Why do bubbles in Guinness sink?

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Stout beers show the counter-intuitive phenomena of sinking bubbles, while the beer is settling. Previous research suggests that this phenomenon is due to the small size of the bubbles in these beers and the presence of a circulatory current, directed downwards near the side of the wall and upwards in the interior of the glass. The mechanism by which such a circulation is established and the conditions under which it will occur has not been clarified. In this paper, we use simulations and experiments to demonstrate that the flow in a glass of stout beer depends on the shape of the glass. If it narrows downwards (as the traditional stout glass, the pint, does), the flow is directed downwards near the wall and upwards in the interior and sinking bubbles will be observed. If the container widens downwards, the flow is opposite to that described above and only rising bubbles will be seen.
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I. INTRODUCTION

Stout beers, such as Guinness, foam due to a combination of dissolved nitrogen and carbon dioxide,[1] as opposed to most other beers which foam due to dissolved carbon dioxide alone. The use of nitrogen results in a range of desirable characteristics of the beer, including a less bitter taste and a creamy long-lasting head which can be attributed to the low solubility of nitrogen and small size of the bubbles.[2,3] This small bubble size is also responsible, at least in part, for another intriguing characteristic of stout beers: the phenomenon of sinking bubbles, observed while the beer is settling, i.e., between the pouring of the beer and the formation of the head.[4]

Experimental studies[5] have demonstrated that the phenomenon of sinking bubbles is real and not an optical illusion, while simulations[6] show that the bubbles are driven by a downward flow, the velocity of which exceeds the upward velocity of the bubble due to the Archimedean force. The existence of such a flow near the wall of the glass implies that there must be an upward flow somewhere in the interior. The mechanism of this circulation is, however, unclear, as is the role of the shape of the glass.

Understanding these types of bubbly flows is important for a number of applications, such as manufacturing champagne glasses engraved with nucleation sites,[7] widget and similar technologies for promoting foaming in stouts,[8,9] designing glasses which minimize the settling time of stouts and, generally, for industrial processes involving bubbly flows (e.g., bubble columns[10]).

In this paper, we put forward an explanation for the sinking bubbles in Guinness, which takes into account the role of the shape of the glass. In Sec. II, we describe the properties of Guinness as a two-phase medium. In Sec. III, we present the results of numerical simulations for several shapes of the glass. In Sec. IV, we explain the basic mechanism that drives bubbles downwards and describe a simple experiment that can be used to confirm our hypothesis. Finally, we give our conclusions in Sec. V.

II. PROPERTIES OF GUINNESS

We shall model Guinness as a liquid of density ρ_l and viscosity μ_l, with randomly distributed bubbles of gas of density ρ_g and viscosity μ_g. For a temperature of 6 °C (recommended for consumption of Guinness by its producer "Diageo"[12]) and normal atmospheric pressure, we have

$$\rho_l = 1007\,\mathrm{kg\,m^{-3}} \quad \mu_l = 2.06 \times 10^{-3}\,\mathrm{Pa}, \tag{1}$$

$$\rho_g = 1.223\,\mathrm{kg\,m^{-3}} \quad \mu_g = 0.017 \times 10^{-3}\,\mathrm{Pa}, \tag{2}$$

where the values for ρ_l and μ_l have been measured by ourselves and verified against the extrapolation formula given in Ref. 4.

To check whether the bubble shapes differ from spheres, we introduce the Bond number

$$\mathrm{Bo} = \frac{\rho_l g d_b^2}{\sigma}, \tag{3}$$

a dimensionless number describing the importance of gravity relative to surface tension in determining the shape of a bubble or droplet. Here, d_b is the characteristic diameter of a bubble, σ is the surface tension of the liquid/gas interface, and g is the gravitational field strength. Assuming $d_b = 122\,\mu\mathrm{m}$ (as reported in Ref. 11) and $\sigma = 0.0745\,\mathrm{N\,m^{-1}}$ (which corresponds to an water/air interface), we obtain $\mathrm{Bo} \approx 0.002$—a value sufficiently small to show that the effects of surface tension are dominant and will give rise to spherical bubbles.

