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Numerical study on characteristics of single droplet impacting on wetted surface

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Abstract

In this paper, the mathematical and physical models of the single droplet impacting on liquid film are established. The axisymmetric numerical simulation of the single droplet impacting on liquid film is carried out by using the Couple Level-set and VOF (Volume of Fluid) numerical simulation method, which is verified by experiment, studying the influence of the liquid film thickness, surface tension, viscosity, and density of liquid on the liquid crown, and analyzing the thickness effect on the neck ejecta sheet. Through the analysis of pressure and velocity field, the mechanism of crown formation is studied. The results show that: (1) experiment and simulation are in good agreement, so CLSVOF method (the Couple Level-set and VOF) is suitable for research of droplet impacting on liquid film; (2) with the increase of liquid film thickness, the expansion radius and height of crown decrease, and the crater depth increases; (3) the surface tension, density, and viscosity of the fluid have influence on the crown; (4) ejecta sheet velocity decreases with the increase of the liquid film thickness but when H^* > 1.0 (ratio of film thickness to droplet diameter), the ejecta sheet velocity does not change; (5) neck ejecta sheet is caused by neck pressure difference.

Keywords

droplet impact
liquid film thickness
CLSVOF method
ejecta sheet

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Research Article

1 Introduction

It is a very common phenomenon that droplets impact on wetted surfaces in industrial production and daily life. For example, the droplets which are generated by steam generator and liquid film breakdown (Wang and Tian, 2019; Wang et al., 2020) impact on the walls of corrugated plate in corrugated plate separator in nuclear power plant; the droplets of fuel impact on the walls of the engine. The study of droplet impacting on the wetted wall not only benefits industrial production, but also explains natural phenomena in daily life. Because of its complex mechanism, interesting phenomenon, and importance to production, it has aroused many scholars' research enthusiasm.

Cossali et al. (1997) studied the morphology of droplet impacting on the liquid film by static photography. Time evolution of various parameters (such as crown diameter, crown height, and daughter droplet diameter) was experimentally obtained by image analysis technology, which was compared with relevant theoretical models. The results showed that the evolution of crown height depends on the influence of *We* ($\rho v^2 D/\sigma$), but its growth rate and the thickness of crown are independent on *We*. Wang and Chen (2000) used a novel method to generate thin liquid film, and observed the splash phenomenon of droplet impacting on very thin liquid film. The experimental results showed that when H^* < 0.1, the critical *We* is independent on the film thickness, and with the increase of viscosity, the critical *We* increases. Liang et al. (2013b) analyzed the spread, crown formation, and splash of droplet impacting on the inclined surface. The experimental results showed that the critical velocity increases with the decrease of the impact angle. Roisman and Tropea (2002) theoretically studied the morphological changes of crown formed by droplet impacting on thin film with different thicknesses, analyzed the motion of discontinuity in kinematics, and obtained the influence of liquid viscosity and film thickness on the size of daughter droplets. Rioboo et al. (2003) published the experimental results of droplet impacting on wetted surface under different liquid and impact conditions. The limits of splashing and deposition crown were determined.

In terms of numerical simulation, Mukherjee and Abraham (2007) numerically simulated droplet impacting on wetted wall by using high-density-ratio lattice-Boltzmann

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model to study crown. The effects of surrounding gas with different viscosity and density on crown were discussed, which was showed that the increase of viscosity and density leads to the decrease of expansion diameter and height. Guo et al. (2014) studied the morphology of crown generated by droplet impacting on horizontal liquid film at different velocities and droplet impacting on different thickness liquid film at the fixed velocities. The phenomenon of bubble entrainment was captured. The results showed that the larger the impact velocity is, the easier the splash phenomenon is, and the crown expansion diameter decreases with the increase of liquid film thickness. However, the range of liquid film thickness studied is relatively small. Liang et al. (2014) used the CLSVOF method to study the effects of gas properties such as gas–liquid density ratio and viscosity on liquid behavior and droplet coalescence when the single droplet impacts on liquid film. It was found that the decrease of liquid–gas density ratio will lead to crown shrinkage, and density ratio has little effects on the process of droplet coalescence. Bussmann et al. (1999) developed a three-dimensional model for droplet impact on asymmetric surface geometries and proposed a simpler model for contact angle as a function of contact line velocity.

It can be seen from the above researches that the phenomenon of droplet impacting on liquid film is the current research hotspot, and there are relatively many researches on the thickness of liquid film. However, most of literatures are about the influence of liquid film thickness on the critical *We* number and the splashing, while there are relatively few literatures on the influence of liquid film thickness on the morphology of crown, especially the influence of liquid film thickness on neck ejecta sheet. In this paper, the CLSVOF method has been used to study the influence of liquid film thickness, surface tension, viscosity, and density of liquid on liquid crown, and analyze the thickness effect on the neck ejecta sheet.

2 Method and verification

2.1 Simulation method and model

In the VOF model, the interface is captured by defining the volume fraction α of the liquid phase in the grid, and the governing equation is

$$\frac{\partial \alpha}{\partial t} + U \cdot \Delta \alpha = 0 \tag{1}$$

where t is the time and U is the velocity vector. $\alpha = 0$ means that grid is the gas phase, and $\alpha = 1$ means that grid is the liquid phase.

