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Visual experimental study of droplet impinging on liquid film and analysis of droplet evolution characteristics

Wenxuan Ju, Yikai Wu, Shixin Lin, Fulong Zhao (✉), Sichao Tan

College of Nuclear Science and Technology, Harbin Engineering University, Harbin 150001, China

Abstract

The evolution characteristics of the droplets colliding with the wet wall surfaces are essential to the performance of the steam-water separator in the nuclear power plant. When the droplets impact the liquid film with different velocities, the diverse phenomena will occur. The collision characteristics of droplets with the wall surface during the movement are experimentally studied. In the experiment the high-speed camera with a shooting speed of 2000 frames per second is used to obtain the spread process of droplets hitting the liquid film vertically at different velocities. The phenomena of the crown with and without splashing are analyzed. The critical parameters of phenomena are recorded, and the qualitative conditions generated by the three phenomena are analyzed. The critical velocity to generate the secondary droplet is 0.021 m/s and the critical velocity to generate the main droplet is 0.017 m/s when a droplet with a diameter of 3.62 mm hits the liquid film. If the kinetic energy of falling droplets can be reduced, the waste caused by the Worthington jet and splashing droplets can be effectively reduced. The present study can lay basis for the design of the steam-water separator and the space droplet radiator.

Keywords

droplet collision
secondary droplet
liquid film
steam-water separator

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Research Article

1 Introduction

The droplet collision with wet wall surfaces is a common phenomenon in the nuclear power plant, for example, the collision of small droplets with wet wall surfaces in the steam-water separator (Li et al., 2007; Zhao et al., 2018) and with the droplet collector wall surface in the space radiation heat exchanger (Totani et al., 2002, 2005, 2006). Actually, the droplet colliding with a liquid film is a complicated process. The droplet velocities can greatly influence the collision performance, such as the spreading width, the crown characteristics with and without splashing. When the droplet velocity reaches a specific value, the secondary droplets can be generated surrounding the coronal fracture edge and the collision center. The secondary droplets can lead to the decrease of the equipment separation or collection efficiency or the efficacy loss. Therefore, it is vitally important to study the droplet collision characteristics with the liquid films, which can improve the efficiency of the space radiation heat exchanger and steam-water separator.

However, there are few studies on the droplet collision with the liquid films, especially the thick liquid film (the thick liquid film is defined as $1.5 < \sigma_f < 4$, $\sigma_f = h_f / D_0$. h_f is the thickness of the liquid film layer, and D_0 is the diameter of the impact droplet.). In addition, there is almost no general formula that can specifically describe the collision process. Thus, many researchers have done a lot of researches on the visualization experiments of the process of the process of droplets hitting the liquid film. Kong et al. (2016) studied the evolution characteristics during the droplets impacting the hydrophilic–hydrophobic and superhydrophilic–superhydrophobic interface with different velocities. Yamamoto et al. (2018) used the visualization method to study the process of droplets impacting on the superhydrophobic surface and the generation of the collapse of the air cavity, so as to obtain the initial conditions of jet generation. Cossali et al. (1997) studied the secondary generation mechanism during the spray droplets impingement on a wet, cold solid surface. Zhu et al. (2014) established a mathematical model for droplet movement in the spray tower, and investigated the effects of droplet diameter, initial velocity, air velocity, and spray density on the droplet movement and distribution characteristics. Zhang (2018) carried out experimental and numerical simulations on the extinction model for the

✉ zhaofulong@hrbeu.edu.cn

droplets colliding with wet and dry walls to lay basis for developing the mathematical models and new software in the future. Loth (2000) used the Euler–Lagrangian method to investigate the two-phase flow of solid particles, liquid particles, and bubbles. Zhang (2016) used fluid dynamics to simulate the process of droplet hitting hydrophobic/superhydrophobic surfaces.

The process of droplets impinging on the liquid film can be described by the dimensionless criterion number, such as Reynolds number, Weber number, Ohnesorge number, Froude number, Splash parameter, etc. In addition, Marengo et al. (2011) pointed that the thickness of the liquid film is divided into four categories, and the effect of the thickness of the liquid film on the impacting characteristics is obtained. The results indicated that the characteristics of the droplet impacting the wall depended on the comprehensive effect of the surface structure and the liquid film thickness. Roisman et al. (2006) presented the possible results when the droplets hit the wet wall surface. However, there is no general rule for the critical conditions of the droplets splashing, which is vitally important for the improvement of the steam-water separator and space radiation heat exchanger.

Therefore, in the present paper in order to figure out the droplet collision phenomenon and the critical conditions of the droplets splashing during hitting the liquid film, the collision characteristics of droplets with the wall surface during the movement are experimentally studied. The phenomenon of the falling droplets with different velocities hitting the liquid film is measured by a high-speed camera. The critical velocity of the initial droplet and the size distribution of the generated secondary droplets are investigated. The phenomena and mechanism of the crown generation are analyzed as well.

