Experimental Study of Single Droplet Impact on a Moving Surface

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Abstract

The motion of single droplet on solid surface is a popular research topic, but most scholars have focused on stationary surfaces, there are few studies related to the motion of droplet on moving surface. In this paper, a visualization platform based on high-speed photography is built to capture the morphology of droplet after impacting on moving surface, and to study the motion characteristics of droplet during impacting on moving surface. The evolution of the overall morphology of the droplet after impacting the moving surface is studied under different parameters such as the moving speed of the surface, the impact velocity of the droplet, the initial diameter of the droplet and the surface material, and the trends of the droplet spreading factor and the height factor are analyzed. The results show that the increase of surface movement velocity, droplet equivalent diameter, and droplet impact velocity all promote the spreading of droplet.

Keywords

Droplet; Moving Surface; Spreading Factor; Height Factor.

1. Introduction

Since Worthington[1] published the first paper on droplet impact on surface studies in the late 19th century, many researchers have been attracted to carry out studies related to droplet impact the on surface. Until the last few years, researchers have turned their attention to droplet impact on moving surfaces. Droplet impingement on solid surfaces is a widespread phenomenon in various industrial application scenarios, such as industrial coating[2], spray cooling[3], inkjet printing, internal combustion engine fuel injection, courier disinfection, vehicle cleaning, and pesticide spraying. When a droplet impacts a solid surface, the droplet's motion pattern is variable and may spread, splash, or rebound [4-7]. The droplet impact velocity[8-11], the droplet physical properties (surface tension, viscosity, etc.)[12-15], the surface physical properties (wettability, roughness, etc.)[16-19], and the surrounding environment (airflow, temperature, etc.)[20,21] all affect the droplet motion process on the solid surface.

Tang[22] et al. studied the morphological evolution of droplet after impact on flat stainless steel surfaces with different roughness using high-speed micrographic techniques. The results showed that the droplet spread in sheets and the increase in Weber number and surface roughness made the droplet more prone to fragmentation to form small droplet. Gou[23] et al. conducted an experimental study on the evaporation process and morphological evolution of diesel droplet on aluminum alloy surface with different wettability and temperature. The results showed that the lipophilic surface facilitated the evaporation, rebound and secondary fragmentation of diesel droplet. Qu[24] et al. investigated the motion process of droplet impacting a nanostructured superhydrophobic surface. The results showed that the relationship between the maximum spreading factor of droplet and Weber number was $\beta max \sim We0.52$. The maximum spreading diameter and retention time of droplet when droplet impacts the high temperature brass surface were experimentally investigated by S. Illias[25] et al.

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The results showed that the surface temperature variation has a small effect on the droplet spreading process.

Luo[26] et al. used VOF numerical simulation to investigate the hydrodynamics and heat transfer of multiple droplet continuously colliding with a cylindrical surface in depth. The results showed that the heat transfer performance could be improved by decreasing the vertical spacing of successive droplet impacting the cylindrical surface or by increasing the cylindrical diameter. Zhang[27] et al. studied the kinetic behavior of droplet impacting a vertical surface using the coupled level set and volume of fluid (CLSVOF) method. As the Weber number increases, the maximum spreading factor and the corresponding normalization time will increase. Hu[28] et al. used the VOF method to study the variation of the impact force on the surface during the droplet impact on a superhydrophobic surface. The results showed that the force exerted by the droplet on the surface showed two peaks with time, and the magnitude of these two peaks was proportional to the inertial force.

Almohammadi[29] et al. studied the dynamic behavior of droplet of different viscosities striking horizontally moving hydrophilic and hydrophobic surfaces. It was shown that droplet diffuse asymmetrically on moving surfaces and the three-phase contact line downstream of the droplet remains almost stationary on hydrophilic surfaces and has a significant backward behavior on hydrophobic surfaces. Zhang[30] et al. experimentally investigated the impact behavior of droplet on moving superhydrophobic surfaces and found that moving superhydrophobic surfaces can reduce droplet contact time compared to stationary superhydrophobic surfaces. They attributed the reduction in droplet contact time to the asymmetric diffusion and shrinkage behavior exhibited by droplet on moving surfaces. Hou[31] et al. used numerical simulations to study the impact freezing process of droplet on a laterally moving cold superhydrophobic surface. The maximum value of the diffusion factor in the moving direction gradually decreased as the temperature of the cold surface decreased, while the maximum value of the diffusion factor perpendicular to the moving direction was almost constant.

Keshavar[32] et al. conducted an experimental study of Newtonian fluid droplet impinging on high-speed moving solid surface with different roughness. The results showed that increasing the roughness of the solid surface reduces the droplet splash threshold and that droplet are more likely to splash as droplet viscosity increases and surface tension decreases. Li[33] et al. investigated the change of droplet motion morphology after impacting a high-speed rotating disk. The results showed that the main factor of droplet splashing is the tangential velocity of the droplet. The impact velocity of droplet had a significant effect on both tangential and radial spreading diameters. Zen[34] et al. investigated the kinematic morphological changes of ethanol droplet impacting solid surface with different tilt angles and different kinematic velocities. The results showed that an increase in the solid surface motion velocity would promote droplet to splash along the solid surface in the opposite direction of motion. Increasing the surface motion velocity can increase the droplet spreading area.

