Crown rupture during droplet impact on a dry smooth surface at increased pressure

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The impact of droplets at increased environmental pressure is important in many industrial applications. Previous studies mainly considered the impact process at standard or reduced environmental pressure, and the effect of high environmental pressure is unclear. In this study, we experimentally investigate the impact of ethanol droplets on dry smooth surfaces at increased environmental pressure. The effects of the environmental pressure on the splashing and rupture of the crown during the impact process are analyzed. The results show that surrounding gas with high environmental pressure can lead to the splashing of the crown in a ‘thread rupture’ mode and the sizes of the secondary droplets from the rim of the liquid crown increase with the environmental pressure. The threshold for the transition from spreading to splashing during the impact process is obtained based on the theory of aerodynamics analysis of the lamella. At increased environmental pressure, the threshold speed of the impact decreases with increasing the environmental pressure because the wedge of the lamella is prevented from moving forward and is driven to detach from the substrate by the air ahead, which has a higher density due to the higher environmental pressure.

I. INTRODUCTION

Droplet impact is of great significance for a wide variety of industrial processes, such as spray combustion, spray coating, spray cooling, and pesticide deposition. Most studies on the impact of droplets were conducted at the standard environmental pressure until Xu et al.\textsuperscript{6} who first revealed the importance of the environmental pressure on the impact dynamics by performing the impact experiments below the atmospheric pressure and found that splashing could be suppressed by reducing the environmental pressure. Since that, several studies of droplet impact\textsuperscript{6–9} have been conducted by decreasing the environmental pressure. For example, Xu et al.\textsuperscript{6} and Hao\textsuperscript{10} investigated the effects of surface roughness and the surrounding gas on the splashing and found that prompt splashing was due to surface roughness, but crown splashing was due to instabilities produced by the surrounding gas. As the environmental pressure is reduced, the corona splash is suppressed to a prompt splash, and on the further reduction of the pressure, prompt splash changes to lamella spread after a droplet impacting on a smooth moving substrate\textsuperscript{11}. In addition, at reduced environmental pressure, Andrzej et al.\textsuperscript{12} found that the crown formation could be suppressed. Numerical simulation\textsuperscript{12} were conducted to investigate the effect of the environmental pressure on the splash after a drop impacting on a smooth surface, and the result showed that lowering the ambient gas density could suppress the splashing. Li et al.\textsuperscript{13} and Lambley et al.\textsuperscript{14} found that at reduced environmental pressure, the air disc entrapped under an impacting droplet became smaller than that at standard environmental pressure. When droplet impacts on the superhydrophobic substrate at reduced environmental pressure, the splashing can be eliminated, and the maximal diameter of the spreading lamella decreases with decreasing environmental pressure.\textsuperscript{13–15}

Besides the impact at reduced pressure, an important problem yet to be solved is the dynamics of droplet impact at high environmental pressure. The impact of droplets at increased pressure is not only a vital supplement to the previous studies at normal or reduced environmental pressure\textsuperscript{16}, but also crucial to many relevant applications such as fuel atomization in internal combustion engines\textsuperscript{16}, spray cooling of high-power electronic devices, and droplet impact in nuclear power plants\textsuperscript{17,18} at high pressure. For example, in nuclear power plants, the wall of the evaporator is unavoidable to be impacted by droplets in dispersed flow, which is an important open question for the safe operation of nuclear power plants. To ensure the safety of nuclear power plants, it is important not only to accurately describe the behavior of droplets impact but also to understand the dynamics of secondary droplets generated during the impact of droplets on the walls of the evaporator in such harsh environment of high pressure.

