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Splashing generation by water jet impinging on a horizontal plate

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\begin{abstract}

The report of COVID-19 virus in municipal wastewater raises the question of whether viruses can become airborne during wastewater transport in sewer systems. The present work experimentally investigates a water jet impinging vertically onto a horizontal plate and the behaviours of the generated tiny droplets. Depending on whether the jet breaks into primary drops before the impingement, three regimes can be defined: non-splashing, jet-splashing and drop-splashing regimes. The splashing ratio, i.e., the portion of jet flow rate becoming splashing droplets, ranges from 1\% to 70\% in the drop-splashing regime, while it remains less than 2\% in the jet-splashing regime. For the splashing droplets, their size and velocity distributions follow log-normal laws. Their diameters are mainly in the range from 0 to 0.3 of the impact jet or drop diameter with the median less than 0.1. Their velocities mostly range from 0 to 3.0 times of the impact velocity with the median around 1.0. The medians of both the dimensionless diameter and velocity of splashing droplets decrease with the impact Weber number. The ejection angles of splashing droplets obey a bell-shaped distribution with the maximum around 70\° and the median ranging from 16\° to 30\°.

\end{abstract}

\section{Introduction}

COVID-19 virus is around 100 nm in size and spreads primarily via respiratory droplets released when someone coughs, sneezes, or talks (Bar-On et al., 2020, Asadi et al., 2020). However, COVID-19 virus has recently been detected in municipal wastewater, hence, there is significant concern whether the viruses can become airborne and transport as virus-laden droplets in wastewater systems during the transport of wastewater (Cheung et al., 2020, Gormley et al., 2020). In wastewater systems, the falling and impact processes of sewage in drop structures are expected to be the main source of droplet generation (Granata et al., 2011, Adriana Camino et al., 2015). The falling sewage breaks into jets and drops depending on the flow rate and falling height (Ma et al., 2016a). While the breakup of ideal liquid jet has received considerable attention, there is relatively little understanding on their impact and splashing characteristics. Knowledge of liquid jet impact and splashing is also important in many industrial applications including quenching, cooling, coating, and cleaning processes.

A continuous liquid jet starts to break into primary drops at a certain distance from the nozzle, which is commonly referred to as the breakup length. The breakup of liquid jet can be divided into the dripping, Rayleigh, first wind-induced, second wind-induced and atomization regimes (Dumouchel 2008). Different breakup regimes correspond to various breakup structures, primary drop sizes, and correlations of breakup length with jet velocity at nozzle exist (Birouk and Lekic 2009).

Depending on whether a liquid jet breaks into primary drops before impingement, the impingement takes the form of impact by continuous jet or primary drop trains. Lienhard et al. (1992) observed the splashing produced by a continuous jet impact when liquid velocity is sufficiently large, and found that the amount of splashing droplets is closely related to the jet Reynolds number and the nozzle-to-plate distance. Trainer (2016) reported that when the jet Weber number is smaller than 1500, the impingement of a continuous jet hardly generates splashing whereas the impingement of primary drop trains always results in splashing. The detailed splashing onset conditions for the impingement of a continuous jet and primary drops still remain unclear. As the splashing droplets are small and fast-moving, the determination of their amount, size and velocity is challenging, and no comparison has been made for these splashing characteristics during continuous jet and primary drop impingement. For the impingement of primary drop trains, Zhan et al. (2018 and 2021) correlated the amount of splashing droplets with the impact Weber number and impact frequency of the primary drops. They also reported that the size distribution of the splashing droplets obeys the log-normal law with the maximum value reaching approximately 25\% of the impact drop diameter.

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The impact of a single drop has received a wealth of scientific interest (see reviews by Liang and Mudawar 2016, and Josserand and Thoroddsen 2016). Two kinds of splashing phenomena are identified: the prompt splashing where small droplets are ejected directly from the corona splashing, Wu (2003) assumed that their size distribution satisfies the log-normal law and established analytical formulas for the parameters characterizing the distribution curve. Davidson (2002) proposed that increasing surface tension increases the diameter of the splashing droplets. Based on Motzkus et al. (2009), increasing liquid viscosity has the same effect on the diameter of the splashing droplets as surface tension. Fallmann et al. (2013) demonstrated that the diameter of the splashing droplets decreases while the velocity increases with the increase in impact velocity.

As a first step towards our understanding of possible virus transport in real sewage systems, the present study experimentally investigates the splashing generated by water jets impacting vertically onto a horizontal plate. The effects of nozzle diameter, jet velocity at nozzle exit and nozzle-to-plate distance are taken into consideration. The flow behaviours caused by the impingement of continuous jet and primary drops are visualized. The thresholds of various splashing regimes are studied. In each splashing regime, the splashing ratio and the size and velocity of the splashing droplets are measured and analyzed.

2. Methodology

The experimental apparatus is shown schematically in Fig. 1. Experiments were conducted at room temperature of 20 °C and the tap water was used. A water jet was produced by a nozzle mounted on the bottom of a supply tank, and the vertical falling jet impacted onto a horizontal plate. Three circular nozzles were used with a diameter $D_0$ of 2.0, 6.0 and 8.0 mm. These nozzles were made of copper and well curved for a smooth outflow. The water head in the supply tank was controlled by a movable overflow weir to produce a mean jet velocity at the nozzle exit $U_0$ varying from 1.59 to 3.17 m/s. These $D_0$ and $U_0$ testing ranges are selected because typically the initial velocity of falling sewage is less than 3 m/s and it breaks into jets and drops with diameters mostly around 2–4 mm. The corresponding jet flow rate $Q_0$ and Weber number $W_{0j}$ and Reynolds number $Re_0$ at the nozzle exit were in the range of $5.0\times Q_0/\mu D_0 < 155.4 \times 10^{-6}$ m$^3$/s, $70 < W_{0j} < 24.689$. The target plate made by plexiglass was circular with a diameter of 30 cm, larger than the maximum diameter of the generated corona sheet during the jet impingement. The nozzle-to-plate distance $I$ was varied from 100 to 600 mm. Table 1 summarizes the main experimental parameters.
During the experiments, the falling and impacting processes of the jet were recorded by a high-speed camera (Phantom v211, Vision Research) coupled with a Nikon AF Micro NIKKOR 60 mm f/2.8D lens and illuminated by a diffuser-LED (SP-E-360D SpectroLED, Genaray) in a shadowgraph configuration. Videos were taken at a resolution of 1280 × 800 pixels at a speed of 2000 frames per second and an exposure time of 2–10 μs. The spatial resolution was 300 μm/pixel for recording the falling jets/drops and 80 μm/pixel for the splashing droplets, given the much smaller size of the splashing droplets.