2 Experimental apparatus

Figure 1 is the overall diagram of the experimental system. The test bench is constructed by plexiglass (Liu, 2015) and is split into a main body and a bottom plate, which can be assembled. The edge of the bottom plate is engraved with a tick mark, by which can calculate the droplet size and falling speed in real time. Small edges about two centimeters high are installed around the bottom plate, so as to put in water to make a centimeter-thick liquid film. The experiment uses a high-speed camera to shoot droplets at a rate of 2000 frames per second. The light source is supplied by the 8.8 W laser. Half of the laser light is made to enter the plexiglass, and uses the internal refraction of the plexiglass to illuminate the plexiglass itself. The remaining laser light illuminates the upside of the plexiglass so that the drop process of droplet can be captured by the camera. A stainless steel object is also equipped by the opposite of the light source to reflect to further complement the light source. The shooting was done indoors without wind. The device is equipped with an iron support, and a droplet ejection device (Zhou et al., 1999; Wei et al., 2004; Xue et al., 2014) is fixed on the iron support. Between the dropper mouth and the plexiglass device table, a set of data is measured every 5 cm to obtain different velocities of the droplets. The light source and the high-speed camera are placed vertically to prevent the laser from damaging the photosensitive elements in the high-speed camera. The data cable is connected to a high-speed camera and a computer.

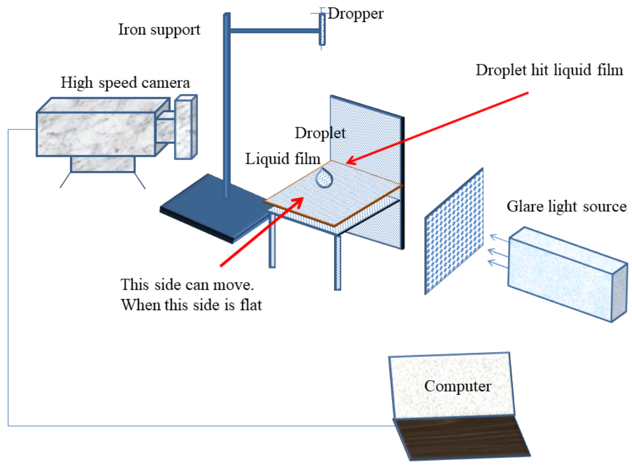


Fig. 1 Diagram of experimental system.

3 Result analysis

3.1 Comparison of droplets hitting dry and wet walls

In the experiment, a droplet with a diameter of 3.64 mm collided with the dry wall surface and the liquid film. Figure 2 is the experimental process of the droplet hitting the liquid film at 0.022 m/s. During the experiment, it can be seen through a high-speed camera that when the droplet collides with the dry wall surface, the droplet spreads on the dry wall surface first, and shrinks to center when reaching the spreading limit. When the droplet hits the liquid film, the droplet assimilates into the liquid film. A coronal liquid film is generated when the edge is above the liquid film, and a vacuole is generated below the liquid film. Then the coronal liquid film gradually degraded, and the center of the liquid film rebounded to produce main droplets (Li et al., 2015).

In order to show the difference between the evolutionary process of droplets colliding with wet and dry liquid films, Fig. 3 shows the evolution process of droplets striking on dry wall surface, and Fig. 4 shows the evolution process of droplets striking on liquid films. When the droplet hits the dry wall surface, the process of collision has a viscous dissipation, which reduces the kinetic energy of the droplet. When hitting the wet wall surface, the droplets merge directly with the liquid surface, which greatly reduces the viscous dissipation, and most of the energy is converted to free energy, which causes the liquid surface to form secondary droplets and Worthington jets. This is the reason why the droplet spreads and shrinks on the dry wall surface but forms a coronal splash on the liquid surface.

The phenomenon when the droplet hits the dry wall surface is as following: first the droplet collides with the wall surface, and then droplet spreads and last shrinks toward to the center.