As with the vast majority of "real" liquids Guinness contains a lot of surfactants, which make the bubbles behave as rigid spheres.[13] This property allows one to estimate the characteristic bubble velocity u_b using the Stokes formula for a rigid sphere

$$u_b = \frac{(\rho_l - \rho_b) g d_b^2}{18\mu_l} \approx 3.96\,\mathrm{mm/s}. \tag{4}$$

Estimating the corresponding Reynolds number

$$\mathrm{Re} = \frac{\rho_l u_b d_b}{\mu_l} \approx 0.24, \tag{5}$$

confirms that the Stokes formula yields a qualitatively correct value for u_b. Furthermore, the fact that u_b is much smaller than the speed of sound shows that the gas can be treated as incompressible.

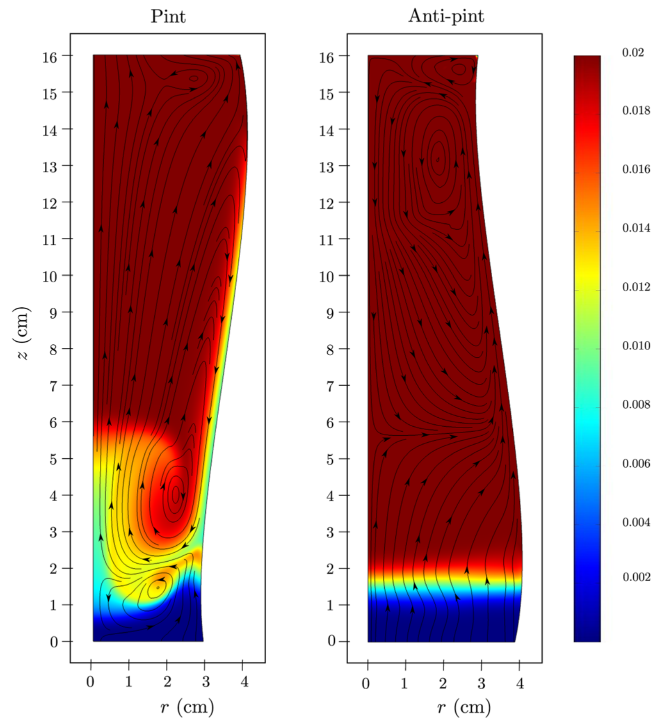

Fig. 1. (Color online) Numerical simulations of bubbly flows for the pint and anti-pint. The curves show the streamlines for the bubbles, the shading (color) shows the void fraction f. The snapshots displayed correspond to $t = 4\,\mathrm{s}$. Observe the region of reduced f near the wall of the pint; the corresponding near-wall region of increased f in the anti-pint is not visible in this figure but can be observed in Fig. 2.

Finally, we introduce the void fraction f, the ratio of gas volume to the total volume of the liquid/gas mixture (a measure of bubble density). For canned Guinness $f \approx 0.05$ (see Ref. 11), whereas for draught Guinness served in pubs $f \approx 0.1$ (according to our own measurements). We note, however, that traditionally, bartenders first fill, say, 80% of the glass and wait until it has fully settled (all the bubbles have gone out of the liquid into the head) before filling the remainder of the glass. Thus, when Guinness is served to a customer the void fraction can be estimated to be $f \approx 0.02$, which is the value used in this work.

III. NUMERICAL MODELING OF THE LIQUID/BUBBLE CIRCULATION

To simulate flows in Guinness, we use the finite element model for bubbly flows included in the COMSOL Multiphysics package. The model's physical foundations are discussed in Appendix and described in detail in Ref. 16. In this model, all of the bubbles are assumed to be the same size. In view of the problem's axial symmetry, the axi-symmetric version of the model is used.

Two geometries of the holding container are examined (see Fig. 1): a pint and an *anti*-pint (i.e., a pint turned upside-down). In both cases, the initial distribution of bubbles is assumed to be uniform and the physical parameters of Guinness are as described above.