The obtained video images were analyzed using the software, ImageJ (Schneider et al., 2012). The size and displacement of the jet and primary drops were measured using the tools of “Line” and “Measurement” in ImageJ. For the splashing droplets, background subtraction and binarization were applied to the video images, extracting the moving splashing droplets on the focal plane with sharp edges. The tool of “Analyze Particles” was utilized to find the edge of the splashing droplets and measure their sizes. The plugin of “TrackMate” (Tinevez et al., 2017) was used to determine the velocity of the splashing droplets using particle tracking velocimetry (PTV). For each jet impact condition, more than 200 splashing droplets were randomly selected, and their size and velocity were measured as soon as they are detached from high-speed video images (within 2.5 ms).

For the splashing rate Qs, a hygroscopic paper (WypAll X80, Kimberly-Clark) was tailored to a shape of isosceles triangular with the vertex angle of 20° and the leg length of 150 mm and was used for capturing the splashing droplets (see Fig. 1(b)). The difference in the weight of the hygroscopic paper was measured over a given time, then, Qs was evaluated by assuming that the splashing rate was axisymmetric. The hygroscopic paper was horizontally placed 20 mm above the plate with its sharp corner close to but not in contact with the jet. From the videos taken by the high-speed camera, it was confirmed that the hygroscopic paper captured the splashing droplets and was out of touch with the film flow on the plate generated during the jet impingement. This measurement was repeated for more than three times for each impact condition, and it was verified that the splashing rate was fairly insensitive to the capturing duration. The measurement variation in Qs was within ±10%.

### Table 1
Range of test parameters.

| D0 (mm) | l (mm) | U0 (m/s) | Qs (10⁻⁶ m³/s) | We0 | Re0 |
|---------|--------|----------|----------------|------|-----|
| 2.0     | 100–600| 1.59–3.17| 5.0–9.9        | 70–275| 3182–6317| |
| 6.0     | 100–600| 1.62–3.11| 45.8–87.9      | 217–798| 9710–18,610| |
| 8.0     | 100–600| 1.60–3.09| 80.4–155.4     | 282–1053| 12,776–24,689| |

3. Results and discussion

#### 3.1. Jet impact and splashing regimes

As the jet impact and splashing phenomena depend strongly upon the prior jet deformation and breakup, the jet breakup length Lb must be studied first. Herein, Lb is defined as the shortest length from the nozzle to the first breakup position measured from a period of 2 s of high-speed video images. According to the experiment of Zhan et al. (2020), Lb becomes fairly constant when the measurement duration is larger than 0.5 s. The difference between the measurements from 0.5 s and 2 s video images was found to be less than 5%. In the present study, the jet initially has smooth surface and then develops nearly axisymmetric disturbances at some distances after the nozzle exit. The disturbances grow as the jet moves downstream, leading to successive detachment of the primary drops as soon as the disturbance amplitude reaches the jet radius. The jet breakup length Lb is observed to increase with the initial...
jet velocity $U_0$, which agrees with the observations of the Rayleigh regime in the literature (Dumouchel 2008). The linear jet stability analysis for the Rayleigh regime (e.g., Mansour and Chigier 1994) indicated that the dimensionless breakup length $L_b/D_0$ is related to $We_0^{0.5}(1 + 3Oh_0)$, where the Ohnesorge number $Oh_0 = We_0^{0.5}/Re_0 = \mu/(\sigma \rho D_0)^{0.5}$. For a water jet, $(1 + 3Oh_0) \approx 1$ as $3Oh_0$ is less than 1% when $D_0 > 1.0$ mm. Therefore, $L_b/D_0$ of the water jet is plotted in Fig. 2 as a function of $We_0^{0.5}$. Our experimental data are compared with that from Trainer (2016) and Mansour and Chigier (1994). It is found that the breakup length $L_b$ increases from 50 to 140 times of the nozzle diameter $D_0$ when $100 < We_0 < 4400$, and all the data can be well predicted by the following simple equation

$$\frac{L_b}{D_0} = 18.7 We_0^{0.25} \text{ within the error of } \pm 30\%$$

Eq. (1) is compared with the correlation from Trainer (2016) who used the same definition of $L_b$

$$\frac{L_b}{D_0} = 3.7 We_0^{0.5}(1 + 3Oh)$$

It is indicated that Eq. (1) has better agreement with these experimental data.

When the nozzle-to-plate distance $l$ is less than the breakup length $L_b$, continuous jet impingement is observed. Based on whether splashing is generated, the continuous jet impingement can be further classified into non-splashing and jet-splashing regimes, and their typical snapshots are shown in Fig. 3(a) and (b). In the non-splashing regime, the jet still has smooth surface or weak disturbances before impingement. The impact jet spreads radially on the plate, creating a film flow usually with smooth free-surface. Sporadic surface waves may occur on the film flow, but they have small amplitude and always remain stable.

In the jet-splashing regime, the jet disturbances become significant when reaching the plate and they are strongly amplified after jet impingement, leading to the creation of an annular upraising wave that originates near the impingement point and travels radially outwards. The wave continues to upraise and sharpen, becoming a sheet bounded by a rim at the crest. During the travel process of the wave, holes firstly appear in the sheet and rapidly expand, finally leading to complete breakup of the sheet and detachment of the rim. The rim is unstable and subsequently breaks up into relatively larger splashing droplets compared to those produced by the sheet breakup. Lienhard et al. (1992) demonstrated that the impingement of the second wind-induced jet is susceptible to splashing and considered the reason as the jet surface disturbances driven by the liquid-side pressure fluctuations caused by the turbulence. Our experiments indicate that for the Rayleigh jet with surface disturbances driven by capillary instability, its impingement can also create splashing when the falling distance is long enough to have significant disturbances.