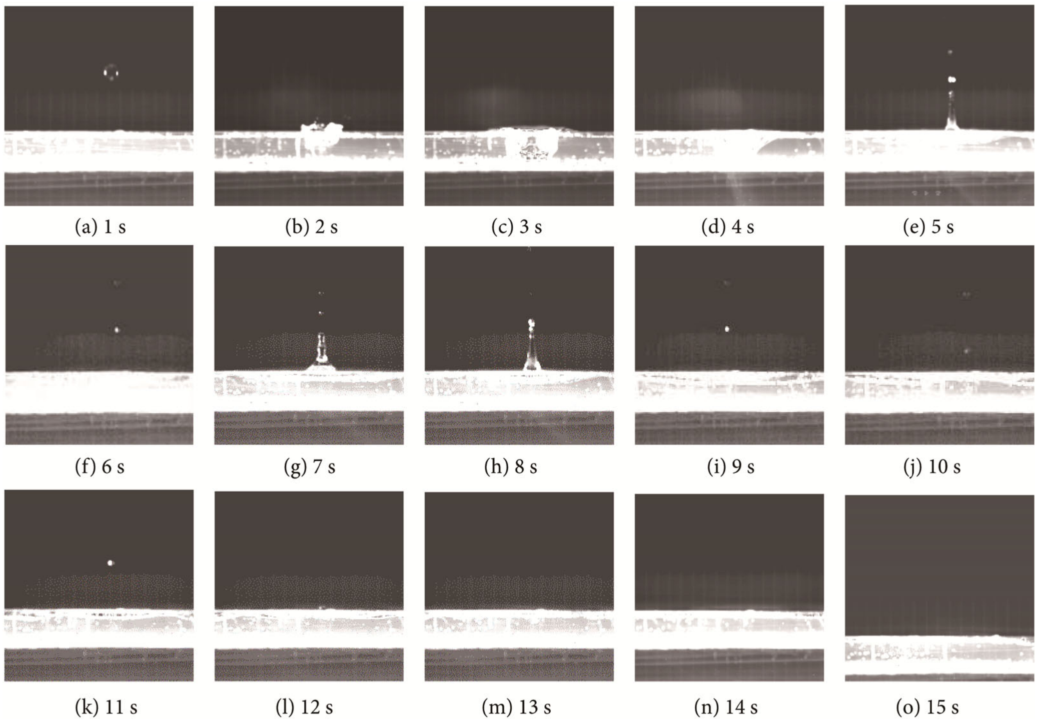


Fig. 2 Evolution characteristics of droplets in contact with liquid film.

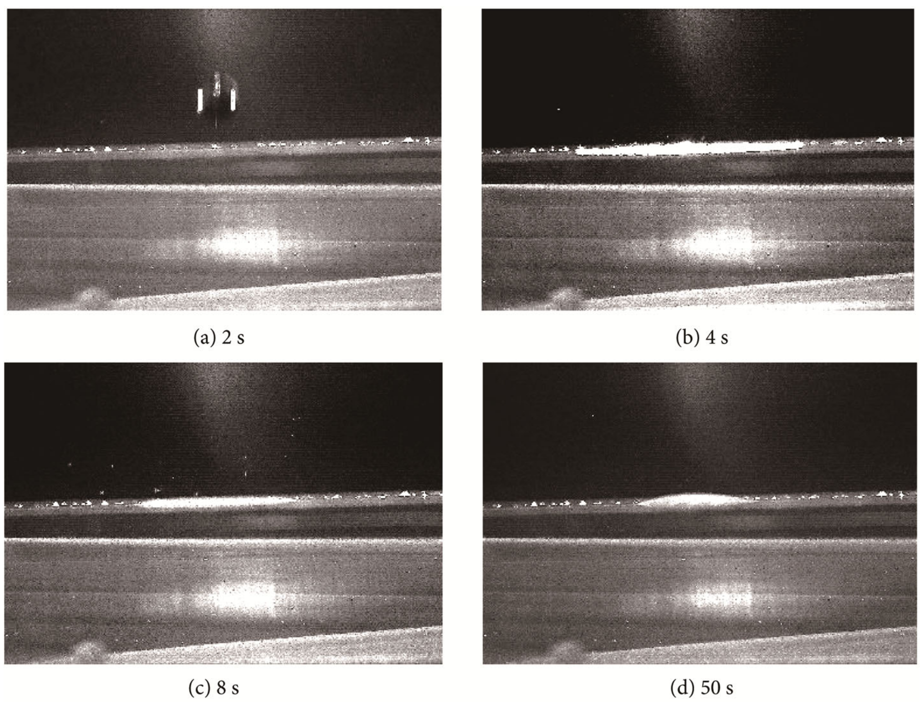
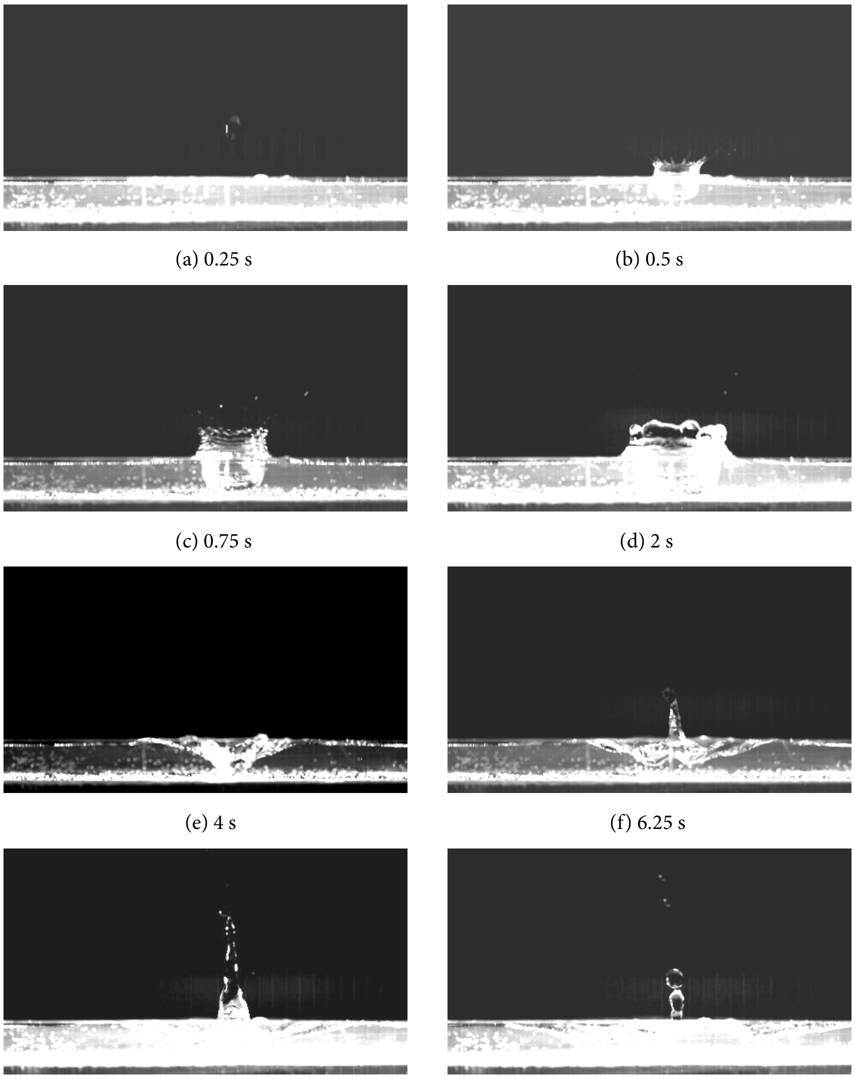


