimental investigations have been carried out on the liquid drainage from the foam. Number of models proposed in the literature have neglected the drainage of liquid through the film but assumed the drainage through the plateau border\(^4\). Some other models\(^5,9\) were modified or reformulated by considering the additional effects or parameters\(^10-14\). They found that the new model gives the better results compared to the old one. Some of the models\(^15-16\) made an impractical assumption that the drainage continues until all the liquid in the foam has drained out. For the development of the model, the foam bubbles were considered to be of \(\beta\)-tetrakaidecahedral structure, although, the many existing theories of foam drainage assume bubbles as pentagonal dodecahedrons\(^8,13\). The liquid drainage in foam was found to be governed by dominant drainage in the nodes (junctions of four channels) rather than in the channels (plateau border) of the foam\(^17\). Thus, most of the models presented till now are all based on the material balance of the liquid in the column, either on macroscopic level or on microscopic level, which describe the gravitational drainage of the liquid through channels in the foam structure composed of dodecahedral bubbles.

The effect of ultrasound has been studied in this work since drainage of liquid by ultrasonic vibrations is fast emerging as a suitable technique for foam control. Earlier the work on the destruction of foam was carried out using the ultrasonic vibrations\(^18-20\). They came to the conclusion that ultrasonic vibrations at first increased the drainage rate of liquid from foam and then fast drainage rate resulted into attaining the critical liquid film thickness at an early stage causing film rupture, leading to the destruction of the foam. In literature, although the effect of ultrasonic vibration in causing faster liquid drainage from the foam has been reported but the experimental data is in
the form of foam collapse rather than faster liquid drainage resulting into an earlier foam collapse.

The thin liquid film drainage is mainly governed by the mechanism of marginal regeneration, which is triggered by squeezing mode surface waves along the film or plateau border boundaries. Such surface waves tend to stimulate liquid film thickness fluctuations leading to faster drainage and film rupture. Thus, the ultrasonic vibrations, which generate surface waves and stimulate flow of liquid, are expected to accelerate liquid drainage in the films leading to films attaining their critical thickness earlier and, therefore, destabilize the foam.

In this paper the simple model developed earlier (Barigou M, Wiggers F N, Deshpande N S & Pandit A B, unpublished work) is verified using experimental results of liquid drainage from the static foam for both the cases i.e. in the absence and the presence of ultrasonic vibrations. A good agreement is obtained between experimental and theoretical results based on this model over a wide range of experimental conditions covered. It has also been shown that, the use of the liquid drainage rate can be made to estimate hydrodynamically equivalent foam cell sizes. This equivalent foam cell size could then possibly be used to predict pressure drop in flowing foams using an analogy of moving packed beds.

**Experimental Procedure**

As shown in Fig. 1, most of the experiments have been conducted on an acrylic column with inner diameter of 25.4 mm having two different sections: foam generation section and foam propagation or foam holding section. Sodium lauryl sulphate (SLS) of purity > 99% was used as a surfactant over the range of concentration 1.4 to 2.1 g/L, which corresponds to 0.58-0.87 of the critical micelle concentration (CMC) and the surface tension of the surfactant liquid is in the range of 40-36.5 dynes/cm. Fresh distilled water has been used throughout the experiments. A typical experiment involves the use of 60 mL of known concentration of the solution, which was poured in the column, and the rate of air inflow was adjusted in the range of 4.8 to 12.16 cm³/s. Two types of spargers, a single point sparger (sparger 1) and a sintered sparger (sparger 2), have been used for the same experimental conditions. After adjusting the gas flowrate to the desired value, the flow was directed to the column. The foam was allowed to reach a maximum height (1168 mm from pressure tapping 2) (Fig.1) before the gas was stopped. The typical foam cell sizes observed visually was in the range of 1-3 mm and 5-15 mm for the sintered and single point sparger respectively.

Pressure tapping 2 ($P_2$) was connected to a micromanometer (Furness Controls Ltd., England) thus giving the hydrostatic head exerted by the foam in section A of the column. The hydrostatic head measured by the micromanometer is indicative of the effective foam density only (i.e. liquid hold-up inside the bulk foam) and liquid film on the wall does not contribute towards the hydrostatic head measured by the micromanometer. In addition to this, similar experiments have also been carried out in two other columns of diameter 32 and 75 mm in order to study the effect of column diameter on the stability of foam.

