Experiments in Fluids 7, 388–394 (1989)

Experiments in Fluids

Phenomena of a liquid drop falling to a liquid surface

Y. K. Cai

Department of Physics, Beijing University, Beijing, P.R. China

Abstract. Two kinds of phenomenon have been observed when a liquid drop falls to a surface of the same liquid. The first, which can nearly always be observed, involves splash and some degree of penetration and "cleavage" and the conditions for this occurrence are identified. The experimental observations are compared with previous computational results. The second kind of colliding phenomena can be observed only by chance in an ordinary falling drop experiment and appears to be random. It includes the two phenomena investigated in this paper: the floating drop and the rolling drop.

1 Introduction

When a water drop falls to a water surface, small jets emerge from the rim of the colliding section of the drop and a crater is created with a column of water subsequently ejected from its center. This phenomenon has been investigated experimentally from several aspects since the development of high speed photographic techniques, for example, Hobbs and Kezweeny (1967) and Gillespie and Rideal (1955). Also, Harlow and Welch (1965) have solved the Navier-Stokes equations of the drop collision numerically using the Marker-and-Cell technique and compared their calculated results with the experimental observations of Worthington (1963).

The present experiments study the collision process and reveal new phenomena.

2 Experimental setup

Alcohol, carbon tetrachloride, and water have been used as drop and pool liquids but, for reasons of economy, all photographs were taken using water with 0.25% thymol blue as the drop material (dark orange in colour), and water with 0.1% sodium carbonate as the pool liquid (colourless and transparent). A mixture of the two liquids is dark blue in colour and makes the collision easy to observe and photograph. When the above visualizing agents were dissolved in water, the surface tension of the water-thymol blue solution decreased from 73.10^{-3} N/m for pure water to 48.10^{-3} N/m, with no other change in the viscosities, densities, and surface tension.

The photographs were taken for a cubic vessel of 200 mm side and made of transparent plexiglass. Round nozzles with diamters from 0.8 to 6.0 mm were used to obtain drops of various dimensions. An electromagnet and a relay were used to control the release of the drop and the start of the camera. To collect data for various falling heights and for various drop dimensions, a transparent plexiglass canal was used to provide flow speed of several centimeters per second. The number of the drops discharged by the nozzle was controlled by the height of the water column in the nozzle. The time at which a drop was discharged was sensed by a photoelectric element and stored in a microprocessor timer. When the camera was in operation, the nozzle released one drop per a half second. After the evidence of the collision had been removed by the flow, the next drop was released by the nozzle from a higher position to fall on the surface of the flow. In this way pictures of the collision with various impact velocity were taken during the rising process of the nozzle.

A hyspeed camera produced by John Hadland Ltd. was used.

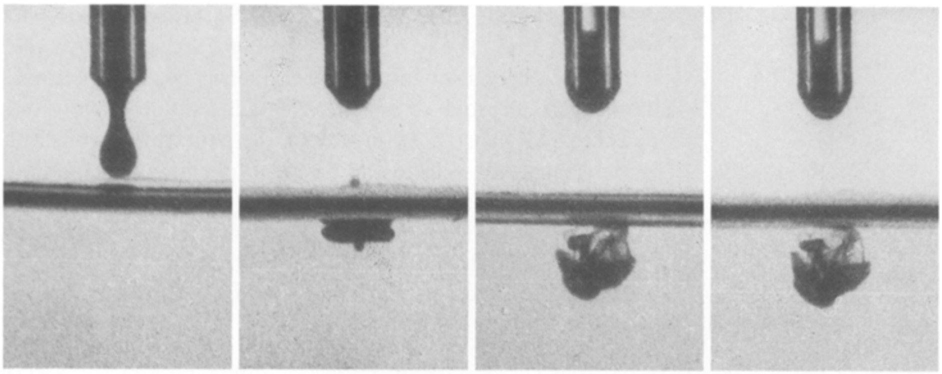
3 Results

A drop is usually considered spherical when its diameter is less than 6 mm, see for example Worthington (1963), and the diameter of the present drops ranged from 3 to 5.2 mm. It was observed that the shape of a water drop with diameter greater than 4 mm deviates from a sphere, and is ellipsoidal with eccentricity of about 0.1. A water drop with diameter less than 4 mm falling from a low height (less than 50 mm) can be taken as a sphere without noticeable deviation.