Fig. 3 Evolution characteristics of droplets in contact with dry wall surface.



(a) 0.25 s (b) 0.5 s

(c) 0.75 s (d) 2 s

(e) 4 s (f) 6.25 s

(g) 6.75 s (h) 10 s

Fig. 4 Evolution of droplets hitting liquid film.

The phenomenon that the droplet hits the liquid film is as following: first the droplet collides with the liquid film, then a crown-shaped splash occurs at the collision edge, later the liquid film generates a hollow bubble, and at last the center rebounds.

It can be seen from the collected images that after the droplet hits the horizontal dry wall surface, the contact area of the droplet with the dry wall surface gradually increases under the action of the collision. The generation of secondary droplet is that the speed or the size of the water surface cannot hold the broken water droplets on the edge. The phenomenon is very different when droplets hit a liquid film.

First, after the droplet hits the liquid film, it will not spread and splash directly, but will fuse with the liquid film. The kinetic energy of the droplet is transferred to the liquid film and the situation similar to that when the droplet hits the dry wall surface will occur. However, unlike the former, which has a coronal thin layer, the latter has a relatively thick corona-spattered liquid film that is not broken easily. When the energy of the droplet hits the dry wall surface, viscous dissipation occurs, and there will be a small droplet splashing in the broken part of the coronal edge after the crown is formed. The liquid film will adhere to the droplets to show the adhesive force, and the liquid film also displays the characteristics of a larger root and a smaller top side, which make coronal edge seem rounded. Because the droplets are not easy to spread after they hit the liquid film, but the collision edge will produce a thin liquid film, the water that generates the thin liquid film does not come from the droplets but from the liquid film, similar to liquid film generated by an object falling into the water. Then the droplet created a bubble on the liquid film, and the shape of the bubble undergoes the evolution from a cylinder to a funnel shape, as shown in Fig. 5 and Fig. 6, and the surface has a wave shape. The size of the cavities is proportional to the speed, and under certain circumstances the bubble may reach the bottom. When the bubble expands to a certain extent, it will start to shrink, and then the rebound force will bounce the water column into the air, which is called Worthington jets.

The earliest theory to explain the surface wettability of solid surface is Yang's equation, $\cos\theta = (\gamma_{SV} - \gamma_{LV})/\gamma_{SL}$, in which γ_{SV}, γ_{LV}, γ_{SL} represent the tensions of solid–gas, liquid–gas, and solid–liquid interfaces respectively, and θ is the contact angle of flat surface. According to the definition of the contact angle, surfaces with $\theta < 90°$ and $\theta < 5°$ are usually called hydrophilic surface and super-clear surface, and the surfaces with $\theta > 90°$ and $\theta > 150°$ are called hydrophobic surface and super-hydrophobic surface respectively. Liquid molecules have molecular attraction, and the range of action of these attractive forces is about 10^{-8}–10^{-6} cm, known as the influence ball. If the distance of a molecule from the free liquid surface is less than the radius of the influence ball, the effect of the molecules in the ball on the molecules cannot be balanced. The thin layer of a thickness less than the radius of the influence ball is called the surface layer. All molecules in the surface layer are uniformly attracted downward, pulling the surface layer tightly into the liquid. Free energy means the value of the thermodynamic function increases with the increase of the surface area. When any liquid molecule enters the surface layer, it must resist the action of this force and must give these molecules mechanical work. This means that the free energy can be transformed into mechanical work. The increase of the free surface means the increase of the free energy, that is, to absorb energy from the surroundings.

