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An experimental study of the wake of gas slugs rising in liquids

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A photographic study of the wakes of slugs rising in tubes of 19 mm and 52 mm internal diameter is presented. The dependence of the flow pattern in the wake upon the Reynolds number of the rising slug, R, is established for different slug lengths. Values of R covered in this study are in the range 25 to 1.3×10^4. For low values of R the flow pattern in the wake is laminar and axisymmetric and values of wake length and wake volume could be determined from the photographs; these values were correlated with the other variables in the system by means of dimensional analysis.

1. Introduction

Large gas bubbles rising in tubes of liquid have an elongated shape and they are generally known as slugs. Over the years several studies have been published about the fluid mechanics of slugs rising both in liquids and in fluidized beds. These studies have concentrated largely on the prediction of the velocity of rise and a description of the flow field around the front and side surface of the bubbles. The present study is concerned with the flow of liquid in the wake of gas slugs, i.e. the region below the bottom of the slugs. Elsewhere, Campos & Guedes de Carvalho (1988) show that this wake region is important in determining liquid mixing in such devices as air-lift reactors.

The purpose of the present study is to characterize the wake of slugs with regard to flow pattern, size of the wake and extent of exchange of liquid between the wake and the surrounding liquid.

2. Experimental technique

Two different techniques were adopted to help visualize the flow of liquid in the wake of slugs. One technique was inspired by the work of Maxworthy (1967). Two sections of transparent acrylic tube (19 mm internal diameter) were connected by a stainless steel ball valve as sketched in figure 1. The ball valve had a 19 mm bore so that it did not disturb the rising slugs, when fully open. At the bottom of the column there was an injection section. This consisted of a conical contraction superposed on a portion of larger cylindrical tube inside which a hemispherical cup could be rotated above the injection nozzle. The injection nozzle was connected to a compressed-air line by means of a solenoid valve, the opening time of which could be adjusted to allow variation of the volume of gas injected.

The liquids used were water, glycerol, and mixtures of the two in different proportions, covering a wide range of viscosities (10^{-3} to 10^{-1} N s m^{-2}). In any one

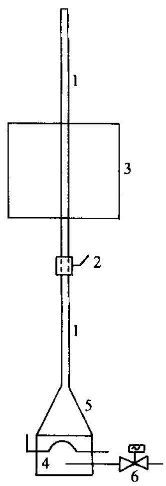


FIGURE 1. Experimental set-up; 19 mm i.d. column (1, acrylic column; 2, ball valve; 3, acrylic box; 4, hemispherical cup; 5, conical contraction; 6, solenoid valve).

experiment a sufficient volume of liquid was taken and divided into two portions. A small amount of Rouge Solophenyle 6BL powder (a strong red dye) was added to one of the portions and the bottles containing the coloured and colourless liquids were placed in a constant-temperature bath for temperature equalization. Following this, the red liquid was poured down the tube until its free surface came above the ball valve; the valve was then closed, the liquid above it was removed, and the upper section of the column was cleaned before filling it with colourless liquid to some level. The ball valve was again opened fully and a volume of gas was injected through the nozzle below the downward-facing cup. Rotation of the cup liberated the gas bubble which rose through the coloured liquid into the colourless liquid and a photograph was taken as it passed the section surrounded by an acrylic box filled with water to minimize distortion due to the curved wall of the column. The opening time of the shutter in the still camera was adjusted to 1/500 s and the pictures were taken against an illuminated white background. This gave black-and-white pictures of good contrast, as shown in figure 4. Vertical and horizontal line segments marked on the walls of the parallel-sided acrylic box made it possible to scale down the prints. Analysis of the prints gave wake length l, wake volume v, slug length L, and slug volume V. The latter was always compared with the volume of gas injected (corrected for hydrostatic pressure) as a check, and the accuracy was always high ($\pm 5\%$). The results obtained are discussed in §4.

