Subsurface Phenomena and the Splashing of Drops on Shallow Liquids

Abstract. *High-speed movies have been taken of the formation of the subsurface cavity and of the Rayleigh jet formed during the splash of a drop on a shallow liquid. They show that the initial increase and subsequent decrease in the rate of rise of the jet and the maximum jet height with decreasing depth of liquid are the result of the interaction of the subsurface cavity with the solid boundary beneath the liquid. This interaction modifies considerably the pressure gradients in the liquid during the formation and collapse of the cavity.*

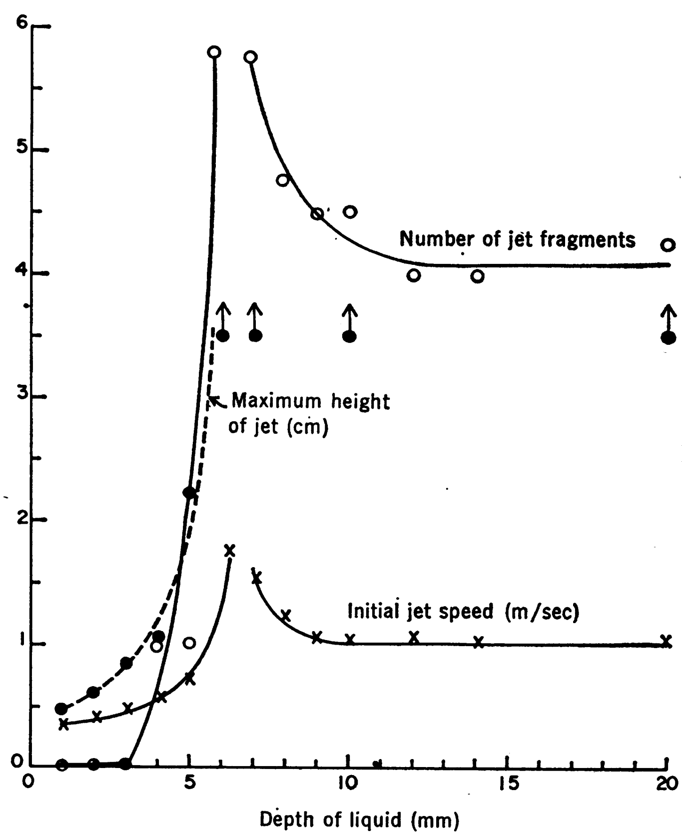
The splashing of raindrops plays an important role in soil erosion and in the dispersal of seeds and microorganisms (*1*). In addition, the electrical charges which are separated during splashing are responsible for waterfall electrification (*2*) and probably also play a role in separating electrical charges in natural clouds.

The phenomena associated with the splashing of a drop in a deep liquid have been described (*3–5*). Following the collision of the drop with the surface, a flared film of liquid is thrown upward and outward from the periphery of the drop. The height of the film increases as the drop penetrates further into the liquid and small jets are shot out from its rim, giving the appearance of a crown. These jets break up to give numerous spray droplets. At the same time, the cavity or hollow which forms beneath the surface, due to the impact of the drop, is enlarged. The walls of the film subside and thicken as the initial kinetic energy is dissipated and, below the surface, the cavity begins to collapse. The pressure gradients established in the liquid during the formation and collapse of the cavity have been discussed by Engel (*4*). The combined effects of the collapse of the cavity and of the subsidence of the film cause a relatively large column of liquid, called the jet, to rise above the surface. This jet may pinch off to form one or more large drops.

The suprasurface phenomena that accompany the splashing of drops on shallow liquids have been investigated experimentally by Hobbs and Osheroff (*6*). They found that the film and the jet vary greatly as the depth of the liquid is decreased from about 20 mm to 1 mm.

The tentative explanation for the variations suggested by Hobbs and Osheroff is incorrect (*7*). In this report we describe the results of experiments in which simultaneous high-speed movie photographs were taken of the subsurface and suprasurface events that occur during splashing on shallow liquids. These observations have revealed the reason for the remarkable variations in the suprasurface phenomena as the depth of a liquid is decreased from 20 mm to 1 mm.

