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Experimental Study of the Phenomenon of Droplet Impact upon a Liquid Surface

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ABSTRACT

This paper experimentally studied the dynamic behavior of a droplet impacting upon a liquid film, by investigating the effects of the droplet velocity and thickness of the liquid film on the impact behavior of the droplet. The formation of the crown, central jet, and disintegrating droplet from the central jet were visualized by time-delay photography. The time evolutions of the diameter and height of the crown and the height of the central jet were obtained, and the size of the disintegrating droplet from the central jet was measured. The crown diameter and the central jet height were mostly affected by the droplet velocity and the thickness of the liquid film, respectively, while the crown height was influenced by both the droplet velocity and the thickness of the liquid film. The diameter and height of the crown were higher for the case of the faster impacting droplet and thinner liquid film. On the other hand, the height of the central jet was higher for the case of the faster impacting droplet and thicker liquid film. The size of the disintegrating droplet from the central jet heavily depends on the velocity of the impacting droplet. Namely, a larger droplet is produced by a faster impacting droplet.

Keywords: Impacting Droplet; Liquid Film; Splashing.

NOMENCLATURE

D_c	diameter of the crown
D_o	diameter of the impacting droplet
D_s	diameter of the secondary droplet from a jet
h	thickness of the liquid film
h^*	dimensionless thickness of the liquid film
H_c	height of the crown
H_j	height of the central jet
V	speed of the impacting droplet
μ	viscosity of the liquid
ρ	density of the liquid
σ	surface tension of the liquid

1. INTRODUCTION

The phenomenon of a single droplet impacting the surface of a solid wall or liquid has been applied to a variety of technical applications, including spray cooling of hot surfaces, spray painting and coating, fuel injection in combustion engines, inkjet printing, spray forming, and fire extinguishing by sprinklers (Crowe *et al*. 1998, Lefebvre 1989). Rein (1993), Yarin (2006), and Moreira *et al.* (2010) have provided comprehensive information on this subject.

In these application fields, droplets initially impact on the surface of a solid wall, but they impact on the liquid film that is formed by previous impacting droplets as time goes on. The characteristics of the impacting droplet on a solid surface or a liquid film are very complex depending on variables such as the condition of the droplet (diameter D_o, velocity V, impacting angle), the thickness of the liquid film h, fluid properties (density ρ, viscosity μ, surface tension σ), and the roughness degree of the solid surface (if the film thickness is thin). The dimensionless parameters associated with this phenomenon are the Weber Number ($We=\rho D_o V^2/\sigma$), the Ohnesorge Number ($Oh=We^{1/2}/Re=\mu / (\rho\sigma D_o)^{1/2}$), and the dimensionless thickness of a liquid film $h^*=h/D_o$.

If a droplet impacts a liquid film, bouncing, coalescence, or splashing phenomena appear sequentially, in accordance with increasing the velocity of the impacting droplet. Splashing is the phenomenon whereby a large number of secondary droplets disintegrate from many protruding jets formed in the rim of the crown shape of liquid film. In application fields such as spray coating or spray cooling, the splashing phenomenon should be suppressed as far as is possible, so that the sprayed liquid can remain on the surface of the solid. In fuel sprays, on the other hand, it is better to promote the splashing phenomenon, because secondary atomization of the injected fuels by the splashing phenomenon is desirable, in addition to the fact that adhered fuels significantly contribute to the pollutants and particles emitted.

Many previous researches have been performed to find out the critical condition under which the splashing phenomenon occurs (Cossali *et al*. 1997, Wang and Chen 2000, Rioboo *et al*. 2003). They usually used the dimensionless parameter, $K=We\cdot Oh^{-0.4}$, which is the combination of the We Number and the Oh Number, to distinguish the boundary of the occurrence of splashing.

Secondary atomization caused by the splashing phenomenon during the droplet impact onto a liquid surface is also an important interest of researchers. The number, size, and total mass of secondary droplets were correlated using the dimensionless parameter, K (Yarin *et al*. 1995, Cossali *et al*. 1997, Okawa *et al*. 2006, Vander Wal *et al*. 2006). Okawa *et al*. (2006) proposed an experimental correlation equation for the ratio of the mass of secondary droplets generated by the splashing phenomenon to the mass of the initial droplet. At the condition of comparatively thin liquid film (h^*~ 0.3~1.1), Cossali *et al*. (2004) analyzed the change of diameter, height, and thickness of the crown, the number of jets, and the number and size of secondary droplets generated by the splashing phenomenon with time.