The other visualization technique adopted was inspired by the work of Filla, Donsi & Crescitelli (1979) and Coutanceau & Thizon (1981) among others. A transparent acrylic column of 52 mm internal diameter was placed inside a parallel-sided acrylic box filled with water to minimize distortion. The gas bubbles were introduced at the bottom of the column by means of a manually operated ball valve and the pictures were taken by a camera which travelled vertically upwards at the same velocity as the slugs. Spotlights on opposite sides of the column illuminated a section of the liquid in the column about a vertical plane containing the axis. Exposure times of 1/15 s and 1/30 s gave a good record of the flow field as seen by an observer moving with the slugs, as shown in figure 5. Small air bubbles were used to trace the

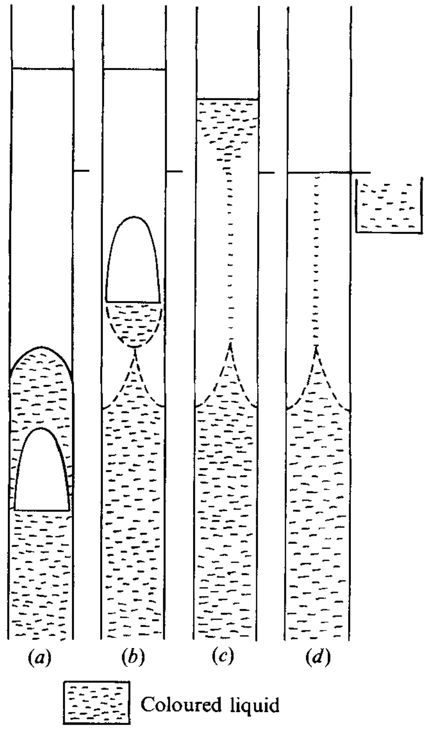


FIGURE 2. Schematic representation of four successive 'shots' during an experiment on tracer entrainment.

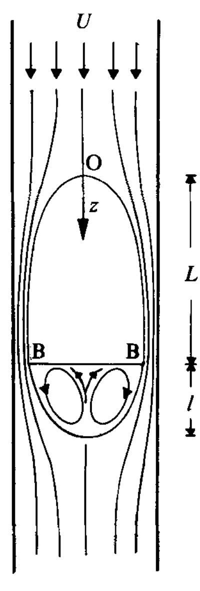


FIGURE 3. Flow pattern around a slug.