The morphological changes and influencing factors of droplet impacting on a stationary solid surface have been studied by scholars at home and abroad, however, the research on droplet impacting on moving surface is less, and the related research does not fully reveal the motion process of droplet on a moving surface, therefore, the following research work is carried out in this paper: build a test platform for droplet impacting on a moving horizontal surface, and collect the motion morphological changes of droplet by high-speed photography. The droplet motion pattern, spreading factor and height factor after impacting the moving surface are studied at different surface moving speed, droplet equivalent diameter, impact speed and surface contact angle.

2. Experimental Setup

The main devices of the droplet impact moving surface test system include a filament slide, DM542 driver, KH-01 stepper motor controller, 24V DC power supply, light source, high-speed camera, microscope head, computer, iron stand, needle, peristaltic pump and deionized water. Fig.1a and Fig.1b are the physical diagram and schematic diagram of the test system site, respectively. The test

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device was arranged on an optical platform, and the height of each device was adjusted using a small manual lift. The light source, droplet impact surface position and high-speed photography are located in the same line. The surface movement direction and the image acquisition direction are perpendicular to each other and both are parallel to the optical stage.

(a)

(b)

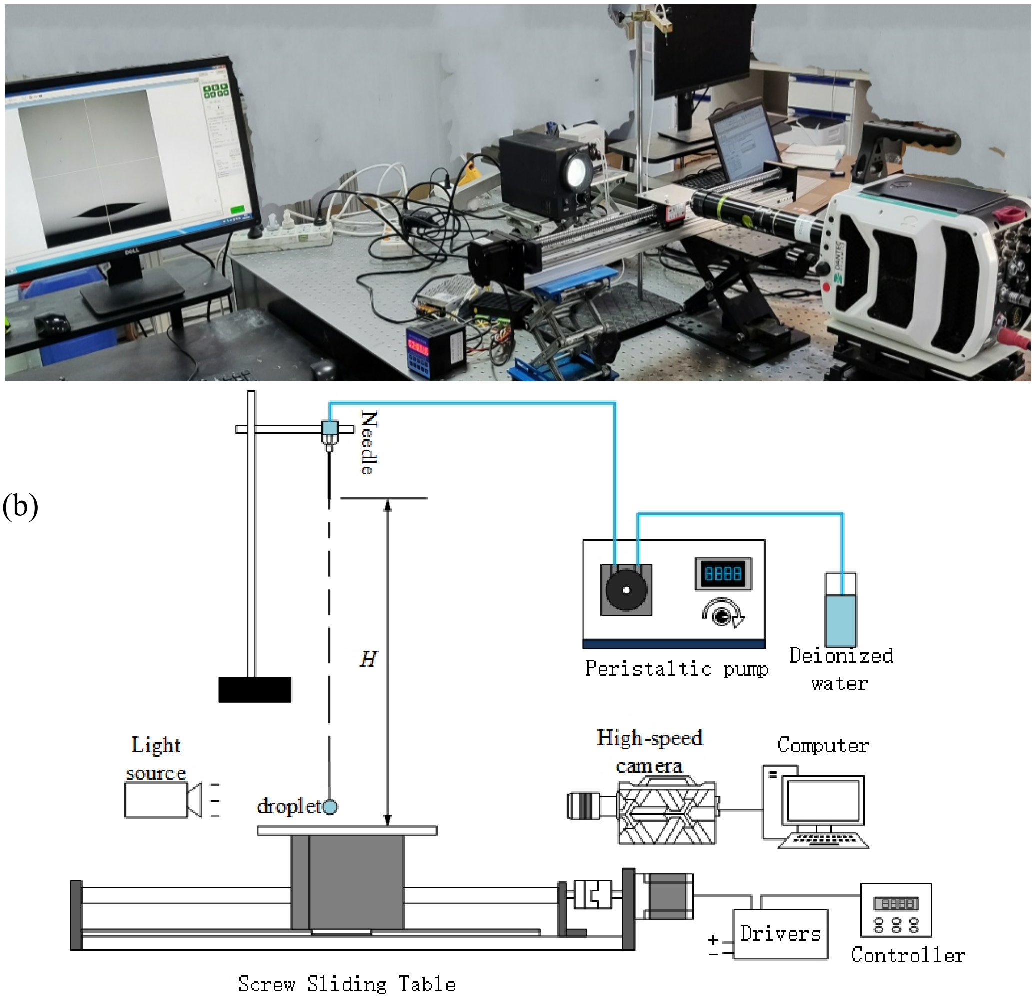

Fig 1. Diagram of the experimental setup: (a) physical diagram and (b) schematic diagram

The high-speed CCD camera used for the test was a Phantom V1610. The resolution of the image acquisition was set to 768×768 and the frame rate was set to 15000fps. The surface materials are 1060 aluminum, 304 steel, h62 copper and acrylic. The screw slide model is 1610, the diameter of the screw is 16mm, the pitch is 10mm, the effective stroke is 600mm. the screw slide is powered by a 57 stepper motor.