When $l > L_b$, the primary drops have already been detached from the jet before reaching the plate, and their impingement always produces splashing. Correspondingly, this phenomenon is named as the drop-splashing regime. Fig. 3(c) presents typical snapshots of primary drop
impingement. The impact drop spreads out radially and a corona-like liquid lamella emerges in the direction normal to the plate. The rim-bending disturbances at the top of the lamella become unstable and consequently form several cusps, which then become the sources of multiple finger-like jets. The breakup of the finger jets produces plenty of tiny splashing droplets. Visualization shows that the liquid film on the plate generated by primary drops impingement has a thickness significantly smaller than the drop diameter. Therefore, the phenomenon of primary drop impingement could be treated as a superposition of single drop impingement on wet surface (Macklin and Metaxas 1976). The splashing morphology is similar to the corona splashing described by Rioboo et al. (2003), while the prompt splashing is not observed. According to Okawa et al. (2021), in the case of single water drop impact onto a quiescent liquid film, the prompt splashing occurs at lower Weber number and generates smaller splashing droplets than the corona splashing. One possible reason for not observing prompt splashing during the drop-splashing regime is that the majority of the primary drops in our experiments have high enough Weber number. Additionally, the relatively limited spatial resolution in the present study also makes small droplets from the prompt splashing difficult to be recorded.

In the present study, the jet length at the onset of splashing, \(L_s\), is defined as the nozzle-to-plate distance where any splashing droplets are observed. As comparison, Bhunia and Lienhard (1994) and Trainer (2016) studied the jet splashing characteristics and defined \(L_s\) as the distance when 5% of the total impinging liquid is splattered. The reason is that the present study concerns the possible generation of virus-laden droplets, in particular these splashing droplets with small sizes as they potentially be transported by sewer ventilation despite with small contribution to the entire splashing rate.

Visualization in the present study and the literature demonstrate that once the primary drops are detached from the jet, their impingement always produces splashing, hence, there exists \(L_s < L_b\). Fig. 4(a) shows the dimensionless onset of splashing \(L_s/D_0\) with a larger \(D_0\) corresponding to a slightly smaller \(L_s/D_0\). Compared with the experimental data from Bhunia and Lienhard (1994) and Trainer (2016), our data for \(D_0 = 2.0\) mm are in close agreement while that for \(D_0 = 6.0\) and 8.0 mm are smaller when \(We_0^{0.5} > 20\). Note that there is difference in the definition of the onset of splashing used by our work and Bhunia and Lienhard (1994) and Trainer (2016). For \(We_0^{0.5} \leq 20\), visible splashing and 5% of the total impinging liquid splattered occur together at the nozzle-to-plate distance \(l = L_b\), while for \(We_0^{0.5} > 20\), visible splashing occurs at shorter \(l\) than 5% of the total impinging liquid splattered. In addition, the nozzle aspect ratio (the ratio of nozzle length to diameter) decreased from 2.7, 2.6 to 2.2 for the nozzles of \(D_0 = 2.0, 6.0\) and 8.0 mm, respectively, which can affect the jet turbulence and surface disturbances at the nozzle exit and therefore \(L_s\) (Birouk and Lekic, 2009).

Based on Figs. 2 and 4(a), a regime map for non-splashing, jet-splashing, and drop-splashing is shown in Fig. 4(b) in the form of \(l/L_b\) versus \(We_0^{0.5}\). The data of \(l/L_b = L_s/L_b\) from the present experiment and from Bhunia and Lienhard (1994) and Trainer (2016) as well as the line of \(l/L_b = 1\) that distinguishes between the impingement of continuous jet and primary drops are plotted for describing the thresholds between various splashing regimes. For the data of \(L_s/L_b\) from Bhunia and Lienhard and Trainer, their values of \(L_s\) are estimated by Eq. (1) as only \(L_b\) values were provided, and they can be well fitted by a logistic correlation in terms of \(L_s/L_b\) asymptotic with respect to 1 and 0 when \(We_0^{0.5}\) tends to 0 and 100

\[
\frac{L_s}{L_b} = \frac{1}{1 + \left(\frac{We_0^{0.5}}{42.7}\right)^5} 
\] (3)

For our experimental data of \(L_s/L_b\), segment fitting seems reasonable considering the relatively limited range of \(We_0\) compared with that of Bhunia and Lienhard (1994) and Trainer (2016)

\[
\frac{L_s}{L_b} = 1 \text{ for } We_0^{0.5} \leq 15
\] (4)

\[
\frac{L_s}{L_b} = -0.034 We_0^{0.5} + 1.5 \text{ for } 15 \leq We_0^{0.5} \leq 33
\] (5)

As shown in Fig. 4(b), the drop-splashing regime occurs beyond \(l/L_b = 1\). In this region, the nozzle-to-plate distance \(l\) is larger than the jet breakup length \(L_b\), therefore, the primary drops are detached from the jet before impingent, always generating splashing. The yellow region between \(l/L_b = 1\) and \(l/L_b = L_s/L_b\) corresponds to the jet-splashing regime where splashing is produced by the unbroken jet impingement. The non-splashing regime falls in the blue region of \(l/L_b < L_s/L_b\). Utilizing the different definitions of the splashing onset causes a transition (green region) between the non-splashing and jet-splashing regimes, and in this condition, although the splashing has been observed because of the continuous jet impingement, less than 5% of jet flow rate is turned
into the splashing droplets. Note that when \( We_j^{0.5} > 15 \), the non-splashing, jet splashing, and drop-splashing regimes are observed successively with increasing \( l \), while for \( We_j^{0.5} \leq 15 \), direct transition from non-splashing to drop-splashing regimes is obtained as \( l \) increases, without generating the jet-splashing regime.

### 3.2. Splashing characteristics in drop-splashing regime

In the drop-splashing regime, the splashing characteristics, including the splashing rate and the size and velocity of the splashing droplets, are mainly determined by the diameter \( D_0 \), velocity \( U_j \) and frequency \( f \) of the impact primary drops. Ma et al. (2016b) showed that before breakup into primary drops, the jet is simply accelerated by gravity, and the jet velocity \( U_j \) is correlated to the falling height \( l \) as

\[
U_j = \sqrt{U_0^2 + 2gl} \quad \text{when} \quad l \leq L_b
\]

where \( g \) is the gravitational acceleration. After the jet breakup when \( l > L_b \), the air friction acting on the primary drops cannot be neglected due to the much larger surface area of the drops (Sallam et al., 2002). Zhan et al. (2018) developed an equation for predicting the velocity \( U_p \) of the primary drops

\[
U_p = \sqrt{\frac{g - (g - C_1 U_j^2) e^{-2(l-L_b)/C_1}}{C_1}}
\]

Herein, \( C_1 = 9.1 \times 10^{-4} C_0/D_0 \) for water jet, with \( C_0 \) being the dimensionless drag coefficient. Zhan et al. (2018) experimentally had \( C_0 = 0.58 \) for \( Re_0 \) from 2000 to 10,000. \( U_j \) represents the jet velocity where jet breakup occurs and can be calculated by substituting \( l = L_b \) into Eq. (6). Fig. 5(a) compares our experimental measurements of \( U_p \) with Eq. (7) prediction. It is found that Eq. (7) predicts the primary drop velocity within an error of \( \pm 15\% \).

