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BRIEF COMMUNICATION

FLOODING, SLUGGING AND BOTTLE EMPTYING

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1. INTRODUCTION

The phenomena of flooding and slugging are well known in gas–liquid flow. Flooding represents a limit to counter-current flow where the gas phase is flowing upwards and the liquid phase downwards. A recent review by Bankoff & Lee (1986) gives many details of the flooding process and of attempts to characterize it. If fairly well defined flowrates are exceeded, then a gross instability occurs and the flow is said to be flooded, see figure 1. The occurrence of flooding has often been correlated by an equation originally due to Wallis (1961):

$$U_G^{*1/2} + U_L^{*1/2} = C, \qquad [1]$$

where

U_G^* = dimensionless superficial gas velocity,

U_L^* = dimensionless superficial liquid velocity

and

C = constant of value approx. 0.8.

The definitions of the dimensionless superficial velocities are

$$U_k^* = \frac{U_k \rho_k^{1/2}}{[gd(\rho_L - \rho_G)]^{1/2}} \qquad [2]$$

where k represents L (liquid) or G (gas),

U_k = phase superficial velocity (m/s),

ρ_k = phase density (kg/m^3),

d = tube diameter (m)

and

g = acceleration due to gravity (9.81 m/s^2).

Flooding has been found to be affected by the tube angle of inclination: Hewitt (1977) found that the flowrates necessary to cause flooding were greatest when the tube was inclined at an angle of 30°–45° to the vertical. It is also well-known that, in sharp-edged tubes, the flooding flowrates are not influenced by the length of the tube, see Hewitt (1982).

Slugging is a particular regime of gas–liquid flow characterized by the presence of large bullet-shaped bubbles, see figure 2. For tubes which are of dia $\gtrsim$ 10 mm, and for non-viscous liquids (viscosity of the order of 10^{-3} N s/m^2), then the well-known equation due to Davies & Taylor (1950) can be used for the rising velocity of the gas slugs:

$$U_p = 0.35 \left[\frac{gd(\rho_L - \rho_G)}{\rho_L} \right]^{1/2}, \qquad [3]$$

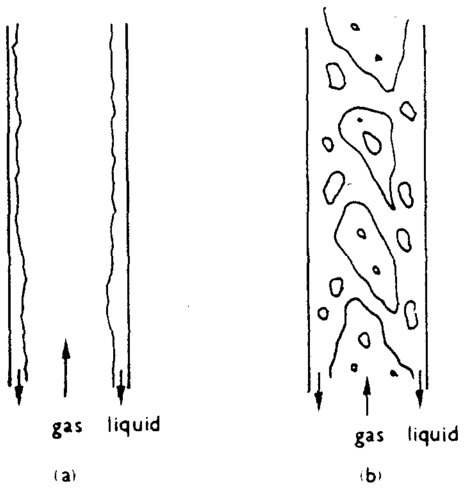

Figure 1. Schematic diagram of flooding: (a) flow just before flooding: (b) flow after one of the phase flowrates has been increased slightly to initiate flooding.

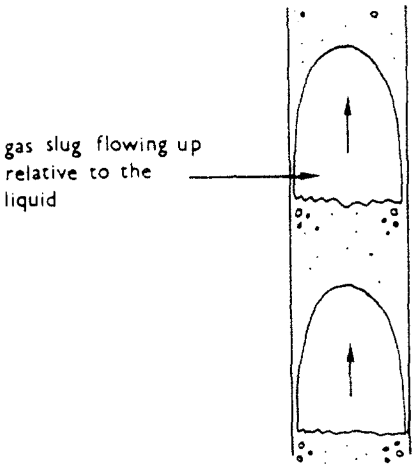

Fig. 2. Slug flow.

where U_p is the actual rising velocity (m/s) of the gas plugs in a vertical tube. Other workers (Runge & Wallis 1965; Zukoski 1966) have found that the slug can rise significantly faster in a non-vertical tube. The maximum velocity occurs when the tube is inclined at an angle in the region of 45° to the vertical.

These phenomena of flooding and slugging have been connected in the past, see, for example, Wallis (1969), but no detailed work on the relation between the phenomena seems to have been done.