The interface position and time evolution equation are defined by the level set method (Level-set):

$$\frac{\mathrm{D}\phi}{\mathrm{D}t} = \frac{\delta \phi}{\delta t} + (v \cdot \nabla)\phi = 0 \tag{2}$$

where v is the velocity of flow field. Equation (2) is the convective transport equation of function ϕ, named as the convection transport equation of Level-set function, which is rewritten into the following form in order to transform to discrete solution easily:

$$\frac{\delta \phi}{\delta t} + v(\nabla \cdot \phi) = 0 \tag{3}$$

ϕ is defined as the distance function to the interface between the liquid and gas, and Ω is the material region in the Level-set method. So, the interface is a zero-level set, and $\phi(x, t)$ is expressed as $\Gamma = \{x \in \Omega | \phi(x, t)=0\}$ in a two-phase system. There are three conditions:

$$\phi(x,t) = \begin{cases} +|d| \\ 0 \\ -|d| \end{cases} \tag{4}$$

d is the distance from x to the interface of the two phases. ϕ = 0 means x at the interface of the two phases, $\phi > 0$ means x in the liquid phase, and $\phi < 0$ means x in the gas phase. All the possible distance from the specified point to the interface has been minimized in order to initialize the ϕ function. The normal vector and curvature of the interface required to calculate surface tension can be estimated as

$$n = \frac{\nabla \phi}{|\nabla \phi|} |_{\phi=0} \tag{5}$$

$$k = \nabla \cdot \frac{\nabla \phi}{|\nabla \phi|} |_{\phi=0} \tag{6}$$

The numerical instability resulting from the ratio of the large density and large viscosity near the interface has been avoided by the Heaviside function which is introduced to smooth the density and viscosity at the interface. The Heaviside function is shown in Eq. (7):

$$H(\phi) = \begin{cases} 0, & \phi < -w \\ \frac{1}{2}\left[1 + \frac{\phi}{w} - \frac{1}{\pi}\sin\left(\frac{\pi\phi}{w}\right)\right], & |\phi| \le w \\ 1, & \phi > w \end{cases} \tag{7}$$

where $w = 1.5h$ (h is the grid size). The density and viscosity are

$$\rho(\phi) = \rho_g + (\rho_l - \rho_g) H(\phi) \tag{8}$$

$$\mu(\phi) = \mu_g + (\mu_l - \mu_g) H(\phi) \tag{9}$$

The continuous surface tension is used to deal with the surface tension (Continuum Surface Force) model:

$$F_s = \sigma k \vartheta(\phi) \nabla \phi \tag{10}$$

$$\vartheta(\phi) = \frac{dH(\phi)}{d\phi} = \begin{cases} 1 + \dfrac{\cos(\pi\phi / w)}{2w}, & |\phi| < w \\ 0, & |\phi| < w \end{cases} \tag{11}$$

where σ is the surface tension coefficient. The model does not use surface tension as a boundary condition, but is added to the Navier–Stokes equation in the form of a volume force.

There are some shortcomings in the methods: the volume fraction is discontinuous at the phase interface in the interface reconstruction in the VOF model; the frequent re-initialization of ϕ is required in Level-set method and makes that the physical quantity (volume or mass) is not conserved.

A Couple Level-set and VOF method was proposed by Sussman and Puckett (2000) to solve the above problems. CLSVOF method adopts continuous distance function ϕ in Level-set method to reduce the deviation resulting from that the volume fraction is discontinuous at the phase interface in the interface reconstruction in the VOF model; the model also adopts conservative volume fraction α to improve conservativeness in the Level-set method.

The method combines the good conservation of the VOF method with the advantages of the Level-set method to deal with the local sharp corners of the interface, greatly improving the above two-interface methods. Liang et al. (2014), Guo et al. (2014), and Dai et al. (2015) used the CLSVOF method to study droplet impacting on liquid film. The simulation results are in good agreement with experiments, and successfully solve some problems in the field of droplet impacting on liquid film.

In this paper, the axisymmetric numerical simulation of the single droplet impacting on liquid film is carried out by using CLSVOF method to study the morphological changes, and the influence of different thickness liquid film on the neck ejecta sheet through the velocity field of fluid.

In this paper, liquid phase is ρ = 998 kg/m^3, μ = 1.003 × 10^{-3} Pa·s, σ = 73 × 10^{-3} N/m, and gaseous phase is air, ρ = 1.205 kg/m^3, μ = 0.018 × 10^{-3} Pa·s. The diameter of droplet D is 1 mm, and the impact velocity v_p is 5 m/s. It can be seen from Fig. 1 that H is the liquid film thickness, r is the radius of the droplet, s is the crater depth, R is the radius of crown, and h_s is the height of crown. The liquid film thickness H, time t, crown radius R, crown height h_s, and crater depth s are dimensionless into $H^* = H/D$, $\tau = v_p t/D$, $R^* = r/R$, $h_s^* = h_s/D$, and $s^* = s/D$ ($D = 2r$). The computational field is 10 mm × 8 mm, and when the number of meshes is 200,000, the simulation results do not change with the increase of the number of meshes. The Fluent software is used in this paper.

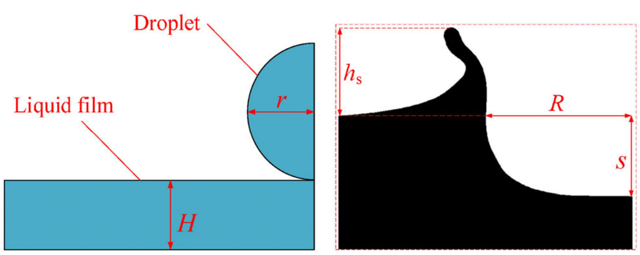


Fig. 1 Physical model.