A droplet impacting on a substrate often splashes like a crown-shaped corona, breaking up into many tiny secondary droplets.\textsuperscript{19–22} The splashing process is driven by the interplay of inertial, viscous, and capillary forces.\textsuperscript{21–23} To quantify the effects of droplet sizes, droplet speeds, and the liquid properties on the crown propagation and splashing, the Weber number $We \equiv \rho U^2 D_0 / \sigma$ can be used to indicate the ratio between inertial and capillary forces, where $\rho$ and $\sigma$ are the density and surface tension of the liquid droplet, $U$ and $D_0$ denote the speed and the diameter of the droplet before the impact, respectively. The Reynolds number $Re \equiv \rho U D_0 / \mu$ can be used to indicate the ratio of inertial and viscous forces, where $\mu$ is the dynamic viscosity of the liquid droplet. The Ohnesorge number $Oh \equiv \sqrt{We/Re}$ can be used to indicate the relationship between

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the inertial, capillary and viscous forces. The detailed mechanism of the ejection of secondary droplets from the crown and the effects of the impact parameters on the size of the secondary droplets are mainly studied at standard environmental pressure. Different models have been proposed to explain the splashing mechanisms at standard environmental pressure, such as rim instability, 26-28 ejection, 29,30 crown breakup, 27,31 and levitated viscous sheet. 32,33 Roisman et al. studied the formation and growth of disturbance in the rim centerline by the transverse rim instability and found that the diameter of the fingers was similar to the size of the rim and also similar to the diameter of the outermost secondary droplets. The diameter of fingers, as it emerges from the base of the droplet, is governed by the viscous boundary layer along the substrate. 24 and considering the unsteady nature of the flow, the diameter of the fingers can be calculated by \[ \frac{d_0}{D_0} \propto \text{Re}^{-0.5} \text{Re}^{0.5}. \]

For the impact of droplets on surfaces, there is a threshold from the spreading of the lamella to the splashing of the crown. 29,33 The impact speed, the diameter, the surface tension, the viscosity, and the density of the liquid droplet have been known to be important for the splashing threshold. 31,34 Previous studies on the threshold of splashing have shown that the threshold is a function of the environmental pressure at reduced environmental pressure. 31,33 For example, silicone oil with different viscosities was used by Stevens et al. 37 to investigate the effect of the environmental pressure and the liquid viscosity on the splashing mechanism of droplets. They found that the threshold pressure of splashing decreased with increasing the viscosity at low viscosities of the droplet, whereas the trend was reversed at high viscosities. The effect of environmental pressure on the threshold for the transition from spreading to splashing was examined experimentally at increased environmental pressure. 39 Liu et al. found that the lamella spread horizontally along the surface at the standard environmental pressure and the spreading of the lamella was transformed to the crown splashing when the environmental pressure was increased to 2 bar after an FC-72 droplet impacting on a glass surface with the \( \text{We} = 97 \). 39

Since the environmental pressure can have a strong effect on the impact process, there is a great necessity to investigate the droplet impact dynamics at high environmental pressure and establish the relationship between the formation of secondary droplets and the environmental pressure. In this experimental study, we varied the environmental pressure in a wide range (from 0.1 to 7 bar) as well as other impact parameters. We found that the high environmental pressure can lead to the splashing of the crown in a ‘thread rupture’ mode. The ‘thread rupture’ is that during the growth of the liquid crown, the crown ruptures into liquid threads like stamens of flowers. The formation of the secondary droplets is from the tip of long liquid threads, which differentiates the breakup of droplets from the rim of the crown directly at the standard environmental pressure.

The rest of this paper is organized as follows. The experimental details are described in Section II. The results are discussed in Section III, including the dynamics of the impact process, the effect of the environmental pressure on the secondary droplets, the liquid crown, and the threshold of the splashing. Finally, conclusions are drawn in Section IV.

