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BRIEF COMMUNICATION

TWO-PHASE FLOW DURING FILLING AND EMPTYING OF BOTTLES

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1. INTRODUCTION

Whalley (1987) explored the possible links between flooding and slugging in two-phase gas–liquid flow by consideration of a number of simple experiments which consisted of timing the emptying of bottles of liquid when up-ended. Flooding represents a limit to counter-current flow where the gas phase is flowing upwards and the liquid phase downwards. If fairly well defined flow rates are exceeded, then a gross instability occurs and the flow is said to be flooded, see figure 1(a). The occurrence of flooding has often been correlated by a widely quoted and used equation (e.g. Whalley 1987), originally due to Wallis (1961). This equation contains a dimensionless parameter C, often called the Wallis flooding "constant". For the particular case of filling and emptying a bottle where the volume flow rates of the two phases must be equal by continuity, the equation can be rearranged to give:

$$C = \frac{(\rho_G^{1/4} + \rho_L^{1/4})}{[(\rho_L - \rho_G)gD]^{1/4}}\left(\frac{4V}{\pi D^2 t}\right)^{1/2}, \qquad [1]$$

where

ρ_G = gas density (kg/m^3),
ρ_L = liquid density (kg/m^3),
D = internal diameter of the bottle neck, D_{neck}(m),
g = acceleration due to gravity (9.81 m/s^2),
V = volume of the bottle (m^3)

and

t = time required to fill or empty (s).

Conventional experiments on flooding in straight tubes have shown that the flow rates at which flooding occurs are dependent upon the detailed geometry of the tube, particularly its ends where the liquid leaves the tube and the gas enters it. The tube at these points can be smooth-edged (in the ideal case, either by having a bell-shaped mouth or by removing the liquid through a porous section of wall) or it can be sharp-edged (where no effort is made to allow the phases to separate). Not surprisingly, the smooth geometry is less prone to flooding than the sharp geometry. This is reflected in the values of C suggested: Wallis (1961) gave values of 0.88 for the smooth situation, and 0.725 for the sharp-ended tube. Later Hewitt & Wallis (1963) modified the sharp-ended value to:

$$\begin{cases} 0.88 & \text{for } U_L^* < 0.3 \\ 1.0 & \text{otherwise.} \end{cases}$$

Here U_L^* is a dimensionless liquid velocity, $U_L\,\rho_L^{1/2}/[gD(\rho_L - \rho_G)]^{1/2}$, and U_L is the liquid superficial velocity (m/s).

