

Rise Velocity of a Spherical Cap Bubble

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The theory of viscous potential flow is applied to the problem of finding the rise velocity U of a spherical cap bubble (see Davies and Taylor 1950, Batchelor 1967). The rise velocity is given by

$$\frac{U}{\sqrt{gD}} = -\frac{8}{3} \frac{\nu(1+8s)}{\sqrt{gD^3}} + \frac{\sqrt{2}}{3} \left[1 - 2s - \frac{16s\sigma}{\rho g D^2} + \frac{32\nu^2}{gD^3} (1+8s)^2 \right]^{1/2},$$

where $R = D/2$ is the radius of the cap, ρ and ν are the density and kinematic viscosity of the liquid, σ is surface tension, $r(\theta) = R(1 + s\theta^2)$ and $s = r''(0)/D$ is the deviation of the free surface from perfect sphericity $r(\theta) = R$ near the stagnation point $\theta = 0$. The bubble nose is more pointed when $s < 0$ and blunted when $s > 0$. A more pointed bubble increases the rise velocity; the blunter bubble rises slower.

The Davies and Taylor (1950) result arises when s and ν vanish; if s alone is zero,

$$\frac{U}{\sqrt{gD}} = -\frac{8}{3} \frac{\nu}{\sqrt{gD^3}} + \frac{\sqrt{2}}{3} \left[1 + \frac{32\nu^2}{gD^3} \right]^{1/2},$$

showing that viscosity slows the rise velocity. This equation gives rise to a hyperbolic drag law

$$C_D = 6 + 32/R_e,$$

which agrees with data on the rise velocity of spherical cap bubbles given by Bhaga and Weber (1981).

1. Analysis

Potential flow is a solution of the Navier-Stokes equations; it satisfies all of the usual equations for inviscid potential flow, like Bernoulli's equation, the Cauchy-Lagrange equation, etc, except the viscous stresses do not in general vanish. Viscous potential flows give rise to excellent physical results for flows with interfaces; for such flows the viscosity enters the analysis explicitly through the normal stress balance. The Rayleigh-Plesset bubble is an exact viscous potential flow analysis of the Navier-Stokes equations; this solution works perfectly for all viscous liquids; it is not an asymptotic result. Viscous potential flow analysis of problems for Rayleigh-Taylor instability (Joseph, Belanger and Beavers 1999, Joseph, Beavers and Funada 2002) for capillary instability (Funada and Joseph 2001) and Kelvin-Helmholtz instability (Funada and Joseph 2002) give rise to solutions dependent strongly on viscosity and closely approximate solutions of the problem in which potential flow is not assumed. Viscous potential flow has zero vorticity and it will certainly fail when vorticity is important.

The spherical cap bubble (figure 1) arises in the motion of large gas bubbles which

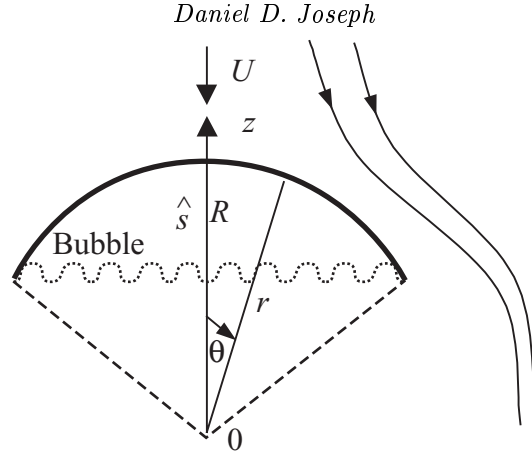


FIGURE 1. Spherical cap bubble. The rising bubble is viewed in a frame in which the bubble is stationary. The origin of z increasing is at the stagnation point \hat{s} . The surface of the cap is given by $z = -h(r, \theta) = -(R - r(\theta)\cos\theta)$. The cap is strictly spherical if $r(\theta) = R$ is constant.

take a lenticular shape. The analysis of the rise velocity of these bubbles which was given by Davies and Taylor (1950) is unusual since it is not computed from a balance of the drag and buoyant weight as it is for spherical gas bubbles (Levich 1949, Moore 1959 and 1963, Taylor and Acrivos 1964, Miksis, Vanden-Broeck and Keller 1982 and Ryskin and Leal 1984). Batchelor (1967) notes that “The remarkable feature of (the Davies-Taylor analysis) is that the speed of movement of the bubble is derived in terms of the bubble shape without any need for consideration of the mechanism of the retarding force which balances the effect of the buoyancy force on a bubble in steady motion.”