3.1 The main phenomena of drop impact

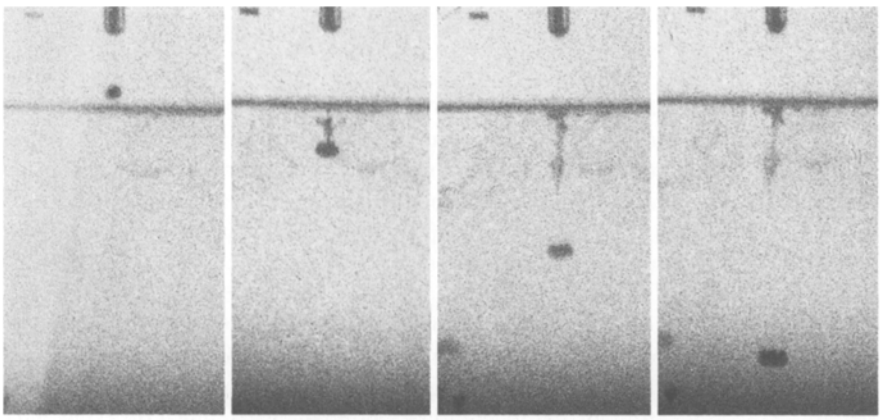
3.1.1 Cleavage

When a water drop falls on water from a small height (impact velocity near to zero), it will submerge and the colli-



a b c d

Fig. 1a–d. Cleavage of a drop, 4.83 mm diameter, falling from a height of 15.0 mm; **a** $t=0$ ms, **b** $t=30$ ms, **c** $t=200$ ms, **d** $t=400$ ms



a b c d

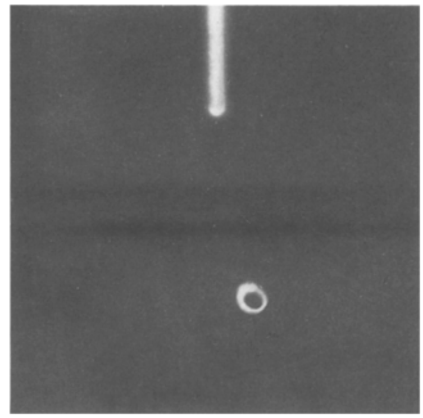


Fig. 3

Fig. 2

Fig. 2a–d. Penetration of a drop, 4.92 mm diameter, fallen from a height of 21.1 mm; **a** $t=0$ ms, **b** $t=81$ ms, **c** $t=243$ ms, **d** $t=810$ ms

Fig. 3. Configuration of a penetrating ring caused by a drop, 4.92 mm diameter, fallen from a height of 21.1 mm

sion disturbance is almost invisible: there is no splashing, no rebounding column, and no crater. Apparently, the submerged drop cleaves in an "inverted cauliflower" below the surface where it can last for several seconds, diffuse and vanish slowly in the water. Figure 1 shows the cleaving process of a drop of 4.83 mm in diameter with a range of falling heights from 0 to 50 mm.

3.1.2 Penetration

As the falling height of the drop increases to a height, say H_1, the "inverted cauliflower" is replaced by a "ring" of drop material. This ring penetrates the water and travels to the bottom of the vessel with a speed of several centimeters per second. This penetration process is shown in Fig. 2 for a drop of 4.92 mm diameter. Except for a black spot, which penetrates the water and reaches the bottom of the vessel, no detailed configuration of the ring could be seen in Fig. 2 so that a second picture of the ring was taken about 0.1 s after the drop had impacted the surface by fitting the camera at an angle of 20° to the perpendicular as shown in Fig. 3.

As the falling height is increased further, penetration disappears and cleavage reappears until at H_2, penetration reappears. Two or three such falling heights for a given sized drop could often be found.

Some characteristics of penetration are revealed below.

Periodicity. An approximate relation exists for H_i,

$$H_{n+1} = 2n H_1 \tag{1}$$

where the subscript refers to the falling heights of penetration in order of their increasing value for a given sized drop, and i or n denotes a positive integer. This means that penetration occurs for the lowest falling height H_1 and for falling heights which are even multiples of H_1.

