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BRIEF COMMUNICATION

OUTFLOW OF LIQUIDS FROM SINGLE-OUTLET VESSELS

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1. INTRODUCTION

Outflow of liquids from single outlet vessels has been recently investigated by several authors, such as Whalley (1987, 1991), Tehrani *et al.* (1994) and Schmidt & Kubie (1995). In such vessels the liquid leaving the vessel through the outlet is replaced by another fluid entering the vessel through the same opening.

Whalley (1987, 1991) and Tehrani *et al.* (1994) investigated the emptying and filling of various commercially available bottles and related the counter-current flow processes involved with the occurrence of flooding, which they correlated with the dimensionless flooding parameter C, originally introduced by Wallis (1961). They showed that both bottle emptying and bottle filling are controlled by flooding with the flooding parameter C being in a reasonable agreement with previous experimental work (Wallis 1961; Hewitt & Wallis 1963). However, the use of commercially available bottles in their experimental work implied that only an integral approach could be employed, and thus that only the total times for the complete emptying and filling of the bottles were investigated.

In the work of Schmidt & Kubie (1995) a simpler problem was investigated: an axisymmetric arrangement of a vertical perspex cylindrical vessel with a sealed top and a central outlet in its base. It was shown that for such an arrangement, and the range of parameters examined, the average liquid discharge velocity is independent of both the liquid level in the vessel and the shape of the outlets, and that it increases weakly with both the diameter of the outlet and the diameter of the vessel.

It is the purpose of this work to extend the previous investigations by examining the pressure variations in the vessel and by considering also the replacement of the primary liquid by another liquid surrounding the vessel. Finally, the present work is compared with the work of other investigators and the flooding parameter is re-examined.

2. EXPERIMENTAL WORK

Two series of experiments were carried out. The basic experimental apparatus, used in both series, is shown in figure 1. The working vessel was a vertical perspex cylinder, with a sealed top and an outlet in the centre of its base.

In the first series of experiments, ordinary tap water at room temperature discharging into air was investigated. The working vessel had the following dimensions: internal vessel diameter, D_V, 170 mm, vessel height, l, 1450 mm and outlet diameter, D, 25 mm. Profiled and cylindrical outlets were used, the outlets were 20 mm long, and in the case of the profiled outlet the radius $r = 0.25\ D$ (as shown in figure 1). The pressure in the air space, p_G, was measured with a 0–30 psi gauge-type pressure transducer and recorded on a Solartron 3530 Orion data logging system. The experimental

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procedure for determining the water level as a function of time was as described previously (Schmidt & Kubie 1995).

In the second series of experiments, ordinary tap water (density $\rho_1 = 998\ \mathrm{kg\,m^{-3}}$) at room temperature discharging into paraffin (density $\rho_2 = 800\ \mathrm{kg\,m^{-3}}$) at room temperature was investigated. The working vessel had the following dimensions: internal vessel diameter, D_V, 240 mm and vessel height, l, 360 mm. Three cylindrical outlets were used with diameters, D, 20, 35 and 50 mm. The working vessel was submerged in a larger vessel, internal diameter of 350 mm, which contained the paraffin. The top of the working vessel was about 200 mm below the paraffin surface, and its base about 400 mm above the base of the larger vessel.

The variation of the pressure in the air space for the 25 mm cylindrical outlet against time t is shown in figures 2 and 3. The results for the outflow of water into air are comparable with those reported previously. The experimental results for the outflow of water, the primary liquid, into paraffin are plotted in dimensionless form as H vs T, where H is defined as h/D, T as $t(g'/D)^{0.5}$ and g' as $g(\rho_1 - \rho_2)/\rho_1$ in figure 4.

