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# BRIEF COMMUNICATION

# FURTHER INVESTIGATION OF FLOW IN SINGLE INLET/OUTLET VESSELS

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## 1. INTRODUCTION

This paper presents an investigation of the flow of fluids into and out of vesels with a single opening. In such vessels the fluid leaving the vessel through the opening is replaced by another fluid entering the vessel through the same opening. This problem has been recently investigated by several authors, such as Whalley (1987, 1991), Tehrani *et al.* (1994), Schmidt and Kubie (1995) and Kordestani and Kubie (1996).

It is the purpose of this work to consider systematically further parameters which may influence the behaviour of these systems, such as the effect of the height of the vessel, the orientation of the outlet, and the difference between the inflow and the outflow of the denser fluid. Some of these parameters were investigated by Whalley (1987, 1991), but the systems investigated in this work are better defined, thus enabling a more rigorous investigation of the various phenomena involved.

## 2. EXPERIMENTAL WORK

In the first series of experiments the effect of the height of the vessel $l$ was investigated. A diagram of the experimental apparatus is shown in figure 1. The base of the cylinder was at $\alpha = 0^\circ$ (horizontal) and the vessel had the following dimensions: internal vessel diameter, $D_V$, 194 mm, outlet diameters, $D = 25$, 40, 55 and 70 mm and vessel height $l = 280$, 550, 1050 and 2170 mm. Water and air at room temperature were used throughout. Further details and the experimental procedure were described previously (Schmidt and Kubie 1995). In the second series of experiments the effect of the orientation of the outlet $\alpha$ was investigated by using the angle of inclinations $\alpha = 0^\circ$, $30^\circ$, $45^\circ$, $60^\circ$ and $75^\circ$, $D_V = 170$ mm, $D = 25$, 40 and 55 mm and $l$ from 1450 to 2360 mm.

In the third series of experiments the inflow of water, rather than outflow of water, was investigated. A diagram of the experimental apparatus, consisting of two perspex vessels, is shown in figure 2. The water level in the top vessel was maintained at constant level $l_1$, which was set at 1100, 560 and 280 mm. The constant level was achieved by supplying water through a perforated distribution ring at a controlled flow rate and installing an overflow pipe at the required level. The working vessel was underneath the top vessel, and the two vessels were joined with a single outlet with $D = 25$, 40 and 55 mm. The working vessel contained initially only air at atmospheric conditions, and the outlet was sealed with a stopper. The opening of the outlet allowed the inflow of water into the working vessel and the outflow of air from the working into the top vessel. The experimental procedure was as described previously (Schmidt and Kubie 1995).

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## 3. EXPERIMENTAL RESULTS AND DISCUSSION

### 3.1. General considerations

The experimental results are generally presented as graphs of the flooding parameter $C$ against $H$, where $H = h/D$ and where $h$ is the height of the air space above the interface. It is shown by Kordestani and Kubie (1996) that

$$C = \frac{U^{1/2}}{A^{1/2}} \frac{\rho_1^{1/4} + \rho_2^{1/4}}{\rho_1^{1/4}}, \qquad [1]$$

where $\rho_1$ is the density of water, $\rho_2$ is the density of air, $A = A_O/A_V$, $A_V$ is the cross-sectional area of the vessel and $A_O$ is the cross-sectional area of the outlet. Furthermore, the dimensionless interfacial vellocity, based on forward differences, is defined as $U = \Delta H/\Delta T$ with $T = t(g'/D)^{0.5}$ and $g' = g(\rho_1 - \rho_2)/\rho_1$, where $g$ is the gravitational acceleration.

Since it was shown previously that the flooding parameter is approximately independent of $H$ when $H$ is in mid-range (more than about 3 from both the top and the bottom of the vessel), only results for the mid-range are presented in this work.

### 3.2. The effect of vessel height

The cyclic features of the process were identical to those observed previously (Schmidt and Kubie 1995). Typical experimental results for the flooding parameter $C$ as a function of $H$ are plotted

