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INVESTIGATION OF DROP FORMATION BY A VORTEX RING IN MICROGRAVITY

Luis P. Bernal and Pepi Maksimovic
Department of Aerospace Engineering
University of Michigan
Ann Arbor, Michigan 48109-2118

ABSTRACT

An investigation of drop formation by a vortex ring propagating through one or more fluid interfaces in microgravity is described. The main goal of the research is to determine the dynamics of drop formation by vortical flows in the capillary limit with large density change across the interface. Dimensional analysis shows that in microgravity experiments the capillary limit can be studied using a relatively large vortex ring diameter to facilitate experimental characterization of the interaction. Results obtained in density matched systems are reviewed to illustrate the complex nature of these interactions.

INTRODUCTION

We consider the propagation of a vortex ring through one or more fluid interfaces. The flow configuration is shown schematically in Figure 1. It consists of a vortex ring formed in the liquid below the interface moving toward one or more fluid interfaces (Figure la). If the vortex ring has sufficient impulse the collision of the vortex ring with the interface(s) will result in the formation of a drop (Figure lb). If the initial condition consisted of several liquid layers the resulting drop is expected to have a layered structure as well. The size of the drop is determined by the volume of fluid carried by the vortex ring. The fluid motion inside the drop is determined by the vorticity distribution in the vortex ring. This relatively simple flow problem captures important dynamical processes relevant to the evolution of fluid interfaces in microgravity and in other flow systems. For a review of the flow characteristics of vortex rings see the review paper by Shariff and Leonard.[1]

The dynamics of fluid interfaces in the case of surface-tension-dominated evolution is important in many practical problems. Atomization of liquid fuels is influenced by the interfacial properties of the fuel as well as by fluid motion within the liquid. For example, several investigators have found important effects of liquid turbulence on the spray characteristics of a nozzle.[2-4] Wu *et al.*[5] investigated primary breakup of a turbulent liquid jet. They used holographic imaging to measure the drop size distribution. The spatial and temporal resolution in these experiments was not adequate to capture the evolution of the breakup process. However they developed a phenomenological model of turbulent breakup that is illustrated in the sketch in Figure 2. In this model the size of the drop is assumed to be of the order of the size of eddies in the turbulent liquid. They obtained good correlation between the measured mean drop size at several Weber numbers and the predictions of the model. The interaction of the vortex ring with a fluid interface resulting in the formation of a drop is viewed as an idealization of the interaction of a turbulent eddy with the liquid surface. These flow processes in typical atomization systems are very difficult to investigate experimentally because of the small size of the droplets. As shown below the limit of interests is the capillary limit, i.e. finite Weber number and infinite Froude number, that is the same as in microgravity. It follows that experiments in microgravity can provide valuable new insights on the dynamics of flow induced atomization.

The study of the interaction of a vortex ring with multiple fluid interfaces is motivated in part by problems in encapsulation technology. The goal of this technology is to produce small drops of a drug solution coated with a membrane of suitable chemical and biological properties. The fluid dynamic processes encountered in this technology have been reviewed by Kendall *et al.*[6] Lin and Wang[7] proposed an encapsulation system using a droplet generator based on the Rayleigh instability of a liquid column. Microgravity experiments of a vortex ring propagating through multiple fluid interfaces can provide new insights on these problems and should contribute to the development of improved encapsulation technology.

The interaction of a vortex ring with a fluid interface in microgravity is a relatively simple flow configuration where the balance between capillary, viscous and inertia forces is similar to that found in a variety of flow problems of practical interest. It is a relatively simple flow configuration that can be easily implemented in existing microgravity facilities. The vortex ring flow has been used frequently to study the dynamics of the interaction of vortical flows with miscible and immiscible fluid interfaces.[9-20] The present experiments extend this work to the case of surface-tension-controlled interface dynamics.

