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A NUMERICAL INVESTIGATION OF DROP FORMED VORTEX RINGS

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ABSTRACT

A validated numerical scheme for simulating incompressible free surface flows has been used to investigate the formation of vortex rings that result from the impact of a water drop onto the surface of a deep water pool. Simulations of a 2.9mm drop impacting at 0.8m/s and 2.5m/s indicates new features of vortex ring formation that have not been reported before. For impact at 0.8m/s, numerical results predict the formation of two vortex rings during collapse of the crater that follows impact. This is significant since previous experimental studies assumed that a single impact produced a single vortex ring. Numerical results for impact at 2.5m/s predict the formation of a small vortex ring during the initial growth of a vertical Rayleigh jet. If confirmed, the formation such vortex rings disagrees with existing theories that vortex rings do not occur for Weber numbers greater than 8.

INTRODUCTION

It has been known for some time that the impact of a liquid drop onto the surface of a deep liquid pool can lead to the formation of an axi-symmetric vortex ring that penetrates beneath the pool surface. By observing the entry of an ink drop into a water pool, Thompson and Newell (1885) made the first observations of this phenomena and suggested that a vortex ring will only occur if the drop is released from heights less than a few drop diameters. Further observations of the patterns formed by a dyed drop have shown that drop formed vortex rings can become unstable to produce complicated three-dimensional structures that bear a remarkable resemblance to the mushroom cloud that follows the detonation of a nuclear bomb (Sigurdson, 1991). Other researchers (eg. Chapman and Critchlow, 1967; Peck and Sigurdson, 1994 and Rein, 1996) have noted that, prior to vortex ring formation, the drop material is distributed over the walls of a shallow crater that follows impact. After reaching a maximum depth, this crater collapses and the drop material appears to "roll up" into a vortex ring.

It is has frequently been reported that, for a given drop diameter and fluid properties, vortex rings only occur when the velocity of the impacting drop is below some maximum value. Hsiao *et al.* (1988) proposed that this upper limit can be expressed in terms of the following Weber number:

$$\mathrm{We} = U_0\sqrt{\rho D/\sigma} \qquad (1)$$

where ρ is the density of the drop and target fluids, σ is the surface tension coefficient, U_0 is the drop velocity at impact and D is the initial drop diameter. According to the mechanism proposed by Cresswell and Morton (1995), vortex ring formation is due to the action of surface tension during the initial stages of contact between the drop and target fluid. Hence, the above Weber number seem a reasonable parameter with which to characterise vortex ring formation. Based on data for water drops, Hsiao *et al.* claimed that the maximum Weber number for the occurrence of vortex rings is approximately 8.

Although drop impact in deep pools has been studied extensively, the conditions necessary for vortex ring formation and the associated flow fields remain poorly understood. This is understandable since vortex ring formation occur over short time scales (typically less than 100ms) making direct flow measurements extremely difficult. In this paper numerical simulations are used to overcome this difficulty to provide flow visualisations that have not been provided by experimental means. These visualisations help to clarify the events that lead to vortex ring formation and indicate new features that have not been reported previously.

NUMERICAL APPROACH

Method

The numerical scheme used to study vortex formation, solves the equations that describe incompressible flows that include free surfaces. The equation for volume conservation is written

$$\nabla\cdot\boldsymbol{U} = 0 \qquad (2)$$

and momentum conservation is

$$\frac{\partial \boldsymbol{U}}{\partial t}+\nabla\cdot(\boldsymbol{UU}) = -\nabla P+\frac{1}{\mathrm{Re}}\nabla^2\boldsymbol{U}+\frac{1}{\mathrm{Fr}^2}\hat{\boldsymbol{g}}+\boldsymbol{S} \qquad (3)$$

where $\boldsymbol{U}$ is the velocity, P is pressure divided by constant liquid density, $\boldsymbol{S}$ is the non-dimensionalised surface tension acceleration, $\hat{\boldsymbol{g}}$ is the unit gravity vector, $\mathrm{Re} = \rho U_0 D/\mu$ is the Reynolds number and $\mathrm{Fr} = U_0/\sqrt{gD}$ is the Froude number. In solving Eqns.2 &3 axial symmetry is assumed. Furthermore, since the density of the gas phase is at least three orders of magnitude less than the liquid phase density, the gas flow is neglected so that the equations are solved in the liquid phase only.

Details of the numerical techniques used to solve Eqns.2 & 3 are described in Morton, 1997. Briefly, the governing equations are discretised using second order accurate finite differences and pressure-velocity coupling is achieved using a two step projection method that includes solution for a pressure correction (δP). Deformation of free surface is modelled using the "VOF" method of Hirt and Nichols (1979) in combination with Youngs scheme (1982) for advecting the volume fraction. Finally, the ideas described by Brackbill *et al.* (1992) and Rudman (1998) are implemented to express the surface tension as a body force that is added to Eqn.3.