In the analysis which follows, I extend the analysis of Davies and Taylor which is based on inviscid potential flow to viscous potential flow and I show that surface tension enters the formula for the rise velocity only when the axisymmetric bubble is not spherical.

The velocity field on the gas bubble and the liquid is derived from a potential $\mathbf{u} = \nabla\phi$, $\nabla^2 = 0$. The velocity at $z = \infty$ is $-U$ (against z) and $\mathbf{g} = -\mathbf{e}_z g$. For steady flow

$$\rho\mathbf{u} \cdot \nabla\mathbf{u} = -\nabla p - \rho\mathbf{e}_z g = -\nabla\Gamma \quad (1.1)$$

where

$$\Gamma = p + \rho g z.$$

Equation (1.1) may be integrated, since $\mathbf{u} \cdot \nabla\mathbf{u} = \nabla|\mathbf{u}|^2/2$, giving rise to a Bernoulli function in the liquid

$$\frac{\rho|\mathbf{u}|^2}{2} + \Gamma = \frac{\rho U^2}{2}, \quad (1.2)$$

and in the gas

$$\frac{\rho_G|\mathbf{u}|^2}{2} + \Gamma_G = C_G, \quad (1.3)$$

where C_G is an unknown constant.

We turn next to the normal stress balance

$$-[[p]] + 2[[\mu\mathbf{n} \cdot \mathbf{D}[\mathbf{u}]]] \cdot \mathbf{n} + \frac{2\sigma}{r(\theta)} = 0, \quad (1.4)$$

where

$$[[\cdot]] = (\cdot)_G - (\cdot)_L,$$

is evaluated on the free surface $r(\theta) = R(1 + s\theta^2)$, σ is surface tension, μ is viscosity and

$$\mathbf{n} \cdot \mathbf{D}[\mathbf{u}] \cdot \mathbf{n} = \frac{\partial u_n}{\partial n} \quad (1.5)$$

is the normal component of the rate of strain. Using (1.1), (1.4) and (1.5) we get

$$-[[\Gamma]] - [[\rho]]gh + 2\left[[\mu \frac{\partial u_n}{\partial n}]\right] + \frac{2\sigma}{r} = 0 \quad (1.6)$$

where $-h$ is the value of z on the free surface.

Following Davies and Taylor (1950), we assume that \mathbf{u} may be approximated near the stagnation point on the bubble which is nearly spherical by the potential for the sphere; thus

$$\phi = -Ur \cos \theta \left(1 + \frac{R^3}{2r^3}\right) \quad (1.7)$$

for the liquid. The form of ϕ in the gas will not be needed. From (1.7) we compute

$$u_r = \frac{\partial \phi}{\partial r} = -U \left(1 - \frac{R^3}{r^3}\right) \cos \theta, \quad (1.8)$$

$$u_\theta = \frac{1}{r} \frac{\partial \phi}{\partial \theta} = U \sin \theta \left(1 + \frac{R^3}{2r^3}\right), \quad (1.9)$$

$$\frac{\partial u_n}{\partial n} = \frac{\partial u_r}{\partial r} = -\frac{3UR^3}{r^4} \cos \theta. \quad (1.10)$$

The functions (1.8), (1.9) and (1.10) enter into the normal stress balance at $r = R(1 + s\theta^2)$. This balance is to be satisfied near the stagnation point, for small θ , neglecting terms that go to zero faster than θ^2 . At the free surface,

$$u_r = -U \left\{1 - \frac{1}{(1 - s\theta^2)^3}\right\} = -3Us\theta^2, \quad u_\theta = \frac{3}{2}U\theta, \\ \frac{\partial u_n}{\partial n} = -\frac{3U \left(1 - \frac{\theta^2}{2}\right)}{R(1 + s\theta^2)^4} = -\frac{3U}{R} \left\{1 - \left(4s + \frac{1}{2}\right)\theta^2\right\}, \quad (1.11)$$

$$u_r^2 = 0, \quad (1.12)$$

$$u_\theta^2 = \frac{9}{4}U^2\theta^2, \quad (1.13)$$

$$h = R - r \cos \theta = R - R(1 + s\theta^2) \left(1 - \frac{\theta^2}{2}\right) = R \left(\frac{1}{2} - s\right)\theta^2. \quad (1.14)$$