Table 1. Parameters of the needle

Needle type	Outer diameter/mm	Inner diameter/mm
1	0.50	0.25
2	0.31	0.16
3	0.23	0.11
4	0.23	0.06

The peristaltic pump model was YX-LP01-31, and the flow rate of the peristaltic pump was set to 0.04 mL/min. A total of four types of plastic steel screw-tipped needles were used, and their inner and outer diameters are shown in Tab.1. The droplet were not standard spheres during the drop, so the equivalent diameter was used to represent the droplet diameter. The droplet equivalent diameter $D = (D_h^2 D_v)^{1/3}$is obtained by averaging the horizontal diameter D_h and the vertical diameter D_v at each moment before the droplet impacts the surface.

The acquired droplet morphology images were post-processed using ImageJ software. After importing the images into the software, the binarization process was first performed with a threshold value set to 40. After that, the image size is calibrated, the pixel size of the outer diameter of the needle is extracted, and the actual size of the needle is input to obtain the ratio of the pixel size to the actual size. Finally, the droplet contour size is extracted for each moment. The equivalent diameters of droplet generated by each model of needle are shown in Tab.2. The horizontal and vertical diameters of droplet in the table are the average of the dimensions at each moment before the droplet impact the surface.

Table 2. The equivalent diameter of droplet

Needle type	Horizontal Diameter /mm	Vertical Diameter /mm	Equivalent Diameter /mm
1	2.43	2.61	2.49
2	2.1	2.26	2.15
3	1.95	2.13	2.01
4	1.92	1.98	1.94

3. Results and Discussion

Fig.2 is schematic diagram of the model of droplet impacting a moving horizontal surface. The velocity of the droplet impacting the surface is v_n, and the velocity of the horizontal surface is v_t. When the droplet spreads on the surface, the ratio of the spread diameter of the droplet in the direction of the surface movement to the equivalent diameter is defined as the spread factor of the droplet, D/D_0. The ratio of the maximum height of the droplet normal to the surface to the equivalent diameter is defined as the height factor, h/D_0.

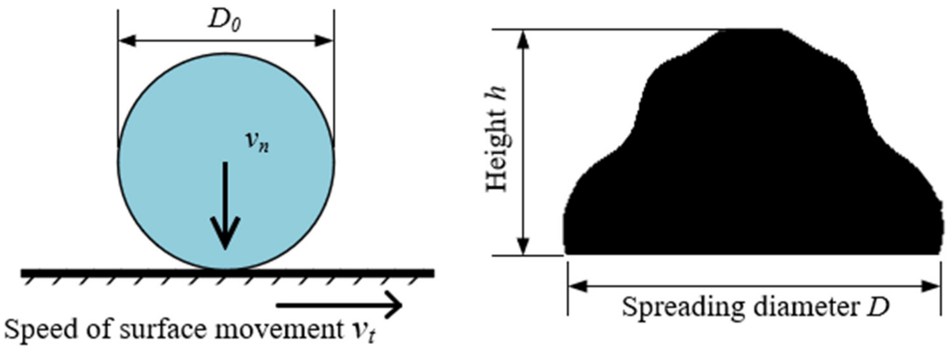

Fig 2. Geometric model of droplet impact on the surface

3.1 Effect of Surface Movement Speed on Droplet Motion Morphology

The variation of droplet motion pattern on the aluminum surface with different moving speed is shown in Fig.3. The speed of the droplet impacting the surface is 0.36m/s, the equivalent diameter is 1.94mm, and the ambient temperature at the time of the test is 24.1°C. The surface moving speed is 0.06m/s, the aluminum surface horizontal movement to the left, and the other three working conditions of the surface movement in the opposite direction. The motion trend of droplet on the surface with different moving speeds is basically the same, all of them are spreading first and then rebounding.

