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Technical Note

Evolution of liquid/solid contact area of a drop impinging on a solid surface

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Abstract

Time evolution of liquid/solid contact area of impacting drop on a solid surface has been investigated experimentally by means of a flash photographic method. The case has been treated where water drops with about 2.4 mm in diameter impinge vertically on a horizontal smooth surface. It has been found that a liquid drop contacts the surface with a ring-shape at the moment of collision. Inside this ring-shaped liquid/solid contact area, air is entrapped between the liquid and the solid surface. Liquid does not contact the surface there. The noncontact area decreases sharply with time, and then becomes constant. The physical phenomena occurring at the liquid/solid interface have been discussed from an experimental point of view. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Collision behavior of liquid drops with a surface; Liquid/solid direct contact; Air entrapment; Bubble

1. Introduction

The collision of liquid drops with solid surfaces arises in various industrial applications such as mist/spray cooling, spray paintings, spray coatings, combustion engines and ink-jet printings. Quantitative as well as qualitative experimental observations of the impact of liquid drops with solid surfaces at room temperature have been reported extensively [1–5]. Thoroddsen and Sakakibara [2] studied the evolution of a liquid/solid contact area of impinging drop on a transparent glass plate experimentally. They showed that an air bubble is formed inside the drop on the surface after the collision. Such a bubble formation was also reported by Chandra and Avedisian [3] and Pasandideh-Fard et al. [4]. Although this phenomenon is well-known experimentally, the detailed process remains unclear.

The present study treats the collision behavior of liquid drops with a dry solid surface at room temperature. Emphasis is placed on the evolution of liquid/solid contact area on the surface just after the collision. A flash photographic method has been used to observe the physical phenomena at the liquid/solid interface. The formation process of bubble has been discussed from a phenomenal point of view.

2. Experimental apparatus

Fig. 1 shows the outline of experimental apparatus to observe the deformation behavior of liquid drops

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impinging on a surface. Distilled water at about 20°C is introduced into the top of the needle unit. A drop is formed at the flat tipped nozzle with 0.20 mm internal diameter, and is detached under its own weight. The falling drop passes though a laser beam to make a trigger signal for a strobe light (Sugawara MP-230A). Then, the drop collides vertically with a horizontal dry surface (an optical prism). The area of the surface on which drops impinge is 300 mm^2 (15 × 20 mm). The surface roughness is 600 nm. During the collision, the strobe light is triggered and the image of the drop is taken by a video camera (Canon XL1). This procedure has been repeated with different timings of flash under the same impact condition.

The video camera, the strobe light, the test piece and a mirror have been set as shown in Fig. 1. The video camera has been adjusted to effectively record the image only by the light of the flash. The duration of flash is 2 μs (specified by the manufacturer). A light originating from the strobe is introduced into the optical prism. The incident angle of the light-beam to the upper surface of the prism has been adjusted to 45°. Since the refractive indexes of air, water and prism are 1.0, 1.33 and 1.52, respectively, the total internal reflection takes place not at the wet upper surface of the prism, but at the dry surface. Therefore, we can obtain clear images of the liquid/solid contact area on which the wet area (liquid/solid contact area) becomes darker than the dry area (noncontact area) [6].

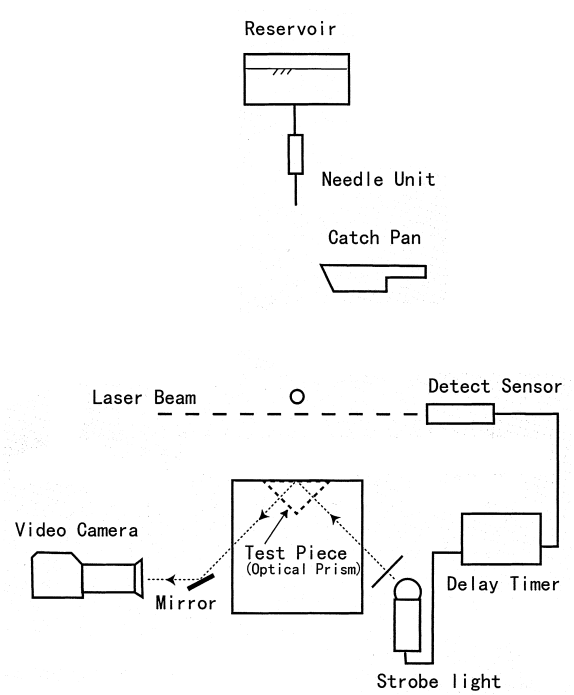

Fig. 1. Schematic of experimental apparatus.