3. DISCUSSION

3.1. Pressure in the air space

Figure 2 indicates that the pressure in the air space initially decreases rapidly towards about 0.86 bar, which approximately corresponds to the hydrostatic pressure there for a column of water about 1450 mm high. Similar results have been also observed by Tehrani *et al.* (1992) in their investigation of a tank draining through vertical tubes. The gradual recovery of the pressure in

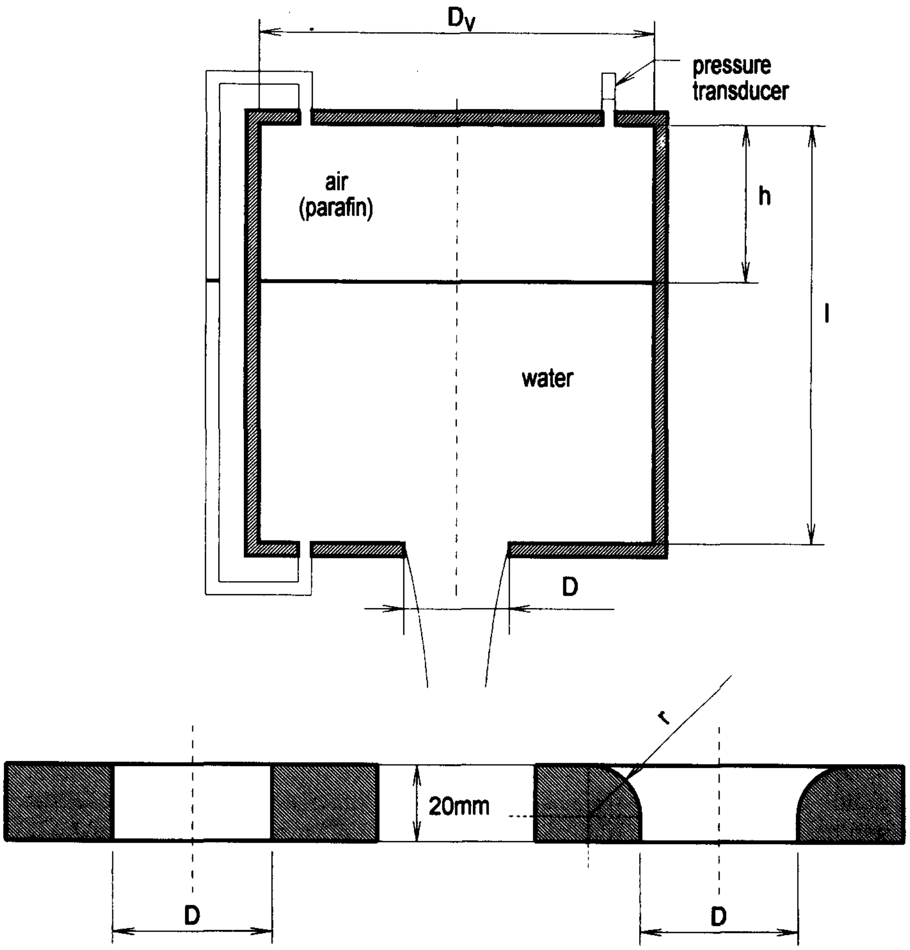

Figure 1. Diagram of the experimental apparatus.