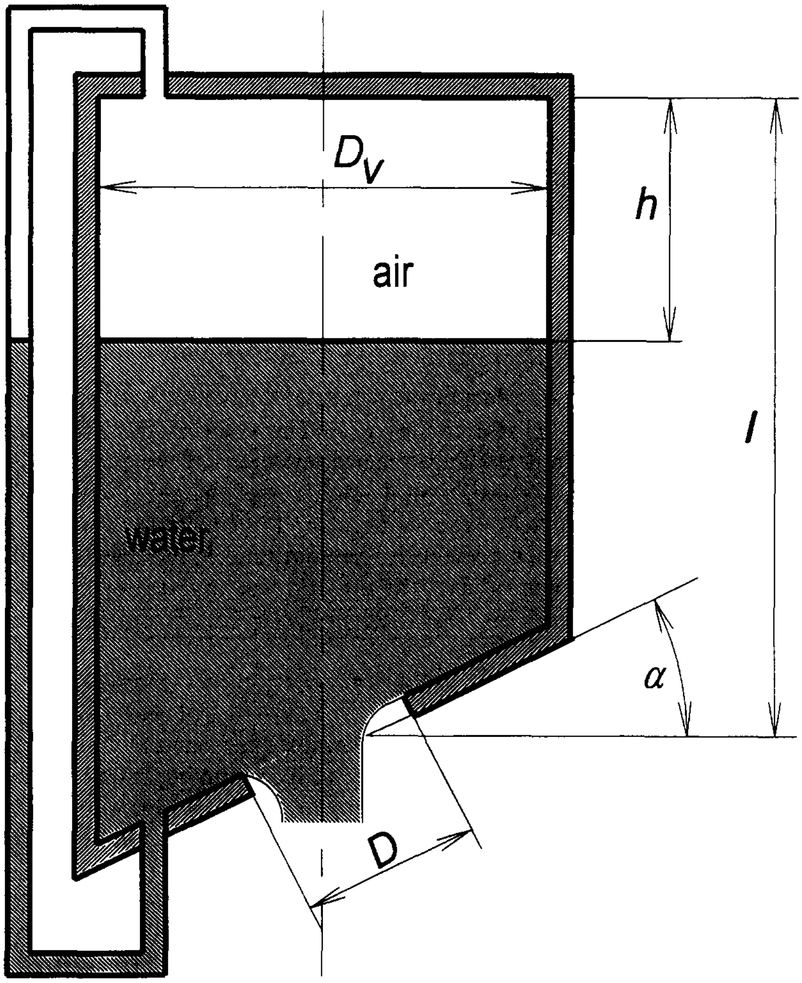


Figure 1. Diagram of the experimental apparatus for the first two series of experiments.

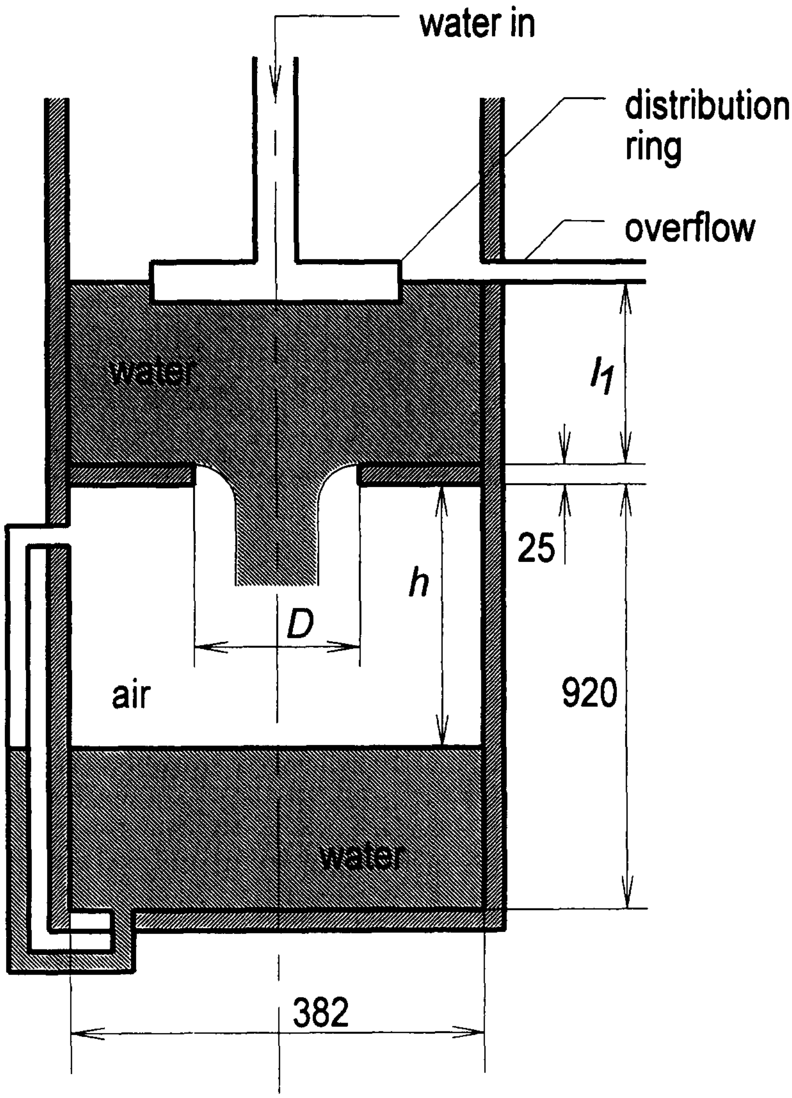


Figure 2. Diagram of the experimental apparatus for the third series of experiments (all dimensions in mm).

for the 25 mm cylindrical outlet in figure 3. Figure 3 indicates that the flooding parameter $C$ is approximately invariant with $H$ in mid-range, but that it increases as $h$ approaches the height of the vessel $l$. All experimental results indicate that the height of the vessel has a negligible influence on the value of the flooding parameters.