For Rayleigh regime jet, Zhan et al. (2020) suggested that \( D_p \) is proportional to the jet diameter at the breakup point, \( D_p = 2Q_0/\pi U_b \) from the mass conservation. Our experimental values of \( D_p \) are plotted against the calculated values of \( D_b \) in Fig. 5(b). It can be seen that \( D_p \) correlates well with \( D_b \) within an error of \( \pm 10\% \)

\[
D_p = 2.04D_b
\]

Variation of the drop impact frequency \( f \) with the nozzle-to-plate distance \( l \) is described as follows: \( f \) remains zero when \( l \leq L_b \) and increases asymptotically to the maximum impact frequency \( f_{max} \) with the increase of \( l \) from \( L_b \) to \( L_{max} \), and finally it becomes fairly constant for \( l > L_{max} \). Compared with the (minimum) breakup length \( L_b \), the maximum breakup length \( L_{max} \) represents the point where the jet is consistently observed to break into the primary drops. In this consideration, Zhan et al. (2018) established a correlation for the dimensionless impact frequency \( f/f_{max} \) with the dimensionless falling height \( (l-L_b)/(L_{max}-L_b) \) as

\[
f/f_{max} = 0.5 \left( \text{erf}\left(\frac{2k(l-L_b)}{L_{max}-L_b} - k\right) + 1 \right)
\]

where \( k \) is a fitting parameter, \( L_{max} \) is assumed to be in proportion to \( L_b \). Our experimental data of \( f/f_{max} \) are plotted against \( (l-L_b)/(L_{max}-L_b) \) in Fig. 6. Herein, \( f \) is measured by image analysis, and \( f_{max} \) is calculated by \( f_{max} = 6Q_0/(\pi D_b^2) \) based on the mass conservation for a jet, which agrees with the measured value by analyzing the high-speed video images at sufficiently downstream from the nozzle (Zhan et al., 2020). It is shown that Eq. (9) achieves fairly good agreement with the data \( R^2 = 0.90 \) when \( k = 1.02 \) and \( L_{max} = 1.77L_b \).

#### 3.2.1. Splashing ratio

The splashing ratio \( Q_{p*} \) is defined as the portion of jet flow rate \( Q_0 \)
turned into splashing droplet rate \( Q_s \)

\[
Q_s^* = \frac{Q_s}{Q_h}
\]

(10)

In the drop-splashing regime, the splashing comes from the impingement of successive primary drops formed following the jet breakup, therefore, the splashing ratio per primary drop impact is written by

\[
V_s / V_p = \left( \frac{Q_s}{Q_h} \right) = Q_s^* (f_{\text{max}} / f)
\]

(11)

where \( V_s \) is the splash volume per impact, and \( V_p \) denotes the primary drop volume. Given that the splashing is promoted by the inertia of the drop while prevented by the liquid surface tension, it is expected that \( Q_s^* (f_{\text{max}} / f) \) can be expressed as a function of the Weber number of the impact primary drop \( W_{ep} \).

Fig. 7 shows the splashing ratio per impact \( Q_s^* (f_{\text{max}} / f) \) plotted against \( W_{ep} \) in the drop-splashing regime. It also depicts a direct comparison between the splashing generated by the vertical jet impingement onto a horizontal plate and the horizontal jet impingement onto a vertical plate, to reflect effects of the impact angle of a jet. The data of these splashing were compared with their experimental data with \( R^2 = 0.91 \)

\[
Q_s^*(f_{\text{max}} / f) = 0.054W_{ep}^{2.5} \text{ for } 550 < W_{ep} < 32,500
\]

(14)

From Eqs. (12) to (14) shown in Fig. 7, we can find that in comparison with the horizontal impact jet, the vertical impact jet produces much less splashing ratio when \( W_{ep} < 1300 \) while slightly more splashing ratio when \( 1300 < W_{ep} < 3500 \), in the drop-splashing regime.

### 3.2.2. Size and velocity of splashing droplets

Visualization shows that the splashing droplets generated in the drop-splashing regime have various sizes and velocities. To explore the size and velocity distributions of these splashing droplets, examples of the probability density distributions of \( D_p / D_0 \) and \( U_p / U_0 \) are presented in Fig. 8, where \( D_p \) and \( U_p \) represent the diameter and velocity of a splashing droplet, respectively. The dimensionless diameter of the splashing droplets mainly locates in the ranges of \( 0 < D_p / D_0 < 0.3 \) with the peak between 0.03 and 0.12, and the dimensionless velocity mainly locates in the ranges of \( 0 < U_p / U_0 < 3 \) with the peak between 0.6 and 1.2. Zhan et al. (2018) observed that the size of the maximum splashing droplet is approximately 25% of the impact drop diameter, and Li et al. (2019) and Burzynski et al. (2020) showed that the maximum velocity of the splashing droplets can be 3–6 times of the impact drop velocity, similar to our results.

Fig. 8 indicates that the distributions of \( D_p^* = D_p / D_0 \) and \( U_p^* = U_p / U_0 \) for the drop-splashing regime follow the log-normal distribution

\[
P_D = \frac{A_D}{w_D} (2\pi)^{-1/2} \exp\left(-\left(\ln(D_p^*/D_0^*)\right)^2/2w_D^2\right) \text{ for size distribution}
\]

(15)

\[
P_U = \frac{A_U}{w_U} (2\pi)^{-1/2} \exp\left(-\left(\ln(U_p^*/U_0^*)\right)^2/2w_U^2\right) \text{ for velocity distribution}
\]

(16)

where \( A_D \) and \( A_U \) are the histogram bin widths, \( D_0^* \) and \( U_0^* \) represent the median dimensionless diameter and velocity of the splashing droplets, respectively, and \( w_D \) and \( w_U \) denote respectively the log standard deviations of the dimensionless diameter and velocity distributions (characterizing distribution width). In Fig. 8, \( D_p^* \) rapidly decreases from 0.095 to 0.038 while \( U_p^* \) decreases slightly from 1.13 to 0.96, when \( W_{ep} \) increases from 550 to 1676. \( w_D \) and \( w_U \) appear to have no direct relation with \( W_{ep} \) and fluctuate within 0.47–0.61 and 0.36–0.49, respectively.