Moreira *et al*. (2010) summarized the effect of the thickness of liquid film, by analyzing the existing researches related to this subject. They showed that the equation proposed as the boundary value of the splashing regime could be applied for the case that the thickness of liquid film is relatively thin ($h^* < 2$); and the effect of the film thickness is not greater, if the liquid film thickness is greater than this value (Wang *et al*. 2000, Okawa *et al*. 2006). Vander Wal *et al*. (2006) also investigated the effect of the thickness of the liquid film on the behavior of a droplet after impact. They showed that a thin liquid film (h^*~0.1) strengthens the splashing phenomenon, but a thick liquid film ($1<h^*<10$) suppresses the splashing phenomenon.

This paper aims to improve our understanding of the dynamic behavior of the droplet impacting onto a liquid surface. The impacting phenomenon of a single droplet on a liquid film was visualized by time-delay photography. The droplet velocity and the thickness of the liquid film were changed as the main parameters. The important characteristics of the dynamic behavior of a droplet after impact, such as the diameter and height of the crown generated by the splashing phenomenon, the height of the jet formed in the center, and the size of the secondary droplet separated from the central jet, were measured and analyzed.

2. EXPERIMENTAL APPARATUS AND CONDITIONS

Figure 1 shows a schematic of an impacting droplet onto a liquid film. D_o and V are the diameter and speed of the impacting droplet, respectively, while h is the height of the liquid film. Figure 2 shows a schematic of typical droplet behaviors after impact. When a droplet impacts onto a liquid surface, a crater forms, and smaller jets protrude from the rising liquid sheet on the rim, which resembles a crown, as Fig. 2(a) shows. D_c and H_c are the diameter and height, respectively, of this kind of crown. As the liquid sheet of the crown goes down, the receding flow towards the center shoots up in the form of a liquid jet, as Fig. 2(b) shows. Above high enough impact velocities of the droplet, a secondary droplet comparable to the size of the initial impacting droplet disintegrates from the end of this jet. H_j is the height of the jet formed in the center of the crown, and D_s is the diameter of the secondary droplet separated from the central jet.

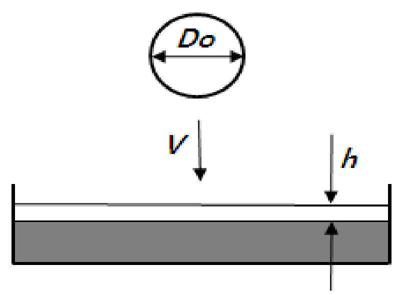
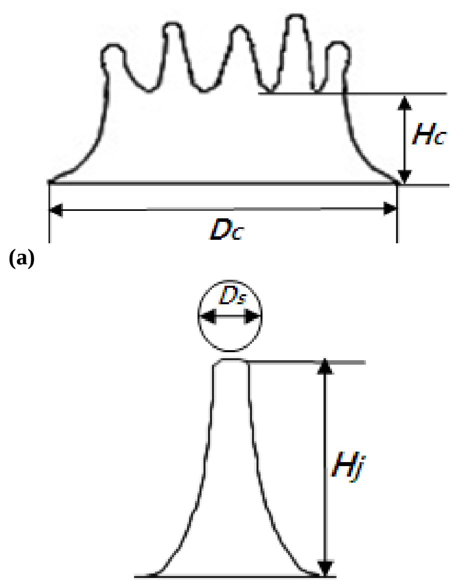


Fig. 1. Impacting droplet onto a liquid film.



(b)

Fig. 2. Schematic of typical droplet behaviors after impact: (a) crown formation, and (b) central jet and secondary drop formation.

Time-delay photography was used to visualize the impact behavior of a liquid droplet onto a liquid surface. Time-delay photography takes time sequential photographs of desired phenomena at time moments that are delayed from a reference moment. Figure 3 shows a schematic diagram of the experimental setup constructed to record the deformation behavior of a single droplet impacting onto a liquid surface. The setup consists of the liquid surface inside a container, the time-delay photography system, and the droplet generating system. Fluid (water) was supplied from a syringe pump to a needle. The ID and OD of the needle were 0.394 and 0.711 mm, respectively.

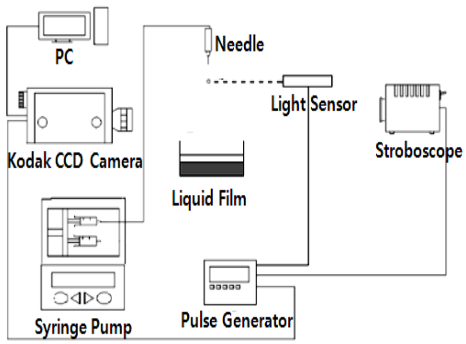


Fig. 3. A schematic diagram of the experimental setup.