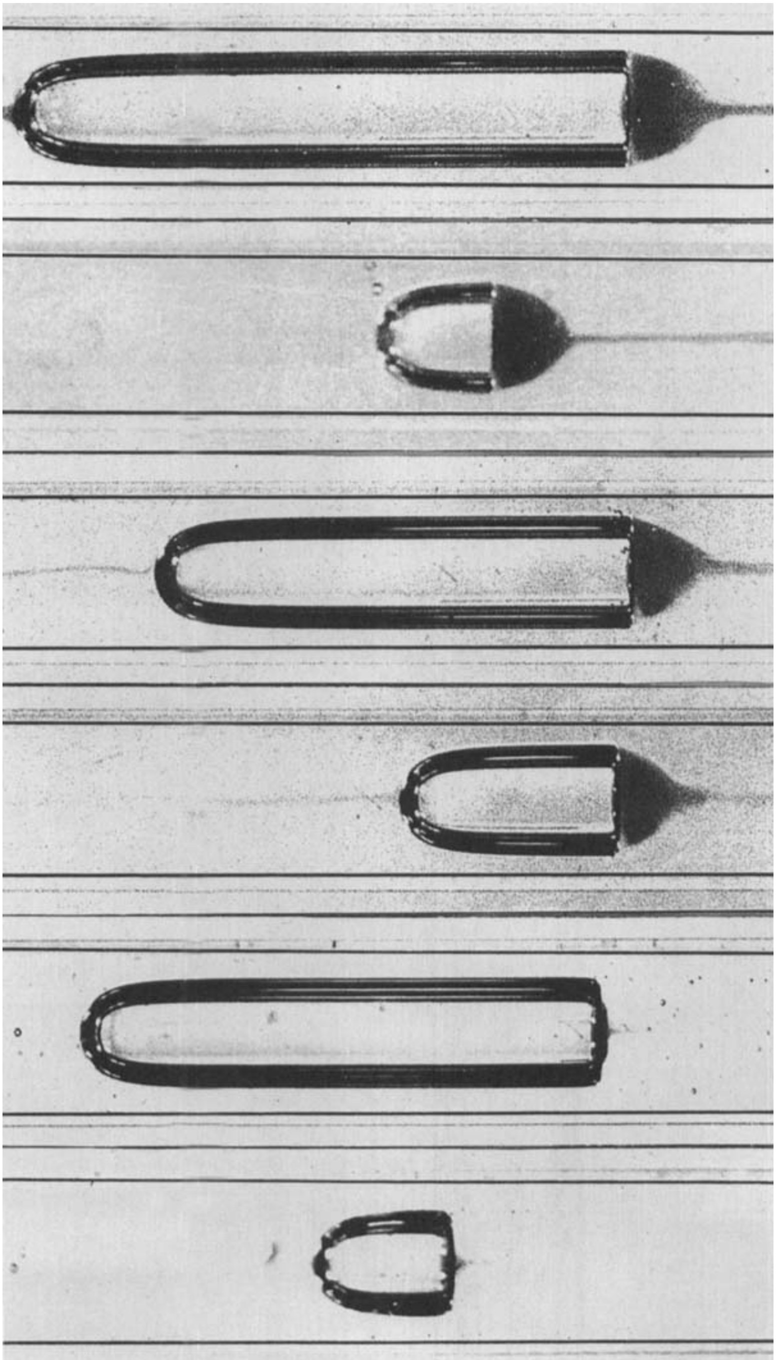