II. EXPERIMENTAL METHOD

The impact was performed inside a pressure vessel as schematically described in Fig. 1. The absolute pressure inside the pressure vessel, \( P \), was varied from 0.1 to 7 bar by connecting to an air cylinder and a vacuum pump (see Table S1 in Supplementary Materials for variation of the air properties with pressure). Unless otherwise stated, the pressure value presented in this paper is the absolute pressure. Ethanol was used as the droplet fluid, and the density, the dynamic viscosity, and the surface tension are 789 kg/m³, 1.2 \times 10^{-3} Pa-s, and 22.3 \times 10^{-3} N/m, respectively. Ethanol droplets were released from a blunt syringe needle, which was connected to a syringe pump (Harvard Apparatus, Pump 11 elite Pico plus). The diameter of the droplets was varied between 2.0 \pm 0.1 and 3.5 \pm 0.1 mm by changing the size of the syringe needle. The speed of the droplets was varied by changing the height of the syringe needle from the substrate, and the size and the speed of the droplets were measured from the side-view images via an image processing algorithm using a customized Matlab program (see Supplementary Materials for the details). Dry smooth glass substrates were used as the target of impact, and they were laid horizontally inside the pressure vessel. The roughness of the glass surface is about 10 nm and the contact angle of ethanol on the surface is 7° (measured from the side-view images). We used a fresh glass substrate in every impact event to avoid contamination by previous droplets. A droplet collector was used to screen the best droplets for impact and to avoid the uncontrolled continuous release of droplets. The processes of splashing and crown rupture were captured from the side-view and the bottom-view by using high-speed cameras (Photron Fastcam SA1.1). The side-view high-speed camera was at the speed of 16000 frames per second (fps) at the resolution of 640 \times 512 pixels, corresponding to a spatial resolution of 22.2 \mu m/pixel, and the bottom-view high-speed camera was at the speed of 8000 frames per second (fps) at the resolution of 1024 \times 752 pixels, corresponding to a spatial resolution of 12.5 \mu m/pixel. Due to the limited space in the pressure vessel, the side-view and the bottom-view images were taken separately using repeated experiments by fixing the parameters of impact. The impact process was illuminated by high-power LED lights (Hecho S5000).
III. RESULTS AND DISCUSSION

A. Impact morphology

Figure 2 shows image sequences of ethanol droplets impacting on glass substrates with We = 450 at different environmental pressures. The first rows in Figs. 2a, 2b, and 2c are the side-view images, and the second rows are the bottom-view images. A phenomenon can be observed that, as the environmental pressure increases, the rupture of the crown after the splashing is from liquid threads, as shown at 0.5 ms at the environmental pressure of 3 and 6 bar, which differentiates the breakup of the droplet from the rim of the crown directly in the standard pressure condition. Here in this section, we mainly consider the rupture of the crown in the splash regime, and the threshold of the environmental pressure in this splash regime will be further discussed in detail in Section III D.

The environmental pressure is vital in determining whether the rupture of the crown is from liquid threads. Figure 2a, (Multimedia view) shows the shape evolution of a droplet impacting on a substrate at the standard environmental pressure (1 bar). At 0.375 ms, the crown bends upwards from the substrate, and some tiny secondary droplets start to eject from the crown rim. As we increase the environmental pressure from 1 to 3 bar, the main difference in the crown film is that the formation of the secondary droplets is from the tip of long liquid threads as shown at 0.5 ms in Fig. 2b, Multimedia view, and this phenomenon is termed ‘thread rupture’ to differentiate the breakup of the droplet from the rim of the crown directly at the standard environmental pressure. At 0.25 ms at the environmental pressure of 3 bar, the crown film has already bent up, as shown in Fig. 2b, and in contrast, at 1 bar, only a weak disturbance occurs along the rim. In addition, the rim of the crown at 0.25 ms in Fig. 2b is darker than the inside of the crown, which indicates that the rim of the crown is thicker than the inside of the crown, resulting in that the outer secondary droplets produced from the tip of the liquid threads are much larger than the inner secondary droplets after crown rupture, as shown at 0.625 ms in Fig. 2b. As the environmental pressure is increased to 6 bar, many thick cusps are developed due to the rim instabilities on the liquid crown, as shown at 0.375 ms in Fig. 2c. At the standard environmental pressure, cusps cannot develop into the liquid threads because of the detachment of secondary droplets from the rim of the liquid crown. In addition, the liquid threads at 6 bar are much shorter than that at 3 bar, as shown at 0.5 ms in Figs. 2b and 2c, (Multimedia view), and this is because as the environmental pressure increases from 3 bar to 6 bar, the resistance of the surrounding air in the direction of the growth of the liquid crown increases due to the density of the surrounding air increases. The larger resistance of the surrounding air at 6 bar makes the length of the liquid crown shorter than the length of the liquid crown at 3 bar. Thus, the liquid threads at 6 bar are shorter...
FIG. 3. Comparison in the rupture of the crown between the droplet impact at standard environmental pressure and increased environmental pressure. (a) The finger jets at the rim of the liquid crown during the impact at standard environmental pressure. The finger jets are formed due to the development of the cusps on the rim of the liquid crown due to the instability of the rim. We = 450, \( P = 1 \) bar. (b) Liquid threads connected to the lamella during the impact at increased environmental pressure. The liquid threads are formed after the rupture of the thin film of the liquid crown. We = 450, \( P = 3 \) bar.