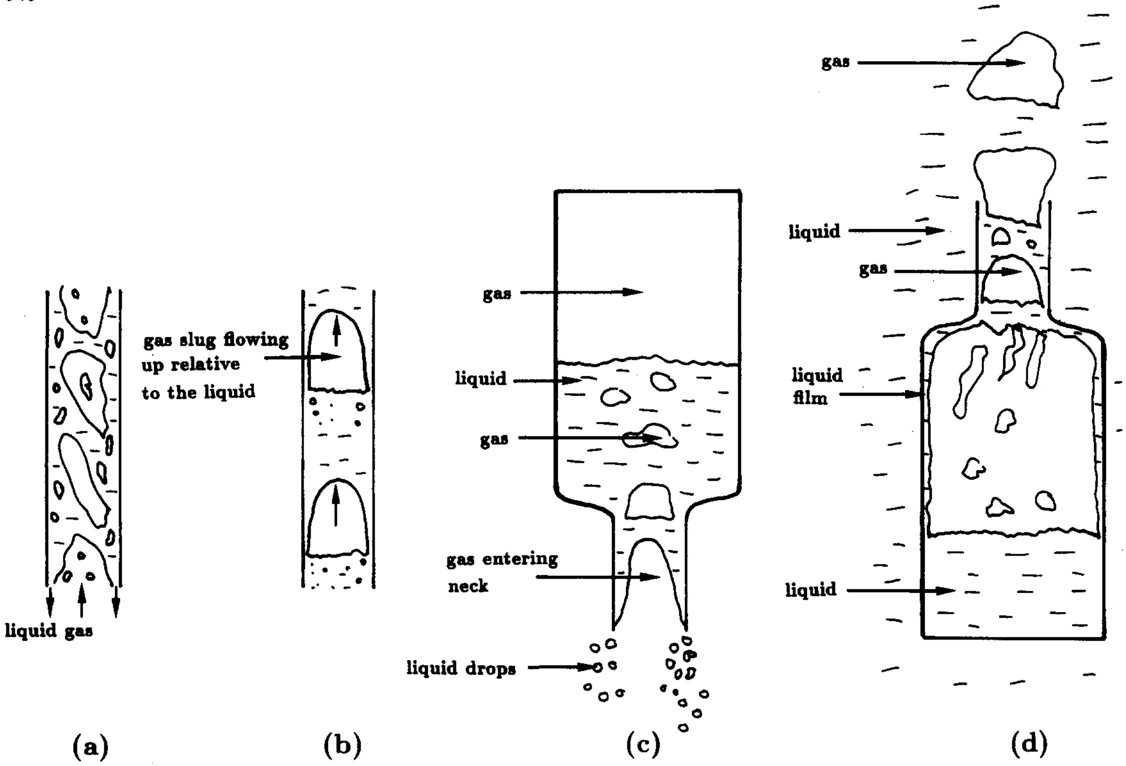

Fig. 1. Schematic diagram of: (a) a flooded flow; (b) slug flow; (c) bottle emptying; (d) bottle filling.

Whalley (1987) considered the relationship of both flooding, see figure 1(a), and slug flow, see figure 1(b), to the bottle emptying process, see figure 1(c). In the experiments on bottle emptying it was possible to reproduce the major findings of many other more complicated experiments on flooding and slugging: principally the effects of tube length (Hewitt 1982) and tube inclination (Hewitt 1977; Runge & Wallis 1965; Zukoski 1966).

Here the previous work is extended: more experiments are reported, and also the related phenomena of bottle filling, see figure 1(d), are studied. The process here is that which occurs when a bottle is plunged below the surface of a large pool of liquid.

Dougall & Kathiresan (1981) studied a similar problem to bottle finding: they had a sealed tank full of air which was filled with water through a long tube which entered the top of the tank. The tube was fed with water from a reservoir. They examined the pressure in the sealed tank and found that the pressure varied periodically. The pressure variation was modelled successfully. They considered there were two significant parts of the cyclic filling process:

(1) The time during which liquid flowed down the tube to pressurize the air in the sealed tank to a pressure corresponding to the head of water in the tube and the upper reservoir (0.75 m in most of the experiments).
(2) The time during which flooding occurred in the tube. During flooding the tube was assumed to be in slug flow and the velocities limited by a Wallis "constant" C of 0.725.

The experiments described here were not such as to make the downflow time significant, as the depth of liquid available was limited. The filling process was thus dominated by the flooding process itself.

2. EXPERIMENTS

Both emptying and filling experiments were performed. In each case the time taken for the bottle to empty or fill was measured, the liquid used in all cases was tap water. The filling experiments

Table 1. Details of the bottles used

Bottle No.	Type (all glass bottles)	Volume (10^{-6} m^3)	Minimum neck dia(mm)	Bottle shape (see figure 2)	Value of C for emptying	Value of C for filling
1	Chemical "winchester"	2830	15.13	a	0.94	0.71
2	Sherry	725	19.65	b	0.98	0.66
3	Mineral water	1070	18.61	c	0.93	0.64
4	Milk	580	26.04	d	0.92	0.71
5	Brandy	730	18.62	e	1.00	0.66

were done by immersing the bottle in a large pool of water. In all the experiments the water temperature was approx. 20°C. Various types and sizes of bottle were used, see table 1, the shapes of the different bottles used are shown in figure 2. Generally the bottles were filled and emptied whilst vertical. A number of basic experiments were performed:

(a) The effect on the filling time of various depths below the surface of the pool of liquid.
(b) The effect of extending the neck of the bottle with tubes of various diameters, see figure 3(a, b).
(c) The effect of extending the neck of the bottle with tubes of various lengths.
(d) The effect of inserting a tube into the neck of the bottle so that it protruded both above and below the neck, see figure 3(c).
(e) The effect of bottle inclination with and without extension tubes. In addition, various special shaped ends to the extension tubes, see figure 4, were tested with the bottle vertical and inclined.

It is well-known that if the liquid flowing out of the botle is swirling, then the emptying times are greatly affected. Filling times are also influenced significantly by the presence of swirl. In these experiments no attempt was made to study the effect of swirl. No discernible swirl was present in any of the flows studied.

Each filling or emptying time experiment was repeated between 6 and 20 times, and the mean and standard deviation (SD) calculated. In almost every case, SD < 5% of the mean value.

3. RESULTS

Tables 1 and 2, and figures 5 and 6 show most of the results for filling and emptying times expressed in terms of C calculated from [1]. The main points to note from the results are:

(a) As long as the top of the neck was more than about 15 mm below the water surface, the filling times were almost unaffected by the depth of immersion.