In addition, the impact velocity of drops has been varied by the nozzle-to-plate distance. The impact velocity has been evaluated with a double-exposure photograph [5]. Dimensions of liquid/solid contact area have been directly measured from video images. The resolutions of measurements, which depend upon the magnification of the lens system, can not be better than 8 μm in the present system.

3. Results and discussion

Some researchers reported that a bubble is formed inside a drop on a solid surface just after the collision. Chandra and Avedisian [3] showed that a single bubble exists inside an *n*-heptane droplet on a polished stainless-steel surface. They suggested two possible mechanisms for the formation of bubbles within a droplet. One mechanism is the entrapment of air at the liquid/solid interface during impact. The other one is the cavitation within the liquid caused by a lowering of the liquid pressure to below its saturation vapor pressure. Thoroddsen and Sakakibara [2], and Pasandideh-Fard et al. [4] also reported that a single bubble is formed in a water droplet on a polished surface because of the entrapment of air in a cusp at the liquid/solid interface.

If the bubble is formed due to the air entrapment, the bubble should appear as soon as the collision occurs. In the case of cavitation, the bubble can not be seen first, and then it should be formed. Hence, we have carefully observed the liquid/solid contact area on the surface at the moment of drop impact by the video camera with high magnifications. Fig. 2 represents a sequence of photographs showing the evolution of liquid/solid contact area on the surface just after the collision. The impact velocity v is 2.1 m/s and the equivalent drop diameter D_p is 2.4 mm, respectively. The Weber number based on v and D_p is We = 145. This event is too short to give an accurate time for each photograph. However, these photographs are regarded to be arranged correctly in time series because the liquid/solid direct contact area increases monotonically with time.

A ring-shaped dark area appears just after the collision ($T \cong 0$ s; T = time). This means that the drop contacts the solid surface with the ring-shape. The liquid/solid direct contact does not occur in a circular light area inside the ring-shaped dark area. From this result, it can be concluded that the entrapment of air happens, at least, in this impact condition. Note that many photographs at liquid/solid interface just after the collision have been taken under the same conditions, and all of them have a circular dry area inside the ring-shaped wet area.