A small droplet made to hang on the sharp tip of the needle gradually became larger, separated from the tip of the needle, and fell a given distance before impacting onto the liquid surface inside the liquid container. The liquid container was made of Aluminum. When the optical sensor senses a falling droplet and sends a signal to the pulse generator, the pulse generator then sends a signal to the CCD camera, and to the stroboscope, after a pre-set desired delay time. Then, droplet images for the behavior of the impacting droplet are taken in time sequence.

Table 1 The experimental conditions

Case	h (mm)	h*	V (m/s)	We	K
1	2	0.6	2.75	344	4,107
2			4.10	765	9,134
3	10	3.0	2.75	344	4,107
4			4.10	765	9,134
D_o = 3.33 mm, Oh = 0.00203					

The velocity and diameter of the impacting droplet were calculated by analyzing the two images that were taken just before impact. The diameter of the droplet, which corresponded to the total area covered by the droplet before the impact, was calculated. The velocity of the droplet was obtained by dividing the distance travelled by the droplet, by the time it took for the droplet to travel that distance. Table 1 shows the experimental conditions. Two thicknesses of the liquid film (h= 2, 10 mm) were tested, with two different droplet impact velocities. The We number is based on the liquid properties, instead of the gas properties.

3. RESULTS AND DISCUSSION

3.1 Droplet Behavior After Impact

Based on the present experimental observation and explanations from previous researchers, the droplet behavior after impact can be generalized as follows. At the sufficiently low droplet velocity, the impacting droplet deposits in the liquid film and the circular ripples are formed. With the slight increase of the droplet velocity, the crown was created after the impact but secondary droplets are not formed so far, which is not the range of the present experiments. If the droplet velocity is further increased, secondary atomization from the crown rim is observed, which is named as the splashing phenomenon. Even though the size of droplets in the collapsing period of crown is larger than that in the growing period, the size of droplets from the crown rim is generally much smaller than the impacting droplet. In the contracting stage, the central jet is formed and the breakup of central jet is observed occasionally. On the contrary to the size of droplets from the crown rim, the size of droplets from the central jet is comparable to the impacting droplet.

Figures 4 and 5 show the behavior of the impacting droplet onto a thin liquid film, h= 2 mm, for two different droplet velocities. In the early spreading stage, a crown forms from the liquid film, pushed by the spreading droplet. Small secondary droplets disintegrate from the bump of the crown edge. No secondary atomization was observed in the collapsing period of crown for the case of the lower droplet velocity, while a little larger size of droplets disintegrates from the crown rim in the collapsing period of crown for the case of the higher droplet velocity. Overall, the dimensions of the crown, namely, the diameter of the crown bottom and height of the crown, are large for the case of the higher droplet velocity. In the late contracting stage, a liquid jet grows in the center, and no disintegration of droplet was observed for Case 1 with the smaller droplet velocity. For Case 2 with the higher droplet velocity, the height of the central jet is higher than that of Case 1, and a comparatively large size of droplet disintegrates from the end of the jet.

The critical condition of droplet splashing was experimentally established by Cossali *et al.* (1997) using water-glycerin mixture as test liquid in the form as

$$K_c = 2100+5880(h^*)^{1.44} \qquad 0.1 < h^* < 1.0 \qquad (1)$$

Okawa *et al.* (2006) showed that K_c is rather constant (K_c ~ 2,100) for pure water. The value of K_c from Eq. (1) at h^*= 0.6 for present Case 1 and 2 is 4,918. For Case 1, the value of K, 4,107, is close to this critical value and it is higher than the critical value of Okawa *et al.*'s, so weak splashing was observed. For Case 2 with K=9,134, strong splashing surely occurred.