Drops of distilled water were forced through a 26-gauge hypodermic needle, using a pressure head of 20 cm of water. The drops fell into a large square tank made of clear plastic which contained distilled water. The drop diameter was 2.3 mm and the height of fall was kept constant at 75 cm. Illumination was by means of diffuse light from behind the tank, and the splashes were photographed by a high-speed 16-mm



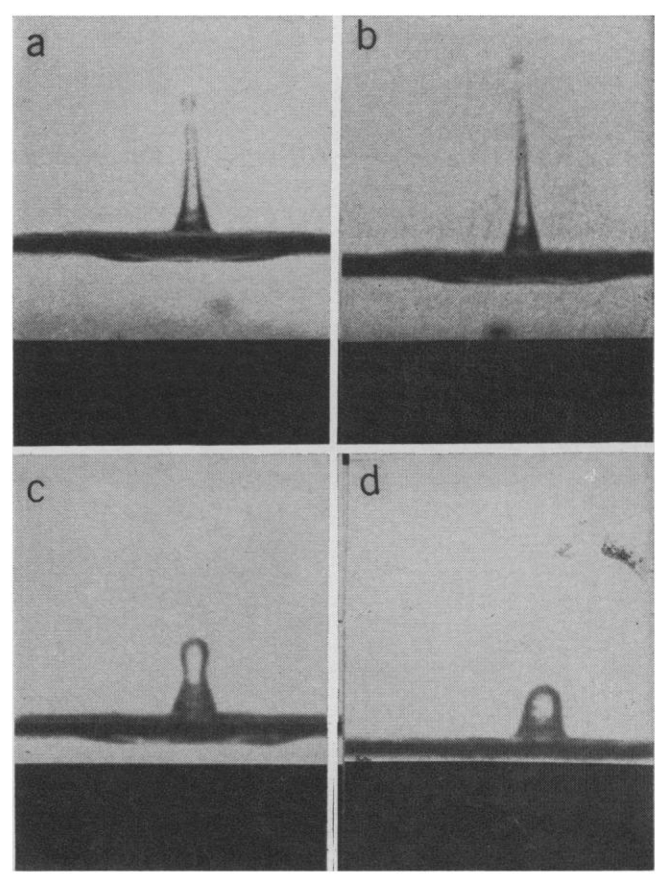


Fig. 1 (left). Experimental results for jet produced by water drops 2.3 mm in diameter impacting at 3.2 m/sec on water. (Arrows attached to experimental points indicate that top of jet went above field of view.) Fig. 2 (right). The jet at times of maximum height for liquids of depths (a) 9 mm, (b) 7 mm, (c) 4 mm, and (d) 2 mm (magnification approximately $\times$ 1.5).

movie camera operated at 480 frames per second.

As the depth of the water into which the drops splashed was decreased from 20 mm to 1 mm, the maximum height of the jet above the surface of the water, the initial speed with which the jet rose, and the number of fragments into which the jet broke changed markedly (Figs. 1 and 2). For comparison with the jet velocity, the speed of the drop on impact was 3.2 m/sec. These results confirm the observations of Hobbs and Osheroff.

An examination of the movie films showed that the manner and rate of formation of the subsurface cavity did not differ for depths of water between 20 and 10 mm. It can be seen from Fig. 1 that the behavior of the jet was also unchanged for depths between 20 and 10 mm. For this range of depths, the cavity expanded as a hemisphere to a maximum depth of 6.0 mm (2.6 drop diameters), which was reached about 12 msec after the drop first made contact with the surface. The rate at which the cavity penetrated into the water decreased in an exponential manner with time, being approximately 1.1 m/sec 1 msec after impact and 0.5 m/sec 10 msec after impact.