The motion of the gas in the bubble is not known but it enters into (1.6) as the coefficient of ρ_G and μ_G which are small relative to the corresponding liquid terms. Evaluating (1.2) and (1.3) on the free surface, with gas motion zero, we get

$$\Gamma = -\frac{9}{8}\rho U^2\theta^2 + \rho \frac{U^2}{2}, \quad (1.15)$$

$$\Gamma_G = C_G. \quad (1.16)$$

Using (1.11) through (1.16), we may rewrite (1.6) as

$$\begin{aligned} 0 &= -C_G + \Gamma + \rho gh - 2\mu \frac{\partial u_r}{\partial r} + \frac{2\sigma}{r} \\ &= -C_G + \frac{\rho U^2}{2} - \frac{9}{8} \rho U^2 \theta^2 + \rho g R \left(\frac{1}{2} - s \right) \theta^2 + \\ &\quad \frac{6\mu U}{R} \left\{ 1 - \left(4s + \frac{1}{2} \right) \theta^2 \right\} + \frac{2\sigma}{R} (1 - s\theta^2). \end{aligned} \quad (1.17)$$

The constant terms vanish

$$C_G = \frac{\rho U^2}{2} + \frac{6\mu U}{R} + \frac{2\sigma}{R}. \quad (1.18)$$

The coefficient of θ^2 also vanishes

$$\frac{9}{8} \rho U^2 + \frac{3\mu U}{R} + \frac{24\mu U s}{R} = \rho g \frac{R}{2} - s \left(\rho g R + \frac{2\sigma}{R} \right). \quad (1.19)$$

Surface tension, which balances the static pressure difference in a sphere or spherical cap, enters the formula for the velocity only when the axisymmetric cap is not spherical. When the spherical cap is perfectly spherical, as in the case treated by Davies and Taylor (1950), $s = 0$ and

$$U = -\frac{4}{3} \frac{\nu}{R} + \sqrt{\frac{4}{9} g R + \frac{16}{9} \frac{\nu^2}{R^2}}. \quad (1.20)$$

Equation (1.20) shows the viscosity slows the rise velocity; when the viscosity is much larger than gravity

$$U = \frac{1}{6} \frac{g R^2}{\nu}. \quad (1.21)$$

which is the velocity of a rising sphere computed by Moore (1959) from viscous potential flow balancing the drag with the buoyant weight.

The general solution of (1.19) with $D = 2R$ is

$$\frac{U}{\sqrt{gD}} = -\frac{8}{3} \frac{\nu(1+8s)}{\sqrt{gD^3}} + \frac{\sqrt{2}}{3} \left[1 - 2s - \frac{16s\sigma}{\rho g D^2} + \frac{32\nu^2}{gD^3} (1+8s)^2 \right]^{1/2}. \quad (1.22)$$

It is convenient to write (1.22) in a dimensionless form

$$\text{Fr} = -\frac{8(1+8s)}{3\Re_G} + \frac{\sqrt{2}}{3} \left[1 - 2s - \frac{16s}{E\ddot{o}} + \frac{32}{\Re_G^2} (1+8s)^2 \right]^{1/2}, \quad (1.23)$$

where

$$\begin{aligned} \text{Fr} &= \frac{U}{\sqrt{gD}} && \text{Froude number,} \\ \Re_G &= \frac{\sqrt{gD^3}}{\nu} && \text{Gravity Reynolds number,} \\ E\ddot{o} &= \frac{\rho g D^2}{\sigma} && \text{Eötvös number.} \end{aligned}$$

These three parameters are the ones and the only ones that enter into correlations for the

rise velocity of long bubbles in round pipes (Wallis 1969, Vania, Pardo, Yáñez, Trallero and Joseph 2002).