The relation is shown by the measured results in Table 1, where the values of these heights range with respect to their subscript as well as drop diameter. No penetration has been observed near a falling height which is an odd multiple of H_1. In practice, penetration occurs when a drop falls from a height slightly greater than $2H_1 n$ and the larger the drop

Table 1. Falling heights of penetration for several drop sizes

D_i	$H_1/\bar{H}_1$	$H_2/\bar{H}_1$	$H_3/\bar{H}_1$	$H_4/\bar{H}_1$	$H_5/\bar{H}_1$	$\bar{H}_1 \pm \sigma_H$
5.20	0.87	2.24				26 ± 3
4.92	0.92	2.13				23 ± 2
4.33	0.85	2.23				15 ± 2
3.92	0.94	2.07	4.13			9.7 ± 0.3
3.60		1.97	4.02	6.06		7.82 ± 0.06
3.40		1.94	3.94	6.40		6.5 ± 0.2
3.10			3.57	6.02	8.80	5.3 ± 0.3

$\bar{H}_1$ denotes the average of H_1's which are those: one is measured directly as listed in the second column of the table, and others are calculated from H_i $(i > 1)$ by Eq. (1), σ_H the standard error of H_1, (mm) is used as the unit of D and H_i

Table 2. Penetration constants for several drop sizes

D/r_i	r_1	r_2	r_3	r_4	r_5
5.20	0.162	0.414			
4.92	0.177	0.412			
4.33	0.156	0.415			
3.92	0.151	0.334	0.666		
3.60		0.330	0.673	1.02	
3.40		0.332	0.651	1.06	
3.10			0.634	1.07	1.57
$\bar{r}_i + \sigma_r$	0.162+0.06	0.37 +0.02 *0.414+0.001 **0.332+0.001	0.656+0.008	1.05+0.02	

size, the larger the deviation from Eq. (1). This tendency for deviation is also shown by the standard error of the average value of H_1 in the last column of Table 1.

If some factor causes periodicity in the penetration phenomena as expressed by Eq. (1), then a disturbance must cause the deviation. We have not done research on the physical mechanism of the deviation, but we have found that the penetration is very sensitive to any small disturbance. For example, disturbances caused by a moving truck a few hundred meters away, or by a heavy falling body in the next room, or by a breeze through a distant window, or by invisible dust particles floating in air can be enough to prevent the appearance of penetration and we guess that this sensitivity causes the accidental phenomena.

Relationship between height and volume. The ratio of the falling height of penetration to the volume of the falling drop

$$r_i = H_i / D^3 \qquad (2)$$

is approximately constant, independent of the size of the drop, and is called the ith penetration constant. Some of these values are listed in Table 2 which shows the small standard error of the average penetration constant. Obvious differences exist between the data for $D > 4$ mm and those for $D < 4$ mm, and in the former case there are considerable deviations of the observed data from Eq. (1) in Table 1. We guess that Eqs. (1) and (2) fit for falling spherical drops but that larger drops, owing to the influence of air resistance, assume an ellipsoid or another irregular shape. If only the data of small drops are considered, the penetration constant is satisfactory. A relationship for the penetration constant also exists, namely:

$$r_{n+1} = 2n\, r_1 \qquad (3)$$

Equations (1) and (2) imply that a falling drop with kinetic energy

$$E_i = 6 r_i\, g\, \varrho\, v^2 / \pi \qquad (4)$$

may cause penetration, where g, ϱ, v are gravitational acceleration, liquid density and volume of drop respectively, and the similar relation

$$E_{n+1} = 2n\, E_1 \qquad (5)$$

also holds. Obviously the kinetic energy E_i can be arranged in an array with respect to the drop diameter and penetration constant as in the case of penetration height. Moreover, if a single measurement for any penetrating drop has been completed, in principle, all other elements of the energy array can be calculated.