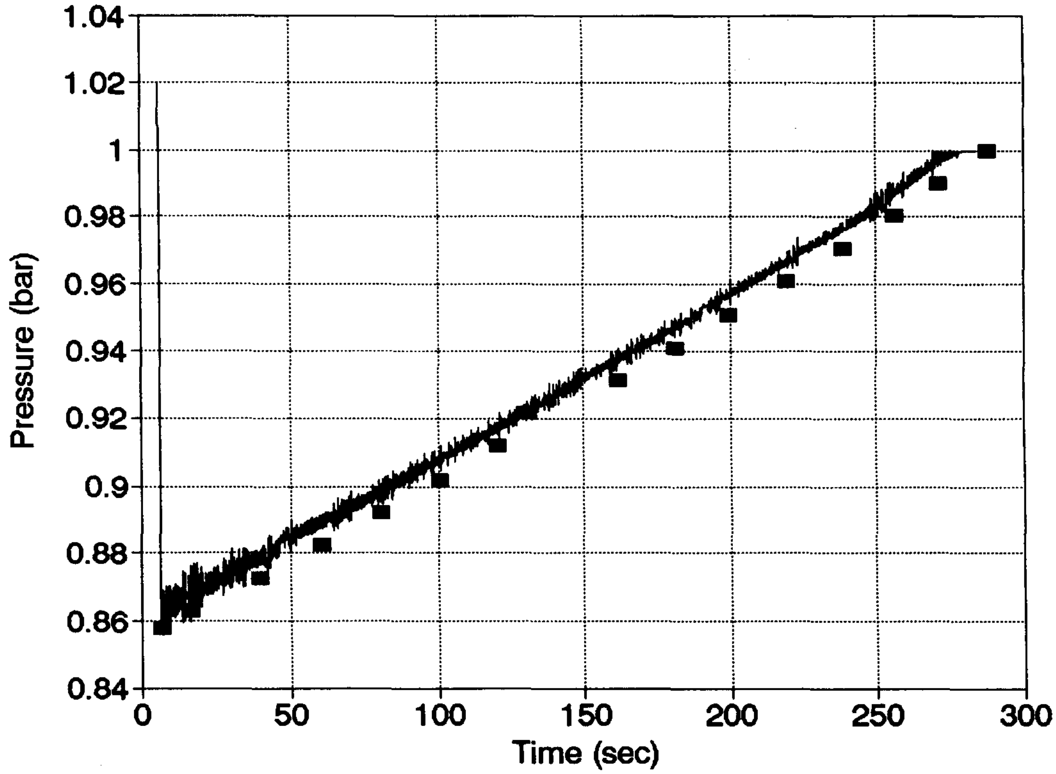

Figure 2. A plot of the variation of the pressure in the air space versus time for the air–water system: directly measured pressure (solid line), hydrostatic pressure, p_H (■).

the air space corresponds to the decreasing level of water in the vessel and the associated decrease in the hydrostatic pressure in the air space above the interface. The hydrostatic pressure in the air space p_H, given as $p_A - \rho_l g(l - h)$, where p_A is the atmospheric pressure, is also included in figure 2. Figure 2 shows that the difference between the hydrostatic pressure and the pressure in the air space is very small and approximately constant, and independent of the level of water in the vessel. This then implies that the processes governing the outflow of liquids from closed vessels are independent of the height of the vessel and governed by the behaviour at the outlet, such as the occurrence of flooding described by Whalley (1991). Figure 3 demonstrates the fluctuation of the pressure in the air space, associated with cyclic expansion of the gas space and partial pressure recovery there, resulting from the arrival of the air bubbles at the gas–liquid interface in the vessel. The cyclic behaviour is less well defined and of higher frequency than observed by Tehrani *et al.* (1992). The probable reason for this difference is the use of the vertical downcomer in the work of Tehrani *et al.* (1992), which allowed for a clear distinction between the various flow regimes.

3.2. *Position of the interface*

Figure 4 demonstrates that the liquid outflow into another liquid is very similar to the outflow of liquid into air, investigated previously (Schmidt & Kubie 1995). In particular, the dimensionless interfacial velocity, defined as $U = \Delta H/\Delta T$ and based on forward differences, is approximately invariant with H. However, the interfacial velocities are considerably lower in the case of liquid–liquid outflow, even if the usual correction for the effect of density of the secondary surrounding fluid is made.

3.3. *Flooding of the outlet*

Following Wallis (1961), the occurrence of flooding can be correlated by

$$U_1^{*1/2} + U_2^{*1/2} = C \qquad [1]$$

where

$$U_k^* = \frac{U_k \rho_k^{1/2}}{[gD(\rho_1 - \rho_2)]^{1/2}} \tag{2}$$

where U_k is the phase superficial velocity and ρ_k is the phase density. Furthermore, from continuity

$$U_1 = U_2 \tag{3}$$

and hence the flooding parameter can be expressed as

$$C = \frac{U_1^{1/2}}{(gD)^{1/4}} \frac{\rho_1^{1/4} + \rho_2^{1/4}}{(\rho_1 - \rho_2)^{1/4}}. \tag{4}$$

It can be further shown by continuity that

$$\frac{U_1}{(gD)^{1/2}} = \frac{U}{A}\left(\frac{\rho_1 - \rho_2}{\rho_1}\right)^{1/2} \tag{5}$$

where A is defined as A_0/A_V, A_V is the cross-sectional area of the vessel and A_0 is the cross-sectional area of the outlet.