A typical experiment consisted of foam generation, drainage and subsequent foam collapse in the absence and the presence of ultrasonic vibrations. The source of ultrasonic vibrations was an ultrasonic bath operating with a frequency of 20 kHz (volume 0.03 m³). The bath has three transducers located at the bottom, arranged in a triangular fashion. Water was taken in the bath as a cavitating medium and was
filled up to maximum height (150 mm) of bath. Sound pressure intensity measurements were carried out in the bath using hydrophone and it was observed that the pressure intensity increases from bottom to top inside the bath. So the horizontal section of the column was adjusted at the location where maximum pressure intensity was detected by the hydrophone. This was necessary, as the sound pressure field in the ultrasonic bath is non-uniform and hence to study the effect of ultrasonic vibrations, a known pressure field is needed. The rate of foam collapse was also monitored by measuring the foam height visually at fixed time intervals.

**Model**

The model (Barigou M, Wiggers F N, Deshpande N S & Pandit A B, unpublished work) was developed for liquid drainage through the foam by taking the balance of frictional force versus gravitational force across the cross-section of the foam bed BC, which is briefly described below (with an assumption of the constant liquid velocity across the cross-section of the bed, this is true for the core of the foam bed neglecting the wall effects). Points B and C indicate the top and bottom levels of the foam respectively.

\[
\frac{(U_b^2 - U_c^2)}{2g\varepsilon_L^2} - \frac{H_f}{U_c} \rightarrow 0
\]

where \(U_b\) and \(U_c\) are the drainage velocities of liquid at positions B and C respectively, \(H_f\) is the height of the foam bed and is equal to the column height if there is no change in the foam height over the time period of experiment and \(\varepsilon_L\) is the liquid hold-up at any instant during the drainage study. Let level C be the datum level.

The analogy considered here for the drainage of standing foam is that of liquid flow through a packed bed. A foam bed has been treated as a packed bed of deformable particles (bubbles/cells) which may be relatively spherical where the foam is wet, or non spherical in dry foam of polyhedral texture. The liquid holdup in the foam bed would be equivalent to the voidage in the packed bed. Assuming liquid drainage rate in the bulk of the foam at point B and C is the same (i.e. \(U_b = U_c\)) one gets,

\[
U_c = \frac{(\phi_v d_b)^2 \rho g \varepsilon_L^3}{\mu (1 - \varepsilon_L)^2} \quad \ldots (2)
\]

where \(d_b\) is the particle diameter, \(\phi_v\) is the volumetric shape factor. The detail derivation of this model for the case of packed bed is already reported. The constant 150 present in the model has a semi-empirical origin based on the skin and form drag coefficient. This has been neglected here, as the static foam of variable size cells and shapes can’t be expressed in the form of such a constant. The origin of this constant (150) has been explained earlier.

Thus, the cross-sectional average liquid drainage velocity in the foam \((U_c)\), consisting of foam cells of average dimensions \(d_b\) and shape factor \(\phi_v\) at any specific liquid hold-up value \(\varepsilon_L\) is given by Eq. (2).

Now the liquid velocity \(U_c\) can also be defined as,

\[
U_c = \frac{\text{Volumetric liquid flow rate}}{\text{Cross-sectional area of the column}} = \frac{H_f d\phi_L}{dt}
\]

Since \(H_f\) is assumed to be constant over the time interval of measurement and indeed it was observed to be so, one can write \(U_c\) as

\[
U_c = \frac{d (\phi_L H_f)}{dt} \quad \ldots (3)
\]

Also, \(H_f \rho_f g = h \rho_L g\) where \(h\) is the hydrostatic head detected by the micromanometer in terms of the water column equivalent and \(\rho_f\) is the density of the foam and \(\rho_L\) is the density of water.

\[
\therefore \rho_f = \frac{h \rho_L}{H_f} \quad \ldots (4)
\]

Also \(\rho_f = \varepsilon \rho_L + \varepsilon_g \rho_g\)