For a certain size of drop, there are two or three H' from which falling may cause penetration. But the appearance of penetration is not the same in each case. From a lower height, say H_i, the penetration is very stable so that penetration, probably could be observed every time a drop fell. The ring displayed a regular configuration with a clear edge and moved rapidly until the bottom was reached. On the other hand, penetration is less stable from a higher falling height, H_{i+1}, and it can be observed only eight or nine times if a drop falls ten times from H_{i+1}. Some small branches appear on the edge of the ring which moves slowly and becomes irregular before it reaches the bottom of the vessel.

3.1.3 Splash

On increasing the falling height after the last penetration, the impact of a drop on the water surface results in a crater and small jets emanate from its rim. When the jets have subsided and the bottom of the crater has returned to the surface, a column of water is ejected from the center of the crater and may throw out one or more droplets.

The diameter of the crater increases rapidly as the falling height increases from 0 to 200 (the diameter of the drop is used as the unit of length), and increases slowly beyond this range. The relationship is shown in Fig. 4. The relationship between the depth of the crater and the falling height of the drop is similar to that between diameter and falling height and is shown in Fig. 5.

The ratio of the depth to diameter for the maximum crater is approximately constant over a large range of falling heights and this implies that the basic character of the shape of the crater remains unchanged as the falling height varies, except for small values of height, for example, falling heights

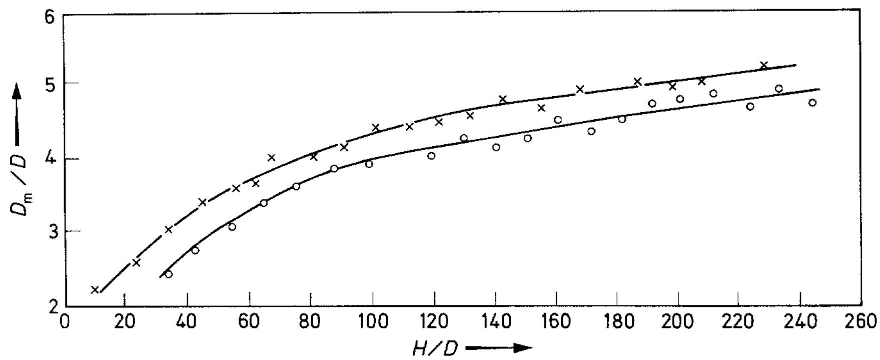


Fig. 4. Diameter of maximum crater (D_m/D) as a function of the falling height (H/D); × $D=3.80$ mm, ⊙ $D=3.04$ mm

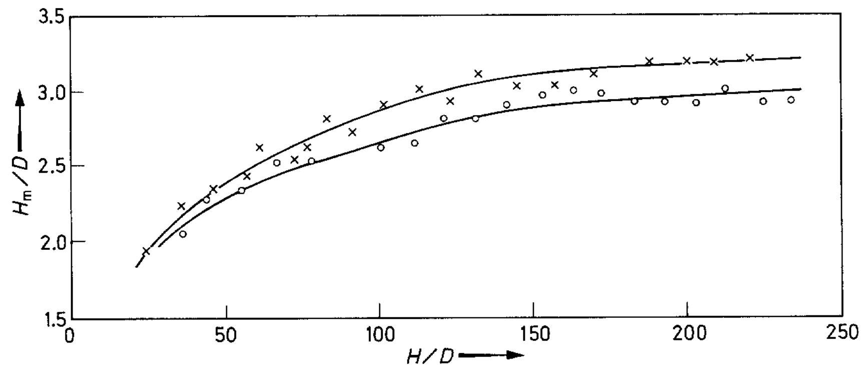


Fig. 5. Depth of maximum crater (H_m/D) as a function of the falling height (H/D); × $D=3.80$ mm, ⊙ $D=3.04$ mm