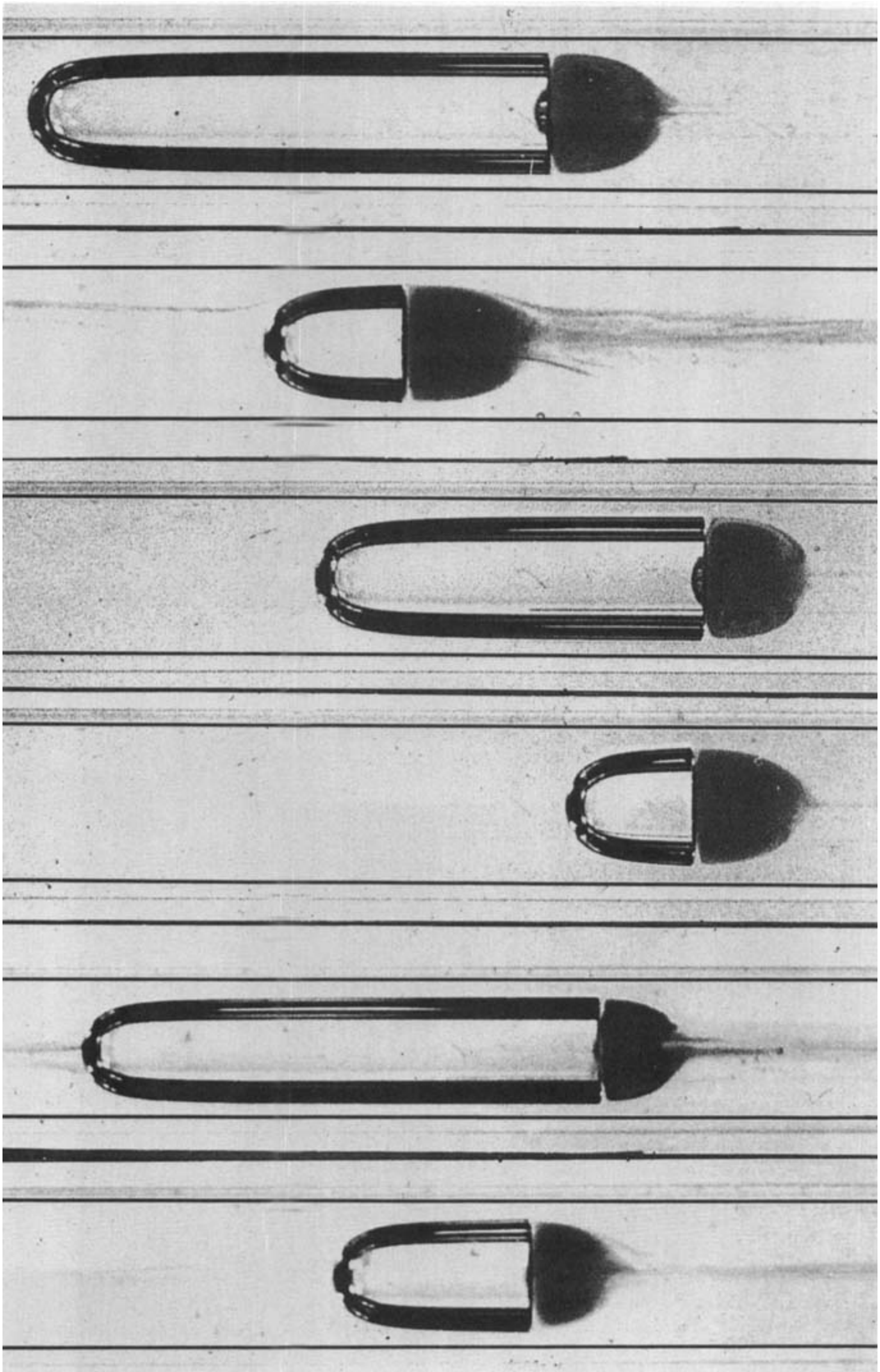