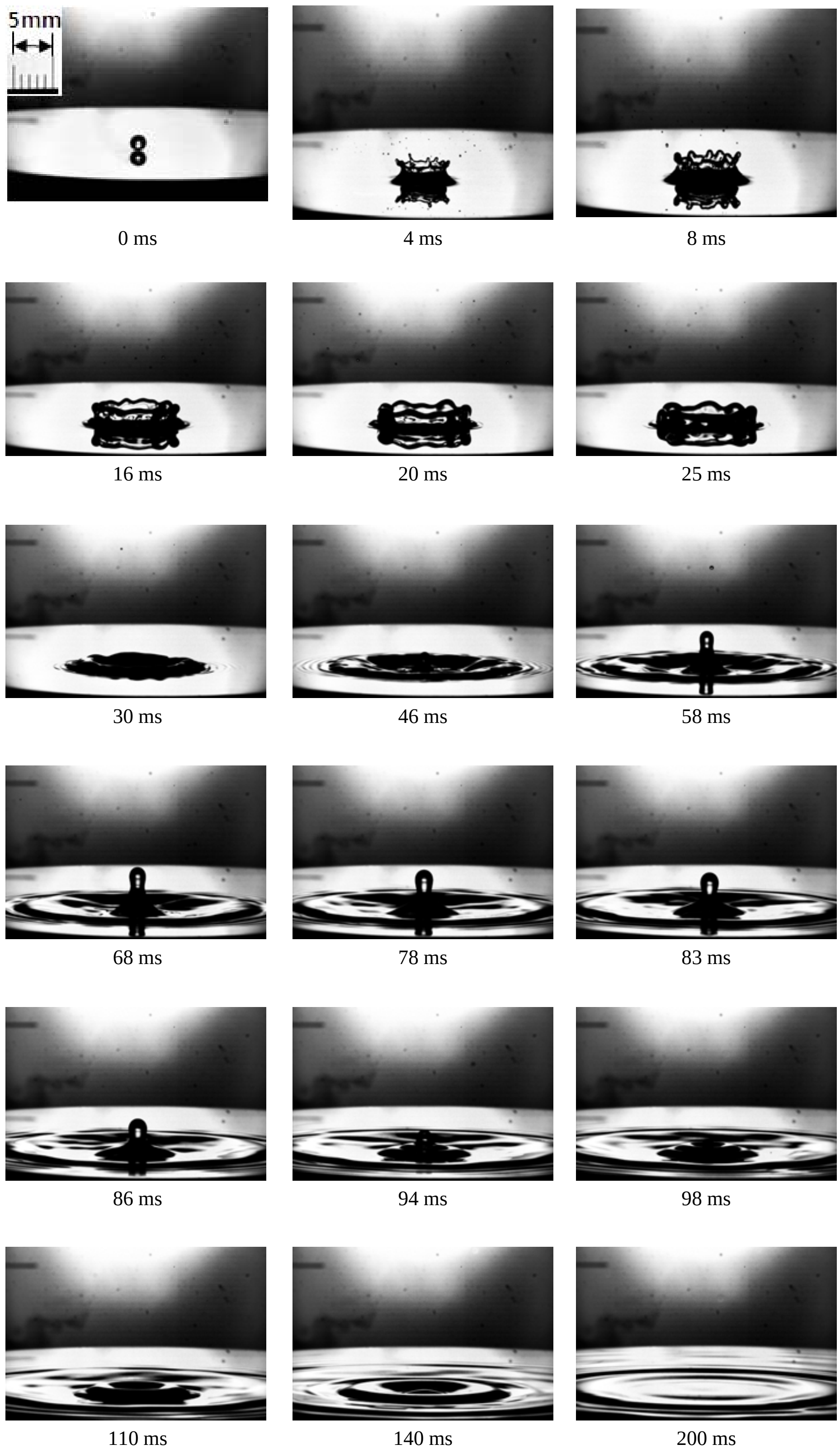


Fig. 4. Behavior of an impacting droplet onto a liquid film, for the case of *h* = 2 mm, *V*=2.75 m/s.