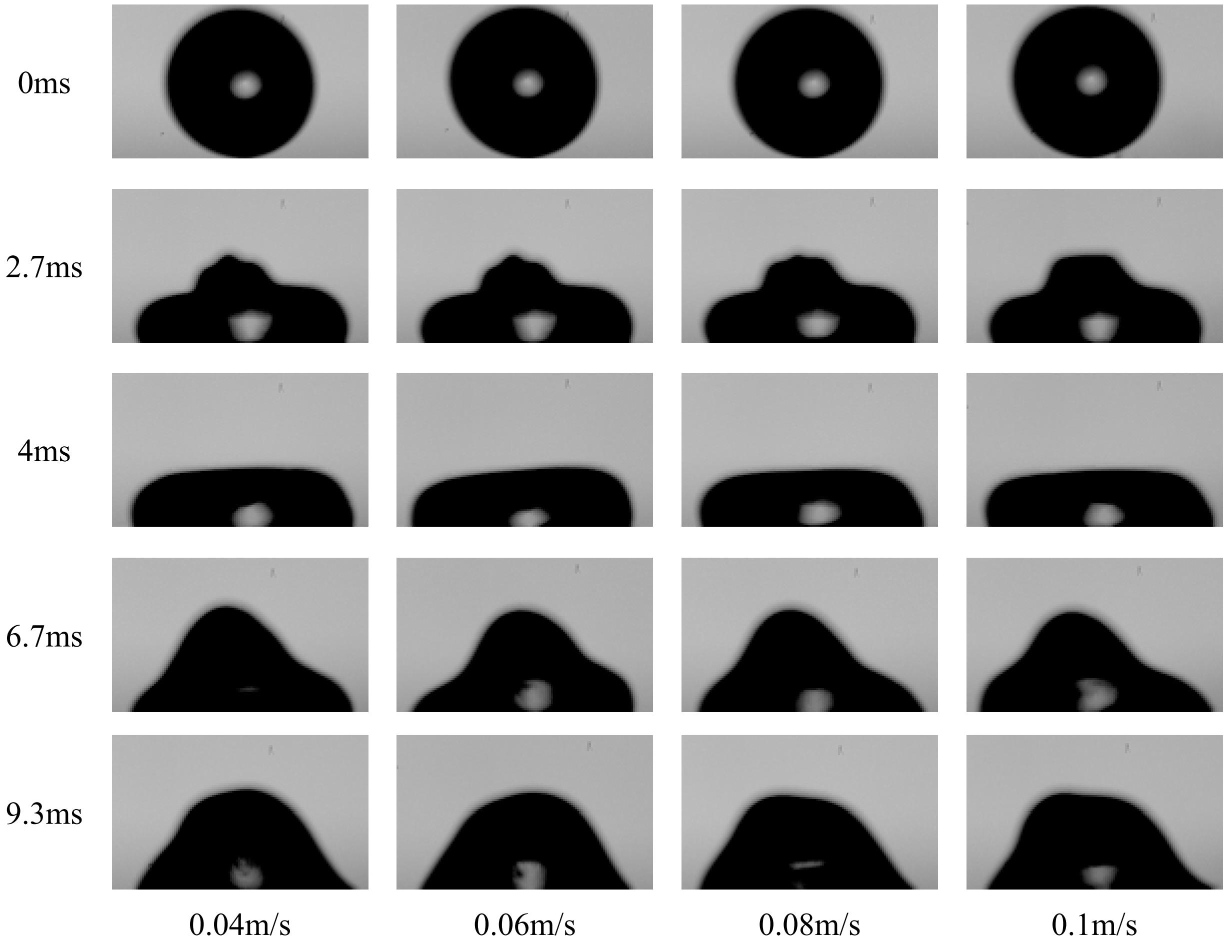

Fig 3. Variation of droplet morphology on the aluminum surface with different moving speeds

At 2.7ms, the droplet was in the spreading stage with a step-like profile shape. The droplet has a clear bump at the top of the surface at 0.04m/s, with three steps. With the increase of the moving speed of the surface, the top bump of the droplet gradually decreases. The top of the droplet on the 0.1m/s surface is relatively smooth with two steps. This indicates that the droplet spreads faster on the faster moving surface. At 4ms, the droplet is near the maximum spreading moment, and the whole droplet is flat on the surface. At 6.7ms, the droplet is in the upward rebound stage, and the liquid gathers from all around to the middle, which makes the droplet height rise continuously. The droplet kept moving up and down, and the droplet still did not return to the stable state when it was out of the image acquisition range.

The variation of the spreading factor during the droplet impingement on the surface with different moving velocities is shown in Figure 4. The spreading factor of the droplet increases with the increase of the moving speed of the surface. The droplet motion pattern is mainly influenced by gravity, surface tension, viscous force and shear force. The shear force exerted on the droplet by the moving surface helps the droplet to spread in the direction of surface movement, and also hinders the droplet to spread in the opposite direction of surface movement. Shear force plays a role in promoting the spreading of the droplet as a whole. As the speed of surface movement increases, the shear force is greater and the droplet spreads faster on the moving surface.

The variation of the height factor during the droplet impact on the surface with different moving velocities is shown in Figure 5. The height factor oscillates with time in a periodic decay. When the droplet spreads to the maximum, the droplet starts to rebound upward under the action of surface

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tension. Afterward, when the droplet reaches the maximum rebound height, it starts to move down again due to the influence of gravity. In the reciprocal motion of the droplet, the potential energy of the droplet is continuously consumed and the height of the droplet rebound is getting smaller. As the speed of the moving surface increases, the height factor of droplet spreading process is smaller. The greater the droplet spreading on the moving surface, the more work is done to overcome the friction, and the greater the energy loss. Therefore, the droplet that spreads easily has a smaller height when it bounces back.

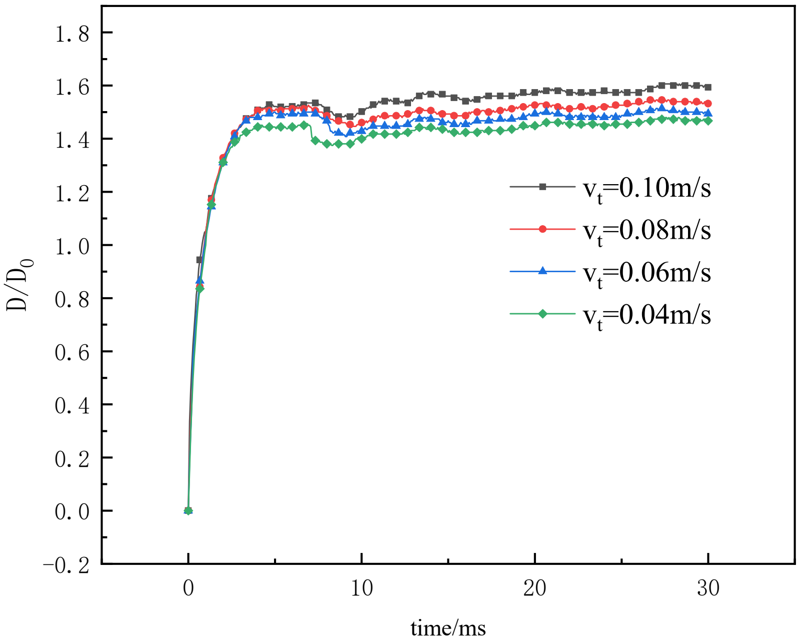

Fig 4. Variation of droplet height factor changes with time at different velocity of surface