DIMENSIONAL ANALYSIS

To help clarify the role of various parameters in the flow we use dimensional analysis for the case of a single interface.[21] The initial state is characterized by the vortex ring diameter, a, and circulation, Γ. The interface is characterized by the densities ρ_1 and ρ_2, the viscosities μ_1 and μ_2, and the interfacial tension σ. The ring moves toward the interface with speed U and collides with it. The collision and the subsequent evolution of the drop depend on fluid inertia, viscosity and surface tension. Therefore the nondimensional numbers characterizing the phenomena are the Weber number, the Froude number and the Reynolds number. These are defined as:

$$We = \frac{\rho_1 \Gamma^2}{\sigma a}, \quad Fr = \frac{\rho_1 \Gamma^2}{(\rho_1 - \rho_2)\, g\, a^3}, \quad Re = \frac{\rho_1 \Gamma}{\mu_1},$$

respectively. In addition, the density ratio $r = \rho_2 / \rho_1$ and the viscosity ratio $\lambda = \mu_2 / \mu_1$ must be specified. Here, the subscript 1 denotes the fluid below the interface and inside the drop and 2 the fluid above the interface. In the experiments of Bernal *et al*[21] r = 0.99 and for a typical liquid/gas interface r ≈ 10^{-3}.

The effect of the gravitational acceleration is best illustrated by a plot of We versus Fr as shown in Figure 3. For fixed vortex ring diameter and interface properties, all possible vortex ring strengths (i.e. circulation Γ) define a straight line. The slope of the line is the Bond number,

$$Bo = \frac{We}{Fr} = \frac{\rho_1 - \rho_2}{\sigma} g\, a^2.$$

Shown in Figure 3 are two lines for 1g. These lines correspond to the interaction of a 1 cm diameter vortex ring with a water/air interface (r ≈ 10^{-3}) and with a silicon-oil/water-methanol interface (r = 0.99). These are conditions typical of what can be obtained in 1g with density matched systems. The corresponding Bond numbers are 14 and 0.4 respectively.

In microgravity experiments the gravitational acceleration is very small, approximately 10^{-5}g in the 2.2 sec drop tower, and consequently the Bond number is at least four orders of magnitude smaller than in 1g. The corresponding lines in Figure 4 coincide with the horizontal axis. This condition corresponds to the capillary limit of finite Weber number and infinite Froude number. Using Bond number scaling it follows that an experiment in microgravity with a vortex ring diameter of 1 cm would be equivalent to an experiment in 1g with a vortex ring diameter of 32 μm. In the experiments of Wu *et al.*[5] the drop size varied from 350 μm to 34 μm as the jet speed was increased.

RESULTS FOR DENSITY MATCHED SYSTEMS

Bernal *et al*[21] studied the interaction of vortex rings with a fluid interface. They consider the case of small density change across the interface. Figure 4 shows the evolution of the interaction as determined by Laser Induced Fluorescence (LIF) flow visualization pictures (first row) and the results of numerical simulations at the same flow conditions (second and third row). These experiments show that at sufficiently high Froude and Weber number the vortex ring penetrates the interface and forms a drop. Before breakup the interface is highly stretched and vorticity is left behind along the liquid column. The location where the interface breaks depends on the strength of the vortex ring. It occurs near the vortex ring at high Froude/Weber number and away from the vortex ring, near the undisturbed interface at low Froude/Weber number. They observed the formation of satellite drops during the interaction that are observed the formation of satellite drops during the interaction that are associated with concentrations of vorticity along the stretched interface. The numerical simulations are in good agreement with the experiments. Computation at several Froude and Weber numbers suggest than in the capillary limit drops form at Weber number greater than ≈4. An interesting observation is the formation of a reflected vortex ring propagating in the direction opposite to the drop motion.

Bernal & Maksimovic[22] studied the propagation a vortex ring through two immiscible interfaces. The top and bottom layer were mixtures of water and methanol and the middle layer was silicone oil. Figure 5 shows the evolution of a relatively weak vortex ring. The Froude and Weber number based on the lower interface properties are 100 and 49 respectively. The thickness of the middle layer is H/a = 3.7. The initial evolution is similar to that reported by Bernal *et al*[21] for a single interface. In this case however, the vortex ring reaches the second interface before the liquid column breaks. The third image in the sequence captures the flow after the vortex ring has penetrated the second interface and the liquid column breakup. The final image in the sequence shows the vortex ring in the liquid layer on top. At these conditions the vortex ring does not carry any silicone oil from the middle layer. Because the top and bottom layer are made of the same components, namely water and methanol, the vortex ring structure that forms in the top liquid layer is not a drop. In this case fluid from the lower layer is transferred to the top layer without a silicone oil coating. The pictures also show the formation of smaller satellite drops below the main vortical region.