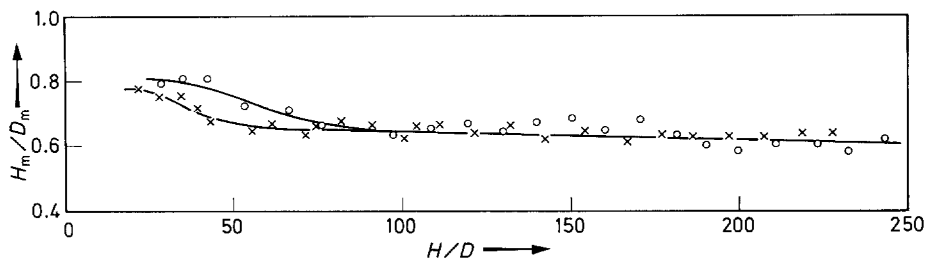


Fig. 6. Depth-diameter ratio of the maximum crater (H_m/D_m) as a function of the falling height (H/D); × $D=3.80$ mm, ⊙ $D=3.04$ mm

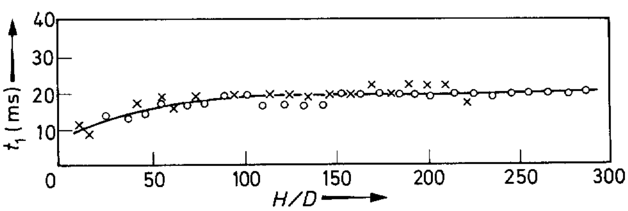


Fig. 7. Time for the crater to grow to its maximum size (t_1) as a function of the falling height (H/D); × $D=3.80$ mm, ⊙ $D=3.04$ mm

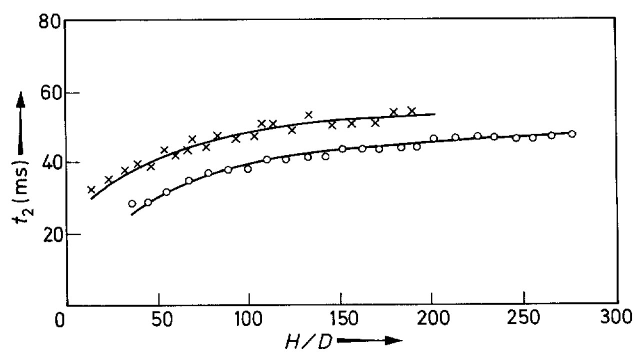


Fig. 8. Time for the central column of water to begin to rebound from the surface (t_2) as a function of the falling height (H/D); × $D=3.80$ mm, ⊙ $D=3.04$ mm

less than 50 for a drop 3.04 mm in diameter. The ratios are similar for various drop sizes in a large range of falling heights as shown in Fig. 6. The time for the crater to grow to its maximum size increases as the falling height increases, and may tend to a limit of about 20 ms, as suggested in Fig. 7. The time for the column of water to begin to rebound as a function of falling height for two different sizes of drops is shown in Fig. 8.

A typical splashing process with 4.85 mm diameter drops, falling from a height of 175 mm, is shown in some detail in Fig. 9. These photographs are chosen from 3000 pictures taken per second to help explain the process. The number labelled on the upper right hand corner of the pictures denotes the sequence of the photo. The time interval between two successive photos is 3/10 of 1 ms. The impact began on the 17th photo and the maximum size of the crater was