It is of interest to consider different effects entering into the formula for the rise velocity U given by (1.22). The Davies and Taylor formula

$$U = \frac{\sqrt{2}}{3} \sqrt{gD} \quad (1.24)$$

arises from (1.22) when $\nu = \sigma = s = 0$. Recall that $s = r''(0)/D$ represents the difference between the deformed spherical cap. When $s = 0$ the spherical cap is exactly spherical; when $s < 0$ the nose of the cap is more pointed than the spherical cap and when $s > 0$ the nose is blunter than a sphere. The Davies-Taylor formula (1.24) arises from (1.22) in the asymptotic limit for large values of \mathfrak{R} and $E\ddot{o}$

$$U = \frac{\sqrt{2}}{3} (1 - 2s) \sqrt{gD} \quad (1.25)$$

holds only when $s = 0$.

Unfortunately the analysis does not give the value s ; the shape of the nose is given when U is known, or if s is known then U is predicted. A more satisfying result would need to relax the assumption that the velocity potential (1.7) does not change when the spherical cap is not exactly spherical. This kind of perturbation analysis requires global data and is well beyond what can presently be obtained by analysis.

2. Experiments

A review of experiments on the rise of spherical cap bubbles prior to 1973 together with an excellent collection of photographs can be found in the paper by Wegener and Parlange (1973). Reviews treating rising bubbles of all types were presented by Harper (1972) and Bhaga and Webber (1981).

The comparison of the prediction (1.23) of the rise velocity of a spherical cap bubble rising from the application of viscous potential flow is unambiguous when the deviation s from sphericity vanishes. There are two cases in which $s = 0$; according to the analysis of Davies and Taylor (1950), the spherical cap which arises for large bubbles is one case. The other case includes the rise of small bubbles, or bubbles with large surface tension, which was considered by Levich (1949) and Moore (1959) and Moore (1963). In the first the sphericity arises from dynamics alone and the effects of surface tension on the spherical cap is negligible. In the case of small bubbles, or bubbles moving very slowly, surface tension can be important in keeping the bubble spherical, but the effect then of surface tension is absorbed totally by the pressure drop $[[p]] = 2\sigma/R$, as in (1.18), and does not enter the dynamics. The effects of surface tension on the rise velocity are associated with the deviation from sphericity; it is a shape effect since the net force and moment on a smooth bubble due to surface forces are zero Hesla, Huang and Joseph (1993).

An efficient description of the effects entering into the deformation and rise velocity of gas bubbles in stagnant liquids can be carried out in terms of dimensionless parameters. The formula (1.23) expresses a functional relation between three parameters, the Froude number, the gravity Reynolds number \mathfrak{R}_G and the Eötvös number $E\ddot{o}$; these three parameters completely describe the rise velocity of Taylor bubbles, which are long gas bubbles capped by a spherical cap rising in tubes filled with stagnant liquid which were discussed in the Davies-Taylor paper. Vania, Pardo, Yáñez, Trallero and Joseph (2002) correlated all the published data, 262 experiments, on the rise velocity, Fr of Taylor bub-

