Experimental study on atomization quality characteristics in mixed fracture Breakup regime

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Abstract. In order to accurately analyze the secondary atomization phenomenon during firefighting jets, in this paper, the acceleration, deformation and breakup of droplets after secondary atomization are studied experimentally, and the characteristics of droplets after secondary atomization are studied. The critical flow rate of secondary water atomization was obtained. By analyzing the relationship between the factors affecting the secondary atomization characteristics and the number of atomized particles in the mixed crushing mode, the results show that the breaking angle decreases first and then increases with the increase of the we number; When $45 < \theta < 60$, the breaking angle is less than the average level, and the instantaneous breaking velocity decreases; The bag diameter before bag-like breaking generally decreases with the increase of the number of broken particles. The relationship between the characteristic quantity of atomization quality and the we number provides an experimental research basis for improving the fire extinguishing efficiency.

Keywords. Droplet; secondary atomization; atomization quality

1. Introduction
Fire fighting is playing an increasingly important role in protecting lives and reducing property damage in modern society. The requirements of the water mist fire extinguishing system for the protection objects of the water mist system are mainly two aspects: on the one hand, to quickly and effectively cool and suffocate the fire field; on the other hand, to save water without water damage. The finer the spray particles, the larger the evaporation surface area, the shorter the time for evaporative heat absorption to turn into water vapor, and the smaller the water damage to the protected object. In the process of fire extinguishing with fine water mist, various properties after water atomization affect the fire extinguishing effect. The atomization process of the water jet includes a primary atomization process and a secondary atomization process. The droplet state after the secondary atomization determines the final atomization quality. Improving the quality of atomization has a key role in improving the efficiency of fire suppression, and finding better atomization conditions has a constructive effect.

When the droplets in the high-speed airflow are accelerated, they will be deformed by aerodynamic forces and eventually break into tiny droplets. This process is called secondary atomization. In 1994, L.P. HSIANG [1-2] conducted experimental research on the deformation characteristics of water droplets caused by shock waves and steady-state disturbances. The secondary atomization is divided into five forms:
vibration crushing mode, bag crushing mode, multi-mode crushing mode, shear crushing mode and destructive crushing mode. The critical We numbers between the modes are divided.

Rolf D. Reitz [3] studied the distortion process and mechanism of droplet breakage through experiments. The We number of a droplet is changed by changing the velocity and density of the gas. According to the qualitative analysis of the experimental results and photos, in each crushing mode, the droplet breaking mode depends on the value of the We number. According to the difference of We number, the secondary atomization crushing mode is divided into packet fracture, shear fracture and catastrophic fracture. The experimental results show that under different gas density and velocity conditions, the crushing of the three crushing methods does not depend on the Reynolds number, and the viscous effect controls the crushing process.

Hui Zhao [4-5] et al. Studied the secondary crushing of bag-shaped droplets by a continuous and uniform air jet. A high-speed camera was used to observe the breaking process of liquid droplets including water, ethanol, and various glycerin mixtures. It is concluded that the viscosity of liquid has a greater influence on the critical Weber number We, and the critical Weber number We increases significantly with the increase of the Euclidian viscosity.

A.K. Flock [6] et al. Conducted experimental research on the crushing deformation of ethanol droplets injected in a continuous jet. The conditions that cause bag-like fragmentation and shear fragmentation are considered. The calculation results include the average drop diameter, trajectory, velocity, and range, as well as the overall average airflow field achieved at the selected time.

In this paper, the characteristics of droplet breakup after secondary atomization are studied experimentally, the critical We number at the time of secondary atomization of water is obtained, and the characteristics of secondary atomization that can increase the fire suppression efficiency are summarized. More suitable for fire extinguishing conditions.

2. Experimental equipment

As shown in Figure 1, the experiment uses water as the secondary atomizing liquid. A centrifugal fan of type CX-100 is used. The air outlet is connected to a circular glass pipe with a diameter of 40 mm. The pipe is 0.6 m long. The air flow meter is at the tail end, and there is a 0.2 m long glass pipe behind the air flow meter, which is convenient for the flow meter to measure. A 5 mm hole is opened on the top of the glass pipe 15 mm from the entrance, and a 0.4 mm-1.6 mm caliber needle is used to drip water from the hole. In the experiment, Photron's FASTCAM high-speed camera Mini AX200 was used to photograph the droplet breaking process in the hole. The maximum shooting speed is 216,000 pixels and the fastest shutter speed is 1 / 950,000.

We number is the ratio of inertial force and surface tension effect, and it is an important dimensionless number describing the characteristics of secondary atomization:

\[ We = \frac{\rho_g v_0^2 d_0}{\sigma_l} \]  

(1)

In the formula, \( \rho_g \) is gas density, \( v_0 \) is initial velocity, \( d_0 \) is initial droplet diameter, and \( \sigma_l \) is liquid surface tension coefficient.