2.2 Experimental verification

The experimental device is shown in Fig. 2. The image captured by the high-speed camera whose resolution is 720 × 640 and shooting speed is 10,000 FPS is processed by MATLAB software. The average velocity in 0.5 ms before droplet impacting on liquid film is droplet impacting velocity. The liquid film thickness is obtained by using Nikon camera. In this experiment, the thickness of liquid film is 1.45 ± 0.006 mm, the impact velocity is 3.08 ± 0.07 m/s, the diameter of droplets is 2.33 ± 0.035 mm, and the physical parameters of fluid are ρ = 998 kg/m^3, μ = 1.003 × 10^{-3} Pa·s, σ = 73 × 10^{-3} N/m. Because it is difficult to measure the inner radius of crown in experiment, the outer radius of crown as shown in Fig. 2 is used for comparative verification. It can be seen from Fig. 3 that radius of the crown increases with time

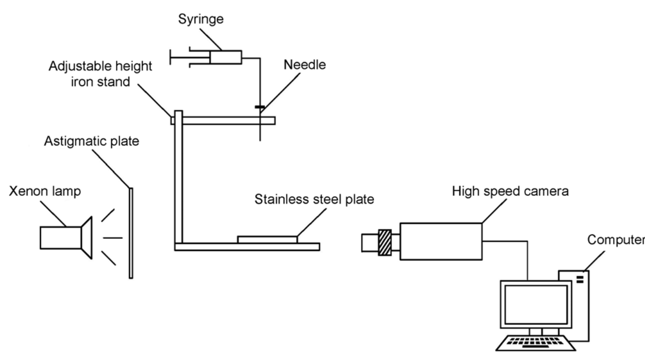


Fig. 2 Experimental device.

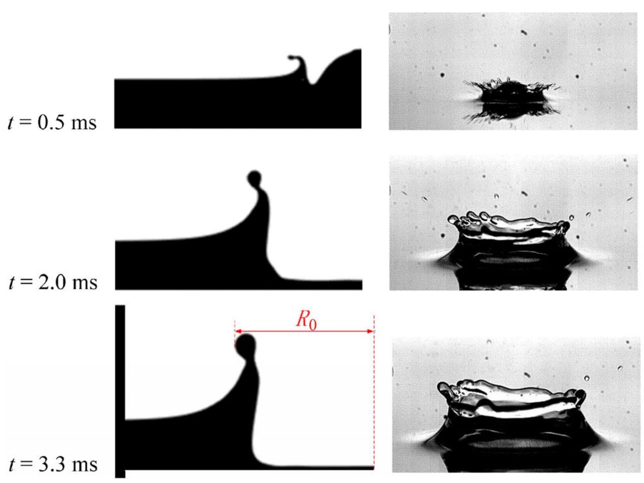


Fig. 3 Qualitative comparison between experiment and simulation.

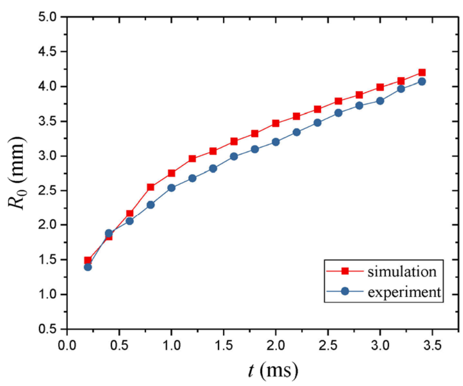
increasing, and there are some fingers at the top of the crown in experiment but the fingers cannot be observed in simulation because of two-dimensional simulation. The morphology of the crown in simulation is the same with that in experiment. Figure 4 shows the quantitative comparison between experiment and simulation. The relationship between radius of crown and time is in good agreement and the maximum error between experiment and simulation is 10%. The height of crown in experiment is in good agreement with simulation, and the maximum error between experiment and simulation is 9.6%. In summary, the simulation method and settings adopted in this paper can be applied to this study.

3 Analysis and results

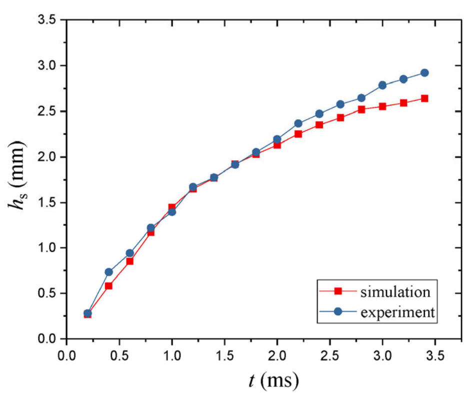
3.1 Analysis of crown morphology with different thickness liquid film

From Fig. 5, it can be seen the crown morphology when droplets impact on different liquid film thicknesses, and according to the definition of splashing by Vander Wal et al. (2006) and Cossali et al. (1997): instant splashing: daughter droplets occur when the crown is developing; delayed splashing: daughter droplets occur when the crown develops largest. In this paper, the splashing generated by droplets impacting on liquid films of $H^* = 0.05$–0.2 is instant splashing, but there is no splashing on the other thickness liquid film. The analysis shows that because the thickness of liquid film is thicker, the liquid film absorbs more energy of droplet impact, which leads to less energy converted into kinetic energy of crown expansion and restrains the splashing. It can be clearly seen that the thickness of the crown is basically the same at the beginning of the impact, but as time goes on, the thicker the liquid film is, the thicker the crown is. Because with the increase of the liquid film thickness, more fluid flows into the crown, which makes the thickness of the crown increase, but due to a certain kinetic energy, there is a limit value for the fluid flowing into the crown, and the thickness of crown does not increase with the increase of liquid film thickness when the thickness of the liquid film reaches a certain value.

As can be seen from Fig. 6, with the increase of the liquid film thickness, the radius of the crown decreases, and at the beginning of the impact, the difference of the crown is smaller,



(a) Comparison of outer crown radius



(b) Comparison of outer crown height

Fig. 4 Quantitative comparison between experiment and simulation.