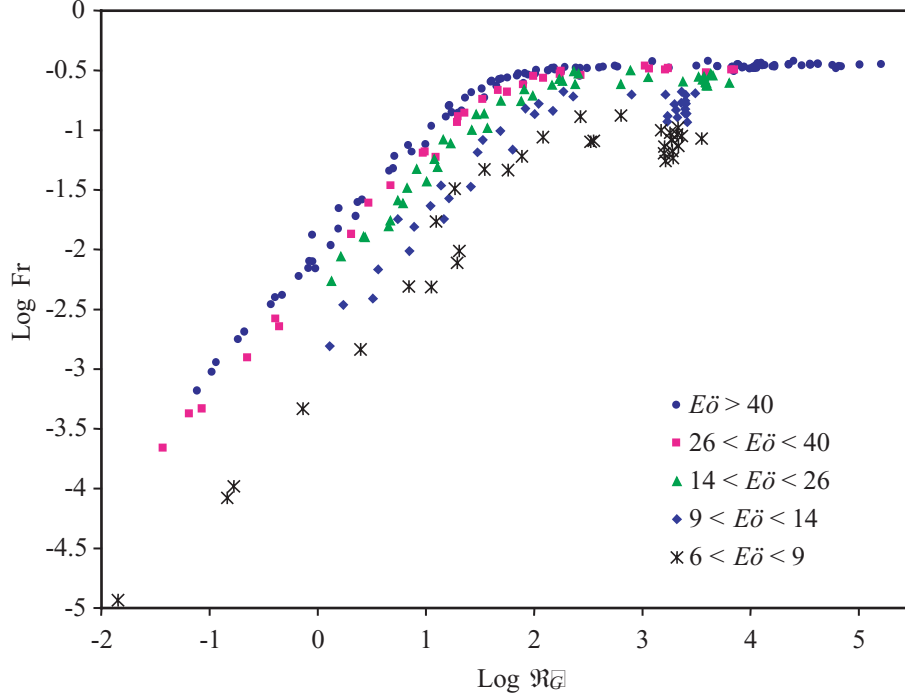


FIGURE 2. (After Vania, Pardo, Yáñez, Trallero and Joseph (2002)). Rise velocity Fr vs. \Re_G for different Eötvös numbers for all published experiments on the rise velocity of Taylor bubbles in round pipes. The rise velocity is independent of $E\ddot{o}$ when $E\ddot{o} > 40$.

bles in round pipes with a highly accurate rational fraction of power of the parameters \Re_G and $E\ddot{o}$; a graph of the data processed by them is shown in figure 2.

Other parameters are frequently used for the description of the rise velocity; these are

$$\begin{aligned}
 C_D &= \frac{4}{3} \frac{gd}{U^2} && \text{Drag coefficient,} \\
 R_e &= \frac{U d_e}{\nu} && \text{Reynolds number,} \\
 W &= \frac{\rho U^2 d_e}{\sigma} && \text{Weber number,} \\
 M &= \frac{g \mu^4}{\rho \sigma^3} && \text{Morton number.}
 \end{aligned} \tag{2.1}$$

The choice of effective diameter is important; two choices are made here: $d_e = D$ where d is the sphere diameter or the diameter of the spherical cap, $d_e = \bar{d}$ where \bar{d} is volume equivalent diameter defined by $V = \frac{\pi}{6} \bar{d}^3$, and Reynolds numbers by $R_e = \frac{U D}{\nu}$, $\bar{R}_e = \frac{U \bar{d}}{\nu}$ based on D and \bar{d} . Any pair of independent dimensionless parameters determine all the others in steady flow; as in (1.23), a dimensionless parameter involving U may be expressed in terms of two other independent parameters.

It is convenient to compare the theory developed here with experiments in which the surface tension, or parameters in which the surface tension is a factor, affect the rise velocity and those for which these parameters are not important; for example, according to figure 2, Fr is a function of \Re_G alone when $E\ddot{o} > 40$.

In the case of a spherical cap bubble, limitations on the bubble size arise from several