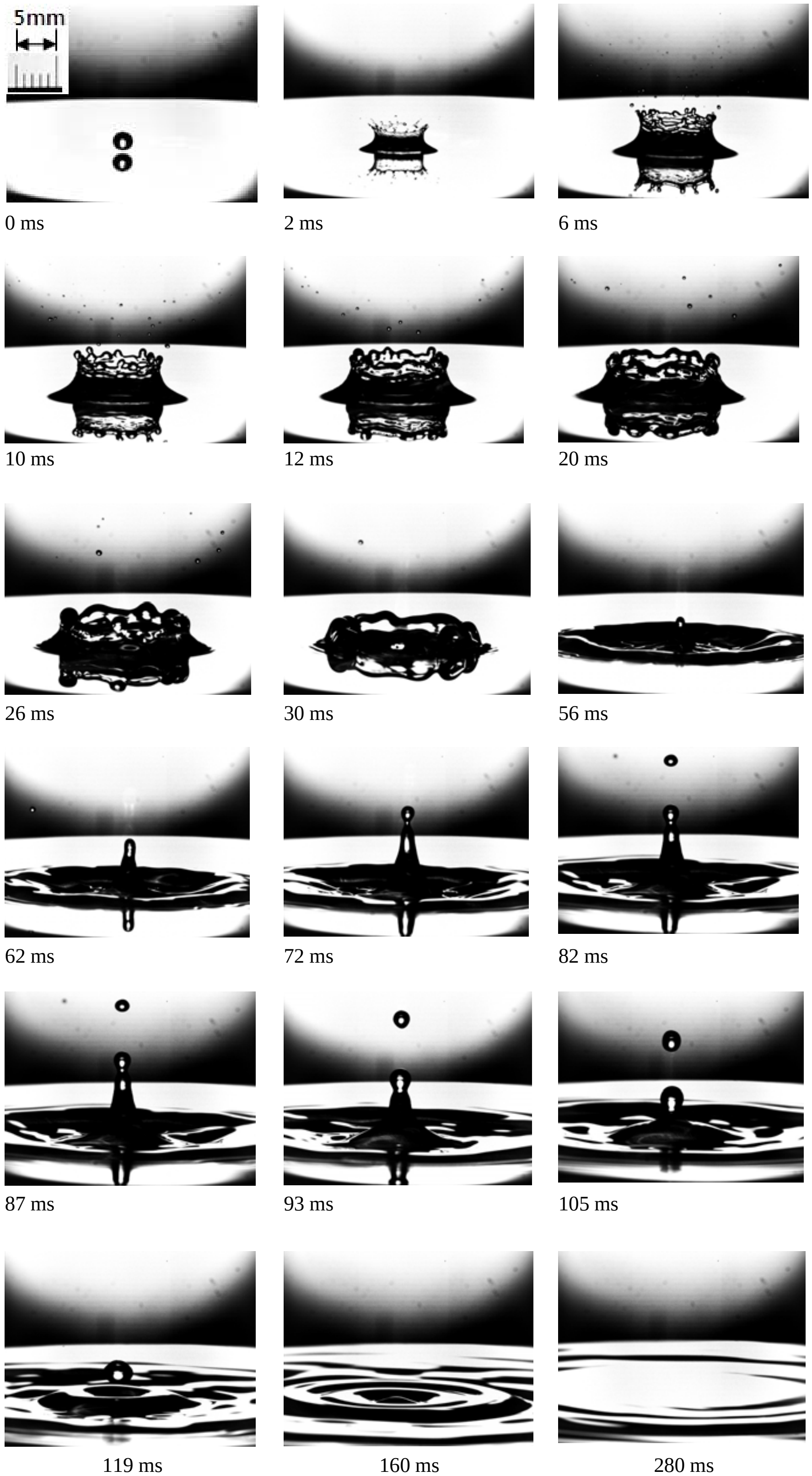


Fig. 5. Behavior of an impacting droplet onto a liquid film, for the case of *h* = 2 mm, *V*=4.1 m/s.