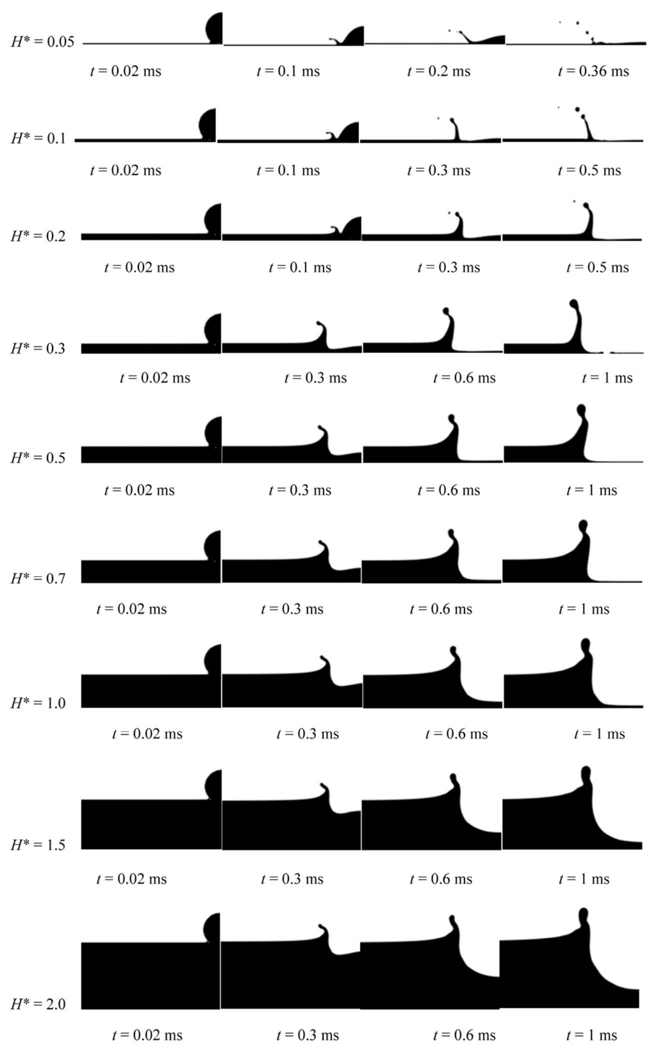


Fig. 5 Crown morphology of different liquid film thicknesses ($D = 1$ mm, $v_p = 5$ m/s).

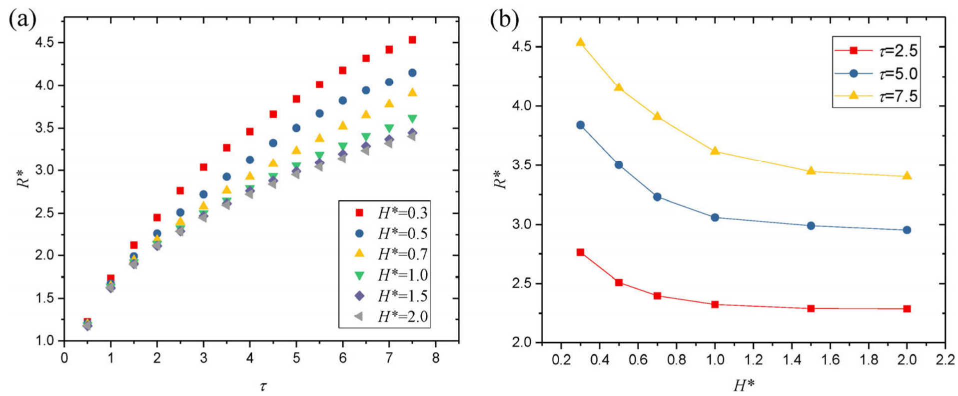


Fig. 6 Relationship between splashing radius and liquid film thickness.

but with the time going, the difference gradually becomes larger. This is because: (1) with the increase of the liquid film thickness, the more energy is consumed by the liquid film when the droplet impacts on the liquid film, and the flow velocity in the horizontal direction decreases, so the kinetic discontinuity is weaker; (2) with the increase of the liquid film thickness, the depth of the crater decreases, the more fluid flows into the crown, and the more fluid around the crown needs to be pushed, so the crown will expand slowly due to the constant kinetic energy of the liquid droplet. The two factors work together to make the crown radius become small with the thickness of liquid film increasing. Because the kinetic energy of droplet is constant, and with the increase of the thickness, the energy consumed by droplet impacting on liquid film is gradually equal, the influence of the thickness of the liquid film on the impact decreases with the increase of the thickness of the liquid film.

In Fig. 6(b), the curve of relation between the crown radius and film thickness increase at $\tau = 7.5$ is steeper than that at $\tau = 2.5$, which shows that the influence of different thickness on crown expansion is greater with time going, because at $\tau = 2.5$, the "crater" depth generated by droplet impacting on liquid film is smaller than that at $\tau = 7.5$, so the fluid volume difference between the different thickness liquid film needed to push is smaller when crown develop in the radial direction. Because the initial kinetic energy of droplets is the same, the radius of the crown varies greatly with the thickness of the liquid film at $\tau = 7.5$.

Yarin and Weiss (1995) believed that there is a certain relationship between R^* and τ, and the equation is

$$R^* = C\tau^n \tag{12}$$

In the formula C is a constant related to the droplet state and Yarin and Weiss (1995) calculated $n = 0.5$. It can be seen from Fig. 5 which is a comparison between the data in this paper and data in Guo et al. (2014), Cossali et al. (2004) that the data in this paper are in good agreement with the above data, which fully proves that CSLVOF is suitable for the research work of this paper.