Since \(\varepsilon_g \rho_g \ll \varepsilon \rho_L\) (since \(\rho_g \approx 1\text{kg/m}^3\)), therefore,

\[
\rho_f \approx \varepsilon \rho_L \quad \ldots (5)
\]

From Eq. 3, 4 and 5, \(U_c\) can also be expressed in terms of the detected hydrostatic head by the micromanometer,

\[
U_c = \frac{dh}{dt} \quad \ldots (6)
\]
Substituting Eq. (5) in Eq. (2),

\[
\frac{dh}{dt} = \frac{(\phi_v^2 d_B^2 \rho g)}{\mu} \frac{\varepsilon_L^3}{(1-\varepsilon_L)^2} \quad \ldots(7)
\]

Since \( \varepsilon_L << 1 \) in dry foam, so from Eq. (7), \( \frac{dh}{dt} \) and \( U_c \) is directly proportional to \( \varepsilon_L^3 \). The validity of the model is for the initial drainage period where the foam is wet and the liquid drainage takes place under the action of gravity only.

Results and Discussion

Estimation of liquid hold-up

Liquid hold-up was calculated by measuring the hydrostatic head of liquid inside the foam as detected by the micromanometer and with the knowledge of foam height with respect to time. The foam density \( (\rho) \) is determined from the Eq. (4) and Eq. (5) was used for the calculation of the liquid hold-up.

Verification of model

Since the model to be verified is based on the assumption of constant foam height, it is valid only for the foam produced using sintered sparger because there was a substantial change in the foam height during the drainage for the single point sparger. Thus, further discussion for the verification of model is based only on the results obtained in the case of sintered sparger. The model developed here is for liquid drainage taking place in the absence of ultrasonic vibrations and has been used to interpret enhance liquid drainage rate in the presence of ultrasonic vibrations.

Figure 2 represents the plot of hydrostatic head and liquid hold-up versus time in the absence and the presence of ultrasonic vibrations. It is observed that the liquid head and hold-up vary exponentially with time. These curves can be divided into two parts, the first (which is up to about first 100 seconds of drainage) has high slope and indicates faster drainage rate of liquid, followed by a flatter curve indicating slow and steady drainage.

To verify the model predictions, it is required to be shown that \( \frac{dh}{dt} \) is directly proportional to \( \varepsilon_L^3 \). \( \frac{dh}{dt} \) was calculated from \( h \) versus \( t \) plot by taking the slopes of the tangents at various time. At the same times \( \varepsilon_L \) was found from the plot of \( \varepsilon_L \) versus time. The exponent over \( \varepsilon_L \) was obtained by fitting a power law type of curve as shown in Fig. 3. This was done for various combinations of gas flow rates and concentrations of the surfactant solution. It was observed that in the absence of ultrasonic vibrations, the exponent over \( \varepsilon_L \) is in the range of 2.5 to 3 and in the presence of ultrasonic vibrations this exponent is in the range of 1.7 to 2. Thus, the exponent over \( \varepsilon_L \) for both the conditions (in the absence and presence of ultrasound) is different from the theoretical value of 3, though the deviation is only marginal for the case where ultrasonic vibrations are absent.

One possible reason for this difference may be due to the fact that during the period of liquid drainage from the foam, foam cell size \( (d_B) \) and volumetric shape factor \( \phi_v \) is assumed to be constant. However, visual observations indicate that as the drainage of liquid proceeds, the foam cells grow in size \( (d_B) \) increases and also become more non-spherical i.e. \( \phi_v \) decreases. The bubble shape changes from spherical to polyhedral due to the coalescence of bubbles. Thus, the value of \( (\phi_v d_B)^2 \), which is assumed to be constant for estimating the exponents over \( \varepsilon_L \), actually varies with time. The closer value of the
exponent over $\varepsilon$ to the theoretical value for drainage under natural conditions (i.e. in the absence of ultrasound) indicates a slower change in the size and shape of the bubbles in the absence of ultrasound, possibly due to slower liquid drainage.

**Estimation of parameter $(\phi, d_B)^2$**

The parameter $(\phi v d_B)^2$ indicates the shape and typical average foam size of bubbles or cells. Hence, it has been used to indicate the changes in the average shape and size of the bubble with respect to time.