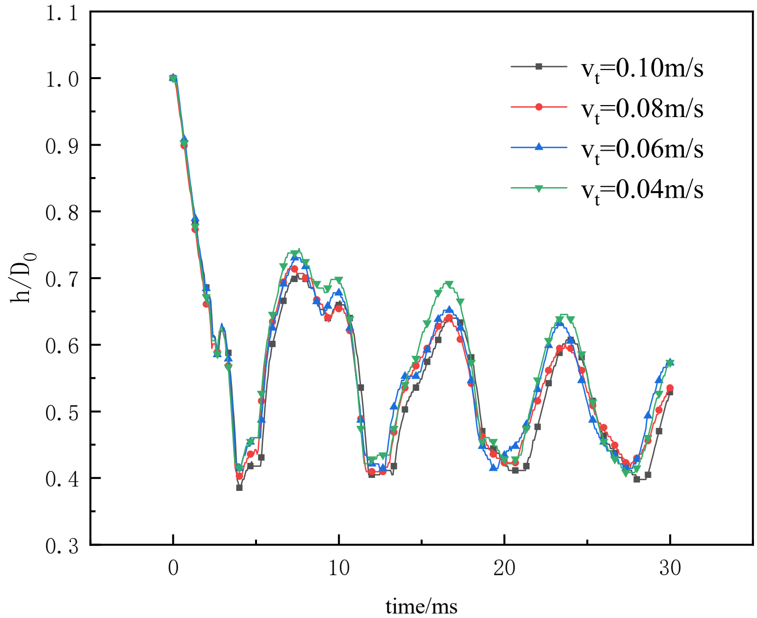

Fig 5. Variation of droplet height factor changes with time at different velocities of surface

3.2 Effect of Droplet Impact Velocity on Droplet Motion Morphology

Figure 6 shows the motion pattern of the droplet after impacting the aluminum surface with different velocities. The moving velocity of the aluminum surface is 0.06 m/s and the equivalent diameter of the droplet is 1.94 mm. The larger the impact velocity of the droplet at the same moment, the larger the spreading area. The increase of droplet velocity significantly promotes the spreading of droplet. The difference between the droplet velocity and the surface motion velocity is large, and the shear

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stretching effect of the surface on the droplet is not obvious. At droplet impact velocities of 1.45 m/s and 2.11 m/s, there was no step change in droplet spreading, and the droplet upper profile was excessively flat. At 2ms, the edge of the upper profile of the droplet at 2.11 m/s was uneven and showed small fluctuations, which was due to the inconsistent air pressure at the edge of the droplet and the airflow disturbing the droplet morphology.

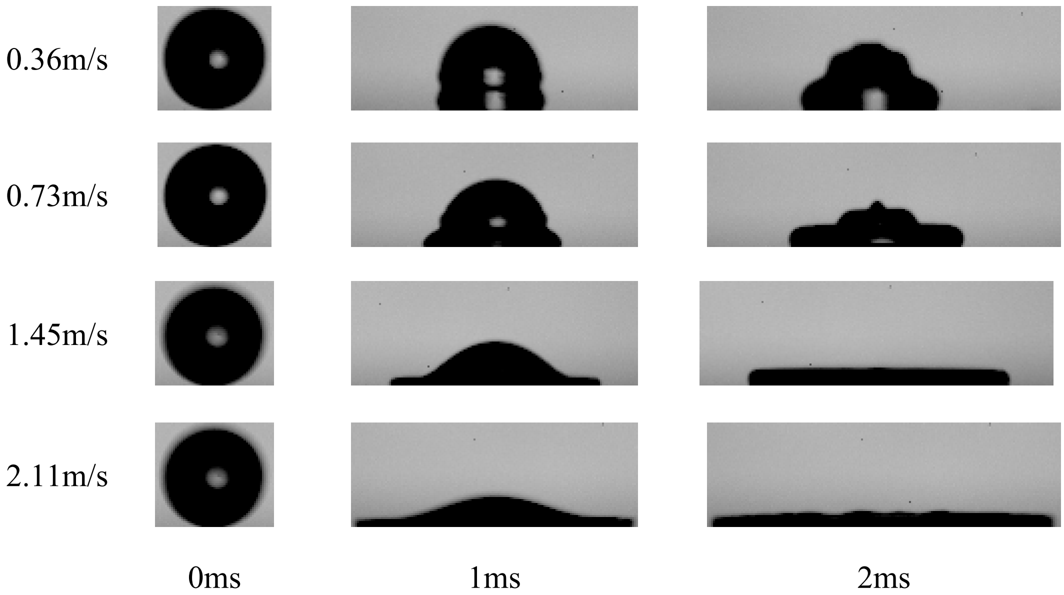

Fig 6. Variation of droplet morphology at different impact speeds

Figure 7 shows the variation of the spreading factor with time during the droplet impact on the aluminum surface at different initial impact velocities. The droplet impact velocity has a more pronounced effect on the spreading velocity of the droplet on the moving surface than the surface moving velocity. The greater the momentum of the droplet impacting the moving surface, the greater the momentum of the droplet gaining spreading along the aluminum surface after impact, and the greater the rate of increase of the spreading factor. With the increase of droplet impact velocity on the moving surface, the droplet has a greater initial kinetic energy. In the droplet spreading process, the droplet is able to overcome the surface tension to spread more.