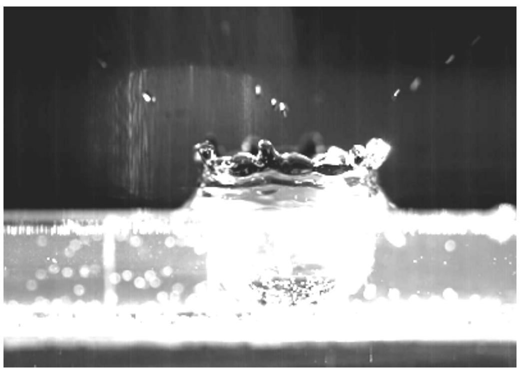


Fig. 5 Cylindrical cavities.

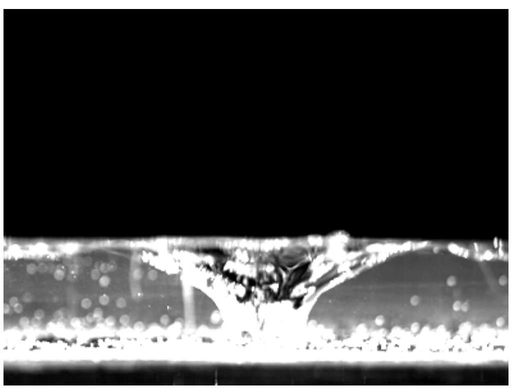


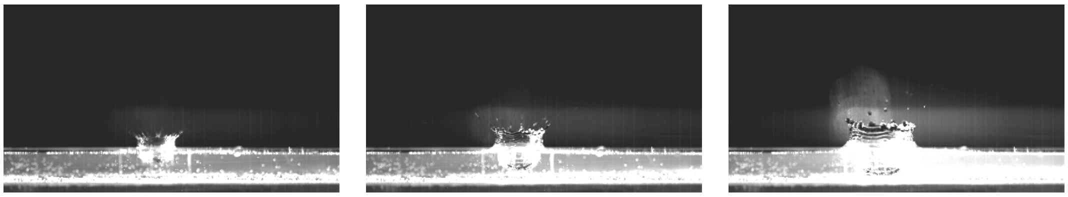
Fig. 6 Funnel shaped vacuole.

Conversely, when the droplet hits the liquid wall to give it energy, the free surface must increase. When the free surface shrinks, the direction of contraction has a strong negative work on the free surface. Surface tension puts the free surface in a stretched state. And then by the tension of the water, the water column will split into one or more water droplets, or the prototype of the water droplets will appear above the water column and drag into the water before being separated when the speed is low. It has been observed that as long as the speed increases, the splash in the center will become more and more obvious, and the height of the Worthington jets will increase significantly. The phenomenon that droplets do not hit the dry wall surface is as follow.

3.2 Evolution of characteristics droplets

In this section, due to the Rayleigh–Taylor instability, the evolution of secondary droplets that are crown broken and produced by the collision edges after the droplets hit the liquid film is briefly introduced. The critical velocity of secondary droplets was found under certain conditions.

Through the speed change produced by the interval of 5 cm upwards, the critical speed of coronal fracture was found by the fine adjustment. Spreading that occurs on dry walls will not occur on the liquid films (Liang, 2013). Generally, secondary droplets are generated on the dry wall surface because the surface tension of water cannot bear the kinetic energy of the secondary droplets. The coronal fracture of a droplet impacting a liquid film is different from the fracture on dry wall surface. The secondary droplets generated by the liquid film absorb different energy with the change of different speed of the falling droplets. The velocities are different. The moment the droplet contacts and fuses in the liquid film, the impact edge will produce a very small and thin crown, and the crown angle starts to produce protrusion. The first batch of secondary droplets will easily splash out from the crown angle and the speed will be very fast. After the crown expands, the crown angle shrinks and becomes larger, and the crown wall becomes thicker. As the surface tension corona breaks, a second batch of secondary droplets is produced. Compared with the first batch, the second batch of secondary droplets has a larger volume and a lower speed. Then the crown thickened and the dwarf crown angle



(a) 0.25 s (b) 0.5 s (c) 0.75 s

Fig. 7 Secondary droplet evolution of droplets hitting liquid film.

contracted and rounded, and the third batch of droplets could not break the surface tension. The coronal outer surface produced by impacting a dry surface is smooth, and the latter's crown will appear corrugated due to the vibration of the liquid film.