The results of typical simulations are shown in Figs. 1 and 2. One can see that an elongated vortex arises near the sloping part of the pint container (left panel). Because the downward velocity due to the vortex ($3\,\mathrm{cm/s}$) is much greater than the upward Stokes velocity of the bubbles relative to the flow ($4\,\mathrm{mm/s}$), we see a downflow of bubbles along the wall of the pint container (top-left panel of Fig. 2). A similar vortex also exists in the anti-pint but it rotates in the opposite direction and, thus, causes an *upward* flow near the wall (right panel of Fig. 1 and top-right panel of Fig. 2).

Another important feature to be observed is the narrow region of low bubble density along the wall of the pint container (left panel of Fig. 1 and the lower-left panel of Fig. 2). In the anti-pint container the bubble density increases near the wall; although it is not visible in the right panel of Fig. 1, it can be clearly seen in the lower-right panel of Fig. 2.

We have also examined the evolution of the global void fraction for the pint and anti-pint, as well as for a cylindrical container of the same volume. Figure 3 shows that while the global void fractions can be significantly different, all three geometries provide more-or-less the same settling time T_s.

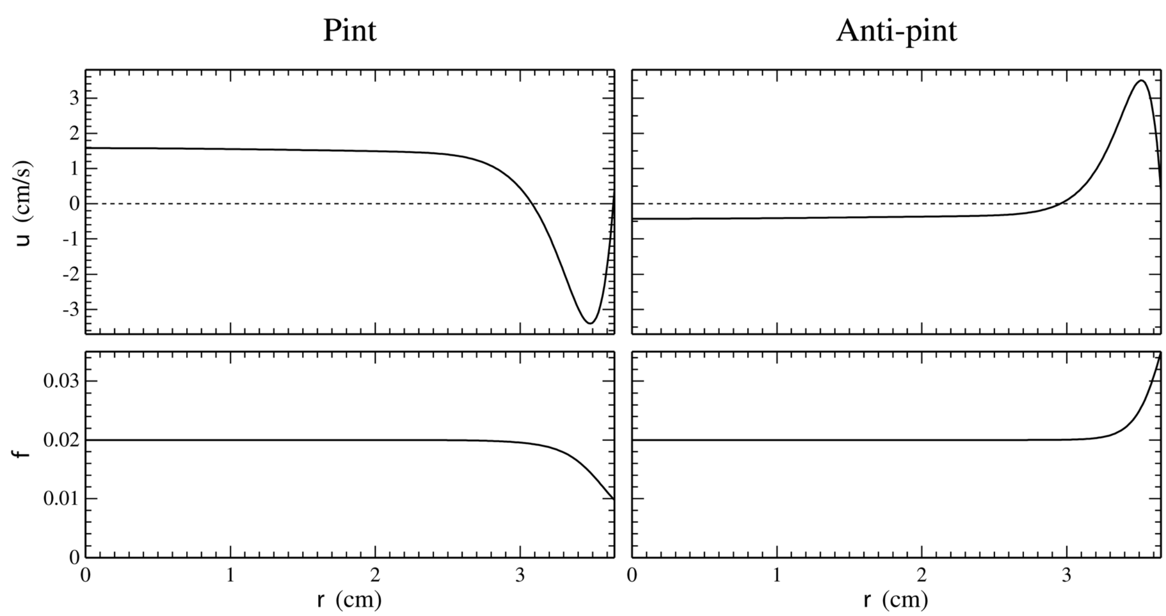

Fig. 2. The half-height ($z = 8\,\mathrm{cm}$) cross-sections of the vertical velocity u and the void fraction f for the pint and anti-pint geometries (these graphs correspond to the (r, z) diagrams shown in Fig. 1). The dotted lines in the upper panels separate the regions of upward/downward flow.