FIGURE 4. For caption see facing page.



$(gD^3)^{\frac{1}{2}}/\nu$ =	325	325	437	437	483	483
R =	114	114	153	153	170	170
L (mm) =	26	69	18	51	18	68
v (cm^3) =	1.30	1.61	1.90	2.17	2.18	2.38

FIGURE 4. Pictures with still camera; slugs in 19 mm i.d. column.

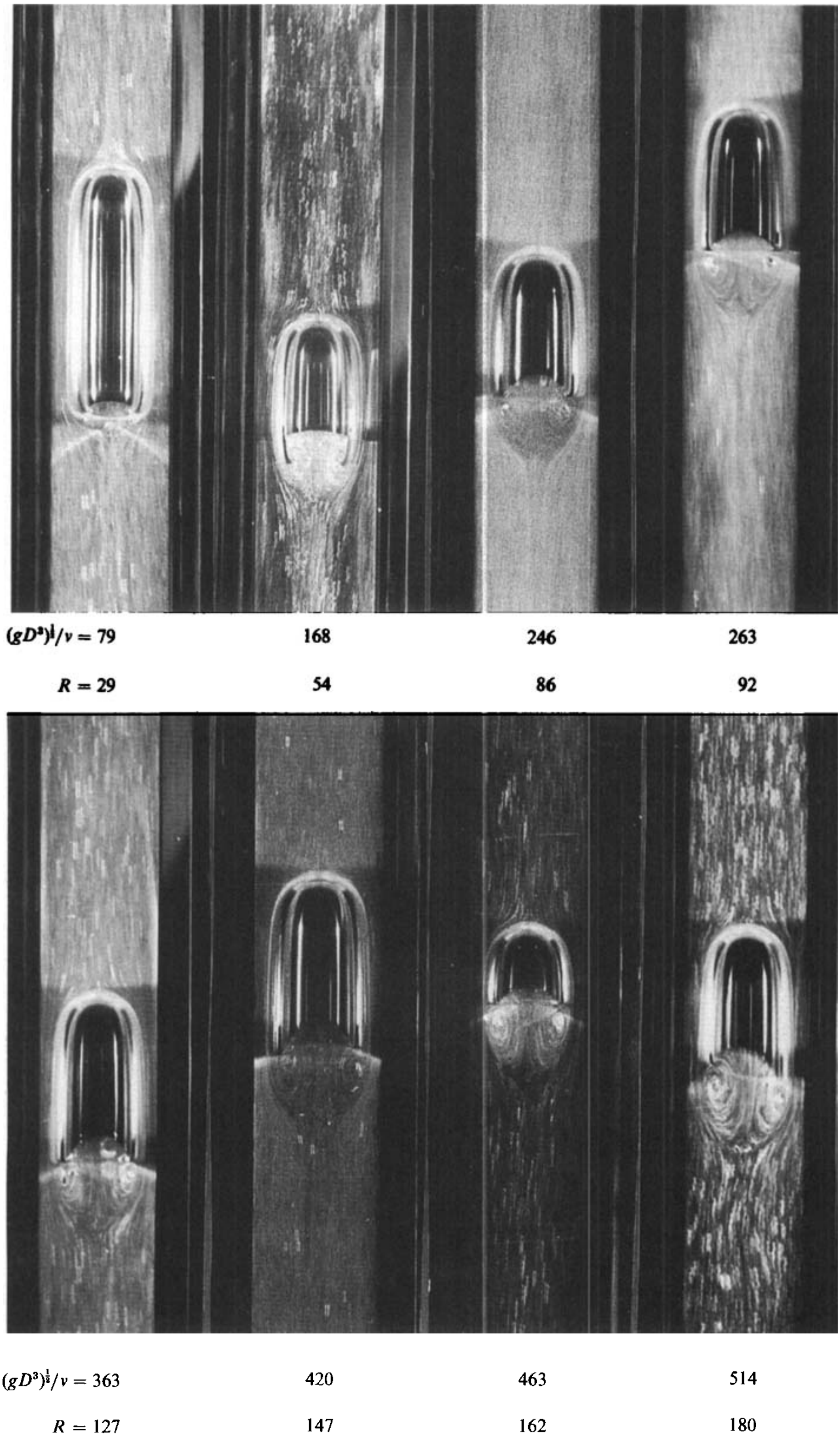


FIGURE 5. For caption see facing page.