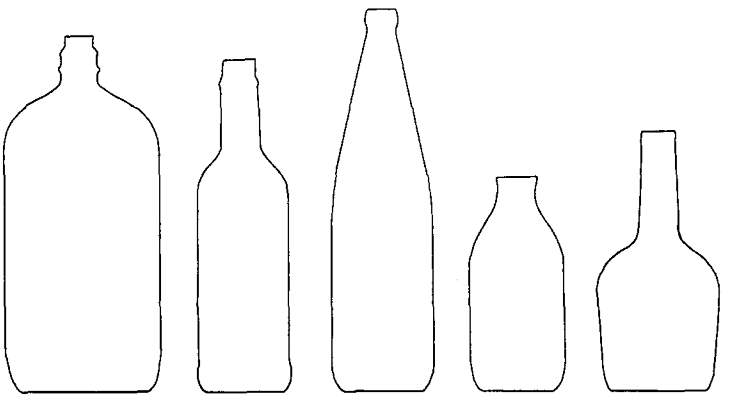

Fig. 2. Bottle shapes: further details are given in table 1.

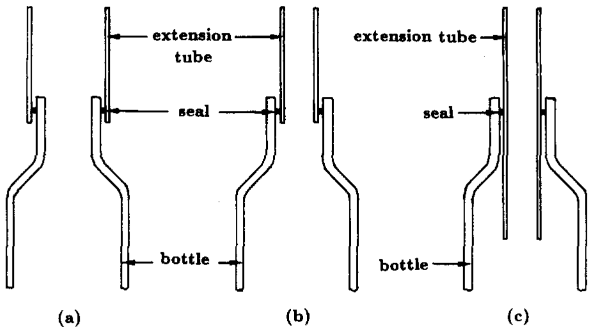

Fig. 3. Extension tubes fitted to the bottle neck: (a) large-diameter extension; (b) small-diameter extension on the end of the neck; (c) small-diameter extension inside the neck.

(b) All the bottles tested took much longer to fill than to empty, see table 1, where the values of C are calculated from [1]. *Note*: a large value of C implies a short time, and a small value of C implies a long time.
(c) Extending the neck of the bottle with a tube which has a diameter at least as large as that of the bottle neck does not increase the emptying time, and can decrease it by up to about 15%. On the other hand, a large-diameter extension can dramatically reduce the filling time. For these large-diameter extensions, the filling and emptying time are almost equal. A small-diameter extension greatly increases both the filling and the emptying time. The percentage increases are almost the same for filling as for emptying. All these trends are summarized in figures 5 in terms of the parameter C calculated using the diameter of the extension tube, D_{ext}, in place of D_{neck} in [1].
(d) The length of a neck extension tube has only a small effect on the emptying time, but a slightly larger effect on the filling time, see figure 6. In figure 6, L_{ext} is the length of the extension tube beyond the neck of the bottle. The effect of length in these experiments was comparatively small.
(e) The effect of a small-diameter extension tube which protrudes into the bottle, as in figure 3(c), is shown in figure 6. The presence of the tube inside the bottle reduces the volume of water which can enter or leave the bottle. Whalley (1987)

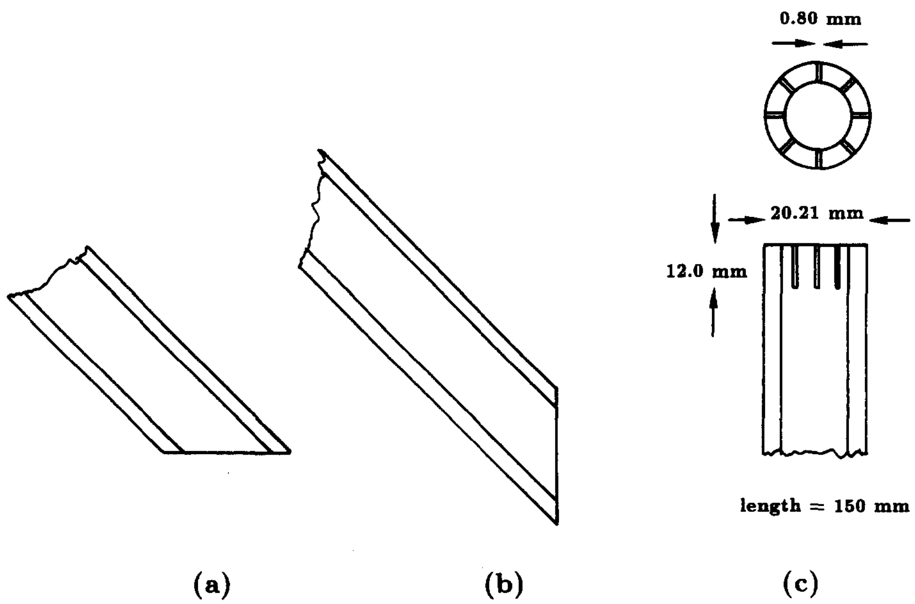

Fig. 4. Extension tubes with various ends: (a) 45° end with cut horizontal; (b) 45° end with cut vertical; (c) castellated end.