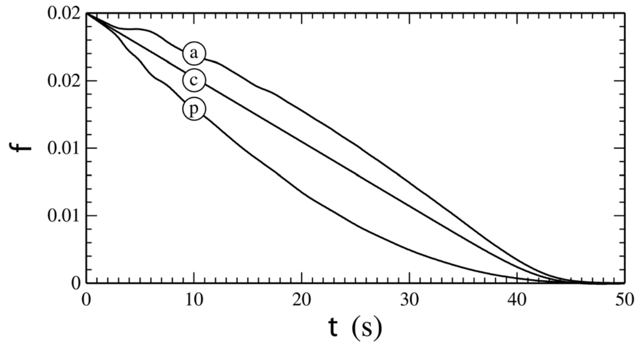

Fig. 3. The global void fraction f (i.e., the proportion of gas in the container) versus time t, for the three cases: the pint (p) and anti-pint (a), both illustrated in Fig. 2, and a cylinder of the same volume (c).

(For a glass of stout, a smaller T_s is generally regarded as an advantage). The settling time is defined here such that $f(t = T_s) = 10^{-6}$.

We can use T_s to explore the extent to which our results depend on the void fraction f and the bubble size d_b (the only parameters with "uncertain" values). Surprisingly (although perhaps suggested by Fig. 3), it turns out that the dependence of T_s on f is very weak—an increase in f from 0.02 to 0.05 results in an increase in T_s from 43 to 46 s. On the other hand, the dependence of T_s on d_b is much stronger—a decrease in d_b from 122 to 90 μm results in an increase in T_s from 43 to 83 s. In all cases, we investigated similar flow patterns were observed, and in particular sinking bubbles were predicted by the simulation.

Note that the settling time of (approximately) 43 s computed for $d_b = 122\,\mu$m and the pint container does not agree with the experimental estimate of approximately 120 s (the time recommended for pouring a pint of Guinness by Diageo, the manufacturers of Guinness). The difference between the two results is probably caused by the fact that all bubbles in our simulations are the same size, whereas in reality they are distributed with a certain dispersion. One can then conjecture that a real glass of Guinness contains some smaller bubbles that take longer to leave the liquid; this would account for the difference between the computed and measured values of T_s.

In what follows, we shall argue that the circulation that develops in the flow is determined by the near-wall variation of the bubble density (as suggested previously in Ref. 14 for bubble columns), and that the bubble density, in turn, is determined by the shape of the container.

IV. THE MECHANISM OF THE EFFECT

To begin, observe that whichever way the bubbles move they exert a drag force on the surrounding liquid. This does not mean that the liquid is necessarily entrained by the motion of the bubbles. Indeed, consider a uniform distribution of bubbles that all move in the same direction. In this case, the drag force would all be in the same direction. If the liquid was entrained by the motion of the bubbles, then the liquid particles would all move in the same way, which effectively means that they cannot move at all due to the liquid's incompressibility and the fact that the container has a bottom. In this case, the drag force would be compensated by a pressure gradient exerted in the fluid.

Let us now assume that there is a region of low bubble density near the container's wall (as there indeed is in the pint container). In this case, the density of the drag force near the container's axis is larger than that near the wall; this creates an imbalance and thus gives rise to a circulation—near the axis the liquid flows upwards and near the wall it flows downwards. If the velocity of the downward flow is larger than the relative velocity u_b of the bubbles, the bubbles will be observed to sink. A similar argument indicates that a near-wall region with *higher* bubble density gives rise to an *upward* flow (precisely what our simulations show for the anti-pint container).

It still remains to identify the mechanism reducing the bubble density near the wall for the pint geometry and increasing it for the anti-pint geometry. In Ref. 6, the circulation is attributed to surface tension slowing down bubbles close to the wall. Another possibility is based on the "lift" force generated by the flow around a sphere moving along a rigid boundary; this force pushes the sphere away from the boundary.[15] In the limit of small Reynolds number, however, the lift force is weak and estimates show that the resulting reduction in bubble density near the wall is negligible. A further shortcoming of these two mechanisms is that they do not seem to distinguish between the pint and anti-pint geometries.