Correlations of these log-normal distribution parameters of \( D_p^* \), \( U_p^* \), and \( w_D \) and \( w_U \) with the state of primary drops at the impingement are studied as follows. As the morphology of the drop-splashing regime is similar to the corona splashing, a physical analysis of splashing droplet diameter and velocity for corona splashing is conducted in the Appendix, based on establishing and analyzing conservation laws between the impact drop, the liquid sheet and the splashing droplets. The expressions for \( D_p / D_0 \) and \( U_p / U_0 \) are derived as a function of the Weber number \( W_{ep} \) and Reynolds number \( R_{ep} \) of the impact primary drops

\[
\frac{D_p}{D_0} = 19.86 \left( W_{ep}R_{ep}^{0.5} \right)^{0.5}
\]

(17)

\[
\frac{U_p}{U_0} = C \left( \frac{W_{ep}}{R_{ep}^{0.5}} \right)^{-0.25}
\]

(18)

where \( C \) is the parameter determined experimentally.

\( D^*_p \) that characterizes the median dimensionless diameter of the splashing droplets are compared with Eq. (17) in Fig. 9(a). The experimental data from the present study and Zhan et al. (2021) regarding the drop-splashing regime as well as that from Stow and Stainer (1977), Mundo et al. (1995) and Li et al. (2019) regarding the single drop impingement are plotted for comparison. It is found that \( D^*_p \) for the drop-splashing regime and the single drop impingement have a similar tendency with \( W_{ep}R_{ep}^{0.5} \), and they can be predicted by Eq. (17) within
According to Eq. (17) and Eq. (7) that correlates $U_p$ with $U_0$ and $l$, the two parameters $D_0$ and $U_0$ dominate the production of the finest droplet fraction that potentially evaporate to generate dry residues, and the number of finest droplets increases with decreasing $D_0$ and increasing $U_0$. In addition, increasing $l$ also promotes the production of the finest droplet in some degree.

$U_c^*$ that characterizes the median dimensionless velocity of the splashing droplets are compared with Eq. (18) in Fig. 10 (a). Besides our experimental measurements, also included are the experimental data for the single drop impingement from Li et al. (2019). $U_c^*$ for the drop-splashing regime agree with that for the single drop impingement. $U_c^*$ is in proportion of $(We_p/Re_p^{0.5})^{0.25}$, showing a good agreement with Eq. (18). When $C = 1.7$, Eq. (18) can well fit the data within an error of $\pm 30\%$.

For $w_D$ and $w_U$ that characterize the log-normal distribution width of $D_s/D_p$ and $U_s/U_p$, our experimental data are compared with that for the drop-splashing regime and single drop impingement from the literature in Figs. 9(b) and 10(b). It is found that $w_D$ and $w_U$ remain almost constant for drop-splashing regime and single drop impingement. For $w_D$, the data from the present study, Stow and Stainer (1977) and Li et al. (2019) agree well with each other, while they are slightly smaller than the data from Mundo et al. (1995) and Zhan et al. (2021). The majority of $w_D$ data falls within $\pm 30\%$ of $w_D = 0.5$. For $w_U$, the data from the present study and Li et al. (2019) can be well fitted by $w_U = 0.4$ within an error of $\pm 30\%$.

**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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**Fig. 8.** Probability density distributions of $D_s/D_p$ and $U_s/U_p$ in drop-splashing regime: (a) $D_0 = 2.0$ mm and $We_p = 550$; (b) $D_0 = 6.0$ mm and $We_p = 1159$; and (c) $D_0 = 8.0$ mm and $We_p = 1676$. 

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The ejection angle $\alpha$ of the splashing droplets is defined as the angle between their initial velocities and the horizontal direction. Visualization shows that in the drop-splashing regime, the maximum of $\alpha$ is always around $70^\circ$. Considering the corona splashing generated by a single drop impingement, Burzynski et al. (2020) experimentally observed that the majority of the ejection angles $\alpha$ are less than $75^\circ$, showing a close agreement with our results. The distributions of $\alpha$ in the drop-splashing regime are presented in Fig. 11 for $D_0 = 2.0, 6.0,$ and $8.0$ mm with $We_p = 942, 1341,$ and $2133$, respectively. The results show that the ejection angles are not uniform: they have a bell-shape distribution with the interquartile ranges covering $14^\circ < \alpha < 47^\circ$. As $We_p$ increases from 942 to 2133, the median of $\alpha$ decreases from $30^\circ$ to $22^\circ$, while its mean decreases from $32^\circ$ to $23.0^\circ$.

### 3.3. Splashing characteristics in jet-splashing regime

#### 3.3.1. Splashing ratio

In the jet-splashing regime, the splashing characteristics are influenced by the velocity $U_j$ and diameter $D_j$ of the impact continuous jet. Fig. 12 compares our experimental measurements of $U_j$ with the prediction of Eq. (6) with a difference less than $\pm 10\%$. Therefore, Eq. (6) will be used in calculating the jet velocity $U_j$, and the jet diameter $D_j$ can be obtained by $D_j = \frac{2Q_0}{\pi U_j}$.

Fig. 13 plots the splashing ratio $Q_s^* = Q_s/Q_0$ in the jet-splashing regime versus the Weber number of the impact jet $We_{j} = \rho U_j^2 D_j/\sigma$. Compared with the drop-splashing regime where $Q_s^*$ varies from 1 to 70%, $Q_s^*$ in the jet-splashing regime is significantly smaller with its value less than 2%. For a given jet, $Q_s^*$ increases with $We_j$. As the jet...
Weber number $W_{e0}$ at nozzle exit increases, the correlation of $Q_s^*$ with $We_j$ has a tendency of moving towards the positive direction of horizontal axis. In the jet-splashing regime, the splashing is caused by the jet disturbances impacting onto the plate. With decreasing $W_{e0}$, the breakup length of Rayleigh jet decreases, which accelerates the growth of jet disturbances. The analytical correlation of jet disturbance amplitude established by Lienhard et al. (1992) shows that the jet disturbances increase as $W_{e0}$ decreases within the range of $330 < W_{e0} < 1060$ in Fig. 13.