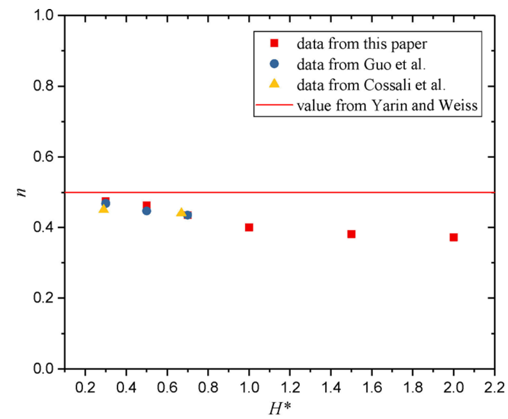


Fig. 7 Comparison of data in this paper with data in other papers (D = 1 mm, v_p = 5 m/s).

It can be seen from Fig. 8(a) that the growth trend of the crown height is gradually slow with the increase of the crown height which decreases with the increase of the liquid film thickness, because more energy is consumed to form the crater with the increase of the liquid film thickness, while the initial kinetic energy of the liquid droplet is the same, resulting in a smaller flow velocity in the crown, making the crown height decrease. Figure 8(b) which is the relationship between crater depth and time under different liquid film thickness, shows that the change of crater depth is basically the same when $\tau < 2.5$ but the crater depth increases with the increase of liquid film thickness when $\tau > 2.5$.

3.2 Analysis of crown morphology with different surface tension coefficient, viscosity, and density

It can be seen from Fig. 9 that when droplet with low surface tension impacts on the liquid film, the crown height is higher and the thickness is thinner. Because when the droplet impacts on the liquid film, the direction of velocity in the liquid film changes from radial to axial and surface tension is one of the resistance factors affecting upward movement

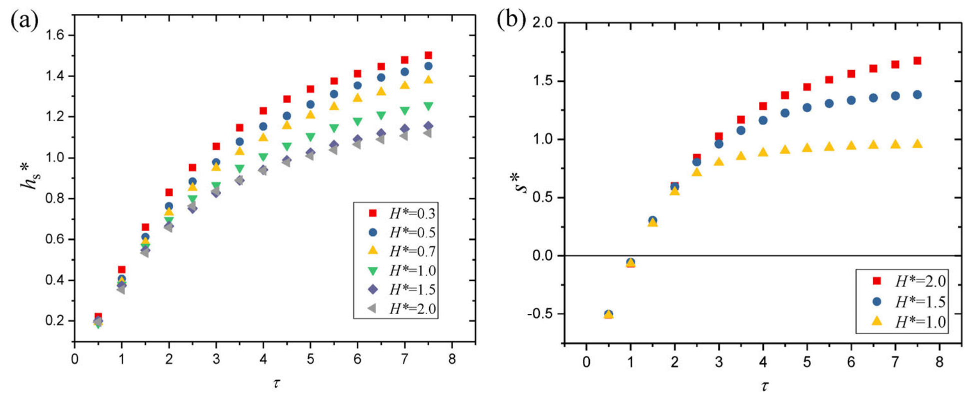


Fig. 8 (a) Relationship between crown height and film thickness; (b) relationship between crater depth and film thickness (D = 1 mm, v_p = 5 m/s).

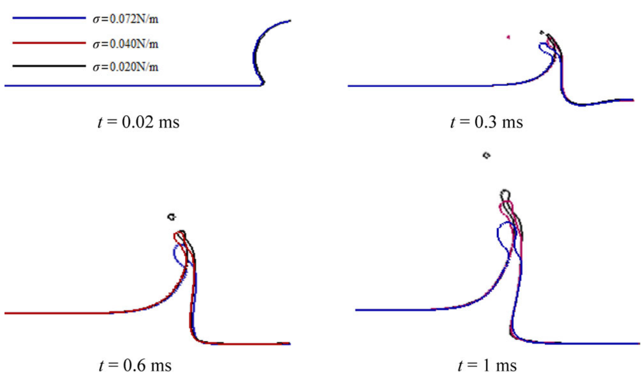


Fig. 9 Crown morphology in different surface tension coefficient (D = 1 mm, v_p = 5 m/s, H^* = 0.5, blue lines represent that σ is 0.072 N/m; red lines represent that σ is 0.04 N/m; black lines represent that σ is 0.02 N/m).

of the crown, so the crown formed by the fluid with low surface tension is higher. The kinetic energy of droplet is transformed into the kinetic energy of crown expansion, the geopotential energy, and the surface energy of the crown, while the radius of crown of different surface tension liquid is basically unchanged. The kinetic energy of radial crown expansion is basically the same, and the initial kinetic energy of droplet is the same, so the thickness of the crown formed by the liquid with small surface tension is higher and thinner. When the surface tension of the fluid is less than 0.04 N/m, the top of crown is separated due to Plateau–Rayleigh instability, resulting in daughter droplets.

When the viscosity of the fluid is 1.003 × 10^{-3} and 1.003 × 10^{-4} Pa·s, the morphology of the crown generated by droplets impacting on the liquid film is basically the same, and the crown expanding radius and height are the same. When the viscosity is 1.003 × 10^{-2} Pa·s, the height of the crown is obviously smaller than that of the former two. The analysis shows that for the fluid with higher viscosity, the larger the viscous consumption is, the greater the loss of kinetic energy of the fluid is, and the less the geopotential energy for the crown is, so the height of the crown is lower.

It can be seen from Fig. 11 that with the increase of density of the fluid, the height of the crown rises gradually, and the thickness becomes thinner. When density of the fluid is 1500 kg/m^3, the splash phenomenon occurs. The analysis shows that when density of the fluid is high, the initial kinetic energy of the droplet is larger, and more energy is transformed into the surface energy and geopotential energy of the crown, which makes the top of the crown unstable to generate daughter droplets because of Plateau–Rayleigh instability.