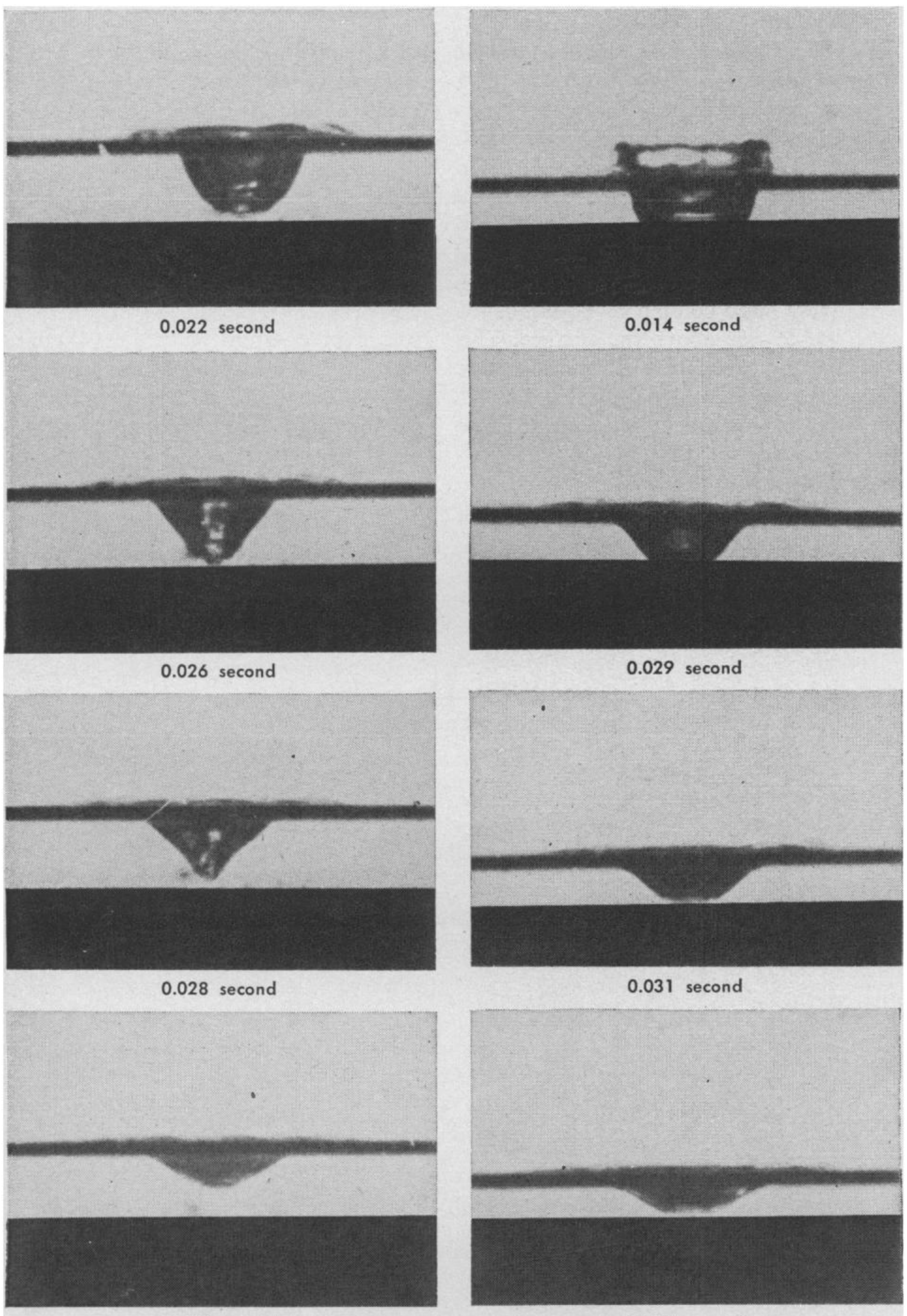


Fig. 3. Collapse of cavity for water depths of 7 mm (left) and of 5 mm (right). Times are measured from the moment of impact of the drop with the surface (magnification approximately $\times$ 1.5).

For water less than about 9 mm deep the shape of the cavity begins to be affected by the proximity of the rigid base of the container. For depths between 9 and 6 mm this causes a slight flattening of the base of the cavity (see photographs in Fig. 3 for a depth of 7 mm) and in this range the energy associated with the jet increases markedly (Fig. 1). Below a depth of about 6 mm, the cavity punctures its way completely through the liquid to the bottom of the container and the manner in which the cavity collapses is now completely different from that at greater depths (see photographs in Fig. 3 for a depth of 5 mm).

It is clear that the explanation of the results shown in Fig. 1 lies in the interaction of the cavity with the bottom of the container. This interaction drastically changes the pressure gradients in the liquid during the formation and collapse of the cavity. At depths between 9 and 6 mm, where the bottom of the cavity becomes increasingly flattened with decreasing depth, the pressure gradients are more vertical than at greater depths. Hence, as the depth of liquid is decreased from 9 mm to 6 mm the jet rises more quickly and becomes increasingly thin. Therefore, the maximum height attained and the number of jet fragments increase. For depths less than 6 mm, the pressure gradients in the liquid are more horizontal than in the case of deeper liquid. Consequently, the jet is much broader and rises more slowly to a lower height.

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