The flooding parameter can then be calculated from [4] and [5], using the experimental data for the dimensionless interfacial velocity U. Since the interfacial velocity is approximately constant for H in the mid-range (more than about 3 from both the top and the bottom of the vessel), the values of the flooding parameters are also approximately constant in the mid-range. Experimental data of Schmidt & Kubie (1995) and of the present experimental work for these constant values of the flooding parameter, C are plotted against the ratio D_V/D in figures 5 and 6 for cylindrical and profiled outlets, respectively. Figures 5 and 6 also show the experimental data of Whalley (1991), but it should be pointed out that the values of D_V/D were estimated for his work and hence that there is some uncertainty.

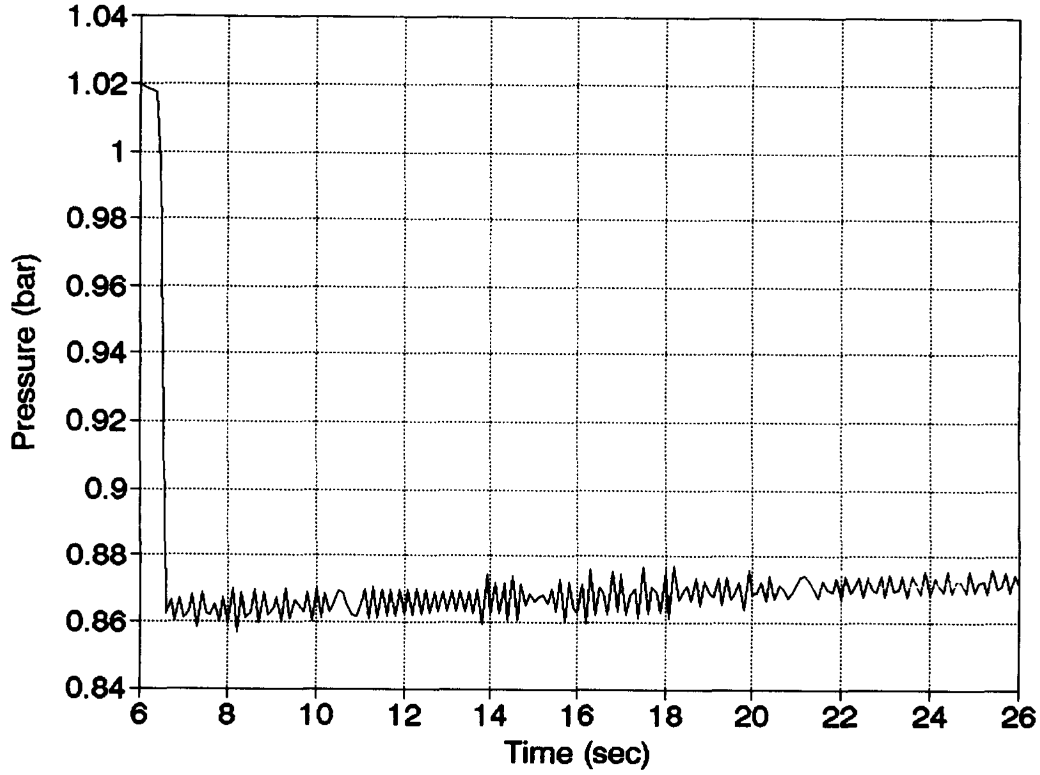

Figure 3. A plot of the variation of the pressure in the air space vs time for the air–water system over shorter time scales: directly measured pressure.