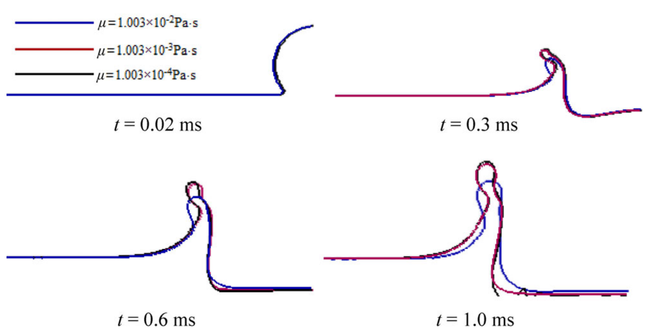


Fig. 10 Crown morphology in different viscosity (D = 1 mm, v_p= 5 m/s, H^* = 0.5, blue lines represent that μ is 1.003 × 10^{-2} Pa·s; red lines represent that μ is 1.003 × 10^{-3} Pa·s; black lines represent that μ is 1.003 × 10^{-4} Pa·s).

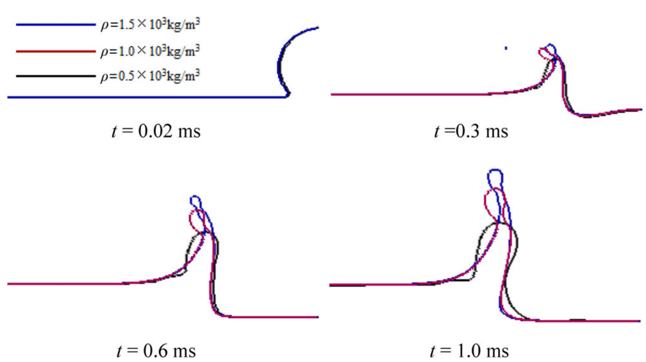


Fig. 11 Crown morphology in different density (D = 1 mm, v_p = 5 m/s, H^* = 0.5, blue lines represent that density ρ is 1.5 × 10 ^{3}kg/m^3; red lines represent that density ρ is 1.0 × 10^3 kg/m^3; black lines represent that density ρ is 0.5×10^3 kg/m^3).

When density is 500 kg/m^3, the crown recesses inward. From Fig. 11, it can be seen that the influence of density on the crown expansion radius is relatively small, and the diameter of crown expansion is slightly smaller when density is 500 kg/m^3.

3.3 Analysis of ejecta sheet and crown formation

Figure 12 shows the morphology change and pressure field distribution of droplets impacting on the liquid film (H^* = 0.5) at 0.04 ms. From Fig. 12, it can be seen that the contact position between droplet and liquid film generates ejecta, which was photographed by Thoroddsen (2002) using high-speed camera. Liang et al. (2013a) used CLSVOF method to simulate droplet impacting liquid film, and explained the phenomenon of neck ejecta sheet. Droplet impacting on the liquid film causes energy to accumulate in the neck, resulting in a large pressure difference which is more than surface tension of neck region, so fluid ejects from the neck at a faster speed.

Figure 13(a) shows that the neck pressure difference and the neck ejecta sheet velocity at 0.04 ms when the droplet impacts on the liquid film. The neck ejecta sheet velocity is much higher than initial impact velocity of droplet and decreases with the increase of the liquid film thickness; however, when H^* > 1.0, the neck ejecta sheet velocity does not change with the change of the liquid film thickness. At the same time, the pressure difference of the neck caused by droplet impacting on the liquid film decreases with the increase of the thickness of the liquid film. With the increase of the thickness of the liquid film, the change of the pressure difference of the neck is smaller. When H^* > 1.0, the pressure difference of the neck region does not change with the thickness of the liquid film, and the change trend of ejecta sheet velocity is basically the same as that of pressure difference in neck region with the thickness of liquid film. It shows that the neck ejecta sheet is caused by the high pressure difference in neck region, which verifies the correctness of Liang et al. (2013a) to analyze the mechanism of neck ejecta sheet. The neck ejecta sheet velocity decreases

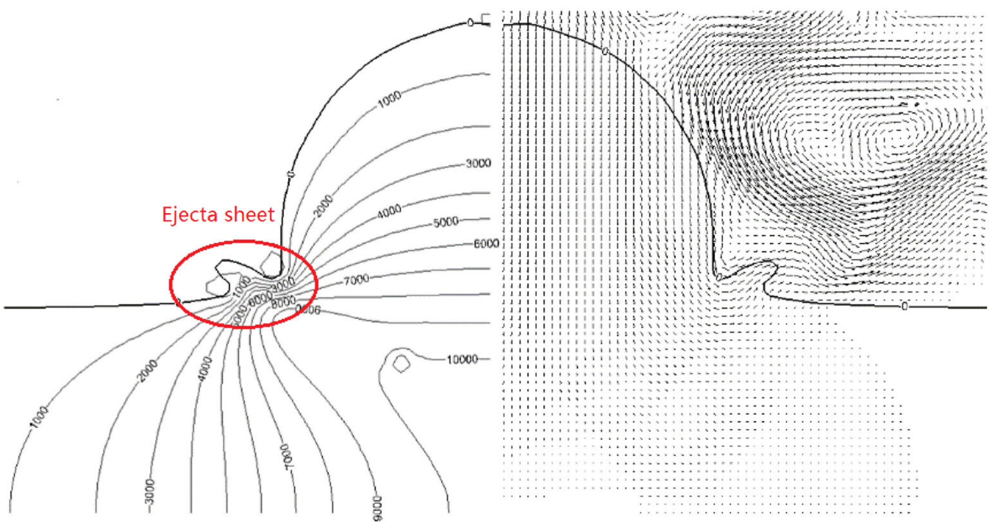


Fig. 12 Neck ejecta sheet (D = 1 mm, v_p = 5 m/s, H^* = 0.5, t = 0.04 ms).