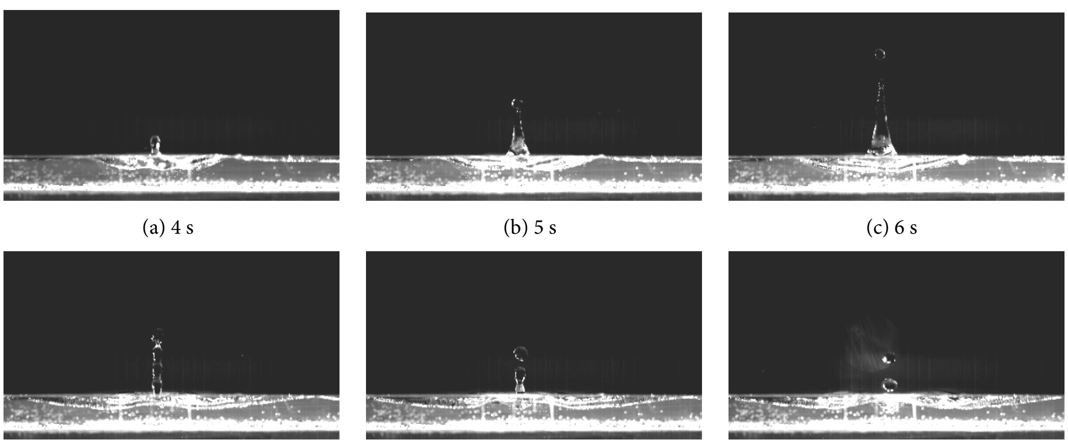
In order to find the critical velocity, the experiment uses binary search. Under the condition of a droplet size of 3.62 mm, find the critical value at a speed of 0.020 m/s and a speed of 0.022 m/s and then take the intermediate speed. After three times, the rough critical speed that no secondary droplets are produced was found of 0.021 m/s.

3.3 Evolutionary characteristics of droplet bounce

Different from the point where the droplet hits the dry wall, the liquid film will rebound due to the impact. The generation of the main droplet is due to the central rebounded liquid column shrinks in a certain part of the liquid column under the influence of surface tension, thereby generating the central droplet. Due to the plateau–Rayleigh instability, it can be seen that the slight disturbance makes the liquid column always unable to maintain a uniform and stable state. From the additional pressure of the curved surface, the Young–Laplace equation shows that the smaller the radius of curvature, the greater the pressure. The external surface is affected by the free surface energy when it does not work on the liquid surface, and the free surface becomes smaller. Therefore, when the liquid column is elongated, there is a tendency to keep its surface area to a minimum, that is, to break into droplets. The main droplets start to leave the liquid column from top of the liquid column.

Generally, main droplets are first generated at the top of the liquid column, and are affected by the height and diameter of the liquid column. It can be known from statistics that at a certain speed interval, the number of main droplets increases with the increase of the speed of droplets. After exceeding a certain speed, the diameter of the liquid column increases, and the main droplets will stick together. The free energy, the kinetic energy, and potential energy of multiple (usually two) droplets transform into each other, showing a complex movement. The number of individual main droplets will decrease. Figure 8 shows the evolution of the droplet in the center of a falling droplet hitting liquid film at the speed of 0.045 m/s. It can be seen from Fig. 9 that the diameter difference of the root length of the unit of Worthington jets increases with time, so the pressure difference also increases, and the jet radius rapidly decreases and shrinks in a very short time.

At the moment of detachment, the droplet can be pulled downward by the adhesion of the liquid column. If it is subjected to a short downward force in a vacuum, the water droplet will still fall back to the liquid film under a gravity-free vacuum. However, droplets that are detached upward during the rebound process will cause waste, and even collide with the subsequent droplets, and the second batch of droplets cannot be recovered due to interception in a vacuum.



(a) 4 s (b) 5 s (c) 6 s

(d) 9 s (e) 10 s (f) 11 s

Fig. 8 Evolutionary characteristics of droplet impacting liquid film.