Table 2. Effect of bottle inclination and extension tube end shape[a]

Experiment	Vertical Fill (s)	Vertical Empty (s)	45° Fill (s)	45° Empty (s)
Plain bottle	30.8	14.9	21.7	12.4
Plane ended extension				
$D = 20.21$ mm, $L = 150$ mm	23.9	13.6	15.0	13.6
45° ended extension				
$D = 20.21$ mm, $L = 150$ mm	17.3	13.6	—	—
cut horizontal, figure 4(a)	—	—	20.9	13.5
cut vertical, figure 4(b)	—	—	17.4	13.8
Castellated ended extension				
$D = 20.21$ mm, $L = 150$ mm, see figure 4(c)	17.2	13.7	14.5	13.1

[a]All experiments were carried out with bottle 3. Extensions (where used) were mounted at the end of the bottle neck. All filling results are with the end at least 150 mm below the water level. Values quoted in this table are the times to fill and empty with the bottle vertical and inclined at 45°.

verified that the flow rate during emptying was approximately constant, the same was also found to be true here for the filling process. From figure 6 it can be seen that the filling and emptying processes for the cases with the re-entrant tube occur at almost the same rate, and that this rate is very similar to the filling rate with a non-protruding extension of the same dimensions.

(f) The effects of tube inclination and specially shaped tube ends are shown in table 2. The emptying times are almost unaffected by inclination except for the case of the plain bottle where, as found by Whalley (1987), an inclined bottle empties more quickly than a vertical one. Having an extension tube, of any of the end shapes tested, had virtually no effect on the emptying time, and destroyed any dependence on the angle of inclination. In constrast, filling times are affected much more by the angle of inclination and the geometry of the end of the tube. Filling times for the results in table 2 vary by a factor of 2.1, whereas emptying times only vary by a factor of 1.2.

In general, throughout these results it can be seen that filling times are much more dependent on parameters such as inclination, extension length and diameter than are emptying times.

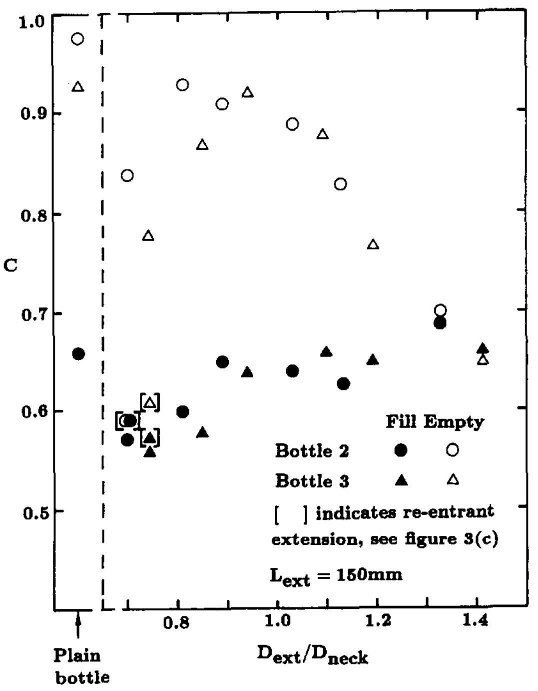

Fig. 5. Effect of extension tubes of various diameters on filling and emptying.

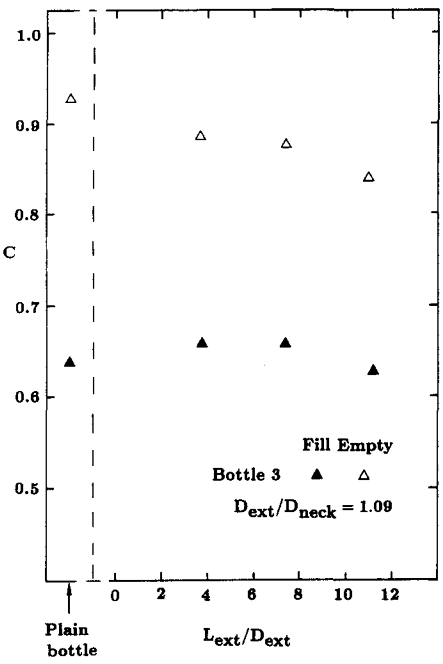

Fig. 6. Effect of extension tubes of various lengths on filling and emptying.