FIG. 4. Schematic diagram of the process of crown rupture: (a) transverse rim instabilities on the film, (b) cusp formation, (c) generation of finger jets on the cusps, (d) thread rupture, and (e) generation of secondary droplets from crown rupture.

than that at 3 bar after the rupture of the liquid crown. The secondary droplets at 6 bar are larger than that at 3 bar, as shown at 0.625 ms in Figs. 2b and 2c.

To highlight the difference between the thread rupture mode at increased environmental pressure and the breakup of the secondary droplet from the rim of the liquid crown directly at the standard environmental pressure, the shapes of the rims of the liquid crown are compared in Fig. 3. At standard environmental pressure, the rim instability of the liquid crown, governed by the Rayleigh-Taylor instability and the Rayleigh-Plateau instability,\(^\text{27,29,31,41,42}\), develops into secondary droplets through the evolution of the finger jets\(^\text{27,30,40,43}\), as shown in Fig. 3a. In contrast, at increased environmental pressure, due to the resistance of the surrounding gas at high environmental pressure, the liquid crown quickly ruptures into long liquid threads. Finally, the threads further rupture into secondary droplets.

B. Influence of environmental pressure on secondary droplets

Figure 5a shows a typical enlarged image of the crown splashing taken from the bottom view at We = 450. We can see that there are many ripples on the crown film, and the ripples are thicker than the nearby liquid crown. After the formation of the liquid crown, due to the resistance of the surrounding air at increased environmental pressure (high density of the surrounding air) in the direction of the growth of the liquid crown, and also due to the ripples on the liquid crown, the liquid crown quickly ruptures into long liquid threads. The outer secondary droplets produced from the rim are larger than the inner secondary droplets, as shown.
FIG. 5. (a) Enlarged image of a droplet impacting with We = 450. There are many ripples on the crown film connecting the rim to the lamella. The rim is much thicker than the liquid crown, and secondary droplets are ejected from the rim of liquid crown. (b) Histograms of the sizes of the outermost secondary droplets for a droplet impacting on a glass surface with We = 450, P = 1 bar. The histogram is an average over ten impact events under the same conditions.

FIG. 6. Effect of the environmental pressure on the scaled sizes of the secondary droplets produced from the crown rupture. The inset shows the sizes of secondary droplets versus environmental pressure in the dimensional form.

at 0.625 ms in Fig. 2). To quantitatively study the influence of the environmental pressure on the secondary droplets, we analyze the outermost secondary droplets ejected from the rim of the liquid crown or from the liquid threads at different environmental pressures. Figure 5b shows the histogram of the sizes of the outermost secondary droplets for a droplet impacting on a glass surface with We = 450. The average diameter of the outermost secondary droplets is 0.052 mm. The sizes and the number of the secondary droplets were measured from the bottom-view images via an image processing algorithm using a customized Matlab program (see the Supplementary Materials for the details).