### 3.3.2. Size and velocity of splashing droplets

The probability density distribution of $D_s/D_j$ and $U_s/U_j$ in the jet-splashing regime are shown in Fig. 14. The dimensionless diameter of the splashing droplets locates in the ranges of $0 \leq D_s/D_j \leq 0.36$ with the peak between 0.03 and 0.09, and the dimensionless velocity locates in the range of $0 \leq U_s/U_j \leq 2.1$ with the peak between 0.6 and 1.2. Similar to that in the drop-splashing regime, the distributions of $D^* = D_s/D_j$ and $U^* = U_s/U_j$ in the jet-splashing regime can be expressed by the log-normal function (see Eqs. (15) and (16)). In Fig. 14, $D^*_s$ and $U^*_s$, representing the median of $D_s/D_j$ and $U_s/U_j$, decrease from 0.100 to 0.086 and from 1.02 to 0.87, respectively, when $We_j$ increases from 1005 to 1224. As the parameters characterizing the log-normal distribution width for $D_s/D_j$ and $U_s/U_j$, $w_D$ is around 0.70 and shows no direct relation with $We_j$ as in the drop-splashing regime, and as comparison, $w_U$ decreases from 0.42 to 0.25 with increasing $We_j$.

For the jet-splashing regime, since the splashing droplets are produced by the breakup of the wave sheet and rim shown in Fig. 3(b), the splashing droplet diameter should be comparable with the sheet thickness and rim diameter. An analysis about the impingement of a continuous jet with significant surface disturbances is shown in the Appendix, and the equations about the dimensionless sheet thickness $h_{sh}/D_j$ and rim diameter $D_r/D_j$ are obtained as a function of the Weber number $We_j$ and Reynolds number $Re_j = \rho U_j D_j/\mu$ of the impact jet:

$$h_{sh}/D_j = 9.69 \left( We_j Re_j^{0.5} \right)^{-0.3} \quad (19)$$
Fig. 14. Probability density distributions of $D_s/D_j$ and $U_s/U_j$ in jet-splashing regime: (a) $D_0 = 6.0$ mm and $We_j = 1005$; and (b) $D_0 = 8.0$ mm and $We_j = 1224$.

Fig. 15. Log-normal distribution parameters of (a) $D_c^*$ and (b) $w_D$ for jet-splashing regime.
Dr = 34.88 \left( \frac{WeRe_{0.5}}{D_0} \right)^{-0.5}

(Dr) = 34.88 \left( \frac{WeRe_{0.5}}{D_0} \right)^{-0.5}

Eq. (20)

Fig. 15 (a) compares the median dimensionless diameter \( D_c^* \) of the splashing droplets with Eqs. (19) and (20). It is found that \( D_c^* \) proportionally increases with \( (WeRe_{0.5})^{-0.5} \). Our experimental data, although significant over Eq. (19), are fitted by Eq. (20) within an error of ±30%. Hence, Eq. (20) can be used for predicting \( D_c^* \) for the jet-splashing regime, reflecting that majority of the splashing droplets are from the rim breakup.

\( w_U \) in the jet-splashing regime is plotted against \( WeRe_{0.5} \) in Fig. 15 (b). \( w_U \) remains almost constant with all the data included within ±30% of \( w_U = 0.7 \), which is larger than \( w_U = 0.5 \) in the drop-splashing regime. The reason may be that the splashing droplets are produced by breakup of the rim and sheet in the jet-splashing regime, while the finger jets are the main sources of the splashing droplets in the drop-splashing regime. Multi-sources of splashing droplet creation in the jet-splashing regime bring about wider size distribution of the splashing droplets.

For the ejection angle \( \alpha \) in the jet-splashing regime, it is found that the maximum \( \alpha \) can reach about 70°, similar to that in the drop-splashing regime. Distributions of \( \alpha \) are presented in Fig. 17. Measurements from four cases are shown, \( D_0 = 6 \) mm with \( We_0 = 1068 \) and 1182, and \( D_0 = 8 \) mm case with \( We_0 = 1434 \) and 1640. \( \alpha \) in the jet-

Fig. 16. Log-normal distribution parameters of (a) \( U_c^* \) and (b) \( w_U \) for jet-splashing regime.

Fig. 17. Distributions of the ejection angle \( \alpha \) in jet-splashing regime.
splashing regime follows a bell-shaped distribution with the interquartile range covers $8^\circ < \alpha < 34^\circ$, which is significantly smaller than that in the drop-splashing regime. Comparison between these cases shows that the median of $\alpha$ decreases from $24^\circ$ to $16^\circ$ while its mean decreases from $24^\circ$ to $18^\circ$ when $W_e$ increases from 1068 to 1640.

4. Summary and conclusions

In the present study, the generation of splashing droplets by water jet vertically impingement onto a horizontal plate is experimentally explored. The key findings including the splashing regimes and the splashing characteristics in various splashing regimes are summarized as follows.

Depending on whether the jet breaks into primary drops before the impingement, three regimes can be defined: non-splashing, jet-splashing and drop-splashing regimes. The non-splashing and jet-splashing regimes occur during the continuous jet impingement and they are distinguished according to whether splashing is generated. As soon as the primary drops are detached from the jet at some distance below the nozzle exit, they already achieve sufficient velocity for producing splashing after impingement (Ribboon et al., 2003). The regime map of jet impingement is established dependent on the Weber number $W_e$ at the nozzle exit and the nozzle-to-plate distance. Increasing $W_e$ and nozzle-to-plate distance both contribute to the splashing generation. Note that the jet-splashing regime only occurs for jets with $W_e^{0.5} > 15$, while for jets with $W_e^{0.5} < 15$, the direct transition from non-splashing to drop-splashing regimes is obtained as the nozzle-to-plate distance increases.