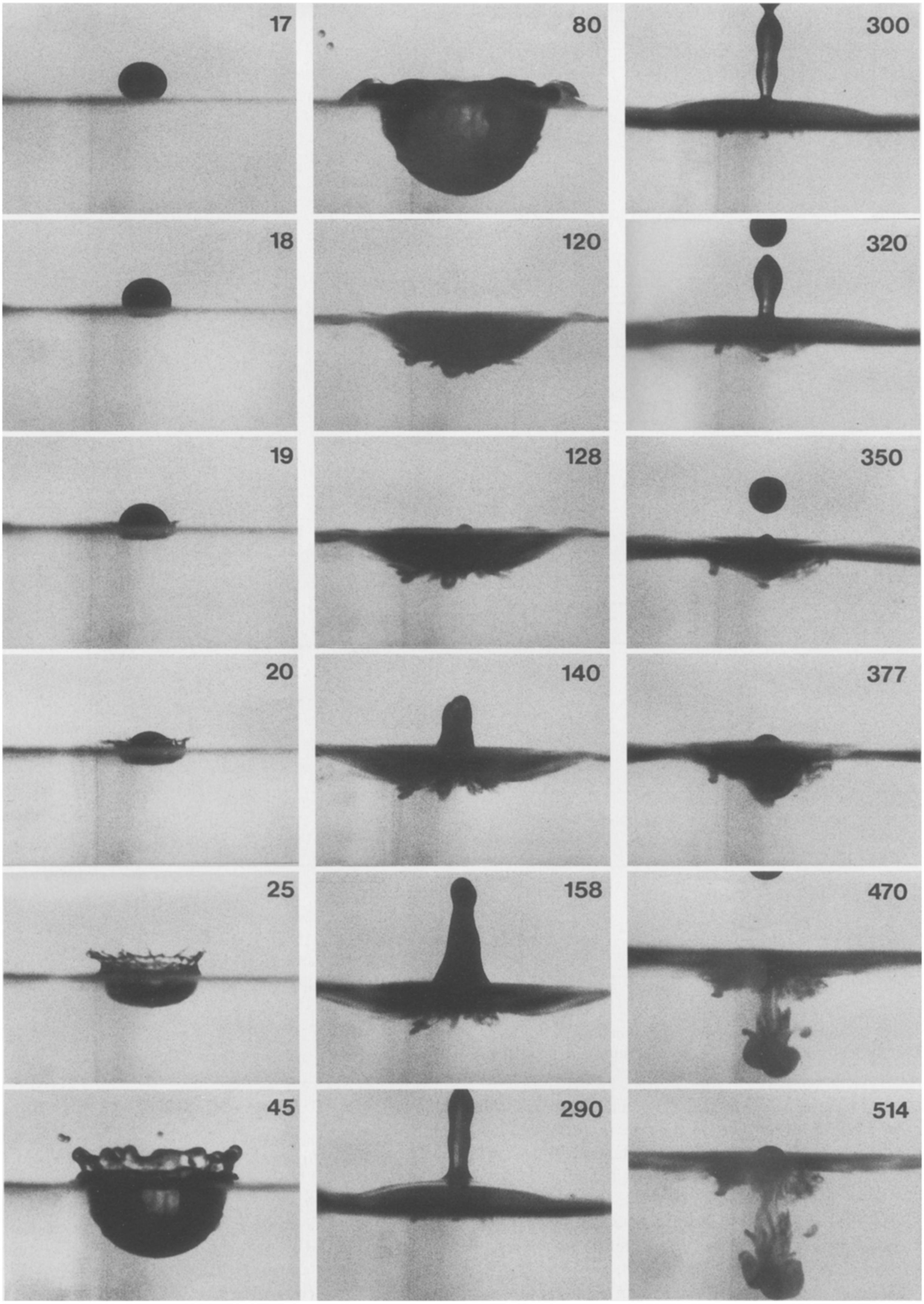


Fig. 9. Typical splashing process of a drop, 4.83 mm diameter, fallen from a height of 175 mm; the numbers denote the sequence of the photographs; the time interval between two successive photographs is about 0.0003 s

reached by the 80th photo. In the 128th photo a rebounding column of water began to rise from the center of the crater and in the 158th photo the top of the rebounding column of water rises out of sight of the picture. After that, two droplets of about 4 mm in diameter, are thrown off from the top of the column. In the 320th photo, one of the droplets has fallen into view and submerges into the water in the 377th photo. Using the formula for a free falling body, from the measured falling velocity, it is known that the droplet had risen to a height of about 15 mm. This is the second droplet separated from the rebounding column. The first separated droplet rose to a height of about 22 mm then fell and entered into view of the 470th photo. In the meantime, the second droplet had formed an inverted cauliflower below the surface of the water. The first droplet submerged into water on the 514th photo. Then the collision process that had taken place above the surface ended.