2. EXPERIMENTS

The experiments performed were very simple: the time required for bottles of water to empty was determined. Various types and sizes of bottle were used, see table 1. Generally the bottles were

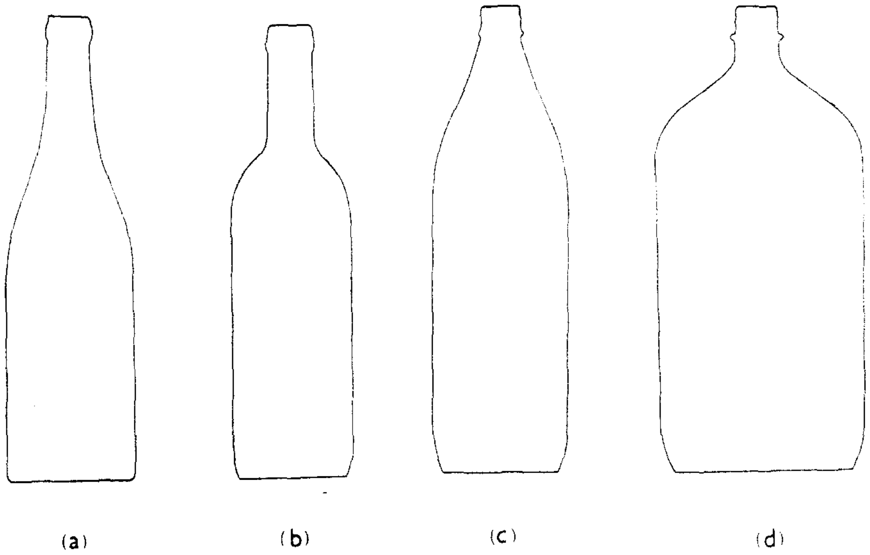

Figure 3. Bottle shapes: further details are given in table 1.

filled with tap water at 20°C and allowed to empty whilst vertical. However the effect of a number of variations to this simple experiment were tested. These were:

(a) The effect of using hot water. As well as the emptying time, the temperature of the gas (air and water vapour) in the bottle after emptying was measured. In separate experiments the neck of the bottle was plunged into a pool of cold water immediately after emptying, and the bottle and its contents cooled to 20°C. In this way, by measuring the volume of water sucked into the bottle, the volume of air which had entered the bottle, measured at 20°C, could be determined.
(b) The effect of extending the neck of the bottle with tubes of various diameters.
(c) The effect of extending the neck of the bottle with tubes of various lengths.
(d) The effect of angle of inclination.

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

3. RESULTS

The results are presented in tables 1–4. The main points about the results are:

(a) Using hot water has a significant effect on the emptying time: the hotter the water the lower the emptying time

Table 1. Details of bottles used

Bottle No.	Type (glass unless stated)	Volume (10^{-6} m^3)	Minimum neck dia (mm)	Bottle shape, see figure 3
1	Soft drink	129	17.50	a
2	Soft drink	192	17.36	a
3	Wine (claret)	765	18.53	b
4	Wine (burgundy)	782	17.24	a
5	Soft drink	1060	17.45	c
6	Wine (sauterne)	1520	19.20	b
7	Chemical "winchester"	2750	20.40	d
8	Polycarbonate soft drink	1060	21.65	b
9	Chemical polythene	583	19.60	d
10	Chemical polythene	1085	29.40	d
11	Wine (champagne)	1615	17.48	a

Table 2. Basic results

Bottle No.	Emptying time at 20°C (s) ± SD	Calculated value of C (20°C)	Emptying time at higher temperatures (% of time at 20°C)	
			50°C	92°C
1	2.78 ± 0.14	0.81	—	—
2	3.37 ± 0.12	0.91	—	—
3	10.08 ± 0.25	0.96	—	—
4	11.06 ± 0.16	1.02	—	—
5	20.17 ± 0.55	0.86	92	72
6	18.66 ± 0.55	0.95	89	—
7	46.00 ± 0.26	0.76	91	—
8	12.12 ± 0.29	0.85	93	—
9	9.97 ± 0.11	0.79	86	76
10	5.65 ± 0.11	0.86	—	—
11	26.13 ± 0.59	0.94	90	—
Average temperature in bottle after emptying out water (°C)			44	73
Average volume of air (measured at 20°C) entering bottle after emptying as a % of the bottle volume			83	40