*3.3. The effect of the orientation of outlet*

The angle of inclination of the outlet affects significantly the ingress of air into the vessel. When the outlet is horizontal, the air bubbles penetrating the vessel are predominantly formed and confined towards the centre of the outlet. However, as the angle of inclination increases the ingressing air bubbles start forming towards the top of the outlet, and this becomes pronounced for the angles of inclination of 60° and 75° and more significant for the sharp-edged cylindrical outlets. Whereas for the profiled outlets the flow pattern generally exhibits the cyclic features described previously, the flow pattern for the cylindrical outlets is more complex. For the cylindrical outlets the flow is generally cyclic, but on occasions long periods of steady counter-current flow can be observed with simultaneous water outflow towards the bottom part of the outlet and air ingress towards the top of the outlet.

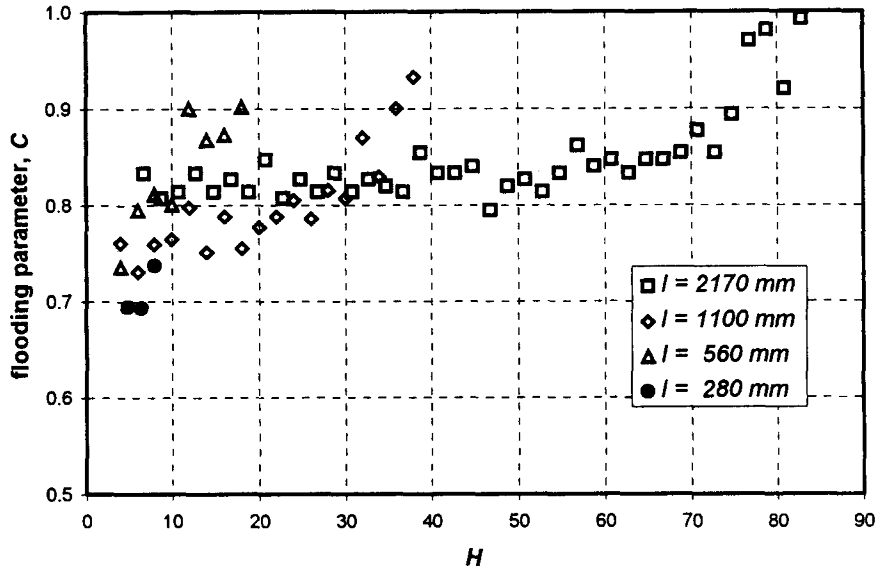


Figure 3. A plot of the flooding parameter $C$ vs $H$ for a cylindrical outlet with $D = 25$ mm: influence of the height of the vessel $l$.

The experimental data for the average value of the flooding parameter (averaged over the mid-range) are plotted vs the angle of inclination of the outlet $\alpha$ in figure 4. For the profiled outlets the figure shows the well-known maximum of the flooding parameter $C$ with respect to the angle of inclination, as observed previously by Whalley (1987) for the emptying of bottles. Since the neck of the bottles can be modelled by the profiled outlet the results are not surprising. However, the figure also shows that for the cylindrical outlets the pattern is different. It appears that for the smallest diameter outlet the flooding parameter is not significantly affected by the angle of inclination, but that for the larger diameter outlets the flooding parameter increases with the angle of inclination. This increase in the flooding parameter is more pronounced as the diameter of the outlet increases.