Figure 6 shows the influence of the environmental pressure on the secondary droplets produced from the crown rupture at different Weber numbers. The inset shows the sizes of secondary droplets versus environmental pressure in the dimensional form. From a fitting of the sizes of secondary droplets in the inset of Fig. 6, the sizes of secondary droplets show an exponential dependence on the environmental pressure $d \propto P^{0.2}$, which can be written in dimensionless form $d/d_0 \propto (P/P_0)^{0.2}$, where $d_0$ is the average diameter of the secondary droplet at the standard pressure $P_0$. It has been reported that the sizes of secondary droplets at the standard pressure are scaled as $d_0/D_0 \propto Re^{-0.5}$, where $Re$ is the Reynolds number of droplet impact and $D_0$ is the initial diameter of the droplet before the impact. Since the density, the viscosity, and the surface tension of the ethanol droplet hardly change with the environmental pressure, by substituting $d_0$ into the formula at increased environmental pressures, the scaling of the secondary droplet size versus the environmental pressures can be described as $(d/D_0)^5Re^{2.5}P^* \propto P^*$, where $P^* = P/P_0$. The experimental data of the diameter of the secondary droplet and the environmental pressure are plotted in the main panel of Fig. 6.
C. Influence of environmental pressure on the liquid crown

The rupture dynamics of the liquid crown is closely related to the morphology of liquid crown before the rupture. Therefore, in this section, the influence of the environmental pressure on the morphology of the liquid crown before the rupture is analyzed. The morphology of the liquid crown at different environmental pressure can be characterized mainly by three parameters: the diameter of the liquid crown rim, the angle of the liquid crown, and the height of the liquid crown, as sketched in the insets of Fig. 7. These parameters are measured at the moment just before the rupture, and they are plotted against the environmental pressure in Fig. 7.

The environmental pressure can suppress the movement of the liquid crown in the horizontal direction. As shown in Fig. 7a, the diameter of the liquid crown decreases with increasing the environmental pressure. The angle of the liquid crown increases with the environmental pressure as shown in Fig. 7b, and this is because the high environmental pressure can lift the liquid crown at larger angles from the substrate than that at the standard environmental pressure. The length of the liquid crown is expected to be larger, but the movement of the liquid crown is suppressed by the surrounding air with higher density in the vertical direction at increased environmental pressure. Therefore, the height of the liquid crown is almost constant than that at the standard environmental pressure. The gas at high environmental pressure suppresses the increase of the height of the liquid crown, but the angle of the liquid crown increases, resulting in that the width of the rim of the liquid crown is shorter than that at the standard environmental pressure. As a consequence, the rim becomes thicker at higher environmental pressure and produces larger secondary droplets, as shown in Fig. 6.

Previous researchers have shown that as the environmental pressure increased from vacuum to the standard environmental pressure, the liquid crown formed and became larger. However, our results show that if we continue to increase the environmental pressure from the standard environmental pressure, the liquid crown can be suppressed instead of becoming larger further, as shown in Fig. 7a (see the Supplementary Materials). The diameter of the liquid crown decreases with increasing the environmental pressure. The reason is that the crown splashing is created by the air drag in the front of the lamella, but after the formation of the liquid crown, the movement of the liquid crown can be suppressed by the surrounding air with higher density if we continue increasing the environmental pressure.