Table 3. Effect of extending the neck of the bottle

Bottle No.	Neck dia (mm)	Emptying times (as a % of the bottle without the extension) for extensions of length L (mm) and dia D (mm)					
		D = 22.26 L = 150	D = 20.38 L = 150	D = 20.38 L = 300	D = 20.38 L = 450	D = 17.60 L = 150	D = 16.00 L = 150
5	17.45	87	86	89	89	92	122
7	20.40	100	97	101	102	114	—

Table 4. Effect of inclination

Bottle No.	Emptying times (as a % of the time for a vertical bottle) for various angles of inclination, degrees from vertical			
	15°	30°	45°	60°
5	84	79	87	95
7	86	78	79	86

(b) Extending the neck of the bottle with a tube which is at least as large a diameter as the bottle neck does not increase the emptying time, and can decrease it by up to about 15%.

(c) The length of a neck extension tube has virtually no effect on the emptying time.

(d) The inclination of the bottle does affect the emptying time: the minimum emptying time occurring at an angle of about 30–45° to the vertical.

Typical standard deviations for the emptying times in the basic experiments are given in table 2. The standard deviation was never greater than 5% of the mean value and was usually much less. The other experiments showed similar standard deviations, so that the effects (a), (b) and (d) above are certainly significant ones.

4. DISCUSSION

Flooding and slugging

When the process of bottle emptying is observed closely, the connection between flooding and slugging becomes apparent. Figure 4 shows a sketch of a typical flow in the region of the mouth of the bottle. The air entering the bottle forms a slug shape at the neck of the bottle. This air slug is sometimes stationary whilst the waters flows downwards around it. At other times the air slug is rapidly released and enters the bottle. If it is assumed that for most of the time the air plug is stationary, then the water must be moving downwards at a superficial velocity of U_p. Alternatively the process can be regarded as a flooding process, in which case the superficial velocities of the air and the water are, by continuity, equal and given by

$$U = \frac{C^2[gd(\rho_L - \rho_G)]^{1/2}}{(\rho_L^{1/4} + \rho_G^{1/4})^2}. \qquad [4]$$

If this velocity is equated to the slug velocity given by [3], then the expression can be rearranged to give an equation for the flooding "constant" C:

$$C = 0.59\left(\frac{\rho_G^{1/4}}{\rho_L^{1/4}} + 1\right). \qquad [5]$$

This equation is plotted against the density ratio ρ_L/ρ_G in figure 5, and it is evident that it gives values of C which are consistent with values obtained experimentally from flooding investigations.

Analysis of basic experiments

Equation [4] can be simply rearranged to give the value of C if the bottle volume, the emptying time and the neck cross-sectional area are known. The results of these calculations are shown in

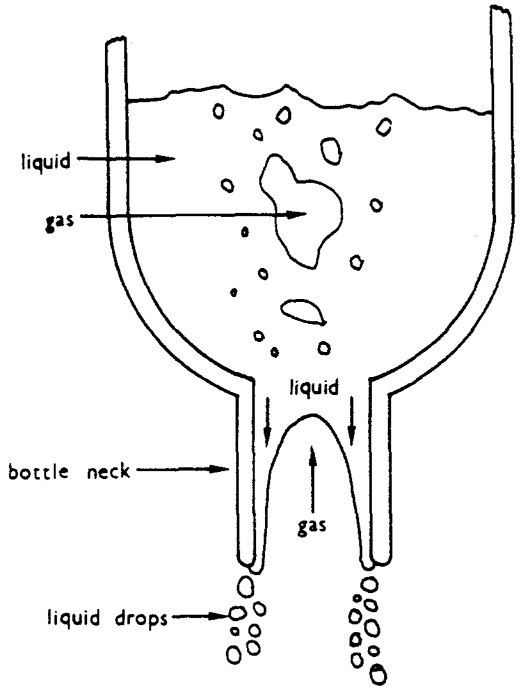

Figure 4. Flow pattern around the neck of a bottle during emptying.