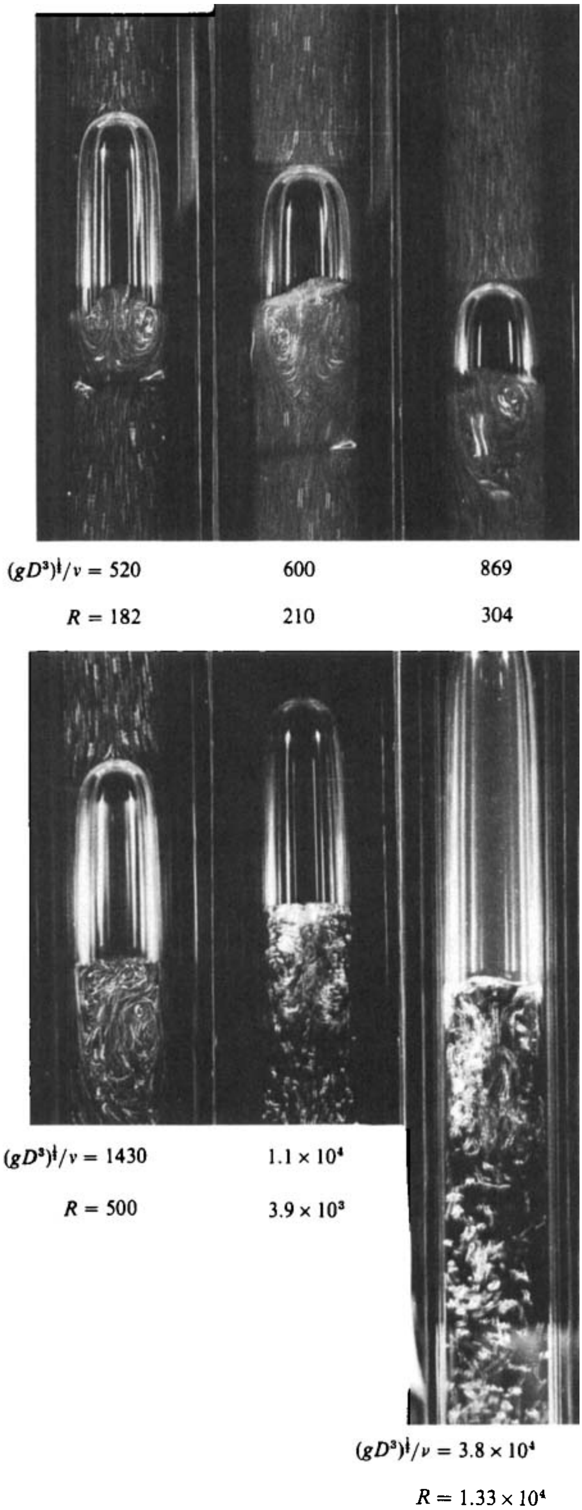


FIGURE 5. Pictures with moving camera; slugs in 52 mm i.d. column.

movement of the liquid. The values of either l or v measured with this technique are not very accurate but a good view of the flow field is obtained.

The installation sketched in figure 1 was also used to determine the amount of liquid exchanged between the slug wake and the surroundings as the slug rose through a 1 m length of clear liquid. As for the flow visualization experiments, the column was filled up to the ball valve with liquid containing tracer (the corresponding concentration, C, was determined by spectrophotometry). A volume of air was retained in the injection section and clear liquid was poured to a height of 1 m above the ball valve. After rotating this valve open, the air bubble was liberated and rose through the column as a slug. Figure 2 sketches events at successive instants thereafter, culminating in the withdrawal of a sample of liquid of volume Q' near the top. The volume Q' was sufficiently large to contain virtually all the tracer in the wake deposited near the free surface. The concentration of tracer in this sample, C', was measured by spectrophotometry and the equivalent volume $Q = (V'C')/C$ was determined. Q is the volume of solution with concentration C that would contain the same amount of tracer as was in the wake when the slug reached the free surface, and it depends both on the actual wake volume and on the amount of tracer that leaks out of the wake as it rises through the clear liquid.

3. Theory

The flow pattern around a slug rising at velocity U in a vertical column of liquid with internal diameter D is sketched in figure 3, relative to a frame of reference moving with the slug.

Knowledge of the rise velocity is important and White & Beardmore (1962) used dimensional analysis to show that $U/(gD)^{\frac{1}{2}}$ is a function of $(gd^3)^{\frac{1}{2}}/\nu$ and $\rho D^2 g/\sigma$, where g is the acceleration due to gravity and ρ, ν and σ are the liquid density, kinematic viscosity and surface tension, respectively. The dependence of velocity on surface tension may be neglected except for small-bore tubes, and if $(gD^3)^{\frac{1}{2}}/\nu > 250$ it is observed that $U/(gD)^{\frac{1}{2}} = 0.35$, in agreement with the work of Dumitrescu (1943) and Davies & Taylor (1950); under those conditions $(gD^3)^{\frac{1}{2}}/\nu = UD/(0.35\nu)$ and this is proportional to the Reynolds number $R = UD/\nu$.

It is important to consider the flow of liquid in the annular region between the tube wall and the slug surface (represented by BOB in figure 3) as described by Nicklin, Wilkes & Davidson (1962) and Batchelor (1967). For low values of z the effect of viscosity on the flow may be ignored except for a thin boundary layer adjacent to the tube wall. Application of Bernoulli's equation along the free streamline (OB) gives a good estimate of the liquid velocity as $(2gz)^{\frac{1}{2}}$. For large enough values of z the boundary layer adjoining the tube wall will have grown to occupy all the annulus of liquid and the viscous force on an element there balances the gravitational force. The velocity profile and the thickness d of the liquid layer will become independent of z and, if $d \ll D$, the approximation of unidirectional flow in a liquid layer with a free surface on a vertical plate is acceptable; the velocity along the free streamline will be given by $u = U + gd^2/(2\nu)$, relative to the slug.