Substituting Eq. (3) in (2),

$$d \varepsilon_L = \left( \phi v^2 d_B^2 \rho g \right) \varepsilon_L^3$$

$$\mu \left( 1-\varepsilon_L \right)^2$$

Since, $(\phi v^2 d_B^2 \rho g)$ is a constant for any value of $\phi v d_B$, $H_t \mu$

one can integrate Eq. (8) to get

$$t = \left( \log \varepsilon_L + \frac{2}{\varepsilon_L^2} \right) H(t) \left( \frac{\mu}{\phi v^2 d_B^2 \rho g} \right)$$

Thus, if the size and shape factor of the bubbles were known then the values of $\varepsilon_L$ can be calculated at various time intervals.

Using the experimental values of hold-up i.e. $\varepsilon_L$, the values of time were calculated using Eq. (9) for various values of $(\phi v d_B)^2$. Figs. 4a & 4b show the comparison of the experimental and the theoretical values of liquid hold-up versus time for the liquid drainage in the absence and the presence of ultrasound respectively. It was observed that the two or three theoretical curves generated from different $(\phi v d_B)^2$ values are required for fitting a single experimental curve. This indicates that the values of $\phi$, $d_B$ changes with time. The various values of $(\phi v d_B)^2$ for various combinations of concentration of surfactant solution and gas flow rates are shown in Table 1. In reality the value of $H_t$ does change by about 80-100 mm. So $(\phi v d_B)^2$ values were also calculated by putting the actual values of $H_t$ in Eq. (9) for each value of $\varepsilon_L$. However the difference in $(\phi v d_B)^2$ values due to this correction in $H_t$ was negligible. Hence, the assumption of $H_t$ being constant is valid.

In general, initially up to about first 100 s, the value of $(\phi v d_B)^2$ for the drainage in the absence and the presence of ultrasonic vibrations is in the range of 1.5 to 2.25 mm² and 1.6 to 3 mm² respectively. The value of $(\phi v d_B)^2$ for both the cases then falls down to about 1.5 to 1 mm² during the second stage of drainage. In certain cases the value of $(\phi v d_B)^2$ further falls down indicating a further change in the bubble size and shape. Thus, the higher initial values of $(\phi v d_B)^2$ for the drainage in the presence of ultrasound indicate that the initial drainage rate in the presence of ultrasonic vibrations is faster as compared to that under natural drainage conditions. The change in the value of $(\phi v d_B)^2$ apparently takes place at a limiting critical value of the liquid hold-up $(\varepsilon_{LC})$ which can be termed as the critical liquid hold-up. This critical hold-up value was found to be in the range of 0.015 to 0.025 and was independent of the condition whether the foam was ultrasonically irradiated or not.

The decrease in the value of $(\phi v d_B)^2$ after the critical liquid hold-up indicates the change in the shape i.e. $\phi$, and size i.e. $d_B$ of the bubbles. Due to the
coalescence of bubbles, the bubble size \( (d_B) \) is expected to increase with time. But as the value of the parameter \( (\phi v d_B)^2 \) decreases with time, it can be concluded that the value of \( \phi v \) must decrease. This decrease in \( \phi v \) value thus indicates the change in the shape of the foam structure from near spherical to more non-spherical i.e. polyhedral with a decrease in the liquid content of the foam bed.

Since the individual values of \( \phi v \) and \( d_B \) are not determined at this stage, the value of the parameter \( (\phi v d_B)^2 \) accounts not only for their individual values but also for the skin and form drag and the tortuous path traversed by the liquid through the column as the constant of 150 has not been used while fitting the experimental drainage rate with appropriate values of \( (\phi v d_B)^2 \). Thus, no separate constant has been incorporated in the final Eq. (8).