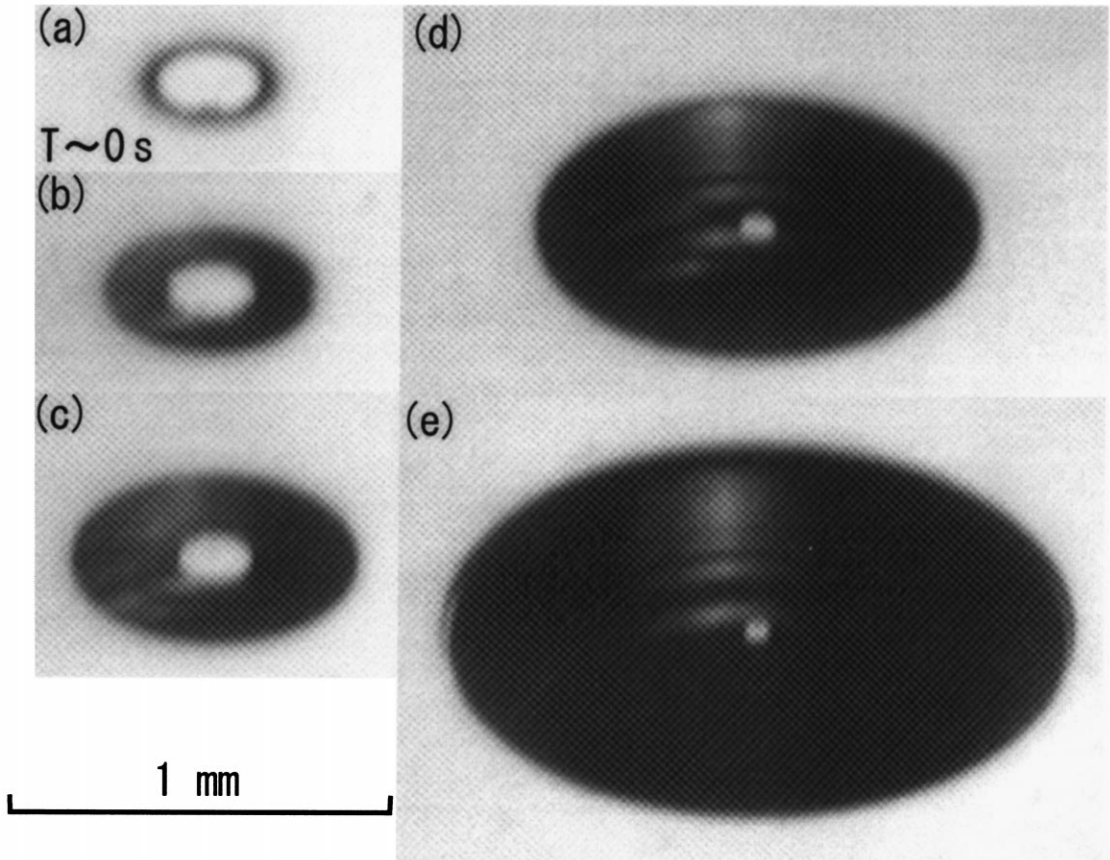

Fig. 2. Time evolution of liquid/solid contact area on the surface just after the collision ($T \cong 0$ s) for $v = 2.1$ m/s and $D_p = 2.4$ mm ($We = 145$).

The circular dry area inside the ring-shaped wet one decreases with time. This fact suggests that the shape of the entrapped air between the liquid and the solid surface varies with time. Incidentally, it is not considered that the total volume of the entrapped air changes drastically. Therefore, the thickness of the entrapped air must become large with decreasing the dry area on the surface. The shape of the entrapped air can be regarded to approach a spherical bubble as time progresses.

Uemura [7] studied the deformation behavior of two liquid droplets on head-on collision. He suggested that high pressure is built up in the gap between droplets just before the collision, and causes flattening of the droplets' surfaces. Ashgriz and Poo [8] showed that an air bubble appears inside a merged liquid after the collision because of the entrapment of air at the moment of the collision. It can be regarded that the air entrapment process studied here is physically similar to the case of binary head-on collisions of liquid droplets.

Next, the evolution of the circular dry area on the surface is discussed quantitatively. Fig. 3 provides the relation between the inner and outer diameters of the ring-shaped liquid/solid contact area on the surface for

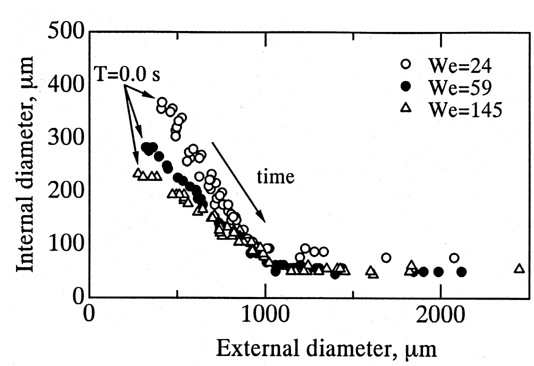

Fig. 3. Relation between the inner and outer diameters of the ring-shaped liquid/solid direct contact area after the collision for $We = 24$, 59 and 145, respectively.

three impact conditions (We = 24, 59 and 145). The drop diameters are the same (=2.4 mm). The impact velocity is varied as a parameter. It is noted that the inner diameter of the ring-shaped contact area coincides with the diameter of the circular dry area. Since the outer diameter of direct contact area increases monotonically with time, the time evolution of the dry area can be followed by this figure. It has been found that the evolutions of the dry area show a similar trend regardless of the impact energy. The dry area is maximum at the moment of impact. It decreases with time, and then becomes almost constant. For the later convenience, the diameter of the dry area which becomes constant is called as terminal diameter. The time at which the inner diameter reaches a constant value is $T = 0.03 \pm 0.02$ ms for We = 145. The terminal diameter of the dry area is about 60 μm. It has been confirmed that the dry area on the surface varies only in a very early time stage.

Throddosen and Sakakibara [2] reported that the diameter of bubble (circular dry area) is of the order of 50 μm in the case where a liquid drop with 5.5 mm in diameter impacts on a glass surface. The Weber number is about 1300. Although their impact conditions are considerably different from the present ones, the bubble diameter reported by Throddosen and Sakakibara is close in value to the terminal diameter of dry area obtained by the present study.