Validation

The suitability of the above numerical scheme for predicting the events that follow drop impacts has previously been proven by comparing numerical results against observations made using speed cinematography (Morton, 1997). Simulations of a 2.9mm water drop impacting a water pool from heights of 170mm and 400mm were shown to be in good qualitative and quantitative agreement with the observations. The simulations were capable of resolving such features as capillary waves on the surface of the cavity that follows drop impact, formation of small bubbles during the collapse of this cavity and formation of a vertical Rayleigh jet which detached secondary droplets. The ability to predict these features indicate the accuracy of the finite difference approximations and free surface modelling is sufficient for the purpose of studying drop impacts.

In addition to the comparison of numerical and experimental results, a grid convergence study was undertaken to determine the minimum number of computation cells required to resolve the flow that occurs after drop impact. In this study, the impact of a 2.9mm water drop from a height of 400mm was simulated using meshes consisting of 128×128, 256×256 and 512×512 meshes of uniform size cells. Figure 1 shows that a 512×512 grid is sufficient to resolve the features of the cavity that appears in the pool fluid after impact. A similar comparison of jet heights, showed that jet behaviour is well resolved by a 512×512 grid to the time at which the jet becomes unstable and a droplet forms at its tip. Observations reported in the literature (eg. Rein, 1995) suggest vortex rings occur well before this time and thus we can confidently use a 512×512 to predict the associated fluid flow.

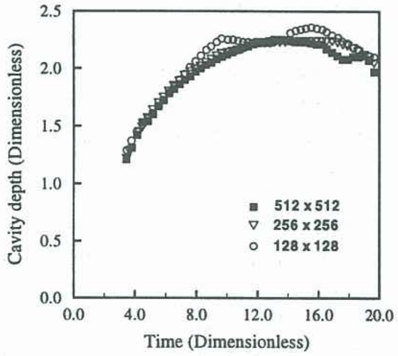

Figure 1: Comparison of cavity depths (determined at the axisof symmetry) predicted by simulations for of a 2.9mm water drop impacting a deep water pool from a height of 400mm.

RESULTS AND DISCUSSION

The validated numerical scheme has been used to simulate the flow that follows the impact of a 2.9mm water drop at 0.8m/s (Fr=4.7 and We=5.0) and 2.6m/s (Fr=15.8 and We=16.9). In both cases, simulations were performed on a 512×512 mesh of computation cells. At the beginning of each simulation, passive tracer particles were randomly distributed inside the impacting drop and subsequently advected with the local velocity. The distribution of these particles provides an indication of the distribution of drop fluid following impact.

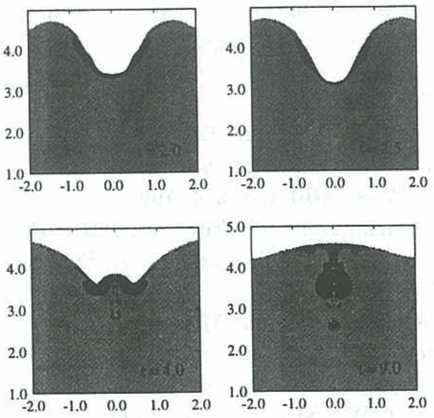

Figure 2: Predicted free surface profiles for a 2.9mm water drop impacting at 0.8m/s (Fr=4.7 and We=5.0). Black regions represent the position of marker particles used to track the drop material. All times are non-dimensionalised with U_0/D.

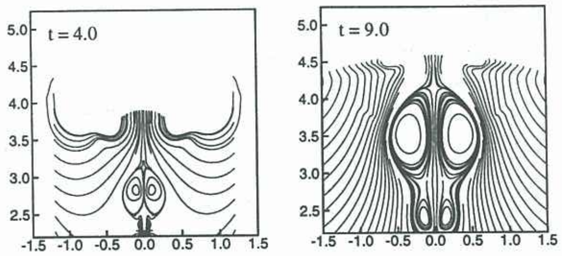

Figure 3: Streamtraces calculated from the velocity fields predicted for a drop impacting a deep liquid pool at 0.80m/s (Fr=4.7 and We=5.0).

Vortex rings at low Weber numbers

In the case of impact at 0.8m/s, drop impact results in a shallow cavity that reaches a maximum cavity depth of 1.4D before collapse commences. During this collapse, the initial drop fluid penetrates downwards into the pool fluid (see $t = 4.0$ & $t = 9.0$ in Fig.2). Streamtraces calculated from the predicted velocity fields (Fig.3), indicate that this penetration is due to the occurrence of two axi–symmetric vortex rings. The first forms during the initial stages of cavity collapse and entrains only a small proportion of the drop material (see $t = 4.0$). The second ring is larger, entrains most of the drop fluid and is not fully developed until cavity collapse is almost complete (see $t = 9.0$).