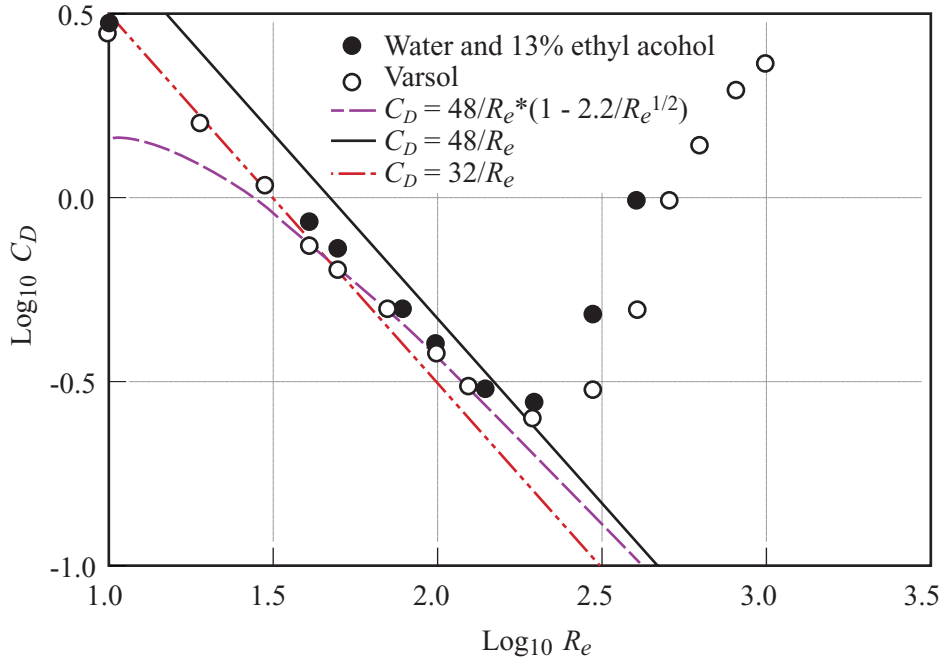


FIGURE 3. (After Batchelor (1967)). The drag coefficient of gas bubbles rising through liquids. The points for two particular liquids are taken from experimental curves given by Haberman and Morton (1953). The line $C_D = 32/R_e$ was added by me. The formulas use effective diameters $d_e = D$ where $R = D/2$ is the radius of the sphere.

sources and restrict the values of the parameters which may be observed. Grace, Wairegi and Brophy (1978) reported the maximum volume of air in bubbles that remain intact in five different liquids in a wide tank but did not identify which of the five were spherical cap. Batchelor (1987) looked at this data in terms of a stability theory which limits the maximum size bubbles. A numerical study by Bolton-Stone, Robinson and Blake (1995) suggests that spherical cap bubbles arise only when the Eötvös number based on an equivalent spherical radius is less than about 32. For higher values of $E\ddot{o}$ an unstable toroidal bubble is formed before breakup.

Figure 3 was presented in Batchelor's (1967) book. He compared experiments with drag laws $C_D = 48/R_e$ computed by Levich (1949) using the dissipation approximation and Moore's (1959) $C_D = (48/R_e)(1 - 2.2/R_e^{1/2})$ correction of this law. Moore tried to correct the pressure jump across the spherical bubble surface for effects of a vorticity boundary layer. Kang and Leal (1987) showed that Moore's result is incomplete because it does not include displacement thickness effects; they got $48/R$ at leading order using a general relationship between the viscous pressure correction and the vorticity distribution for a spherical bubble in an arbitrary axisymmetric flow. The values of C_D given by Stoke's flow, viscous potential flow and the dissipation are $16/R_e$, $32/R_e$ and $48/R_e$, respectively.

It seems to me that the experiments in figure 3 are not convincing evidence for any of the three drag laws just mentioned. The deviation from a linear law, say $32/R_e$ rather than $48/R_e$, might be interpreted in terms of changes in drag due to bubble deformation rather than any effect of vorticity on the pressure jump. This interpretation is consistent with the experiments and with the analysis of Taylor and Acrivos (1964) and Ryskin and Leal (1984), who showed that bubbles resembling spherical caps arise when the Weber

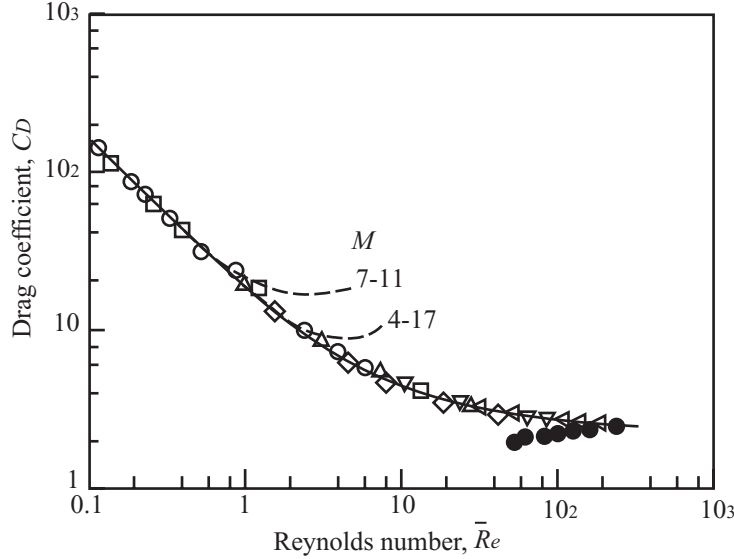


FIGURE 4. (After figure 7 in Bhaga and Weber 1981.) $\bar{C}_D (= 4g\bar{d}/U^2)$ vs. $\bar{R}_e (= U\bar{d}/\nu)$. Taylor and Acrivos 1964 - - -, \bar{C}_D given by (2.2) —, $M = 1.64 \times 10^{-3}$ ●.