Validation of the model

The model proposed earlier has been verified for the liquid hold-up values that are less than or equal to about 3%. To verify if this model fits for higher liquid hold-up (wetter foam) values, the experimental data from the literature\(^7\) has been used as shown in Fig. 5. As seen from the figure, the hold-up values reported are very high, about 10 times more than reported in this work. Fig. 5 shows that the liquid drainage velocity is dependent on the liquid hold-up to the power of 2 to 2.5. This proves that the model-developed earlier can be used to explain the drainage rate of liquid inside the stationary foam column at various values of liquid hold-up. Also it has been found that a 2-fold increase in the initial liquid hold-up of the foam results in about a 4-fold increase in the initial liquid drainage velocity\(^8\). This again suggests that the liquid drainage velocity varies with the square of the liquid hold-up.

Effect of sparger

Figure 6 shows the effect of the ultrasonic vibrations on the foam collapse height for the sintered sparger. It is observed that the ultrasonic vibration enhances the foam collapse rate. As shown in Fig. 3, ultrasonic vibration enhances the initial drainage velocity causing a quicker attainment of the critical

<table>
<thead>
<tr>
<th>Drainage in the absence of ultrasonic vibrations</th>
<th>Drainage in the presence of ultrasonic vibrations</th>
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<tbody>
<tr>
<td>( Q_g ) (cm(^3)/s)</td>
<td>( (\phi v d_B)^2 )</td>
</tr>
<tr>
<td>4.86</td>
<td>1.56</td>
</tr>
<tr>
<td>8.1</td>
<td>2</td>
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<tr>
<td>9.73</td>
<td>1.56</td>
</tr>
<tr>
<td>12.16</td>
<td>2.25</td>
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<tr>
<td>( C ) (g/L)(^=1.4)</td>
<td>( C = 1.4 )</td>
</tr>
<tr>
<td>1.02</td>
<td>0.75</td>
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<tr>
<td>1.23</td>
<td>1.56</td>
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<tr>
<td>0.79</td>
<td>0.6</td>
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<tr>
<td>( C = 1.6 )</td>
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<tr>
<td>2.19</td>
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<td>2.56</td>
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<tr>
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<tr>
<td>1</td>
<td>2.56</td>
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<tr>
<td>1</td>
<td>0.66</td>
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<td>1.56</td>
<td>0.9</td>
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<tr>
<td>( C = 2.1 )</td>
<td>( C = 2.1 )</td>
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</table>
film thickness and ultimately faster foam collapse. The time required to attain the critical film thickness reduces by nearly half (about 25 s) with the use of ultrasonic vibrations. Even after attainment of critical liquid film thickness, continued irradiation of ultrasonic vibration enhances the film rupture rates as is evident from Fig. 6. The destabilization of the liquid films by the ultrasonic vibrations leads to their rupture at possibly higher critical liquid film thickness. Thus, the propagating sound wave (pressure wave) is the major source for faster foam collapse.

In the case of sparger 1 also, ultrasonic vibration enhances the foam collapse rate as shown in Fig. 7. The foam collapse begins as soon as the gas flow is stopped. Thus there is no period of constant foam height as in the case of sparger 2. This is due to the large diameter bubbles (5-15 mm) with lower liquid content and thus the bubble lamella is very thin and reaches the critical thickness earlier causing a faster foam collapse as compared with sparger 2. The rate of foam collapse is about 5 times more for the foam produced by the single point sparger as compared with that produced by the sintered sparger and this collapse rate further increases by about 8 times in the presence of ultrasonic vibrations as shown in the Figs 6 and 7.

Effect of column diameter

Considering the analogy that the drainage of liquid in a standing foam is that of liquid through a packed bed and it is an established fact that the voidage in a packed bed is highest at the wall and least at the center, resulting into a tendency for the liquid to migrate to the wall following the path of least hydraulic resistance. Therefore, the draining liquid always prefers the path having more cross sectional flow area. To confirm the hypothesis of liquid flowing preferentially to the wall following the path of least hydraulic resistance, drainage experiments were carried out in two other columns of diameters 32 and 75 mm using sintered sparger in the absence of ultrasound under the same conditions of gas flow rate and concentration of the surfactant solution. The liquid drainage velocity and collapsed foam height was then compared in these three columns under the same conditions of gas flow rate and concentration of the surfactant solution. From this study, effect of column diameter on the stability of the foam (i.e. drainage and subsequent foam collapse rate) has been investigated.