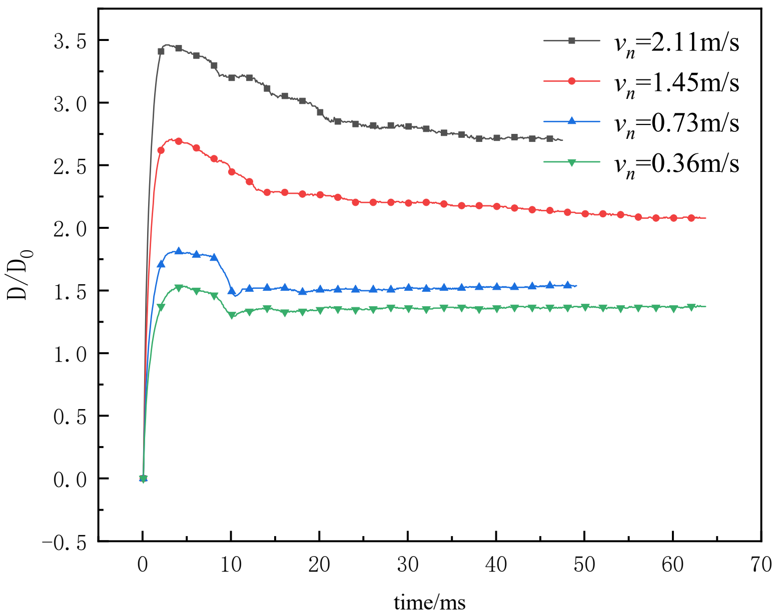

Fig 7. Variation of droplet spreading factor with time at different velocity of droplet impact

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The time for droplet with different initial impact velocities to reach the maximum spreading factor was all around 3ms, and the overall spreading process time was less different. There is no significant correlation between the initial impact velocity of droplet and the length of the spreading process. After the spreading factor reaches the maximum value, the droplet starts to rebound and gather. The spreading factor then becomes smaller, and the change is gradually flattened to a stable value. The larger the maximum spreading factor of the droplet, the larger the stability value.

Figure 8 shows the variation of the height factor with time during the impact of droplet with different initial impact velocities on the surface. At the droplet impact velocity is 2.11m/s, there is no obvious periodic oscillation of the height factor. This is because the droplet is hindered by the larger frictional force of the surface, which affects the rebound process of the droplet.

At the droplet impact velocity is 1.45m/s, the droplet height factor fluctuates less time and oscillates less up and down. The results show that when the initial impact velocity of droplet is small, the period of height factor oscillation decreases and the amplitude is larger, and it is more difficult to reach the steady state. With the increase of droplet impact velocity, the difference between surface tension and friction becomes smaller, and the influence of surface friction in the droplet rebound process becomes larger.

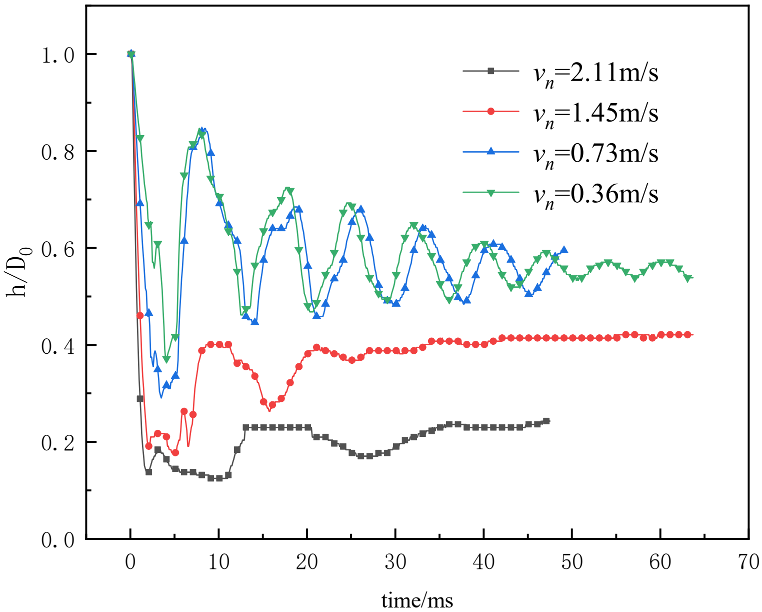

Fig 8. Variation of droplet height factor with time at different velocity of droplet impact

3.3 Effect of Droplet Impact Velocity on Droplet Motion Morphology

The spreading factor change law during the impact of droplet with different equivalent diameters on the moving surface is shown in Figure 9. The droplet with larger equivalent diameter has a smaller rate of increase of spreading factor in the spreading process, but the spreading time of the droplet is longer and can reach a larger spreading factor. The droplet impact velocity is the same, and the surface moving velocity is the same, so the droplet diffuses outward at the same rate as the outer contour line of the contact surface of the surface in the spreading process. When the droplet spreading diameter increases at the same rate, the larger the droplet equivalent diameter, the smaller the spreading factor. As the droplet equivalent diameter increases, it is potential energy and kinetic energy also increase accordingly, and the droplet can spread larger. Droplet with smaller volume undergo the rebound process faster and the spreading factor stabilizes at a smaller value.