D. Influence of environmental pressure on the threshold of splashing

Upon the impact of droplets on solid surfaces, the splashing phenomenon occurs only when the inertia is sufficiently large and there is a threshold from the spreading of the lamella to the splashing of the crown. In this section, the threshold of splashing at increased
environmental pressure is analyzed. We firstly consider the widely used theory based on the “water hammer” effect to analyze the effect of the environmental pressure on the threshold of splashing proposed by Xu et al.\textsuperscript{53} When the ratio between the destabilizing stress due to the gas $\Sigma_G$ and the stabilizing stress due to surface tension $\Sigma_L$ (i.e., $\Sigma_G/\Sigma_L = \sqrt{\gamma M_g P_0} \sqrt{\frac{\Delta P}{\kappa T}}$) where $\gamma$ is the adiabatic constant of the gas, $M_g$ is the molecular weight of the gas, $k_B$ is the Boltzmann constant, $T$ is the gas temperature, $\nu_l$ is the kinematic viscosity of the liquid) is greater than the critical number 0.45, the crown splashing occurs. The regime map of $\Sigma_G/\Sigma_L$ versus the speed of droplet impact at different environmental pressure is shown in Fig. \textsuperscript{8}. A threshold scenario of droplet impact is obtained, as shown in the inset images in Fig. \textsuperscript{8}. In the spreading condition, the lamella spreads horizontally along the substrate without any lift up. In contrast, in the splashing condition, the lamella lifts up from the substrate. In the threshold scenario shown in Fig. \textsuperscript{8} (the inset image labeled with ‘Threshold of splashing’), the secondary droplets emit from the lamella directly without any lift up of the lamella. The criterion by Xu et al.\textsuperscript{53} is only applicable to reduced environmental pressure, but cannot predict the threshold of splashing at increased environmental pressure, as shown in the regime of impact in Fig. \textsuperscript{8}.

As the criterion by Xu et al.\textsuperscript{53} cannot predict the threshold of splashing at increased environmental pressure, we consider the criterion proposed by Riboux and Gordill\textsuperscript{53} for splashing based on the aerodynamics analysis in which the resistance from the air ahead drives the lamella to detach from the substrate. The criterion applies to the low viscosity liquids ($Re^{1/6}Oh^{2/3} < 0.22$) and the millimeter droplets and was later demonstrated for reduced pressure.\textsuperscript{12,22} In this criterion, the expression of the droplet speed before the impact, $K_l$, is used to predict the threshold of splashing. In the limit $We_\lambda > 3(\mu g/\mu)^{3/4}Oh^{1/4}$, where $\lambda$ is the mean free path of the gas molecules, $\mu$ is the viscosity of the gas, and $We_\lambda \equiv We\lambda/D_0$, the threshold of splashing can be expressed as

$$U = K_l \sim \ln \left[ \frac{1 + K_a We^{1/12}Oh^{1/2}}{C We_\lambda} (1 + C We_\lambda) \right]$$

where $K_a$ is a proportionality constant $K_a = 0.7$ and $C$ is a fitting constant $C = 1$\textsuperscript{52}. The mean free path of gas molecules follows

$$\lambda = \lambda_0 \frac{T P_0}{T_0 P}$$

where $\lambda_0 = 6.5 \times 10^{-8}$ m is the mean free path of gas molecules at $T_0 = 300$ K and $P_0 = 1$ bar. In addition, in the limit $We_\lambda < 3(\mu g/\mu)^{3/4}Oh^{1/4}$, the threshold of splashing can be expressed as

$$U = K_l \sim \ln (A l_\mu l_g)$$

where $l_g$ is the slip length of liquid at the substrate under the wedge of the lamella $l_g = We_\lambda (1 + K_a We^{1/12}Oh^{1/2})^{-1}$, $l_\mu$ is the slip length at the gas-liquid interface under the wedge of the lamella $l_\mu = l_g + (\mu/\mu_g)^{-3/4}Oh^{1/4}$, $A$ is a fitting constant. In the derivation of Ref.\textsuperscript{22} the expression of $l_\mu$ is simplified to $l_\mu = (\mu/\mu_g)^{-3/4}Oh^{1/4}$ by neglecting $l_g$. However, at different environmental pressure varied from 0.1 to 7 bar, $l_g$ is an important contribution to $l_\mu$ and cannot be neglected because $l_g$ depends on the mean free path of the gas molecules $\lambda$, which depends on the environmental pressure as described by Eq. \textsuperscript{2}. For example, at the threshold of splashing, when the environmental pressure is 0.4 bar, $l_g/l_\mu \approx 0.9$, and when the environmental pressure is 1 bar, $l_g/l_\mu \approx 0.6$. Therefore, $l_g$ is an important contribution to $l_\mu$, and its contribution should be considered.