In the drop-splashing regime, the splashing ratio ranges from 1% to 70% and exponentially increases with the Weber number $W_e$ of impact primary drops. Compared with the horizontal impact jet, the vertical impact jet produces much less splashing ratio when $W_e < 1300$ while slightly more splashing ratio when $1300 < W_e < 3500$. The produced splashing droplets are small and fast-moving, and their size and velocity distributions follow the log-normal law. Their diameters are mainly in the range from 0 to 0.3 of the impact drop diameter with the peak between 0.03 and 0.12. Their velocities mostly locate from 0 to 3.0 times of the impact velocity with the peak between 0.6 and 1.2. As the log-normal distribution parameters, $D_r^*$ and $U_r^*$ characterizing the median diameter and velocity of the splashing droplets both decrease with $W_e$, $w_D$ and $w_U$ characterizing the distribution width of the splashing droplet diameter and velocity remain almost constants of 0.5 and 0.4 respectively. The ejection angle of the splashing droplets follows a bell-shaped distribution with the interquartile range smaller than that in the drop-splashing regime. The median of the ejection angle ranges between $16^\circ$ and $24^\circ$ and decreases with increasing $W_e$.

Our established correlations for the splashing onset and the splashing characteristics in the jet-splashing and drop-splashing regimes make the prediction possible by using the nozzle diameter, jet velocity at nozzle exit, and nozzle-to-plate distance. While this study was initially motivated by the possible generation of virus laden aerosols in sewer systems, the current work focused on much larger sizes of droplets, which have a great chance of settling before they evaporate to produce airborne aerosols. The current work, however, is a first step towards a better understanding of possible virus transport in complicated sewer systems. In addition, the generated splashing droplets in drop-splashing regime have much larger splashing ratio, smaller size and larger velocity of splashing droplet, and larger ejection angle, therefore could potentially carry viruses and be transported by the sewer ventilation, causing potential risk to operation and maintenance personnel. In future studies, characteristics of the aerosols (smaller than 50 µm) generated by jet impingement should be analyzed, on the other hand, virus surrogates should be added into test liquid as the tracers of virus, and their influences on splashing morphology, their concentrations in splashing droplets/aerosols, and their airborne lifetime and settlement should be carefully studied to tackle Covid-19 airborne resuspension threat by liquid jet fragmentation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Analytical study of splashing droplet diameter and velocity for drop-splashing and jet-splashing regimes

Drop-splashing regime

For the drop-splashing regime, its morphology is similar to that of the corona splashing. Therefore, physical analysis about the splashing droplet diameter in the drop-splashing regime is conducted based on Wu (2003) for the corona splashing by single drop impingement, and further analysis is added about the splashing droplet velocity.

Fig. A1 schematically depicts the liquid transformation progress of drop impingement and splashing. The impact drop is first transformed into a corona sheet, and the flow instability at the corona top produces finger jets along the circumferential direction which finally disintegrate into splashing droplets.

The conservation laws between the corona sheet and the finger jets are considered. Assuming that the average spacing between the adjacent finger jets is $l_f$, the mass conversation can be written as

$$ h_{SL} l_f U_{at} = \frac{\pi}{4} D_j^2 U_f $$

(A1)

(\text{Appendix})
where \( h_{sh} \) is the thickness of the corona sheet, \( D_f \) is the diameter of the finger jet, and \( U_{sh} \) and \( U_f \) are the liquid velocities inside the sheet and finger jet respectively.

The total energy including the kinetic energy and the surface energy is conserved during the transformation of the corona sheet to finger jets, yielding the energy conservation equation as

\[
\frac{1}{2} \rho U_{sh}^2 + \frac{3}{2} \rho D_f^2 U_f^2 + \sigma D_f U_f = \frac{1}{2} \pi \rho D_f^2 U_f^2 + \sigma D_f U_f \tag{A2}
\]

The momentum conservation equation is given as

\[
\rho U_{sh}^2 + h_{sh}/(p_a - p_s) - 2U_f = \frac{3}{4} \rho D_f^2 U_f^2 + \frac{3}{4} D_f^2 (p_f - p_s) - \pi D_f \sigma \tag{A3}
\]

Herein, \( p_{sh} \) and \( p_f \) are the pressures in the sheet and finger jets respectively, and the Laplace formula provides their relationships with the atmospheric pressure \( p_a \) as \( p_{sh} = p_a \) and \( p_f = p_a + 2\sigma/D_f \), respectively. Substituting the above formulas into Eq. (A3) leads to

\[
\rho U_{sh}^2 - 2U_f = \frac{3}{4} \rho D_f^2 U_f^2 - \frac{1}{2} D_f \sigma \tag{A4}
\]

The energy and momentum conservation equations of Eqs. (A2) and (A4) can be simplified by using the mass conservation equation of Eq. (A1) to eliminate \( U_f \)

\[
\frac{1}{4} \rho D_f^2 U_f^2 + \frac{3}{4} D_f^2 U_f^2 = \frac{1}{4} \rho U_{sh}^2 + 2D_f \sigma
\]

\[
\frac{3}{4} \rho D_f^2 U_f^2 - 2U_f = \frac{3}{4} \rho D_f^2 U_f^2 - \frac{1}{2} D_f \sigma
\]

Assuming \( D_f \) and \( U_f \) are in proportion to \( h_{sh} \) and \( U_{sh} \) respectively, Eqs. (A5) and (A6) can be solved to yield

\[
D_f = 2.24h_{sh}
\]

\[
U_f = 1.12U_{sh}
\]

According to Yarin and Weiss (1995), when the finger jets formed on the top edge of the corona sheet, the relationship between the local velocity \( U_{sh} \) and thickness \( h_{sh} \) of the corona sheet can be estimated by the Taylor formula

\[
U_{sh} = \sqrt{2\sigma/p_{sh}}
\]

Therefore, both of \( D_f \) and \( U_f \) can be directly related to \( h_{sh} \) based on Eqs. (A7) and (A8). The relationship between \( h_{sh} \) and the state of the impact primary drop is analyzed by establishing the conservation equation linking the total energy of the primary drop and corona sheet.

\[
A \left( 2\sigma + \frac{1}{2} \rho U_{sh}^2 \right) + E_d = \pi D_f^2 \sigma + \frac{1}{2} \left( \frac{1}{6} \pi D_f^2 \rho \right) U_f^2 \tag{A10}
\]

\[
A = (\pi/6) D_f^2 (1/h_{sh})
\]

\[
E_d = \int_0^\infty \int_{\psi_f} \phi dV d\tau = \frac{1}{6} \pi D_f^2 \bar{\psi}
\]

where \( t_i \) marks the characteristic time scale for the drop impingement, \( \phi \) is the local energy dissipation, and \( \bar{\psi} \) represents the average value of \( \phi \). By estimating \( t_i = D_f/U_f \) and \( \bar{\psi} = (U_f/h_{sh})^2 \), Eq. (A11) can be reduced to