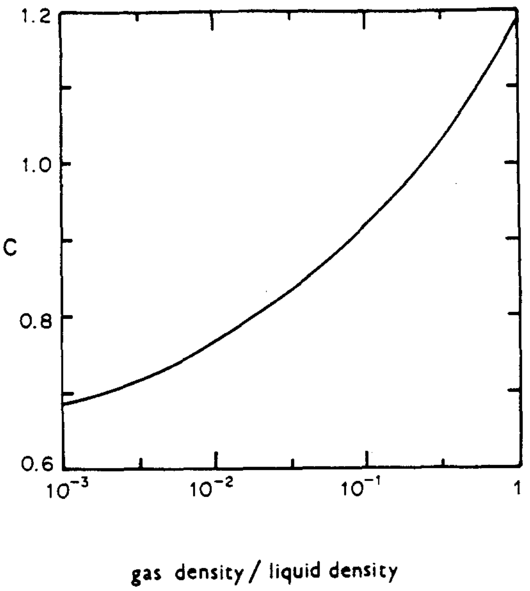

Figure 5. Values of the flooding "constant" C calculated from [5].

table 2: again the values of C are consistent with values normally found in flooding experiments. However, it is difficult to see any definite pattern about the relative magnitudes of the various values.

The value of C seemed to remain constant during the bottle emptying. This was tested in the larger bottles by stopping the emptying when the bottle was about half full. Then C was calculated from the time for which emptying was allowed to continue, and the volume of water which was left in the bottle after this time. Also there did not seem to be any change in the nature of the events occurring at the bottle neck during the emptying process, nor was there any significant change in the slug frequency during the emptying.

Effect of neck extensions and angle of inclination

These results are totally consistent with previous results from both flooding and slug flow experiments.

Effect of water temperature

This is a very much more difficult effect to understand. The thermal expansion of the bottle and the neck is a negligible factor, but does the difference in the results occur because of the change in the fluid physical properties or because less air enters the bottle (see table 2)?

With regard to the physical properties, it seems unlikely that the air properties are much changed at the flooding point because the flooding occurs at the neck of the bottle where the air has only just come into contact with the hot water. The water properties on the other hand are substantially changed by the increased temperature. In particular the water viscosity and the surface tension will be altered:

Temperature (°C)	Water viscosity (N s/m^2)	Air–water surface tension	Water density (kg/m^3)
20	0.00102	0.073	998
50	0.00054	0.068	988
92	0.00031	0.060	964

The effect of these physical properties on flooding and slug flow is not altogether clear. McQuillan (1985) found in experimental studies of flooding that the effect of decreasing the liquid viscosity was generally to increase the flooding velocity, and therefore, in this case, to decrease the emptying time. This effect of liquid viscosity was rather small and not universally observed. One set of data (Clift *et al.* 1965) showed that decreasing the liquid viscosity by a factor of 70 increased the gas velocity at flooding by only 20%. According to McQuillan (1985), the effect of surface tension is more clear cut: decreasing the surface tension will decrease the flooding velocity and therefore increase the emptying time. There appears little hope of explaining the effect of hot water by means of the different fluid physical properties.

The change in the volume of air entering the vessel however does offer an explanation. If the ratio of the volume of air (measured at 20°C) entering the bottle to the total bottle volume is r, then the superficial velocities of the phases are also in this ratio. Here it is assumed that the air temperature does not change significantly before the flooding point. Then, if the flooding "constant" C is unchanged, the ratio of the emptying time for hot water (t_h) to the emptying time for cold water (t_c) should be:

$$\frac{t_h}{t_c} = \frac{(r^{1/2}\rho_G^{1/4} + \rho_L^{1/4})^2}{(\rho_G^{1/4} + \rho_L^{1/4})^2}. \qquad [6]$$

Substitution of values into this equation does not give a large enough effect. The calculated values of the ratio t_h/t_c are 0.97 and 0.87 for hot temperatures of 50 and 92°C, whereas the actual values are 0.90 and 0.74. Thus the reason why bottle emptying occurs more quickly with hot water than with cold water cannot be fully explained.

Experimentally it was noted that with hot water the slug frequency in the bottle neck appeared greater than with cold water.

5. CONCLUSIONS

Flooding and slug flow are closely related phenomena. Bottle emptying can be regarded as either flooding and slugging, both of which account for almost all the major features observed experimentally, the exception being the effect of water temperature. It is anticipated that this work can be extended to the emptying of various types of tanks via a bottom exit. The time required for emptying could be calculated using either flooding or slugging equations.

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