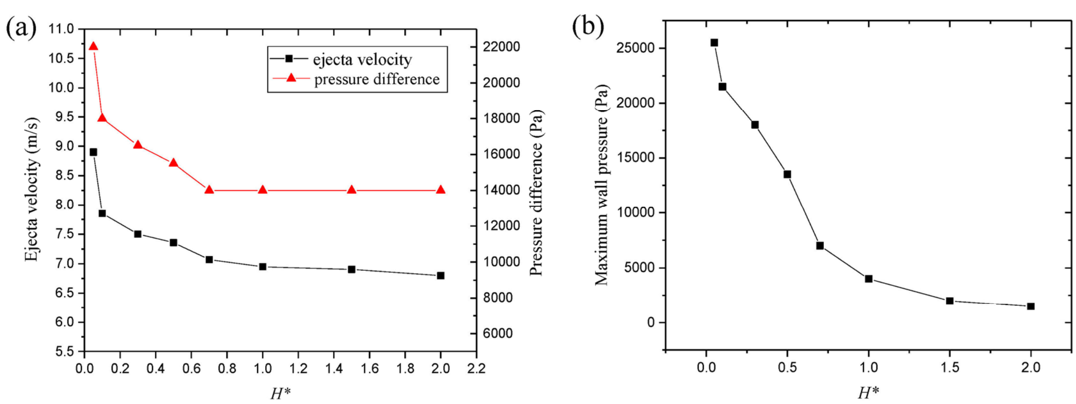


Fig. 13 (a) Relationship between jet velocity and liquid film thickness and relationship between neck pressure drop and liquid film thickness; (b) relationship between maximum wall pressure and liquid film thickness (D = 1 mm, v_p = 5 m/s).

with the increase of liquid film thickness, and the neck ejecta sheet eventually turns into crown, which is one of the reasons for the radius of crown decreasing with the increase of liquid film thickness. The influence of liquid film thickness on drop impact has been produced at the initial time of droplet impact, and the influence decreases with the increase of liquid film thickness.

In this paper, the maximum thickness of the liquid film is 2 mm, so the pressure generated by gravity is only 20 Pa. Therefore, the pressure generated by the thickness of the liquid film is neglected. From Fig. 13(b), it can be seen that the maximum pressure on the wall decreases with the increase of the thickness of the liquid film. Compared with the pressure difference at the neck, the change of the thickness of the liquid film has a greater influence on the maximum pressure on the wall and the difference between the maximum pressure on the wall of $H^* = 0.05$ and $H^* = 2.0$ is nearly 17 times.

It can be seen from Fig. 14 that when the droplet impacts on the liquid film, the flow direction of the liquid changes from the axial direction to the radial direction, while the fluid inside the liquid film is in a static state. Therefore, there is kinetic discontinuity in the root of the crown, which makes the liquid flow into the crown, and the height and radius of the crown become larger. The theory of kinetic discontinuity was first proposed by Yarin and Weiss (1995) through theoretical deduction and then many researchers proved the correctness of the theory through experiments and numerical simulation. There is a clockwise vortex (Fig. 14) inside the crown resulting that the crown recesses inward when the fluid density is 500 kg/m^3.

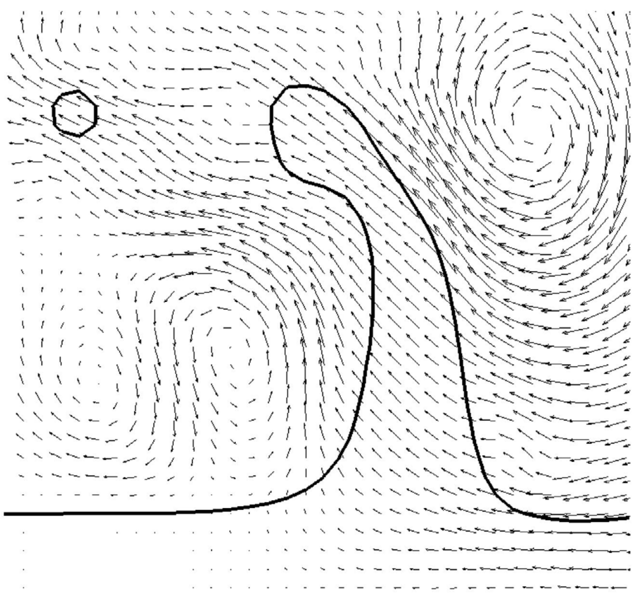


Fig. 14 Splashing morphology and velocity field distribution (H^* = 0.1, t = 0.2 ms, D = 1 mm, v_P = 5 m/s).

In the expansion stage, daughter droplets are generated at the tip of the crown. There is no consensus on the mechanism of daughter droplets, but many scholars believe that the tips are generated because of Rayleigh–Taylor instability, and then the daughter droplets are generated at the tip because of Plateau–Rayleigh instability. It can be seen from Fig. 15 which is the three-dimensional numerical simulation of the edge of the crown that when t = 0–4 ms, the tip of the crown is mainly affected by Rayleigh–Taylor instability which generates protrusions and jets, and when t = 8–15 ms, the tip of the crown is mainly affected by Plateau–Rayleigh instability, resulting in the long jet which is broken by surface tension, forming daughter droplets. From the distribution of the velocity field of crown (Fig. 14), it can be seen that the inner and outer sides of the crown form vortexes (the inner side is clockwise, and the outer side is counterclockwise), which is conducive to the crown expansion and the generation of daughter droplets.