4. DISCUSSION

Previously, Whalley (1987) has drawn the analogy between flooding and the bottle emptying process, and also between flooding and slugging. However, the present results now raise the question as to the most suitable analogue for flooding in conventional tube geometry: is it bottle emptying or is it bottle filling?

Table 1 shows the calculated values of C for the basic results. In particular, the average values of C for filling (0.68) and emptying (0.95) can be seen. In these experiments $U_L^* > 0.3$ and, therefore, the relevant values of C from previous flooding experiments are 0.725 for sharp-edged tubes and 1.0 for smooth-edged tubes. These are quite close to the average experimental values of C quoted above.

These results are consistent with the work of Bharathan *et al.* (1979), who showed that a considerable increase in the value of C is obtained when the liquid film is introduced smoothly: the results of Bharathan *et al.* are shown in figure 7. Bottle emptying can be interpreted as a smoother establishment of the liquid film (because of the smooth profile of the neck shape) than bottle filling, where the liquid suddenly enters the narrow neck in a sharp-edged manner.

This hypothesis that bottle emptying is controlled by flooding in a sharp-edged tube and that bottle filling is controlled by flooding in a sharp-edged tube, will now be examined in the light of the other experimental results.

(a) Effect of extension diameter (see figure 5)

Using a large-diameter extension, significantly larger than the neck internal diameter, tends to make the filling and emptying times almost equal. In this case flooding is still ultimately controlled by the neck diameter but the extension tube tends to cause the neck to act as a smooth-edged tube in both filling and emptying. With a small-diameter extension, smaller than the neck internal diameter, the difference between filling and emptying are preserved. Here the flooding is controlled by the diameter of the extension tube. However, as the extension tube diameter becomes very small, then the emptying process begins to be more like flooding in a sharp-edged tube.

(b) Effect of extension length (see figure 6)

The trend of the results in this case is not very strong, and no conclusions can be drawn.

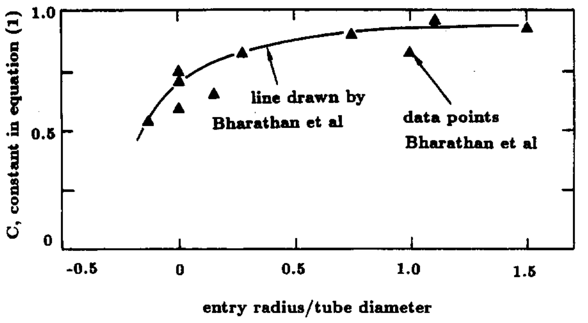

Fig. 7. Effect of tube entry geometry on C; results of Bharathan *et al.* (1979).

(c) Effect of re-entrant extension tube as shown in figure 3(c) (see figure 5)

The re-entrant extension tube should make emptying and filling occur at the same rate, as the flow "sees" the same entry geometry in the two cases. This is confirmed by the results in figure 5. It can also be seen that, as expected, the rate of emptying and filling wth the re-entrant tube is almost the same as for filling in the case with an extension tube mounted at the end of the neck. Both filling and emptying with the re-entrant extension are like flooding in a sharp-edged tube.

(d) Effect of special tube ends (45° cuts and castellated ends) and the effect of inclining the tube (see table 2)

Here it would be expected that the emptying rate would be unaffected by the geometry of the tube end, but that the filling rate would be altered. This is found to be the case. A more difficult result to explain is that inclining the bottle effects the filling rate very significantly, but only alters the emptying rate by a comparatively small amount.

A general experimental result was that filling times were much more dependent on parameters such as inclination, extension length and diameter than was emptying time. Emptying, it now appears, is controlled by the flow up to and inside the neck of the bottle. This is, necessarily, difficult to influence. On the other hand, filling is controlled by the flow on the outside of the neck and is relatively easy to influence. Thus, it is not surprising that filling times were much more dependent on external parameters.

5. CONCLUSIONS

It appears that the emptying of conventionally shaped bottles is controlled by flooding, and the particular characteristics of the flooding are analogous to flooding in a smooth-edged tube. The filling of such bottles, when they are plunged beneath the surface of a pool of liquid, is likewise controlled by flooding. In this case the flooding is analogous to that occurring in a sharp-edged tube.

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