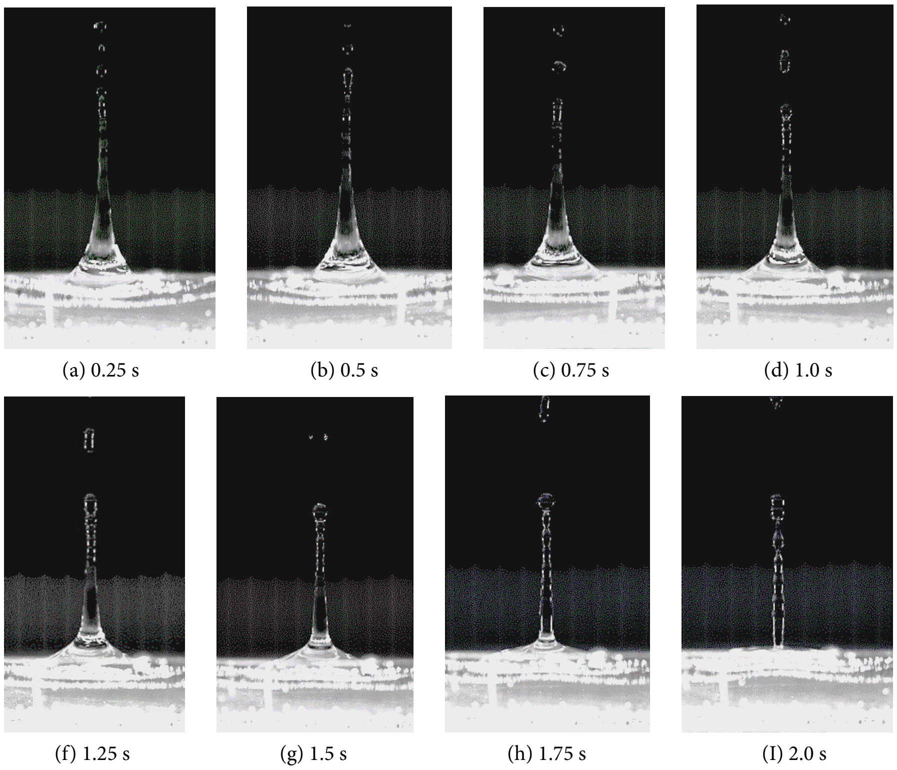


Fig. 9 Plateau–Rayleigh instability.

Table 1 shows the number of main droplets produced when 3.62 mm droplets hit a centimeter-level liquid film at a drop height of every 5 cm under a windless condition. In Table 1, the actual falling distance refers to the distance from the droplet begins to fall to the liquid film; the experimental data distance refers to the actual height of the droplet from the surface of the experimental table; due to the influence of air resistance and experimental error, and the theoretical speed is determined by the most basic speed formula, the theoretical and actual velocities differ greatly.

Table 1 Number of main droplets produced by droplets hitting the liquid film changes with different velocities

Actual drop distance (m)	Experimental drop distance (m)	Theoretical droplet velocity (m/s)	Actual droplet velocity (m/s)	Main droplet count
5	18.7	0.98990	0.0175874	0
10	23.7	1.40000	0.0172694	3
15	28.7	1.71464	0.0222318	3
20	33.7	1.98000	0.0273404	4
25	38.7	2.21359	0.0318464	4
30	43.7	2.42487	0.0325059	5
35	48.7	2.61916	0.0391747	5
40	53.7	2.80000	0.0435835	5
45	58.7	2.96985	0.0449911	6
50	63.7	3.13050	0.0448163	7
55	68.7	3.28329	0.0456738	5
60	73.7	3.42929	0.0531206	4
65	78.7	3.51693	0.0510638	4

Table 2 shows the change of the horizontal diameter of the Worthington jet generated when the droplets fall at different height with time. The unfilled part is the case when the horizontal surface has shrunk into a small liquid column, and it has no reference value, so it is omitted.

The experimental results are similar to the research results of Tsinghua University (Zhang, 2018). The diameter of the Worthington jet generated by the liquid film after the droplet impacts on the horizontal plane are basically similar to the change of the spreading diameter of the droplet impacted on the solid wall at a low speed.

Table 2 Law of the diameter of the Worthington jet at the horizontal plane at different velocities with time

Drop distance (m) \ Time (s)	1	2	3	4
18.7	1.8	4.2	8	—
23.7	2	4.8	7	8.4
28.7	3.2	5.2	8.4	9.6
33.7	3.8	6.2	7.7	10
38.7	4.8	8	7.4	10.3
43.7	4.1	6.9	8.2	11.8
48.7	3.8	6	8	14.4
53.7	4.8	7.1	9.2	12.1
58.7	6.6	8.7	12.3	16.9
63.7	7.4	9.5	13.1	19.7
68.7	8.2	9.7	13.3	19.7
73.7	7.2	7.9	7.1	—
78.7	8.7	10.3	14.4	21.5

The number of main droplets in Table 1 does not include droplets that show a rough outline in the liquid column without separation. Comparing the Worthington jets splashed at different velocities, it can be seen that the radius of the Worthington jet is relatively large when at a high speed, and the free surface is enlarged. According to the Young–Laplace equation, the difference in radius is relatively small, so the pressure difference per unit distance is also relatively small. This makes it difficult to shrink to form droplets (Ogawa et al., 2006). It can be seen from the data of the first two rows that when the droplet approaches a certain speed, one or more main droplets are suddenly and randomly generated. Secondary droplets can be avoided by reducing the energy generated during a collision, weakening the rebound or separation effect from the second, such as reducing speed or reducing droplet size. Both are designed to reduce the energy generated during a collision, thereby weakening the rebound or separation effect.