The threshold speed of droplet impact for splashing, dependent on environmental pressure, is drawn in Fig. \textsuperscript{9}. When the speed of impact is greater than 3 m/s, the threshold pressure decreases slowly with increasing the speed of impact. However, when the speed of impact is less than 2.5 m/s, the threshold pressure decreases quickly with increasing the speed of impact. There is a non-monotonic interval of the threshold pressure of splashing versus the speed of droplet impact as the environmental pressure increases, which is consistent.

![FIG. 8. Regime map of $\Sigma_g/\Sigma_L$ versus the speed of droplet impact at different environmental pressure. The red dot shows the threshold of splashing, and the horizontal spreading is indicated by the solid black square, and the crown splashing is indicated by the solid blue triangle. The solid red line is the approximate threshold of splashing, obtained according to the threshold point. When droplets impact at reduced environmental pressure, $\Sigma_g/\Sigma_L$ at the threshold decreases with increasing the speed of droplet impact.](image)
Threshold of splashing by Xu et al.

Crown splashing

Horizontal spreading

\[ P(T) \]

\[ U(m/s) \]

FIG. 9. Threshold pressure versus the speed of droplet impact. Below the threshold of splashing, the horizontal spreading of droplets occurs, while above the threshold, the crown splashing of droplets occurs. The black squares indicate the threshold data of splashing from this study, and the blue dots indicate the threshold data from Xu et al.\textsuperscript{5} The lines indicate the thresholds in Eqs. (1) and (3) where the contribution of \( \ell_g \) to \( \ell_\mu \) is considered. The fitting constant \( A \) is \( A = 6.6 \times 10^{-7} \).

IV. CONCLUSIONS

This paper experimentally investigates the impact of droplets on dry smooth surfaces by using high-speed photography at increased environmental pressure. The effects of the environmental pressure on the splashing and rupture of the crown during the impact process are analyzed. With increasing the environmental pressure, a phenomenon of thread rupture occurs during the crown splashing. The formation of secondary droplets from the crown splashing includes several stages, namely rim instability, cusps along the rim, jets, thread rupture, and finally the formation of secondary droplets. The sizes of the secondary droplets are measured from the high-speed images, and the results show that high environmental pressure can promote the crown rupture, and the size of the secondary droplets from the rim of the liquid crown increases with the environmental pressure. The threshold for the transition from spreading to splashing during the impact is obtained from our experimental data, and is analyzed based on the theory of aerodynamics analysis of the lamella. At increased environmental pressure, the surrounding gas plays an important role on the threshold of the splashing because the wedge of the lamella is prevented from moving forward and is driven to detach from the substrate by the air ahead, which has a higher density due to the higher pressure. The threshold speed of the impact decreases with increasing the environmental pressure, and the slope of the threshold pressure versus the impact speed increases with increasing the environmental pressure.

This paper studies droplets impacting at increased environmental pressure. There are still many open questions for the impact process at the increased environmental pressure, such as the development of the azimuthal instability of the rim, the pinch-off of secondary droplets from the rim, and the liftoff of the lamella. The study of droplet impact at increased environmental pressure will not only deepen our understanding of the impact dynamics, but also will be useful for the optimization of the relevant applications.

SUPPLEMENTARY MATERIALS

See the Supplementary Materials for the properties of the air at different environmental pressures (Sec. S1), the details of image processing (Sec. S2), the effects of the droplet size on the threshold pressure of splashing and the size of the secondary droplets (Sec. S3), and the threshold pressure from the splash enhancement to the suppression of liquid crown (Sec. S4).

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CONFLICT OF INTEREST

The authors have no conflicts to disclose.
DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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