The height factors of droplet of different equivalent diameters during impact with moving surface are shown in Figure 10. The height factors of droplet with larger equivalent diameters can reach smaller values in the spreading process and can reach larger values in the rebound process. It is worth noting that this is slightly different from the results in the previous two sections, where the smaller the valley

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value of the height factor during spreading, the smaller the peak value. The large droplet height factor fluctuates more up and down and has a lower vibration frequency.

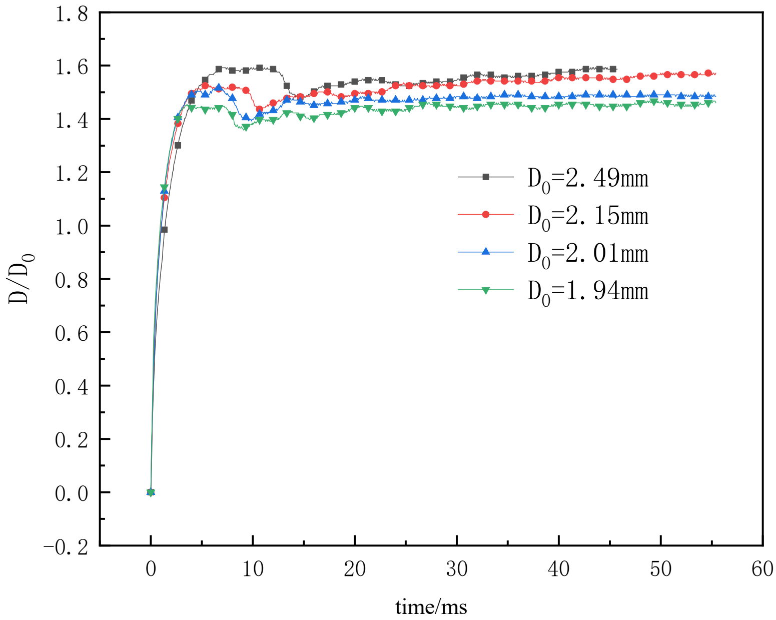

Fig 9. Variation of droplet spreading factor with time at different equivalent diameter of droplet

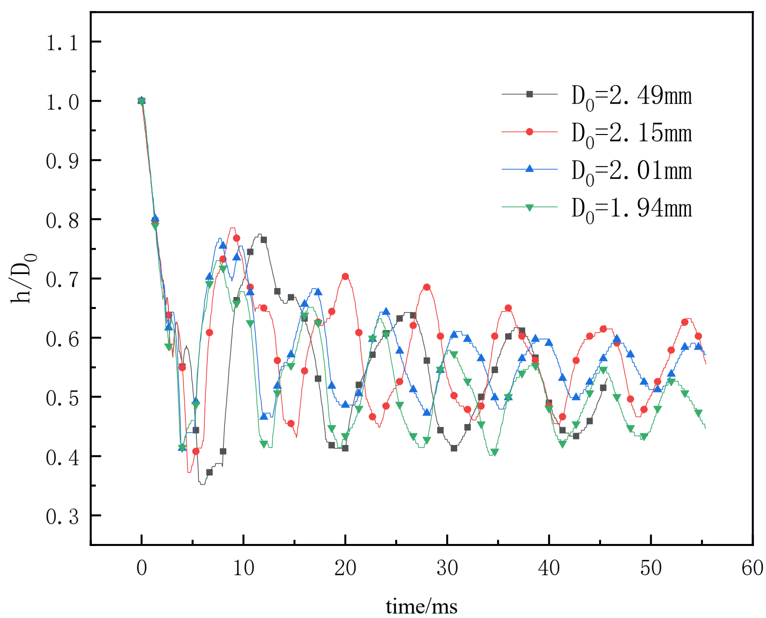

Fig 10. Variation of droplet height factor with time at different equivalent diameter of droplet

3.4 Effect of Surface Material on Droplet Motion Morphology

The spreading factor variation law during the droplet impacting the moving surface of different materials is shown in Figure 11. The droplet spreading on the acrylic surface is the largest, and the smallest spreading on the copper surface. The smaller the static contact angle of the surface during the movement of droplet on copper, steel and aluminum surfaces, the larger the spreading factor. Droplet in the overall process of movement on the acrylic plate, in addition to the initial spreading and rebound phase, after the change in the spreading factor is also in line with the above law. Droplet in the process of surface movement, the surface contact angle is not constant. The dynamic contact angles of copper, steel and aluminum surfaces have the same magnitude relationship as the static contact angle. The dynamic contact angle between the droplet and the acrylic surface during the

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spreading process is smaller than the contact angle of the aluminum surface, so the peak spreading factor of the droplet on the acrylic surface is the largest. During the movement of droplet on the copper surface, the spreading factor has more obvious periodic fluctuations with small fluctuations.