The numerical results are significant since, for the first time, they suggest that a single impact can lead to multiple vortex rings. Previous experimental studies (eg. Chapman and Critchlow, 1965; Peck and Sigurdson, 1994 Rein, 1995) have reported a single rings only. The vortex rings observed in these studies corresponds to the second, larger ring predicted here. In the experiments, patterns formed by a dyes drop were used to indicate the presence of a vortex ring. Hence, it is not surprising that the smaller ring may have been missed since it entrains only a small amount of drop material and would be difficult to detect visually. Nevertheless, further experimental evidence (ie. velocity measurements) is required in order to confirm the presence of the first, smaller ring.

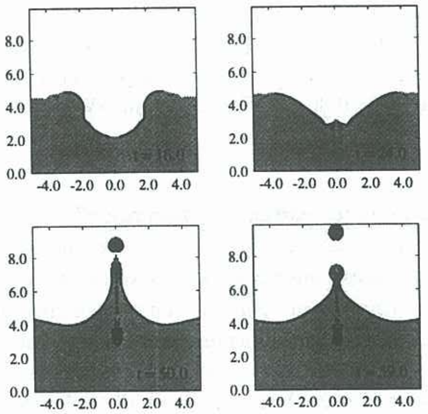

Figure 4: Predicted free surface profiles for a 2.9mm water drop impacting at 2.6m/s (Fr=15.8 and We=16.9). Black regions represent the position of marker particles used to track the drop material. All times are non-dimensionalised with U_0/D.

Vortex rings at high Weber numbers

Simulations of drop impact at 2.6m/s (Fr=15.8 and We=16.9) predict that a deep cavity forms in the pool fluid and attains a maximum depth of 2.3D. The collapse of this cavity results in the formation of a vertical Rayleigh jet which is unstable and ejects two droplets (see Fig.4). The first of these drops contains only drop fluid and accounts for approximately 50% of the initial drop mass. At $t = 59.0$ in Fig.4, the distribution of the passive marker particles suggest that a small proportion of the remaining drop material is entrained beneath the free surface. Streamtraces evaluated at $t = 59.0$ in the region where this entrainment occurs, reveal this behaviour is due to a small vortex ring (Fig. 5). Further investigation of the predicted velocity fields indicate that this vortex begins to form during the initial stages of jet formation when the fluid at the lowest point of the collapsing cavity begins to move upwards. Like the smaller vortex rings predicted for impact from 0.8m/s, this ring has not been reported previously due to difficulties in detecting it without the aid of velocity measurements. Such velocity measurements would improve visualisations and are required in order to confirm whether vortex rings formation can occur simultaneously with Rayleigh jet formation.

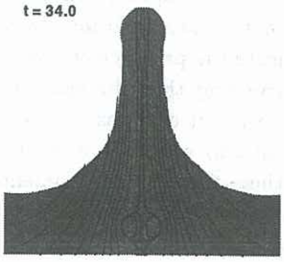

Figure 5: Streamtraces showing the small vortex ring that occurs during the initial formation of the Rayleigh jet that follows the impact of a 2.9mm water drop at 0.80m/s (Fr=15.8 and We=16.9).

Conditions for vortex ring formation?

The numerical results reported here raise some interesting issues concerning the conditions under which vortex rings form. Firstly, the vortex ring predicted for impact at 2.6m/s occurs at We=16.9 which is more than twice the critical Weber number reported by Hsiao et al (1988). Hence, providing the existence of this vortex ring can be validated, it's existence casts doubt on previous reports that there is a critical Weber number above which no vortex rings occur.

A second issue is related to the observation that, for certain combinations of Froude and Weber number, drop impact can lead to a cavity that collapses in a manner the leads to a small air bubble being entrained into the pool fluid (Pumphrey and Elmore, 1990). Additional simulations of a 2.9mm water drop impacting at 1.5, 1.83 and 2.0m/s predict this phenomena and indicate that when bubble entrainment occurs there are no vortex rings formed (Morton, 1997). This result, combined with the predictions of vortex ring formation reported here, suggest that the mechanisms for bubble entrainment interferes with the mechanisms for vortex ring formation to prevent rings from occurring. The exact nature of this interference is the subject of an ongoing study

CONCLUSIONS

Numerical simulations of the events following the impact of a 2.9mm water drop have predicted features of drop formed vortex rings that have previously been unreported. Simulation of impact at 0.80m/s suggest that a single impact at a low velocity (ie. low Weber number) can result in the formation of multiple rings. Results for a drop impacting at 2.6m/s indicate that vortex rings can occur for impact conditions that result in the formation of a vertical Rayleigh jet. If these new phenomena can be validated experimentally, they suggest a need to re-examine existing theories that vortex rings do not occur for We > 8. Furthermore, new observations highlight the need for an improved understanding of the mechanisms of vorticity generation during drop impact and the subsequent formation of vortex rings.

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