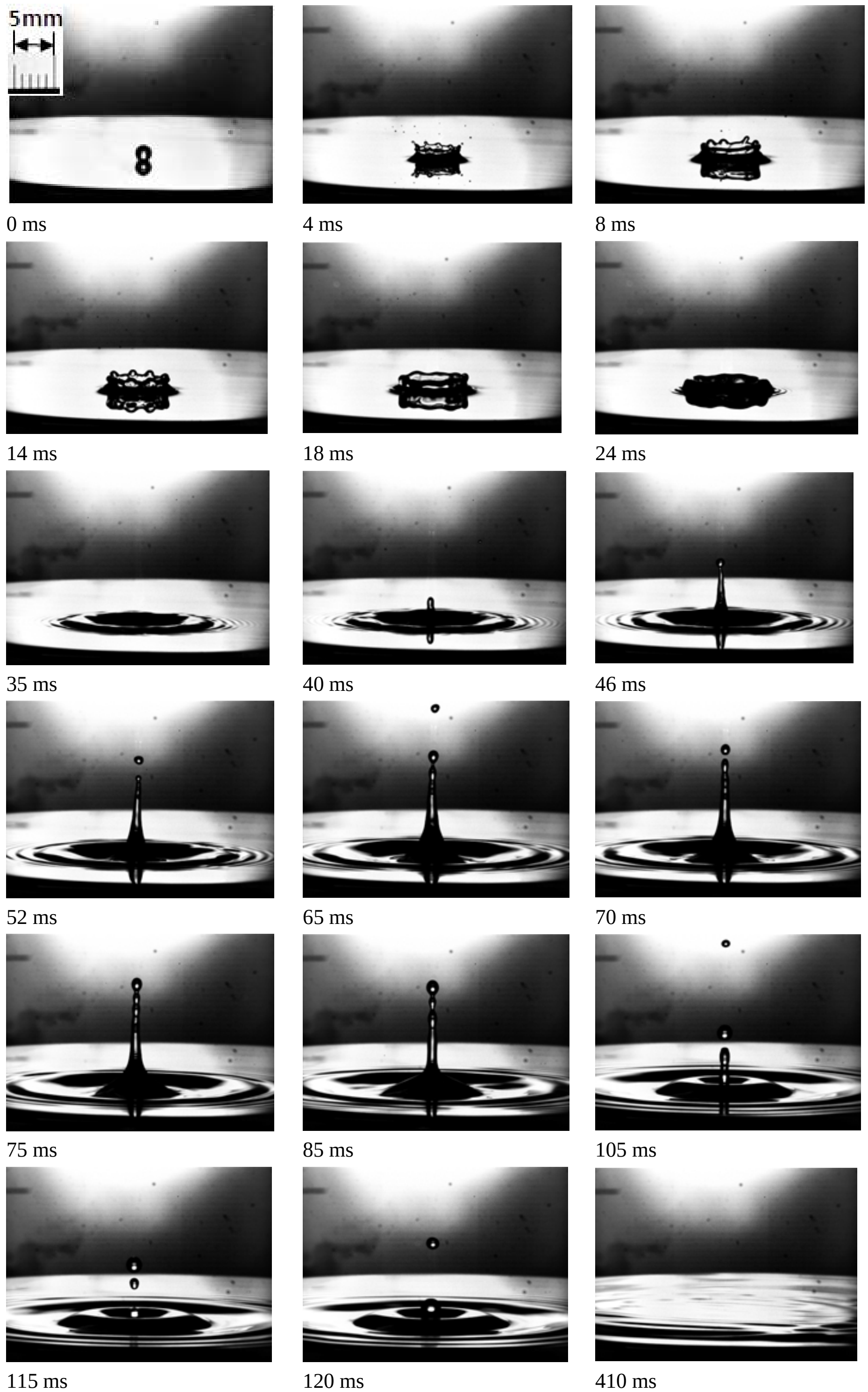


Fig. 6. Behavior of an impacting droplet onto a liquid film, for the case of *h* = 10 mm, *V*=2.75 m/s.

Figures 6 and 7 show the behavior of the impacting droplet onto a thick liquid film, h= 10 mm. Even though the liquid film is five times thicker than Case 1 and 2, no secondary atomization in the collapsing period of crown was observed for the case of the lower droplet velocity and secondary atomization was observed for the case of the lower droplet velocity as in the case of the thin liquid film. The size of the crown is larger for the case of the high droplet velocity, as in the case of the thin liquid film. Noticeable difference between the thin and thick liquid films occurs at the same low