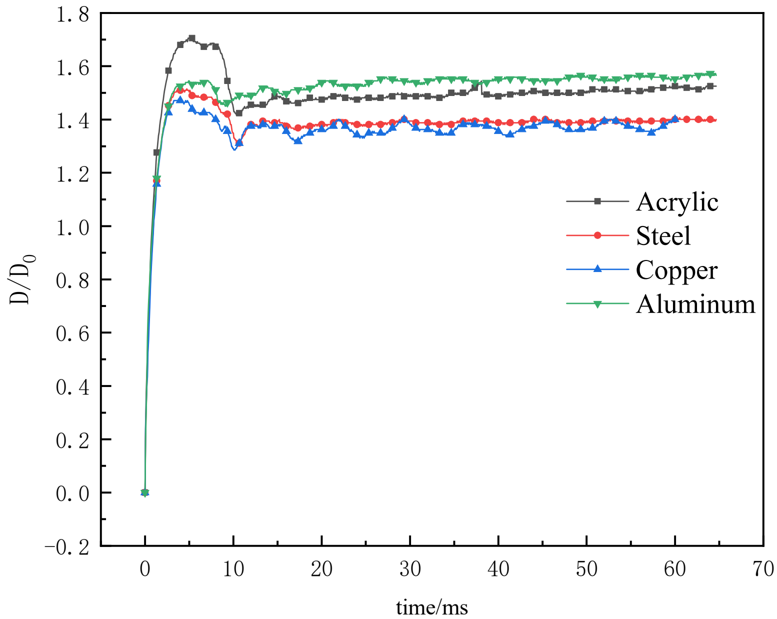

Fig 11. Variation of droplet spreading factor with time on different surfaces

The law of height factor variation during the droplet impact on the moving surface of different materials is shown in Fig.12. Corresponding to the spreading factor, the height factor valley of the droplet on the acrylic surface during the first spreading is the smallest. In the subsequent height factor periodic vibration, the droplet on the aluminum surface has the smallest height factor valley and the fastest vibration frequency. The droplet movement on the copper surface is the largest amplitude of height factor vibration. The height factors at all moments on the steel and copper surface surfaces are very close to each other due to the small difference in the dynamic contact angles of the droplet on the surface of these two materials.

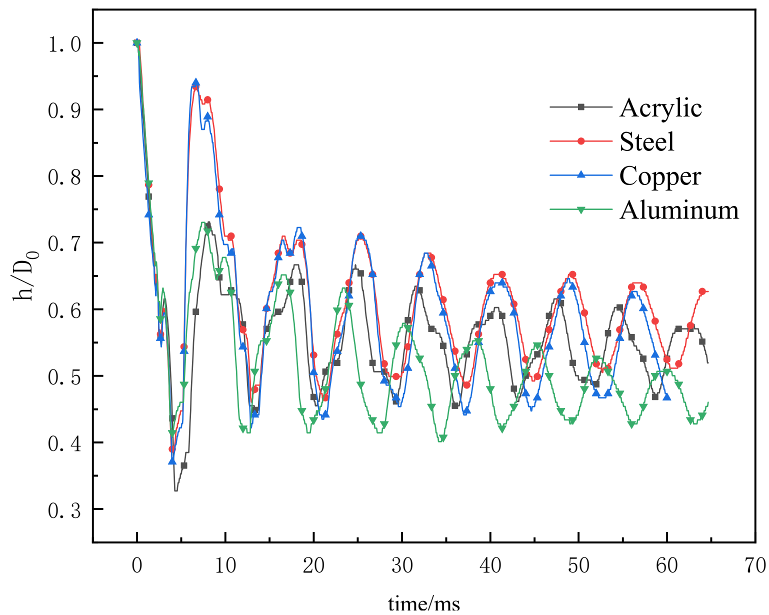

Fig 12. Variation of droplet height factor with time on different surface

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4. Conclusion

A droplet impact test system was built to capture the changes in droplet motion during impact with moving surface at different working conditions by means of a high-speed CCD camera. The effects of surface movement velocity, droplet initial impact velocity, droplet equivalent diameter and surface material on droplet morphology during droplet impact on moving surface were investigated and concluded as follows:

(1) With the increase in surface moving speed, droplet spreading is greater, droplet spreading speed change is not obvious, the droplet height at each moment is smaller, the smaller the spreading of the droplet is the easier to rebound.

(2) As the impact velocity of droplet increases, the spreading velocity of droplet increases significantly and the maximum spreading factor is larger. The height factors of droplet with lower velocities oscillate more rapidly and have larger up and down fluctuations.

(3) The morphological changes during the impact of droplet of different equivalent diameters on the moving surface are basically similar. In the spreading process, as the droplet equivalent diameter increases, the droplet spreading speed decreases slightly, and the maximum spreading factor of droplet is larger. The height factor of larger droplet has the smallest valley value during spreading and the largest peak value during rebound.

(4) When the surface contact angle is small, the droplet spreads more easily, and the droplet spreading factor is larger and the height factor is correspondingly smaller. When the surface contact angle is larger, the droplet height factor peak is larger, the vibration amplitude is larger, and the vibration frequency is lower.

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