3.2 Probability and accidental phenomena

The above drop collision experiments have been described statstically so that, if a drop of 3.60 mm in diameter falls

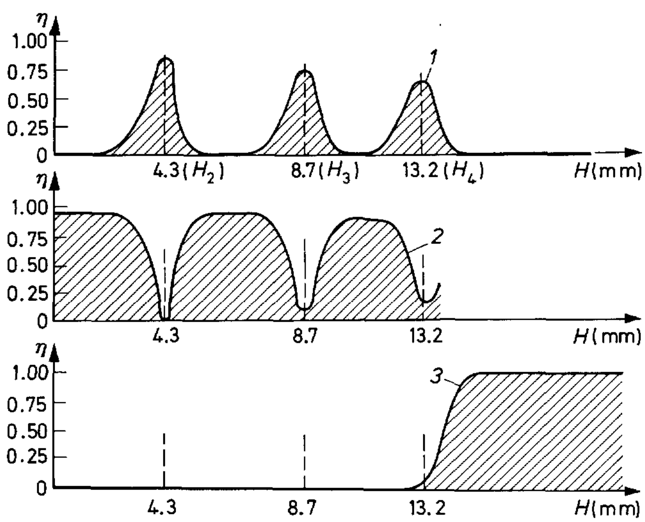


Fig. 10. Several typical probabilities (η); --- falling height (H/D); diameter of falling drops is 3.6 mm; probability of *1* penetration occurring, *2* cleavage occurring, and *3* splash occurring

from a height of 31.4 mm into water, it cannot be guaranteed from the data of Table 1 that penetration must occur. The experimental data only implies that the occurrance of penetration has a large probability.

We are not concerned with the basic physical argument about the causuality and the probability. The latter is emphasized only to indicate that random disturbances exist in the circumstances of our experiment and the process of drop collision is sensitive to them. Had the experiments been carried out with the disturbances decreased to the lowest level, more precise results would have been obtained and more substantial physical relations would have been revealed.

The probability of occurrence of penetration in the collision process as a function of the falling height is shown by the curve *1* in Fig. 10, the probability of cleavage by curve *2*, and the probability of splash by curve *3*. The sum of the probabilities of these three phenomena is not unity especially in the range of low colliding velocity. The sum of probabilities is obviously less than unity because phenomena other than cleavage, penetration, and splash, occasionally appear. Two such phenomena were investigated further in our experiment.

A falling drop, occasionally, did not merge into the liquid pool but floated on its surface. It often oscillated up and down at the same location for several seconds before merging into the pool liquid. It was discovered that the floating drop can be observed when the size of the drop is small, for example $D < 2$ mm, and falls from an appropriate height, for example $H = 3\ D$. An easy way to make a small drop is to select a liquid with small surface tension. A floating drop of alcohol can be observed in Fig. 11 with a probability of about 90%.

Another accidental result is observed with a flowing liquid, where a falling drop thrown from the rim of a splashing crater occasionally rolled over the liquid surface and merged into the liquid a few seconds later. The rolling drop is easily observed when the colliding drop has a velocity component along the liquid surface. Larger drops or drops with a large impact velocity will not merge into the surface but will roll upon it. Very rarely it can be observed that the drop rebounds upwards from the colliding surface. Rolling drops occurred when drops were thrown out horizontally or at a

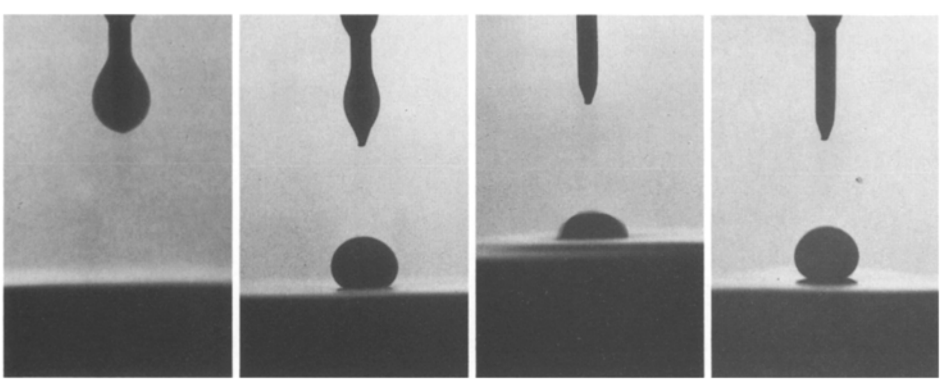


Fig. 11. Fallen alcohol drop floating on the surface of a cup of the same liquid; the surface tension of the liquid is $20 \cdot 10^{-3}$ n/m; the visualizing agent is thymol blue; $D = 2.0$ mm