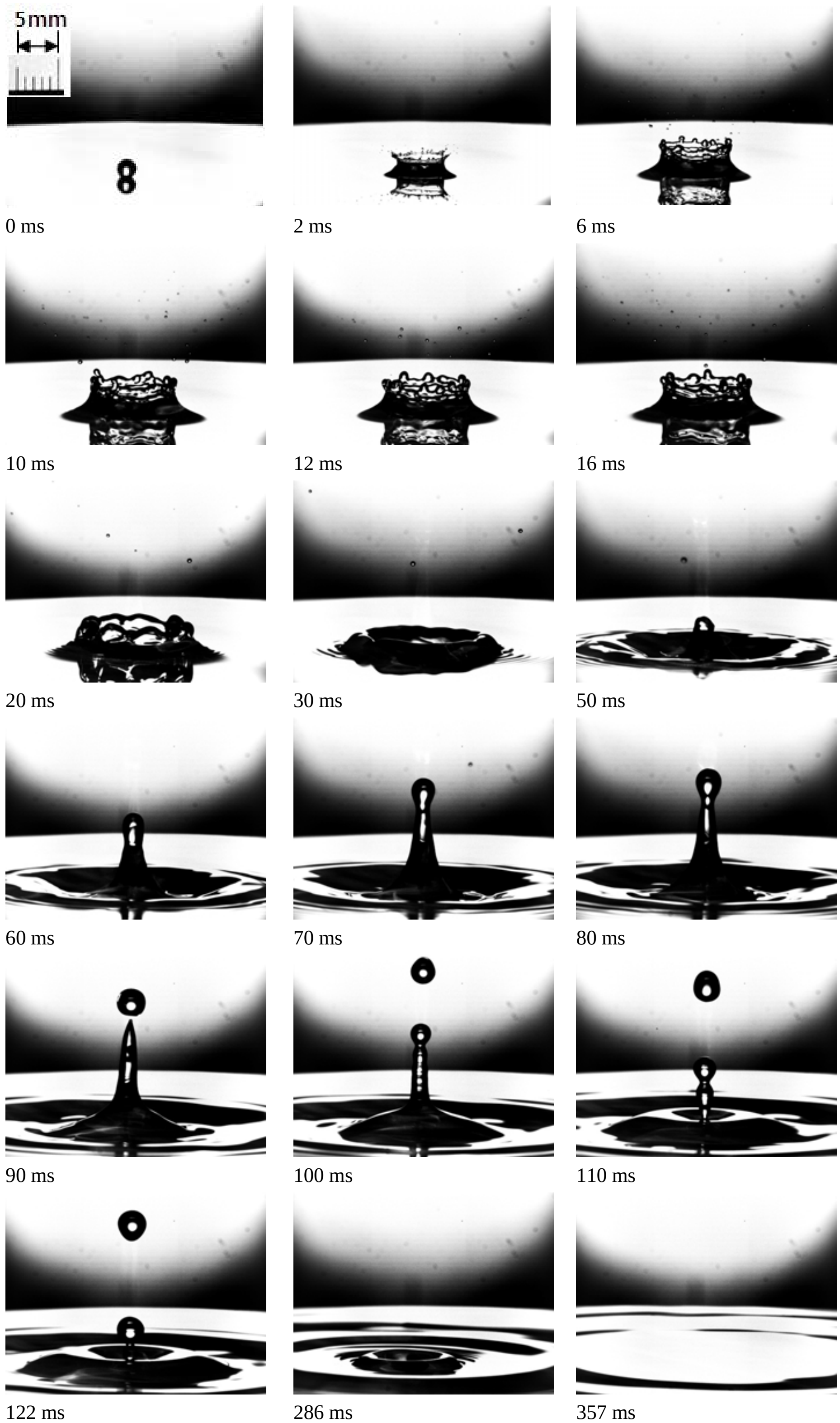


Fig. 7. Behavior of an impacting droplet onto a liquid film, for the case of *h* = 10 mm, *V*=4.1 m/s.

droplet velocity. A droplet disintegrates from the end of the central jet for the thick liquid film, which phenomenon does not occur for the thin liquid film. For the thick liquid film, the diameter of the droplet disintegrating from the central jet is much bigger for the high droplet velocity.

3.2 Characteristics of the Crown

Figures 8 and 9 show quantitative measurements of the diameter and height of the crown with time, respectively. The diameter and height of the crown are non-dimensionalized by the initial diameter of the impacting droplet. The starting time to measure the size of the crown was set as zero second. The approximate uncertainty of measurement errors was evaluated as follows. If we assume errors of ±2 pixels in measuring the length of the diameter from the droplet images, the error of the diameter measurement becomes ±0.1 mm by the conversion factor, and its non-dimensionalized value, D_c/D_o, is ±0.03.

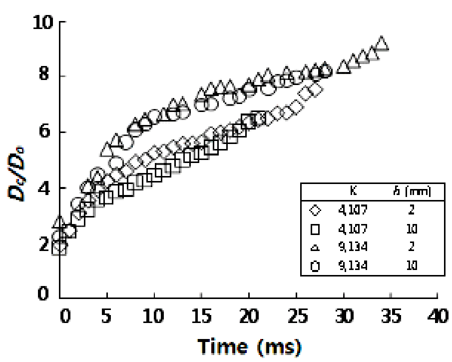


Fig. 8. Time history of the crown diameter.

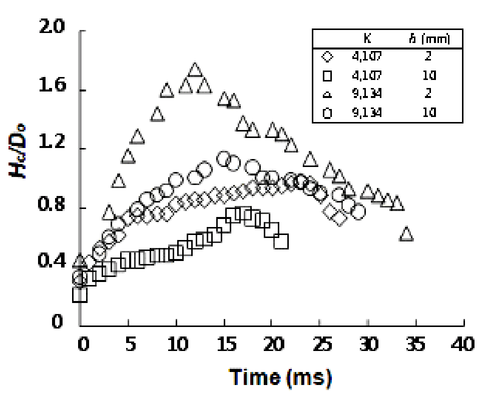


Fig. 9. Time history of the crown height.

As Fig. 8 shows, the crown diameter is mainly affected by the droplet velocity, while the effect of the liquid film thickness is not severe. The diameter of the crown is large with the high droplet velocity, because the kinetic energy of the droplet is larger for faster droplets. At the same droplet velocity, the diameter of the crown is a little greater for the thin liquid film. The greatest diameter of the crown occurs for Case 2, namely, the high droplet velocity and thin liquid film.