To explore the effect of the geometry, assume that the container is not cylindrical but narrows slightly toward its bottom (as the pint). Then, even if the bubbles were initially distributed uniformly, their upward motion immediately creates a bubble-free zone along the wall (see Fig. 4). On the other hand, in a container that *widens* toward its bottom (as the anti-pint), the initially upward motion of bubbles *increases* the near-wall bubble density. We believe that this simple kinematic effect is responsible for the circulation observed in Guinness.

This effect, although not previously discussed in the context of Guinness, is well known in sedimentation theory as the Boycott effect.[17,18] It was first observed in test tubes containing red blood cells when it was discovered that sedimentation times could be significantly reduced by inclining the test tubes.

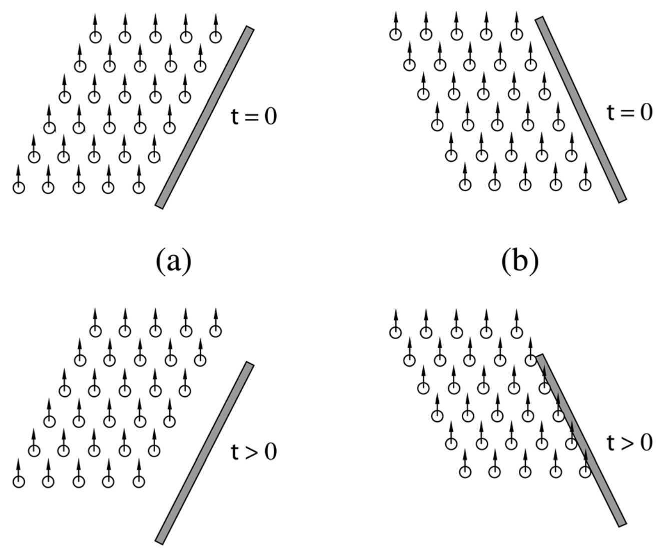

Fig. 4. Schematic diagram of the evolution of bubbles near the wall for: (a) container narrowing downwards (the bubbles move away from the wall), and (b) container widening downwards (the bubbles move towards the wall, and eventually accumulate there) (enhanced online) [URL: http://dx.doi.org/10.1119/1.4769377.1].

Finally, our conclusions can be readily verified experimentally. If Guinness is poured into a tall cylindrical container (e.g., a laboratory measuring cylinder) and the container is tilted, bubbles will be observed to move upward near its upper surface and downward near its lower surface, in precise agreement with the proposed mechanism.[19]

V. CONCLUSIONS

The sinking bubbles of Guinness and other stout beers have intrigued beer-drinking physicists and their students for some time. Building on previous experimental and simulation work, we complete the explanation of this phenomenon by describing the role that the shape of the Guinness pint glass plays in promoting the circulatory flow responsible for the sinking bubbles. Interestingly, understanding the physics underlying the shape of the pint glass raises the intriguing question—is the shape of the Guinness pint glass the most efficient possible, or could the settling time be significantly reduced by some other, possibly non-axisymmetric, shape of pint glass?

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APPENDIX: MODEL DETAILS

The bubbly flow equations treat the liquid and gas phases as interpenetrating continua, and make use of the following simplifying assumptions:

(1) The gas density may be neglected in comparison with the liquid density.
(2) The motion of the bubbles relative to the liquid is determined by a balance between pressure and viscous drag forces.
(3) The two phases share the same pressure field.

These assumptions mean that inertial effects associated with bubble motion are neglected and bubbles instantly acquire the velocity associated with the force balance described in assumption (2). In particular, no initial condition for bubble velocities is necessary. Furthermore, this eliminates the need for a bubble momentum equation: momentum exchange between the gas phase and liquid phase can be tracked using an overall momentum equation (which by assumption (1) only includes terms associated with the liquid phase). Boundary conditions at a wall are zero velocity (no-slip) for the liquid phase and zero gas flux through the wall for the gas phase.

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