An estimate of the value of z, say $z \approx Z$, for which the boundary layer near the wall reaches the free streamline may be obtained by setting $(2gZ)^{\frac{1}{2}} = U + gd^2/(2\nu)$ to yield

$$Z \approx \frac{[gd^2/(2\nu) + U]^2}{2g}.$$

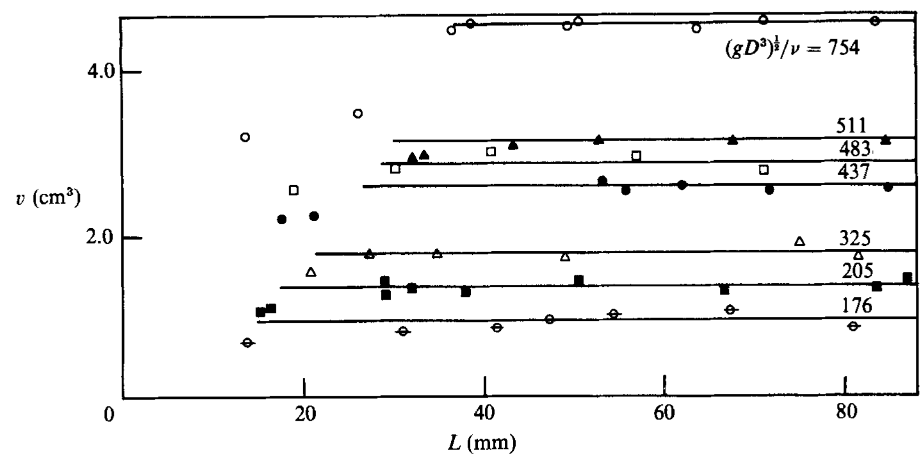


FIGURE 6. Dependence of wake volume on slug length for 19 mm i.d. column.

The importance of the wake of slugs is referred to by Clift, Grace & Sollazo (1974) and Duckler, Maron & Brauner (1985) among others, but no systematic study of that region is known to the present authors. The flow pattern in the wake of a gas slug rising in a tube is likely to depend on the diameter of the tube D, the properties ρ, ν and σ of the liquid, the length of the slug L, and the value of g. Dimensionless analysis may be used to show that the flow pattern and therefore the dimensionless wake volume v/D^3, and the dimensionless wake length l/D^3, depend on L/D, $(gD^3)^{\frac{1}{2}}/\nu$ and $\rho D^2 g/\nu$; dependence on the latter group is likely to be negligible except for small-bore tubes. The flow pattern in the wake is expected to be independent of L for slugs with L greater than the value of Z given by the expression derived above. This is because the velocity profile in the annular region surrounding the slug near its base will be insensitive to slug length for such long slugs, and it is that velocity profile which determines the flow pattern in the wake.

4. Experimental results

The photographs in figure 4 show the shape of the slug wakes in the 19 mm i.d. column, for a range of values of R and different slug lengths. The flow patterns are better elucidated by the photographs in figure 5, showing slugs in the 52 mm i.d. column. It may be seen that for $R < 180$ the wakes are axisymmetric while in the range $180 < R < 304$ the vortex ring in the wake starts to oscillate. At higher values of R flow in the wake is best described as turbulent, but the recirculatory motion is still obvious.

The dependence of wake volume on slug length which exists before the onset of this transition in the flow pattern is shown in figure 6, for the 19 mm i.d. column. The existence of a limiting value for v corresponding to long slugs is well brought out; for each value of $(gD^3)^{\frac{1}{2}}/\nu$, the horizontal line indicates the range of values of L satisfying the condition $L > Z$, with Z predicted as indicated in §3. If the limiting values of wake length and wake volume are denoted by l^* and v^*, respectively, it is expected that l^*/D and v^*/D^3 depend only on $(gD^3)^{\frac{1}{2}}/\nu$, except for small-bore tubes. The plots on figure 7 give the experimental data, which should be valid for other tube diameters as well (no data from the 52 mm i.d. column were used in the plot of