Figure 10 shows the curve of the number of center droplets as a function of droplet velocity. At velocities below 0.021 m/s, there are no main droplets. At a speed of 0.021 m/s and a speed of 0.045 m/s, the number of main droplets increased uniformly from 3 to 7. Between 0.045 and 0.051 m/s, the number of main droplets slowly decreases. The diameter of the rebound liquid column increases with the increase of the droplet velocity, and the generation of the main droplet is related to the diameter of the liquid column. Within the critical velocity, thinner liquid columns can produce fewer main droplets. Levin and Hobbs's (1971) research believes that the secondary droplets will decrease after exceeding a certain speed, which is consistent with the experimental results. Exceeding the critical velocity, the liquid column cannot easily be divided by surface tension, so the main droplets generated are gradually reduced.

Figure 11 presents the change in diameter of the Worthington jet in the horizontal plane with time, and it can be seen that the overall diameter increases over time. Due to the influence of limited experimental accuracy and measurement accuracy, some experimental data are disordered. It will be improved in future experiments.

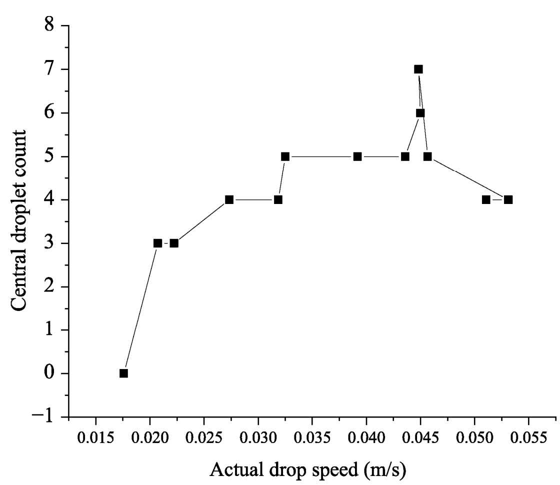


Fig. 10 Number of main droplets produced by droplets hitting the liquid film changes with different velocities.

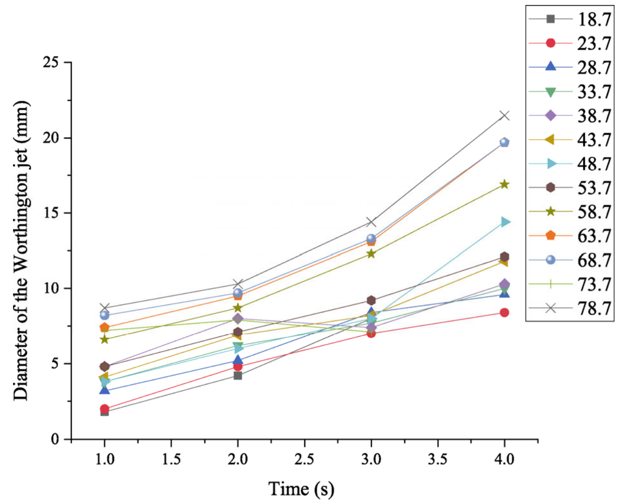


Fig. 11 Relationship between the diameter of the Worthington jet at the horizontal plane at different velocities and time.

4 Conclusions

In the present study, conditions that the secondary droplets and main droplets generated are experimentally studied during the droplet impinging on the liquid film. The specific conclusions are as follows.

(1) The process of the droplet colliding with the liquid film is more complicated than that of impacting the dry wall surface. Since the droplets give the liquid film kinetic energy, the free surface energy of the liquid film increases, and thus the free surface of the liquid film also increases. The liquid film consumes energy by releasing secondary droplets, oscillating the free surface and forming a Worthington jet. The central droplet generated by the liquid film will cause greater waste of droplet than the secondary droplet generated by general crown fracture.

(2) Under the conditions of the collision of a droplet of 3.62 mm, the crown edge produced by the collision will break and generate a secondary droplet at a speed of about 0.021 m/s.

(3) Under conditions of the collision droplets of the size of 3.62 mm, a main droplet will be generated at a speed of about 0.017 m/s.

(4) This paper studies the change of the number of main droplets produced by the Worthington jet in the velocity range from 0.0176 to 0.0511 m/s. It fits well with the results obtained from the aspect of energy. The experiment found that the number of primary droplets will decrease

after a certain speed, which is similar with Levin and Hobbs's conclusion that the number of secondary droplets generated by collisions of droplets exceeding a certain speed will decrease.

(5) The splashing liquid loss of a droplet is related to the size and speed of the droplet. Generally, with the larger the droplet velocity and the size, the splash loss will become larger. The splash loss of a droplet is related to the size and velocity of the droplet. The experimental conclusion can provide a basis for the steam-water separator and droplet radiation radiator.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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