Figure 6, also for a three layer system, shows the evolution of a stronger vortex ring and a larger depth of the middle layer. The Froude and Weber number based on the lower interface properties are 324 and 144 respectively. The thickness of the middle layer is H/a = 5.9. In this case the vortex ring penetrates the interface and forms a drop of liquid from the lower layer in the middle layer. The drop forms before reaching the second interface in the first image. The last three images show that the interaction with the second interface results in the formation of a drop of dyed fluid in the top layer covered by a layer of silicone oil. The dyed liquid originated in the lower layer while the silicone oil originated in the middle layer This "drop-within-a-drop" structure indicates that at these flow conditions the drop engulfs a significant amount of silicone oil as it moves through the middle layer.

SUMMARY

Microgravity experiments could be used to study flow induced atomization processes at a larger scale than in 1g experiments and, consequently , detailed measurements can be obtained more easily. The vortex ring flow is a useful model for the interaction of vortical flows with fluid interfaces. Experiments in density matched systems show several interesting phenomena. The results show that regions of concentrated vorticity play an important role in the formation of satellite drops.

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FIGURES

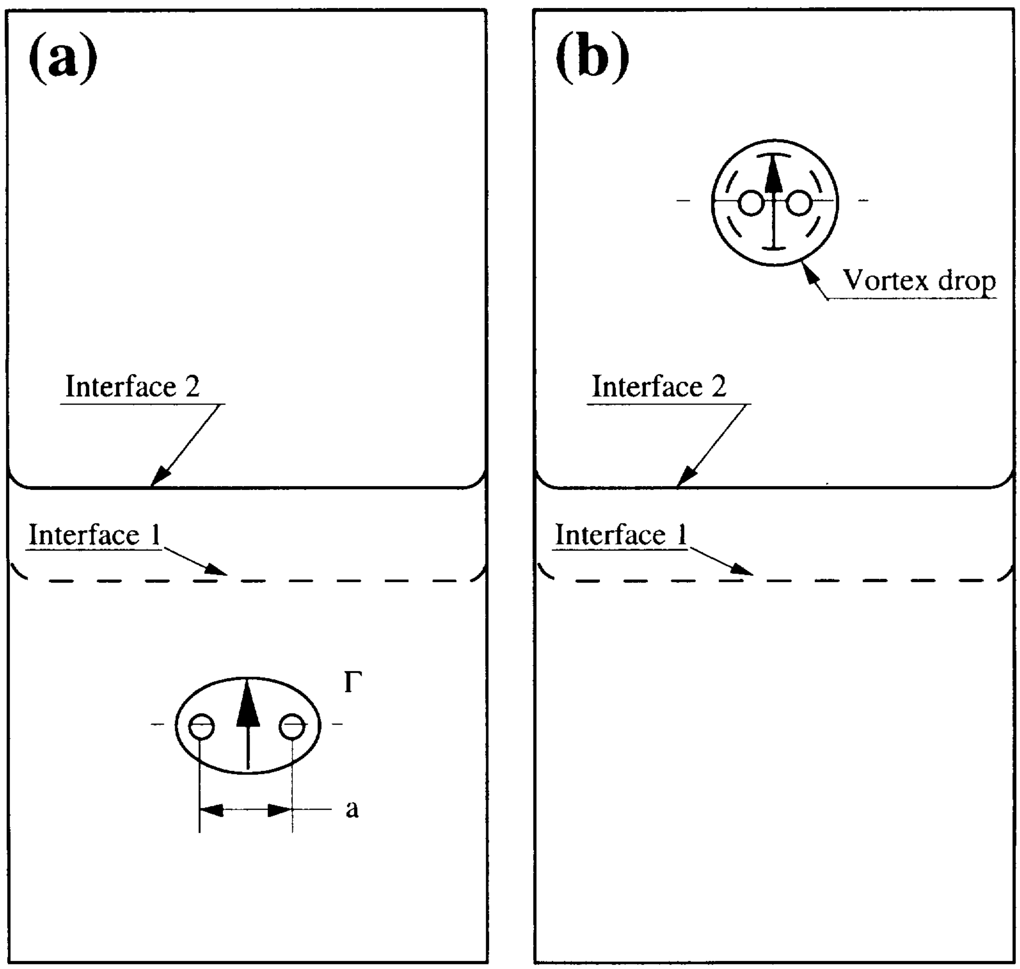


Figure 1 Schematic diagram of the interaction of a vortex ring with fluid interfaces. (a) Idealized picture before the interaction. (b) Idealized picture after the interaction. Note that the multiple interface structure in (a) is expected to result in a layered structure of the drop in (b).