number is large as in the points past the minimum, and maybe before the minimum C_D in figure 3. Evidently, it is not very easy to do experiments in which $48/\bar{R}_e$ drag law is actually realized.

The data shown in figure 3 are quite different than the data presented in figure 4. The data in figure 3 does not apply to the spherical cap bubble that is considered in this paper. The large R_e limit leading in figure 4 to the Davies-Taylor limit is in excellent agreement with experiments and is not likely to be greatly improved by a boundary layer analysis, even if it could be carried out.

Harper (1972) makes a distinction between high and low Morton-number liquids. He characterizes the high- M liquids as those for which C_D decreases monotonically with \bar{R}_e as in figure 4, and the low- M liquids as those for which C_D vs. \bar{R}_e has a minimum as in figure 3. Bhaga and Weber (1981) identify this critical value as $M = 4 \times 10^{-3}$; a low- M liquid response is identified by the solid circle data points in figure 4.

The monotonic curve through the high- M open symbol points in figure 4 are described by an empirical formula

$$\bar{C}_D = [(2.67)^{0.9} + (16/\bar{R}_e)^{0.9}]^{\frac{1}{0.9}} \quad (2.2)$$

in which \bar{C}_D is determined by \bar{R}_e alone. The shapes of the bubbles move from spheres to spherical cap bubbles as \bar{R}_e increases; since \bar{C}_D and \bar{R}_e are defined here using the volume equivalent diameter \bar{d} which decreases from the sphere diameter D at low \bar{R}_e to a value $\bar{d} < D$ for a spherical cap bubble which can be estimated from the results of Davies and Taylor (1950) and those given here.

Consider the case in which the deviation from sphericity $s = 0$. In this case equation (1.20) holds. We may rewrite this equation as a drag relation

$$C_D = 6 + 32/R_e, \quad (2.3)$$

where $C_D = \frac{4}{3} \frac{gD}{U^3}$, $R_e = UD/\nu$ and $D = 2R$ is the diameter of the spherical cap. The large R_e limit of (2.3), $C_D = 6$ is the value of drag coefficient which was established in