Figure 9 clearly demonstrates the effects of the film thickness and the droplet velocity on the time history of the height of the crown. Like the diameter of the crown, the height of the crown is greater for the high droplet velocity. At the same droplet velocity, the height of the crown for the thin liquid film is greater than that for the thick liquid film, because the amount of liquid for the spreading droplet to push is small for the thin liquid film. The size of the crown is the biggest for Case 2, the high droplet velocity and thin liquid film and smallest for Case 3, the low droplet velocity and thick liquid film. At this condition for Case 3, the droplet doesn’t possess high enough momentum to push the liquid film, and the liquid film is too thick for the droplet to push away.

3.3 Characteristics of the Central Jet

Figure 10 shows the change in height of the jet formed in the center with time. The effect of the droplet velocity is not severe for the thick liquid film but the jet height is affected much by the droplet velocity for the thin liquid film. The thick liquid film produced a higher central jet than the thin liquid film. If the liquid film is thick, the contracting droplet after maximum spreading shrinks on the liquid film, resulting in less loss of kinetic energy of the droplet, compared with the case that the droplet contracts on the solid surface. This is in contrast to the result that the thin liquid film produces a crown of great height. In other words, if the droplet velocity is the same, the thin liquid film produces a crown of great height in the spreading stage, and the thick liquid film produces a central jet of great height in the contracting stage. The height of the central jet is the smallest for Case 1, the low droplet velocity and thin liquid film.

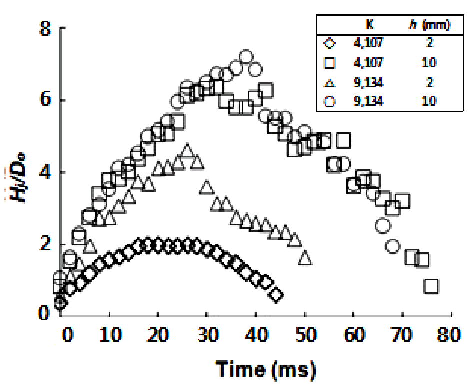


Fig. 10. Time history of the central jet height.

Table 2 shows the maximum dimensionless values of the diameter (D_c/D_o) and height (H_c/D_o) of the crown, and the height of the central jet (H_j/D_o). As mentioned before, the maximum values of the diameter and height of the crown occur for Case 2, the high droplet velocity and thin liquid film. On the contrary to the size of the crown, the thick liquid film, Case 4, showed the greatest height of the central jet at the same high droplet velocity.

Table 2 Maximum values of the diameter, height of the crown and central jet height

Case	D_c/D_o	H_c/D_o	H_j/D_o
1	7.54	0.98	1.99
2	9.25	1.74	4.63
3	6.50	0.76	6.37
4	8.21	1.13	7.21

Table 3 shows the diameter of the secondary droplet that detaches from the end of the jet while the central jet becomes high. At low droplet velocity, this kind of secondary droplet is not produced in the thin liquid film (Case 1), or a much smaller secondary droplet is formed in the thick liquid film (Case 3). At high droplet velocity, the diameter of the secondary droplet is even larger than that of the initial impacting droplet due to the receding liquid with high momentum. The largest secondary droplet is formed for Case 4, the high droplet velocity and thick liquid film.

Table 3 Diameter of the secondary droplet

Case	1	2	3	4
D_s (mm)	none	3.52	1.53	4.76

4. CONCLUSION

This research experimentally studied the dynamic behavior of a droplet impacting upon a liquid film. The impacting phenomenon of a single droplet onto liquid film was visualized by time-delay photography. The main parameters are the droplet velocity and the thickness of the liquid film. Photographic images showed the formation of a crown, a central jet, and a disintegrating droplet from the central jet. The diameter and height of the crown generated by the splashing phenomenon, the height of the jet formed in the center, and the size of the secondary droplet separated from the central jet were measured and analyzed.

The crown diameter and the central jet height were mostly affected by the droplet velocity and the thickness of the liquid film, respectively, while the crown height was influenced by both the droplet velocity and the thickness of the liquid film. The diameter and height of the crown were greater for the case of the high droplet velocity and thin liquid film. On the other hand, the height of the central jet was greater for the case of the high droplet velocity and thick liquid film. The size of the disintegrating droplet from the central jet heavily depends on the velocity of the impacting droplet. Namely, a larger droplet is produced by the high droplet velocity.

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