It has been found from Fig. 3 that the initial dry area is larger for smaller Weber numbers. The reason why the initial dry area depends upon the Weber number might be due to the shape of drop just before the impact. Since drops are formed by a drip-type method, a drop is detached from the needle with an oval sphere-shape. The falling drop oscillates slightly. The shape of drops just before the collision has been measured directly from side-view video images of drops. The vertical diameters of the drops are 2.5, 2.4 and 2.3 mm for We = 24, 59 and 145, respectively. The vertical diameter is larger than the horizontal one for We = 24, while the vertical diameter is smaller than the horizontal one in the case of We = 145. The local curvature of the liquid surface facing the solid surface is larger for larger Weber numbers at the moment of collision. Further, the drops with larger Weber numbers push aside the air between the liquid and the surface easily at the moment of impact because

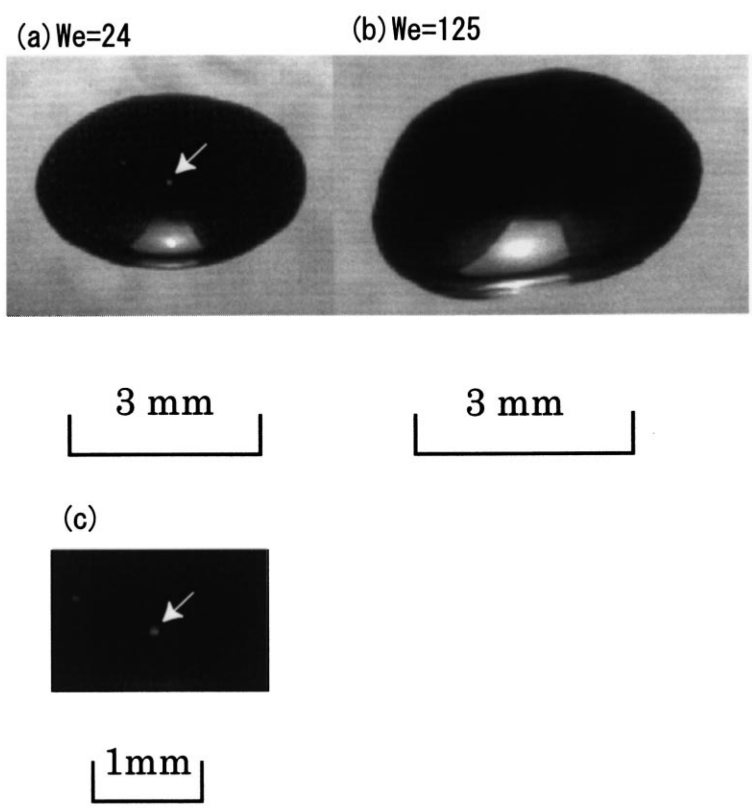

Fig. 4. Bottom-view photographs of drop in a stationary state for We = 24 (a) and *145* (b), respectively, and enlarged bottom-view photograph (c) near the bubble for We = 24.

of higher impact energy. Therefore, the initial dry area might be larger for smaller Weber number.

Finally, the case where the liquid reaches a stationary state on the surface is treated. Fig. 4 shows the liquid/solid contact areas in the stationary state for $We = 24$ (a) and 145 (b), respectively. Some bright areas can be seen in both figures. These areas are not the liquid/solid contact areas. These bright areas on the images are obtained due to the reflection of light at the upper surface of liquid (liquid/air interface). It has been found that there is no circular dry area for $We = 145$. This is because the bubble leaves the solid surface due to external drag force exerted by surrounding liquid flow as well as buoyancy force. The bubble rises into liquid during the collision. On the other hand, the bubble indicated by an arrow exists on the surface for $We = 24$ (see also Fig. 4c). There are some reasons why the bubble stays at the surface. The first reason is that the terminal dry area for $We = 24$ is a little larger than that for $We = 145$ as shown in Fig. 3. The adhesion between the bubble and the surface is larger for larger terminal dry area. The second is that the external drag force to the bubble is small. Since the initial momentum (or kinetic energy) is small, the liquid velocity around the bubble must be small in the whole process compared with the case of $We = 145$. Therefore, the bubble exists on the surface even in the stationary state.

4. Conclusion

Time evolution of liquid/solid contact area of impacting drop on the solid surface has been investigated experimentally by means of the flash photographic method. Just after the collision, the drop contacts the solid surface with the ring-shape. Inside this ring-shaped liquid/solid contact area, air is entrapped between the liquid and the solid surface. This noncontact area decreases sharply with time, and then becomes constant. It has also been found that the noncontact area depends on the Weber number. This may be due to the shape of the drop at collision. Further, the bubble stays on the surface even in the stationary state for a low Weber number condition.

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