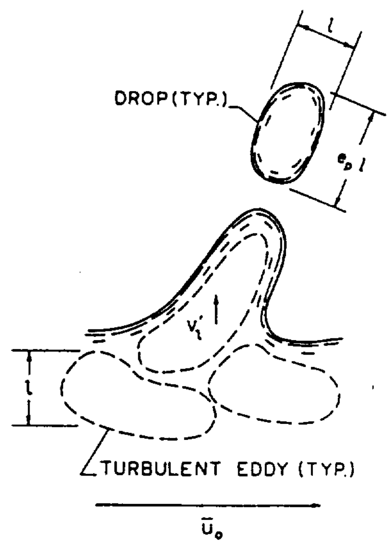


Figure 2 Sketch of turbulent primary breakup at a liquid surface (from Wu *et al*[5])

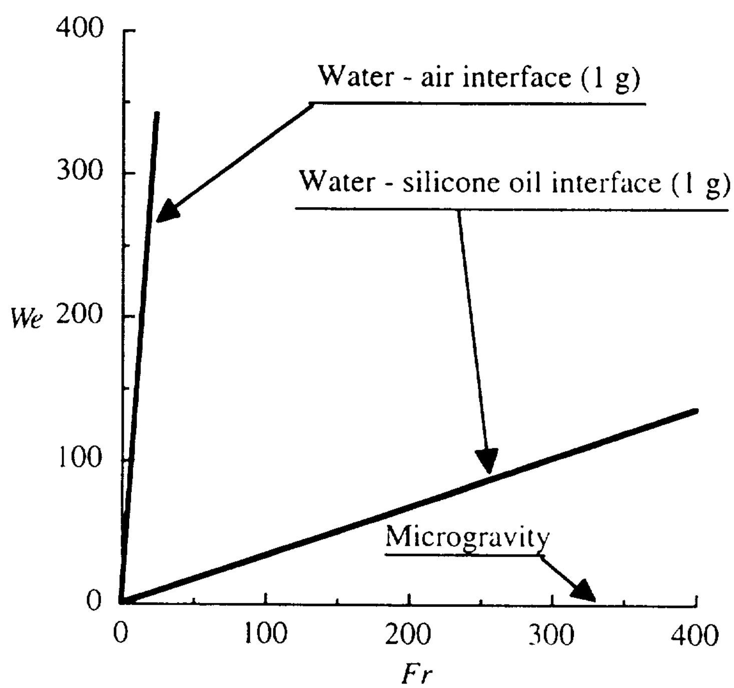


Figure 3. Plot of the Weber number vs the Froude number for typical interfaces on earth based systems (1 g) and in microgravity.