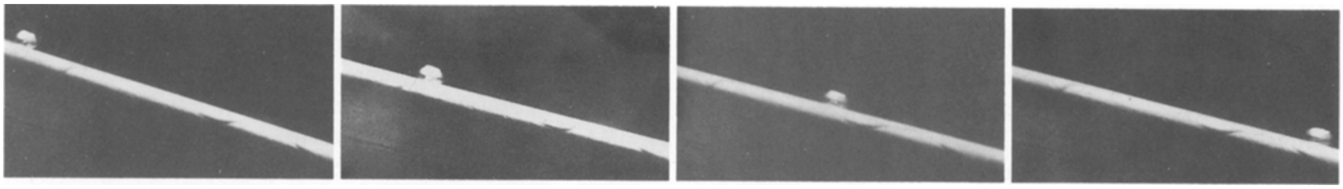


Fig. 12. Oil drop rolling on a surface of the same kind of oil spread on a slope of 1 : 3.7; time interval between two successive photographs is about 0.05 s; viscosity of the oil is $5.0 \cdot 10^{-2}$ pa s; surface tension of the oil is $33 \cdot 10^{-3}$ n/m; $D = 4.5$ mm

small angle to the horizontal so as to collide with a horizontal surface or when a free falling drop was allowed to impact a sloping liquid surface. In this way, Fig. 12 was taken and corresponds to a falling height of 3 D to 5 D with oil used to form a steady slide and a fixed liquid depth.

4 Comparison of our experimental results with the computations of Harlow and Welch

Harlow and Welch (1965) compared their calculations with the measurements of Worthington (1963) and the results appeared to agree well. However, Worthington implied that all the material of his drops was contained in the rebounding column and Harlow and Welch showed that only a part of the original drop material rose as the coating to the rebounding column, and that much of the drop material was trapped in a pocket below the surface. In our experiment the drop water is orange in colour, the water in the vessel is colourless and completely transparent. When collision occurs, the mixture of the drop water and the vessel water appears dark blue in colour so that the mixture and the vessel water are easily distinguished. In photos 290–300 of Fig. 9, the volume of the rebounding has increased to approach a maximum and the whole column is dark in colour. In the meantime dark water spreads on the surface of the transparent vessel water round the center of the original crater. It must contain some of the drop water and, as pointed out by Harlow and Welch this floating drop material might not be visible in Worthington's experiment where the drop was made visual with milk. But the remaining dark material is floating on the surface of the vessel water and is not trapped in a pocket below the surface.

It is shown in Fig. 7 that the time at which the maximum crater is formed increases as the falling height increases. The time when the central column begins to rise from the surface also increases as the falling height increases, as shown in Fig. 8. These two facts are contrary to the calculated results of Harlow and Welch, where both these times decrease as the falling height increases.

It should be pointed out that the range of falling height, which caused the computational splash, is $H/D = 0.5$ to 8.0 whereas, there is no corresponding splash in the experiment. Penetration or cleavage do, however, occur as described in the earlier part of this paper, with splash only observed in the range $H/D > 10$.

Acknowledgements

The author thanks D. Huang, whol helped to select the topic of this paper and made many valuable suggestions. Particular thanks are due to C. L. Li for the photographic work, B. Wang and B. L. Song for part of the photographic work, and to Z. S. Zhao for offering the microprocessor timer which he designed and made. The author is much indebted to A. F. Li, who read the manuscript and corrected mis-statements.

References

Gillespie, T.; Rideal, E. 1955: On the adhesion of drops and particles on impact at solid surfaces, II. J. Colloid Sci. 10, 281–298

Harlow, F. H.; Shannon, J. P. 1967: The splash of a liquid drop. J. Applied Phys. 38, 3855–3866

Harlow, F. H.; Welch, J. E. 1965: Numerical calculation of time-dependent viscous incompressible flow of fluid with free surface. Phys. Fluid 8, 2182–2189

Hobbs, P. V.; Kezweeny, A. J. 1967: Splashing of a water drop. Science 155, 1112–1114

Worthington, A. M. 1963: A study of splashes. New York: MacMillan

Received September 4, 1988