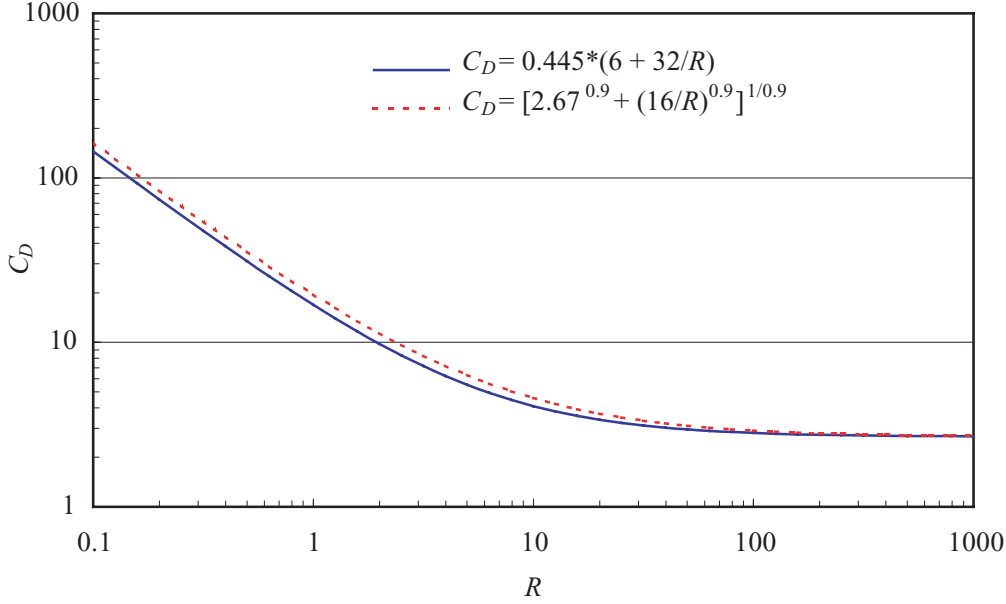


FIGURE 5. Comparison of the empirical drag law (2.2) with the theoretical drag law (2.6) scaled by the factor 0.445 required to match the data in figure 4 with the experiments of Davies and Taylor (1950) at large R_e .

the brilliant experiments by Davies and Taylor (1950). The asymptotic large \bar{R}_e limit of (2.2) is in $\bar{C}_D = 2.67$. These two limits should be the same, hence

$$\frac{\bar{C}_D}{C_D} = \frac{2.67}{6} = \frac{\bar{d}}{D}.$$

If this limit is a spherical cap bubble the volume equivalent diameter is

$$\bar{d} = 0.445D \quad (2.4)$$

of the spherical cap diameter $d = 2R$. The ratio of the volume of the spherical cap bubble to the volume of a sphere of radius $R = D/2$ is

$$\bar{V} = \frac{\bar{d}^3 V}{D^3} = 0.0881. \quad (2.5)$$

The volume of the spherical in this computation is a little less than 1/10 the value of the volume of the sphere from which it is cut.

In comparing (2.2) and (2.3) we must convert \bar{R}_e to R_e and though this cannot be done generally, it can be done empirically for the limiting case of large R_e for which $R_e = 0.445\bar{R}_e$. In figure 5 we compare the empirical relation (2.2) to a rescaled plot of (2.3)

$$\tilde{C}_D = 0.445 \left(6 + \frac{32}{R_e} \right). \quad (2.6)$$

The agreement between (2.6) and (2.2) is spectacular but possibly misleading since the relation between \bar{d} and D is not generally known.

A direct comparison of (2.3) with numerical results is tentative because the spherical cap bubble limit is beyond the capabilities of the numerical methods which have been

applied to the problem. The calculations of Ryskin and Leal (1984) seem reliable and they work well for Weber and Reynolds numbers in which the spheres are greatly distorted. Their figure 1 is a plot of \overline{C}_D vs. \overline{W} with \overline{R}_e as a parameter which is in agreement with (2.2) for $\overline{R}_e < 20$. The empirical formula could not be tested for the large values of W for which the cap bubbles arise but the \overline{R}_e variation for smaller values of \overline{W} are also consistent with (2.2).

The comparison of theory and experiment for the case when the deviation s from sphericity is not zero is complicated. In this case the curvature of the nose of the bubble is different than the spherical radius R used in our calculations and those of Davies and Taylor. We have already noted that the analysis leading to (2.2) neglects some of the changes in the potential function which arise from the change in the shape of the domain. The computation or measurement of s will not be undertaken here but the comparison made in figures 1 and 2 of the paper by Miksis *et al.* (1982) for distorted bubbles in lenticular shape, but far from spherical caps may point the way.

3. Conclusions

Viscous potential flow is as a potential flow solution of the Navier-Stokes equations in which the vorticity vanishes and no slip conditions at interface are not enforced. This solution does not require that the viscosity be put to zero and it is not a good idea to put it to zero. Using this theory, we extended the analysis of Davies and Taylor (1950) of the spherical cap bubble to include effects of viscosity, surface tension and the effects of the deviation of the bubble nose from sphericity. The result of these analyses are expressed by the rise velocity formula (1.22) and the drag formula (2.3). These formulas are in good agreement with experiments of Bhaga and Weber (1981) at the high Morton numbers for which the cap bubbles arise with the caveat that the conversion of the spherical radius to an effective volume equivalent radius is ambiguous. The possible effects of vorticity boundary layers on the rise velocity have not been analyzed here; it is not possible to use the same methods that work for spherical gas bubbles and it is unlikely that the results of such analysis would greatly improve the agreement between theory and experiments documented here.

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