---

**Fig. A1.** Liquid transformation progress of drop impingement and splashing.
where, $We_p = \rho U_p^2 D_p / \sigma$ and $Re_p = \rho U_p D_p / \mu$ are the Weber and Reynolds numbers of impact primary drop. Thus,

\[
\frac{h_{sh}}{D_p} = \sqrt{9 + \frac{2We_p (We_p + 12)}{Re_p} + 3} \left( We_p + 12 \right)^{-1}
\]  

It is known that the finger jets disintegrate into the splashing droplets because of the Rayleigh-Plateau instability, that is, the finger jets of diameter $D_f$ produce the splashing droplets with a diameter $D_s = 1.889 D_f$. Combining Eqs. (A7) and (A14) gives the correlation of the dimensionless splashing droplet diameter $D_s / D_p$ with $We_p$ and $Re_p$

\[
\frac{D_s}{D_p} = 1.889 \frac{D_f}{D_p} = 1.889 \times 2.24 \frac{h_{sh}}{D_p} = 4.23 \sqrt{9 + \frac{2We_p (We_p + 12)}{Re_p} + 3} \left( We_p + 12 \right)^{-1}
\]  

As $We_p \geq 230$ in the present study, the above formula can be simplified as

\[
\frac{D_s}{D_p} = 4.23 \left( \sqrt{9 + \frac{2We_p^2}{Re_p} + 3} \right) We_p^{-1} = 4.23 \left( We_p Re_p^{0.5} \right)^{-0.5} f_1 \left( \frac{We_p^2}{Re_p} \right)
\]  

with

\[
f_1 \left( \frac{We_p^2}{Re_p} \right) = \sqrt{9 + \frac{2We_p^2}{Re_p} + 3} \left( \frac{We_p^2}{Re_p} \right)^{0.25}
\]

Compared with $\left( We_p Re_p^{0.5} \right)^{-0.5}$, $f_1(We_p^2/Re_p)$ can be treated as almost a constant of 4.69 for $6 \leq We_p^2/Re_p \leq 140$ in the present study. Hence, Eq. (A16) can be further simplified as

\[
\frac{D_s}{D_p} = 19.86 \left( We_p Re_p^{0.5} \right)^{-0.5}
\]  

Fig. A2. Sketch of impact jet in jet-splashing regime.
Combining Eqs. (A8) and (A9), it can be shown that

$$\frac{U_s}{U_p} = 1.12 \frac{U_s}{U_p} = 1.12 \sqrt{\frac{2\sigma}{\rho \beta D_j h_{sh}}}$$

Substituting Eq. (A14) into Eq. (A19), we obtain

$$\frac{U_s}{U_p} = 1.12 \frac{2}{W_e} \left( \frac{\text{We}^{0.5} \text{Re}^{0.25}}{4.7} \right) = 0.73 \left( \frac{\text{We}}{\text{Re}^{0.8}} \right)^{-0.25}$$

As the velocity of the splashing droplets $U_s$ are closely related to that of the finger jets $U_f$, there should be the following correlation for the dimensionless splashing droplet velocity $U_s/U_p$

$$\frac{U_s}{U_p} = C \left( \frac{\text{We}}{\text{Re}^{0.8}} \right)^{-0.25}$$

where $C$ is the parameter determined experimentally.

Jet-splashing regime

For the jet-splashing regime, splashing is observed when large jet surface disturbances reach the plate as shown in Fig. A2. It is considered that the splashing droplets are produced by the impingement of an ellipsoidal drop enclosed by the symmetric disturbances. Therefore, the analysis about the spherical drop impingement can be adopted for the ellipsoidal drop impingement after the following modifications.

The ellipsoidal drop is elongated in the vertical direction and its projection in the horizontal plane is a circle. Assuming a spherical drop with the diameter of

$$D_j = \frac{\pi (D_0 D_2 / 4) - \alpha x D_2}{\pi}$$

For the ellipsoidal drop impingement, the characteristic time scale shown in Eq. (A11) is expressed by $t_s = D_2 / U_j = 4D_j / (\alpha^2 \pi U_j)$, and Eq. (A14) can be rewritten to yield the correlation of the dimensionless sheet thickness $h_{sh}/D_j$ with the Weber number $W_e = \rho U_j^2 D_j / \sigma$ and Reynolds number $Re_j = \rho U_j D_j / \mu$ of the impact jet

$$\frac{h_{sh}}{D_j} = \left( \frac{W_e}{\text{Re}} \right)^{0.5}$$

with

$$f_2 \left( \frac{W_e}{\text{Re}} \right) = \sqrt{9 + 8 \pi^{-1} \alpha^{-1} \left( \frac{W_e^2}{\text{Re}^2} \right) + 3 \left( \frac{W_e^2}{\text{Re}^2} \right)^{2.5}}$$

Bhunia and Lienhard (1994) and van Hoeve et al. (2010) indicated that when the jet disturbances are large enough for splashing, $D_j$ is expected to approximate to the optimum wavelength of Rayleigh jet, $\lambda_{opt} = 1.41 \pi D_j$. Therefore, $D_j = D_j / \alpha^2 = 1.41 \pi D_j$, yielding $\alpha = 0.66$. Eq. (A24) can be treated as a constant of 9.69 over the range of 25 $\leq W_e^2/Re \leq 120$ in the present study. Hence, Eq. (A23) can be further simplified as

$$\frac{h_{sh}}{D_j} = 9.69 \left( \frac{W_e}{\text{Re}} \right)^{0.5}$$

For the rim at the crest of the liquid sheet generated by the impingement, our experiments show its diameter $D_j$ is 2.8–4.4 times of the sheet thickness $h_{sh}$. Experimentally, Negeed et al. (2011) gave $D_j = 2.86 h_{sh}$, and Raux et al. (2020) indicated that $D_j$ is around 3 times of $h_{sh}$, showing close agreement with our result. Using the average value of the ratio between $D_j$ and $h_{sh}$ in the present study, $D_j / h_{sh} = 3.6$, we obtain

$$D_j / D_j = 34.88 \left( \frac{W_e}{\text{Re}} \right)^{-0.8}$$

As the splashing droplets are produced by the breakup of the sheet and rim in the jet-splashing regime, the dimensionless splashing droplet diameter $D_j / D_j$ should be comparable with the dimensionless sheet thickness $h_{sh}/D_j$ and rim diameter $D_j / D_j$.

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