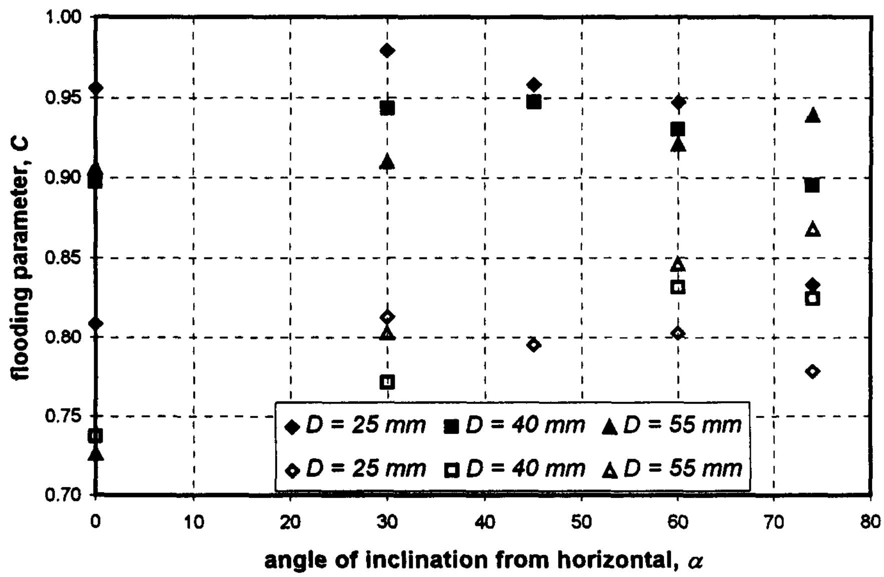


Figure 4. A plot of the flooding parameter $C$ vs the angle of inclination of the outlet $\alpha$ for profiled (solid symbols) and cylindrical (open symbols) outlets.

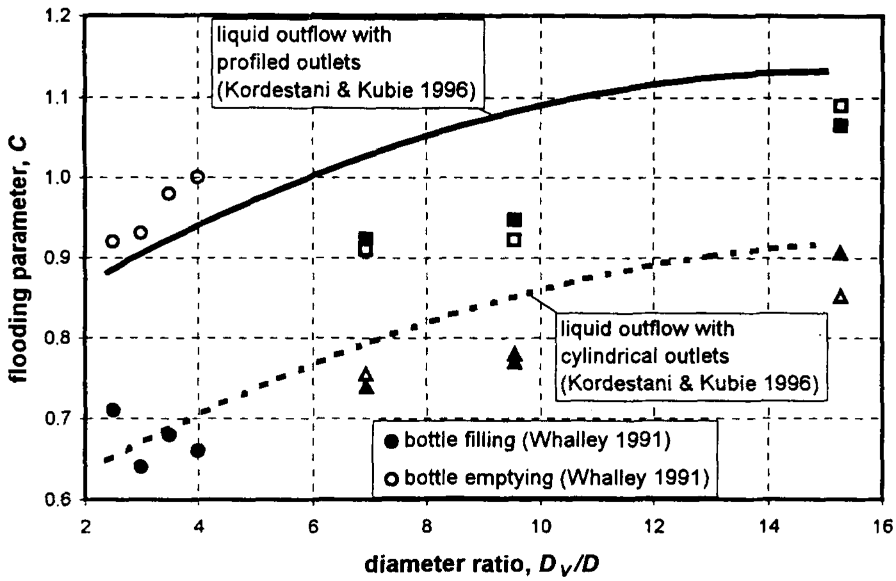


Figure 5. A plot of the flooding parameter $C$ vs $D_V/D$—comparison of liquid inflow with liquid outflow: liquid inflow with profiled outlets and $l_l = 1100$ mm (■), liquid inflow with profiles outlets and $l_l = 280$ mm (□), liquid inflow with cylindrical outlets and $l_l = 1100$ mm (▲), liquid inflow with cylindrical outlets and $l_l = 280$ mm (△).

### 3.4. *Liquid inflow*

The general chatacter of the liquid inflow is very similar to that observed for the liquid outflow; the process exhibits the same cyclic features identified previously. All experimental results of the average value of the flooding parameter $C$ for the highest ($l_l = 1100$ mm) and the lowest ($l_l = 280$ mm) levels and all outlets are plotted against the diameter ratio $D_V/D$ in figure 5, which also shows the experimental results of Whalley (1991) and the correlations for the liquid outflow obtained by Kordestani and Kubie (1996). The figure indicates that, similarly to the liquid outflow, the level in the top tank has negligible influence on the phenomena observed. Furthermore, as expected, it shows that the flooding parameters are greater for the profiled outlets and that the corresponding flooding parameters for the outflow are about 10% higher than for the inflow. Finally, it should be noted that the effect of the shape of the outlet is more important than the effect of the flow direction. This confirms, as pointed out by Whalley (1991), that bottle emptying is controlled by flooding of a profiled outlet, whereas bottle filling is controlled by flooding of a cylindrical or sharp outlet.

## 4. CONCLUSIONS

Further investigation of flow in single inlet/outlet vessels has been undertaken. It has been shown that the flooding parameters for the liquid inflow exhibit the same characteristics as the flooding parameters for the liquid outflow, but that the flooding parameters for the liquid outflow are typically about 10% higher than the corresponding flooding parameters for the liquid inflow. It has been also shown that the influence of the orientation of the outlet is strongly affected by the geometry of the outlet. For profiled outlets, the flooding parameters go through a maximum as the angle of inclination increases, whereas for the cylindrical outlets the flooding parameters are either unaffected by the angle of inclination or may increase with it. Finally, the height of the vessel has a negligible influence on the flooding parameters.

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