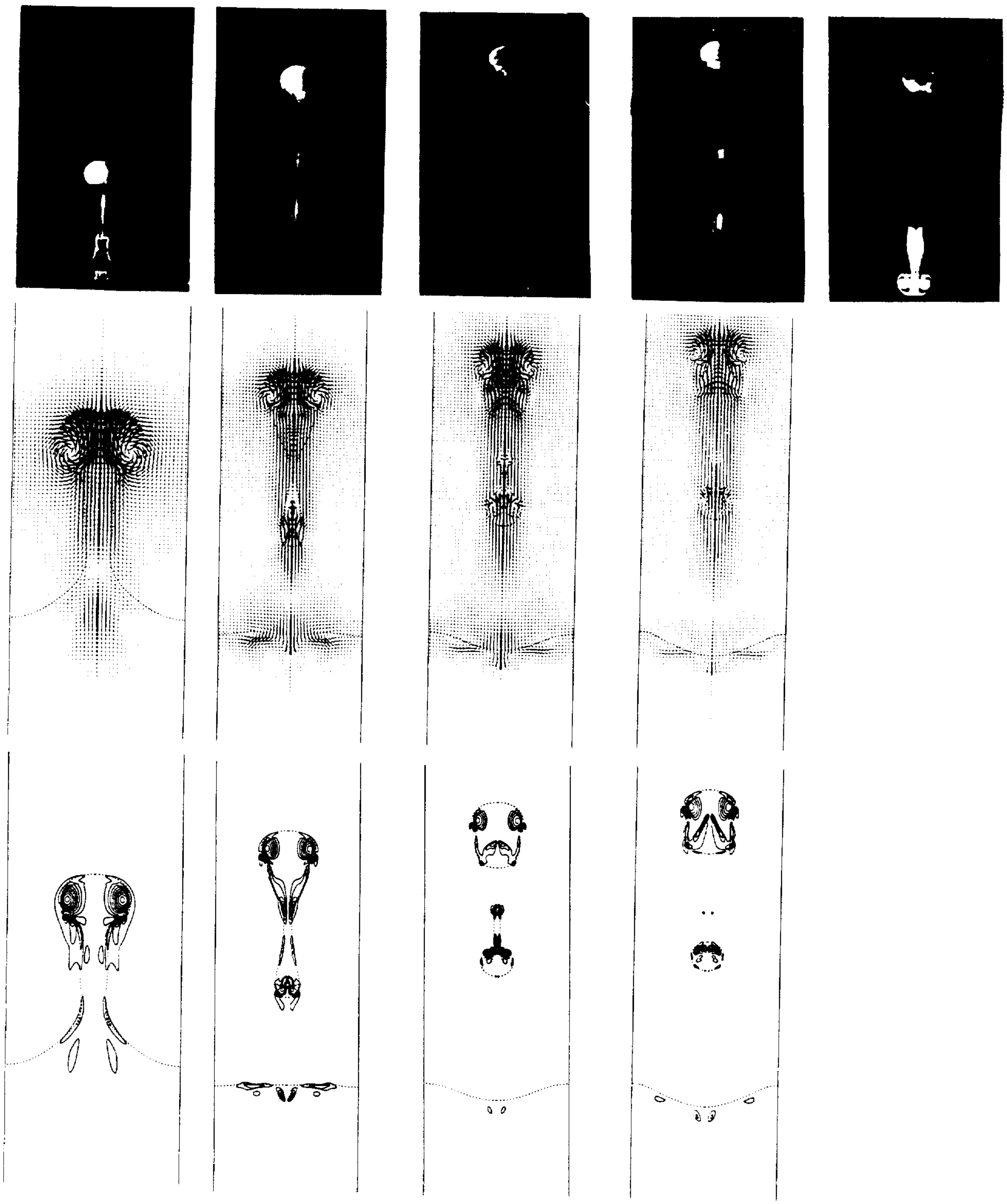
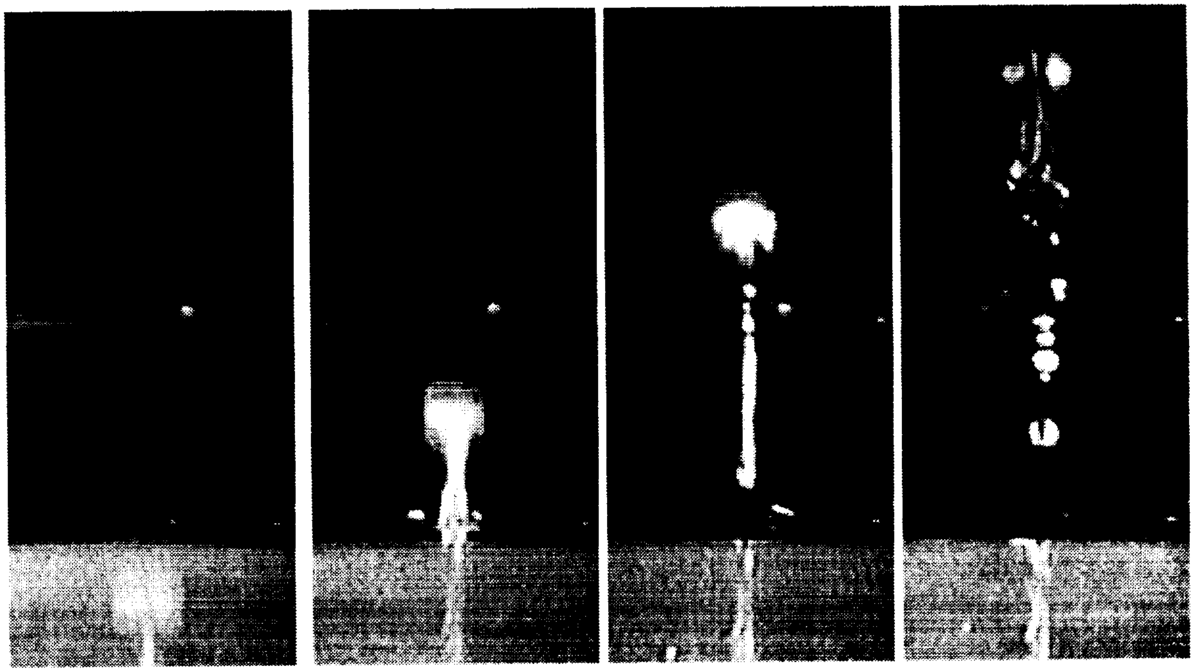
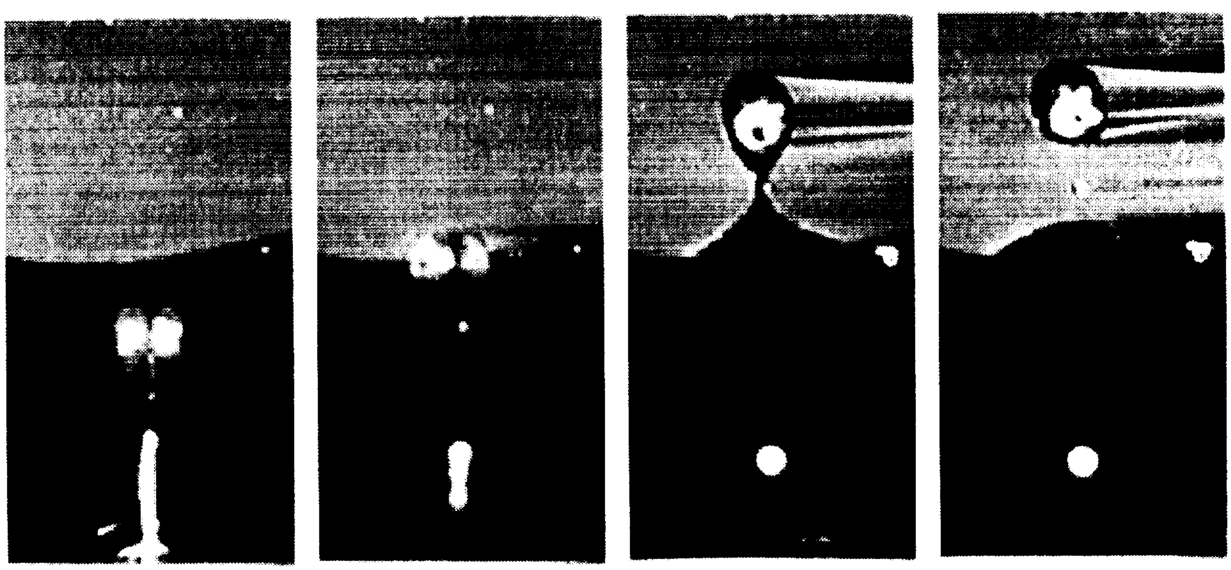


Figure 4. Interaction of a vortex ring with a fluid interface at Fr = 63, We = 22 and Re = 1200. First row flow pictures obtained a Ut/a = 7.1, 10.34, 11.88, 12.35, 16.66 (from left to right). Second and third row - Computational results obtained at Ut/a = 6.26, 9.22, 10.3, 11.48(from left to right). Second row - velocity vector plot and interface elevation. Third row - vorticity contours. (From Bernal et al.[21])



(a) t=0.078 s (b) t=0.218 s (c) t=0.378 s (d) t=0.587 s

Figure 5. Propagation of a vortex ring through two fluid interfaces. Froude number Fr_1 = 100, Weber number, We_1 = 49, Reynolds number 1920.



(a) t=0.218 s (b) t=0.318 s (c) t=0.988 s (d) t=1.118 s

Figure 6. Propagation of a vortex ring through two fluid interfaces. Froude number Fr_1 = 324, Weber number, We_1 = 144, Reynolds number 3373.