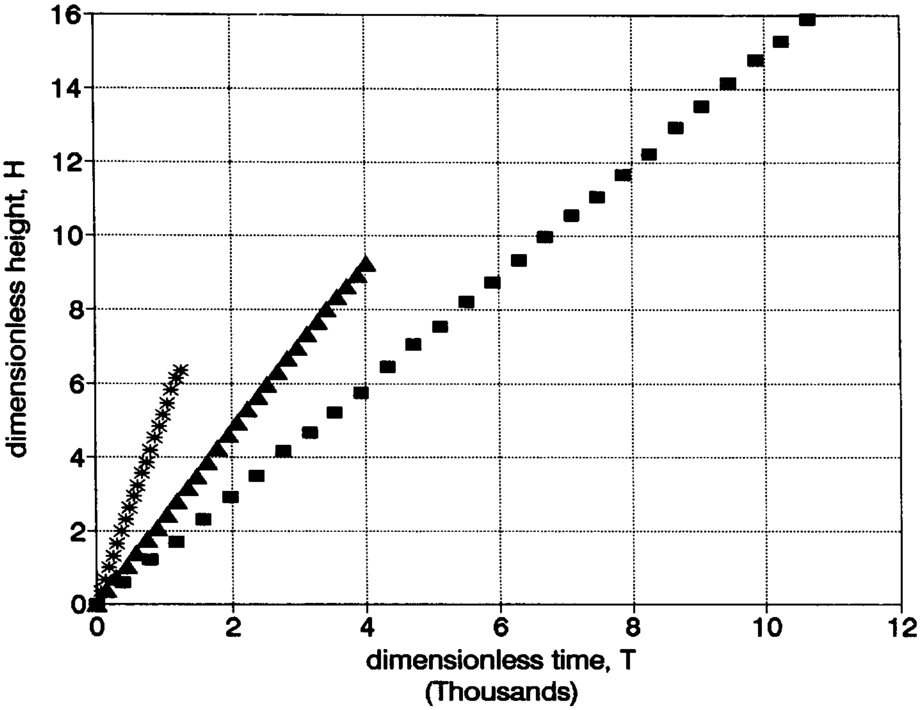

Figure 4. A plot of H vs T for the paraffin–water system and three cylindrical outlets: $D = 20$ mm (■), $D = 35$ mm (▲), $D = 50$ mm (*).

Several observations can be made. First, the flooding parameter C for outflow from single outlet vessels correlates reasonably well with the ratio D_V/D, for both extremes of the two fluid systems investigated: air–water and paraffin–water systems. Even the integral data of Whalley (1991) are in a reasonable agreement with the correlation. Second, the flooding parameter increases quite

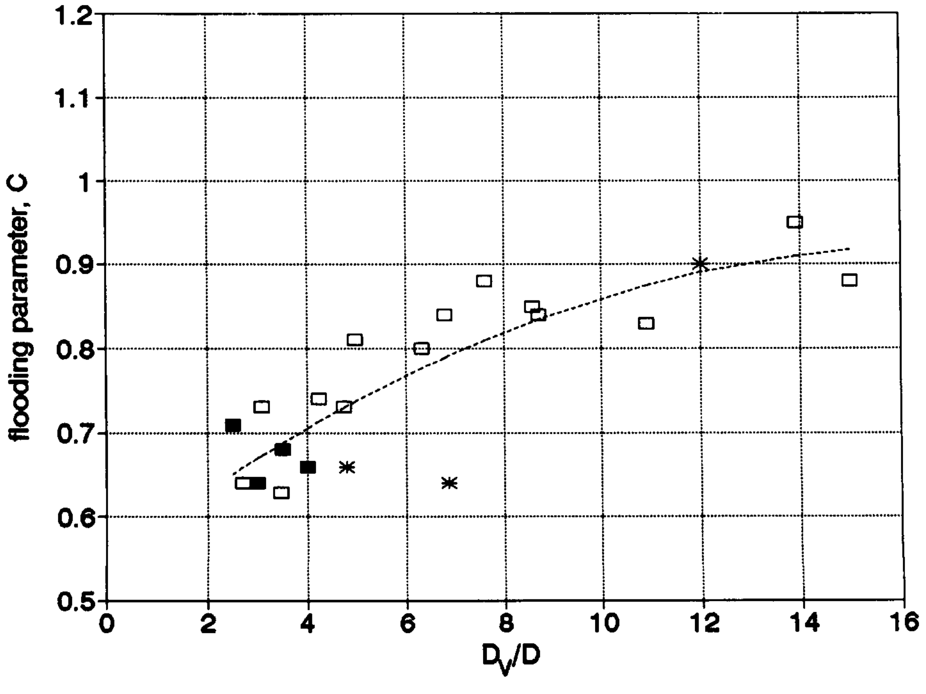

Figure 5. A plot of the flooding parameter C vs the diameter ratio D_V/D for cylindrical outlets: air–water systems (□), paraffin–water systems (*), Whalley (1991) (■), [6]—dashed line.