As seen from the Fig. 8, the cross sectional average liquid drainage velocity increases with a decrease in the diameter of the column. This increase in liquid drainage velocity enhances the foam collapse rate as shown in Fig. 9. This confirms the theory-developed earlier (Barigou M, Wiggers F N, Deshpande N S, & Pandit A B, unpublished work)
that the draining liquid in a foam bed first move to the wall of the column and then drains down. As the distance to be travelled by the draining liquid to reach the wall reduces with a reduction in the column diameter, the foam in smaller diameter column is likely to be less stable. It has also been found that the liquid film at column wall makes large contribution to the overall liquid drainage process in foam. Recently, it has also been shown that wall effects plays important role on the pressure drop in the packed bed. The Erguns equation has been modified taking into account wall effects, which shows dependence on Reynolds number. However, the effect of column diameter was not observed earlier on foam drainage. Due to the small difference in two-column diameter any effect on foam drainage could not be observed. The visual experiments here clearly indicated a preferential migration of the coloured dye solution towards the column wall on introduction at the center of the column, whereas addition of the dye solution near the wall showed very little or no migration towards the center.

The column cross sectional average liquid drainage velocity in the smaller diameter column is much higher than in the two larger diameter columns and thus the collapsed foam height reaches a much lower value in the smaller column than the larger columns at the end of the experimental time of 600 s. This phenomenon has significant industrial implications. For example in processes where there is a need to transport stable foam, the diameter of the pipe should be as large as economically possible. On the other hand, in processes where undesirable foaming takes place in pipelines or reactors, the foam passage could be made as small as possible, so that the foam would be highly unstable and will collapse faster. This shows that the liquid film at the column wall plays considerable role in liquid drainage in foam.

**Conclusions**

From the above studies, the following conclusions may be drawn,

(i) The analogy of liquid drainage in foams to that of liquid drainage through packed bed has been successfully applied for the wet foam. Theoretical and experimental results show that the drainage of the liquid inside the foam can be explained by the model by considering the changes in the bubble shape and size with time. This model is also applicable to explain the drainage-taking place in the presence of ultrasonic vibrations.

(ii) The value of the parameter \( \phi d_B \) changes as the drainage proceeds indicating the change in shape and size of the bubbles.

(iii) Liquid drainage velocity as well as foam collapse rate increases in the presence of ultrasonic vibrations.

(iv) Single point sparger produces highly unstable foam whose collapse rate is much higher compared to that produced by a sintered sparger as a result of larger foam cell sizes in the former, extending the application of the packed bed analogy.

(v) The diameter of the column also has an effect on the liquid drainage velocity. Smaller the diameter of the column, higher is the liquid
drainage velocity. Foams of same quality (same size and shape cells having similar liquid hold-up) are more stable in larger column diameter.

Acknowledgements

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References


Nomenclature

\[ \phi_v = \text{volumetric shape factor} \]
\[ = \frac{\text{Surface area of spherical bubble (foam cell)}}{\text{Surface area of non-spherical bubble (foam cell) of equal volume}} \]

\[ D = \text{diameter of column, (mm)} \]
\[ C = \text{concentration of surfactant solution, (g/L)} \]
\[ \frac{dh}{dt} = \text{drainage rate of liquid, (mm/s)} \]
\[ d_B = \text{bubble diameter, (mm)} \]
\[ g = \text{acceleration due to gravity, (m/s}^2) \]
\[ h = \text{hydrostatic head, (mm of H}_2\text{O)} \]
\[ H = \text{height, (mm)} \]
\[ T = \text{time, (s)} \]
\[ U_B \text{ and } U_C = \text{steady state drainage velocity of liquid at position B and C, (mm/s)} \]
\[ V = \text{liquid drainage velocity, (mm/s)} \]
\[ Q = \text{volumetric flow rate, (cm}^3\text{/s)} \]

Greek Symbols

\[ \rho = \text{density, (kg/m}^3) \]
\[ \mu = \text{viscosity of liquid, (kg/m.s)} \]
\[ \varepsilon = \text{phase hold-up} \]

Subscripts

\[ l = \text{liquid} \]
\[ f = \text{foam} \]
\[ g = \text{air} \]