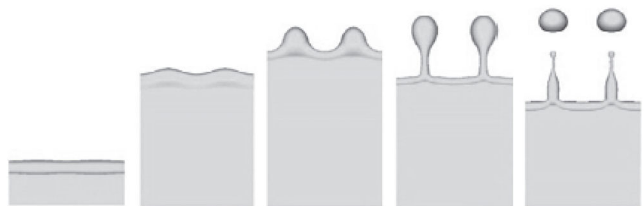


Fig. 15 Generation mechanism of daughter droplet (Agbaglah et al., 2013; Liang and Mudawar, 2016).

4 Conclusions

In this paper, CLSVOF method is used to simulate droplet impacting on liquid film to study the effect of different thickness of liquid film, surface tension, viscosity, and density of liquid on crown morphology and the mechanism of ejecta sheet. Through the analysis of pressure and velocity field, the following conclusions are drawn:

(1) Experiment and simulation are in good agreement, so CLVSOF method is suitable for research of droplet impacting on lquid film.

(2) Within the study scope, with the increase of liquid film thickness, the expansion radius and height of crown decrease, and the crater depth increases. The increase of liquid film thickness inhibits the generation of splash.

(3) With the increase of the surface tension and viscosity of the fluid, the crown height decreases but the thickness of the crown increases. With the increase of the density of the fluid, the crown height increases but the thickness of the crown decreases. However, the three factors have relatively small effect on the radius of crown.

(4) Within the scope of this study, the liquid film thickness affects the ejecta sheet velocity at the neck

region, which decreases with the increase of the liquid film thickness but when $H^* > 1.0$, the ejecta sheet velocity does not change.

(5) The change trend of neck pressure and ejecta sheet velocity with the thickness of liquid film is consistent, which verifies the correctness of Liang et al. (2013a) in explaining the mechanism of neck ejecta sheet, that is, neck ejecta sheet is caused by neck pressure difference.

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References

Agbaglah, G., Josserand, C., Zaleski, S. 2013. Longitudinal instability of a liquid rim. *Phys Fluids*, 25: 022103.

Bussmann, M., Mostaghimi, J., Chandra, S. 1999. On a three-dimensional volume tracking model of droplet impact. *Phys Fluids*, 11: 1406–1417.

Cossali, G. E., Coghe, A., Marengo, M. 1997. The impact of a single drop on a wetted solid surface. *Exp Fluids*, 22: 463–472.

Cossali, G. E., Marengo, M., Coghe, A., Zhdanov, S. 2004. The role of time in single drop splash on thin film. *Exp Fluids*, 36: 888–900.

Dai, J.-F., Fan, X.-P., Meng, B., Liu, J.-F. 2015. A coupled level-set and volume-of-fluid simulation for splashing of single droplet impact on an inclined liquid film. *Acta Phys Sin*, 64: 094704. (in Chinese)

Guo, Y., Wei, L., Liang, G., Shen, S. 2014. Simulation of droplet impact on liquid film with CLSVOF. *Int Commun Heat Mass*, 53: 26–33.

Liang, G., Guo, Y., Shen, S. 2013a. Analysis of liquid sheet and jet flow mechanism after droplet impinging onto liquid film. *Acta Phys Sin*, 62: 024705. (in Chinese)

Liang, G., Guo, Y., Shen, S. 2014. Gas properties on crown behavior and drop coalescence. *Numer Heat Tr B: Fund*, 65: 537–553.

Liang, G., Mudawar, I. 2016. Review of mass and momentum interactions during drop impact on a liquid film. *Int J Heat Mass Tran*, 101: 577–599.

Liang, G.-T., Shen, S.-Q., Guo, Y.-L., Chen, J.-X., Yu, H., Li, Y.-Q. 2013b. Special phenomena of droplet impact on an inclined wetted surface with experimental observation. *Acta Phys Sin*, 62: 084707. (in Chinese)

Mukherjee, S., Abraham, J. 2007. Crown behavior in drop impact on wet walls. *Phys Fluids*, 19: 052103.

Rioboo, R., Bauthier, C., Conti, J., Voué, M., de Coninck, J. 2003. Experimental investigation of splash and crown formation during single drop impact on wetted surfaces. *Exp Fluids*, 35: 648–652.

Roisman, I. V., Tropea, C. 2002. Impact of a drop onto a wetted wall: Description of crown formation and propagation. *J Fluid Mech*, 472: 373–397.

Sussman, M., Puckett, E. G. 2000. A coupled level set and volume-of-fluid method for computing 3D and axisymmetric incompressible two-phase flows. *J Comput Phys*, 162: 301–337.

Thoroddsen, S. T. 2002. The ejecta sheet generated by the impact of a drop. *J Fluid Mechs*, 451: 373–381.

Vander Wal, R. L., Berger, G. M., Mozes, S. D. 2006. Droplets splashing upon films of the same fluid of various depths. *Exp Fluids*, 40: 33–52.

Wang, A., Chen, C. 2000. Splashing impact of a single drop onto very thin liquid films. *Phys Fluids*, 12: 2155–2158.

Wang, B., Chen, B., Li, R., Tian, R. 2020. Analysis of fluctuation and breakdown characteristics of liquid film on corrugated plate wall. *Ann Nucl Energy*, 135: 106946.

Wang, B., Tian, R. 2019. Study on fluctuation feature and breakdown characteristic of water film on the wall of corrugated plate. *Int J Heat Mass Tran*, 143: 118501.

Yarin, A. L., Weiss, D. A. 1995. Impact of drops on solid surfaces: self-similar capillary waves, and splashing as a new type of kinematic discontinuity. *J Fluid Mech*, 283: 141–173.