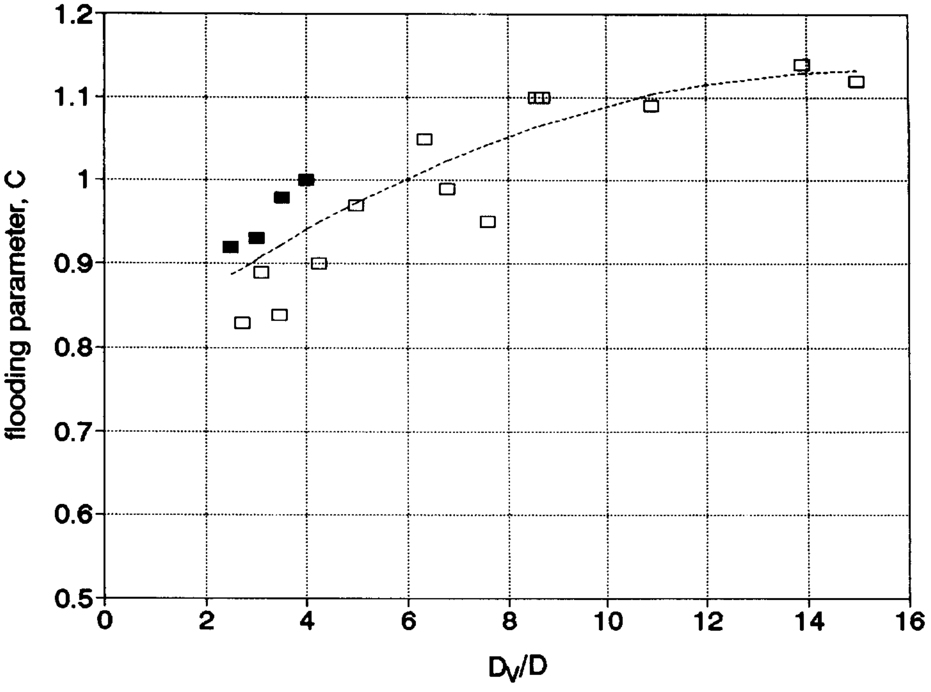

Figure 6. A plot of the flooding parameter C vs the diameter ratio D_V/D for profiled outlets: air–water systems (□), Whalley (1991) (■), [7]—dashed line.

appreciably with the ratio D_V/D. The following correlations can be obtained for cylindrical and profiled outlets, respectively,

$$C = 0.55 + 0.044\frac{D_V}{D} - 0.0013\left(\frac{D_V}{D}\right)^2 \qquad [6]$$

$$C = 0.78 + 0.046\frac{D_V}{D} - 0.0015\left(\frac{D_V}{D}\right)^2 \qquad [7]$$

both valid for

$$2.5 < \frac{D_V}{D} < 15. \qquad [8]$$

The correlations given by [6] and [7] are compared with the experimental data in figures 5 and 6, respectively.

Finally, the data in figures 5 and 6 demonstrate that the flooding parameters for the profiled outlets, C_P, are appreciably higher than the corresponding flooding parameters for the cylindrical outlets, C_C. Further analysis shows that the average value of the ratio C_P/C_C is about 1.28 with a standard deviation of 0.1. It is interesting to note that this average value is very similar to the square root of the ratio of the discharge coefficients for the two types of outlet. The discharge coefficient, c_D for the cylindrical outlet is about 0.6 and for the profiled outlet about 1.0, giving the square root of the ratio as about 1.29. This suggests that it is the actual velocity in the outlet which governs the physical processes involved.

3.4. Concluding remarks

Further analysis of the outflow of liquids from single outlet vessels has been undertaken. It has been shown that the flooding parameter C correlates well with the diameter ratio D_V/D for the two extremes of the two fluid systems investigated: water discharging into air and water discharging into paraffin. It has been further shown that the flooding parameter increases appreciably with the diameter ratio, and that for the profiled outlets it is, on average, about 30% higher than for the cylindrical outlets.

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