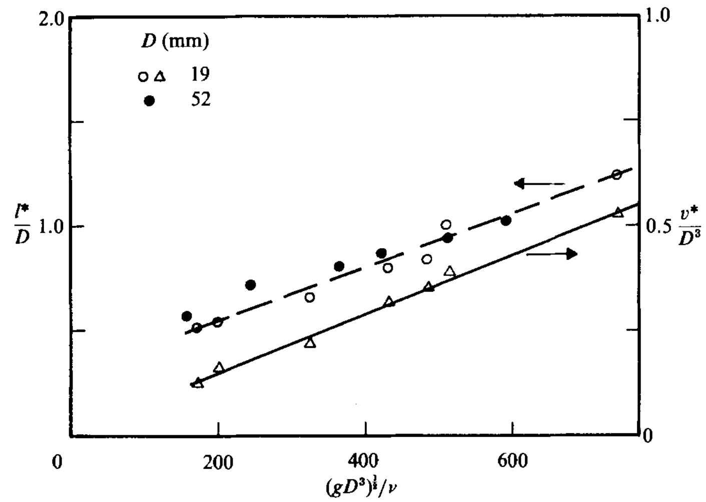


FIGURE 7. Dependence of dimensionless limiting wake length and wake volume on $(gD^3)^{\frac{1}{2}}/\nu$: ---, $l^*/D = 0.30 + 1.22 \times 10^{-3}(gD^3)^{\frac{1}{2}}/\nu$; ——, $v^*/D^3 = 7.5 \times 10^{-4} \times (gD^3)^{\frac{1}{2}}/\nu$.

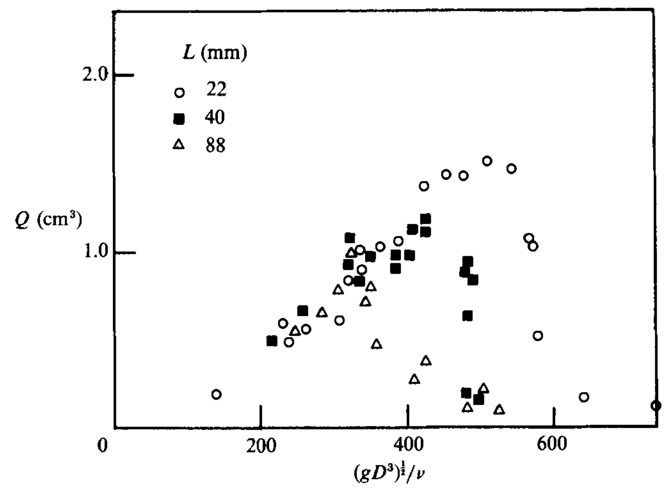


FIGURE 8. Dependence of tracer entrainment on $(gD^3)^{\frac{1}{2}}/\nu$ for 19 mm i.d. column.

v^*/D^3 because of lack of accuracy). The experimental data plotted suggest a linear variation of l^*/D and v^*/D^3 with $(gD^3)^{\frac{1}{2}}/\nu$ and best-fit straight lines were determined by a least-squares technique.

Further evidence of the transition in flow pattern in the wake may be gathered from figure 8; in this figure a plot is shown of the amount of tracer carried by one wake rising up a 1 m height of clear liquid, as a function of $(gD^3)^{\frac{1}{2}}/\nu$, for three values of slug length. For the lower range of values of $(gD^3)^{\frac{1}{2}}/\nu$ flow is laminar in the 'closed' wake and Q increases with $(gD^3)^{\frac{1}{2}}/\nu$ as a result of the increase in wake volume shown by figure 6. Further increases in the value of $(gD^3)^{\frac{1}{2}}/\nu$ lead eventually to a sudden drop in the value of Q, as the wake starts to 'leak', and this is probably associated with the transition in the flow pattern. The three sets of points in figure 8 show that slug length is important in determining the value of $(gD^3)^{\frac{1}{2}}/\nu$ at which transition in the flow pattern starts to take place. This dependence of flow pattern on slug length will not be observed for long slugs, as explained in §3. The longer slugs used to obtain the data in figure 8 satisfied the criterion $L > Z$ and therefore the points marked by the open triangles on that figure should be typical of long slugs.

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