Oh number is a dimensionless number used to measure the relationship between viscous force, inertial force and surface tension.

\[ Oh = \frac{\mu_l}{\sqrt{\rho_l d_0 \sigma_l}} \]  

(2)

In the formula, \( \mu_l \) is a liquid viscosity force coefficient, and \( \rho_l \) is a liquid density.
3. Analysis of experimental results

3.1. Determination of the critical We number

In the secondary atomization process, the droplet breakage does not occur when the We number is small. As the number of We increases, the degree of deformation of the droplets increases, and then bag-like fragmentation occurs. The critical We number is the We number when bag-shaped fragmentation occurs. The critical We number is also an important parameter in the secondary atomization. The critical We number is different for different liquids. Many scholars have obtained the empirical value of the critical We number of secondary atomization through experiments [7]. When the Oh number is small (Oh < 0.1), the critical We number of the secondary atomization of the droplet is approximately equal to 12; when Oh > 0.1 or Oh is large, the droplet breakup becomes difficult, and it may not be possible in the end. Brodkey [8] proposed an empirical formula for the critical We number with bag breaking. Pilch and Erdman [9] confirmed that this formula holds when Oh < 10.

\[
We = 12(1 + 1.077Oh^{1.4})
\]  

(3)

In the experiment, 2.5 mm droplets were used, and the droplets were passed through a constant velocity airflow, and the velocity gradually increased from 5 m/s to 20 m/s. The experimental results found that when the incoming flow velocity was 17 m/s, the droplets began to break up in bags. We can calculate the We number at this time: 12.97 (and Oh = 1.7 × 10^-4 < 0.1), which is basically consistent with Bordkey’s experimental formula. It also proves that this experimental scheme is empirical and can be used for the next experimental content.

3.2. Multi-mode broken atomization analysis

The multi-mode crushing mode is a crushing mode in which a bag crushing mode and a shear crushing mode coexist. In the center of the airflow direction, there is a flat liquid flow, and the outside is like a bag. In this mode, the liquid film in the middle bag-shaped part is broken first, then the liquid film in the bag ring part around it is broken, and finally the liquid flow in the center is broken. During the fire extinguishing process, most of the secondary atomization crushing modes are multi-mode crushing modes. The deformation process of bag breakup regime is shown in Figure 2, and the deformation process of multi-mode breakup regime is shown in Figure 3.
The breaking angle of the liquid film when it was broken was calculated by experiments. The larger the inclination angle of the atomization can provide a large range of fire suppression. Taking the middle flow as the center, tangent to the edge of the bag is defined as the breaking angle of the droplet. As shown in Figure 4, the break distribution angle of droplet breakage can be measured.

The experiment also calculated the instantaneous speed of the farthest part of the liquid film at the moment when the liquid bag was broken. The instantaneous crushing speed can describe the spraying distance after the droplets are broken. The larger the instantaneous crushing speed, the farther the liquid mist spraying distance is, the better the atomizing effect is. The instantaneous breaking speed of the farthest liquid film is shown in figure 5.

Figure 2. Deformation process of bag breakup regime

Figure 3. Deformation process of multi-mode breakup regime

Figure 4. Breaking angle

Figure 5. Instantaneous breaking speed of the farthest liquid film
Figure 6 shows the relationship between the breaking angle and the We number. It can be seen that in the mixed crushing mode, the crushing angle decreases first and then increases, and in the range of $45 < \text{We} < 60$, the crushing angle is smaller than the average level.

![Figure 6. Scatter plot of breaking angle and We number](image)

Figure 7 shows the relationship between instantaneous crushing speed and We number. With the increase of the We number, the instantaneous crushing speed decreases and decreases, but the overall trend decreases. This may be because as the We number increases, more energy is needed to perform bag-shaped crushing during atomization, so the speed during instant crushing will decrease.

![Figure 7. Line chart of the relationship between instantaneous breaking speed and We number](image)

In the multi-mode breakup regime, the time from the beginning of the atomization, that is, the formation of the bag shape, is defined. The time from the moment the bag is broken is called the crushing time under the multi-mode atomization. The crushing time is related to the speed of the secondary atomization. The atomization rate plays a key role. The dimensionless crushing time $T=\frac{v}{v_0/\epsilon}1/2d_0$ is used for subsequent data analysis, where $\epsilon$ is the ratio of the liquid phase density to the gas phase density.
The relationship between the dimensionless crushing time and the We number is shown in Figure 8. It can be seen that as the We number increases, the dimensionless crushing time decreases and becomes linearly correlated. Fitting a linear curve can obtain:

\[
\begin{align*}
T1 &= 3.1 - 0.306 \text{We}/10 \\
T2 &= 3.2 - 0.356 \text{We}/10 \\
T3 &= 3.3 - 0.279 \text{We}/10
\end{align*}
\]  

(4)

Figure 8. Measurement method of $L_{bag}$

$L_{bag}$ is the length of the bag before it is broken into small droplets, as shown in Figure 9 $L_{bag}/d_0$ is used to dimensionless the bag length to describe the bag size before rupture. Figure 10 is a line chart of the change of $L_{bag}/d_0$ with the number of We. It can be seen that as the number of We increase, the size of the bag decreases as a whole. This may be because as the number of We increase, the droplet breaking speed accelerates and the fragment It is caused by the shortening of the time before the formation of the pouch. Also, when the We number is the same, the larger the initial speed, the larger the total crushing size of the bag.

Perform a quadratic fit on the curve. The relationship between $L_{bag}/d_0$ and We number is

\[
\begin{align*}
L_{bag}/d_0<1/2> &= 2.39 + 0.035 \text{We} - 3.1 \times 10^{-4} \text{We}^2 \\
L_{bag}/d_0<2/2> &= 2.76 + 0.02 \text{We} - 2.75 \times 10^{-4} \text{We}^2 \\
L_{bag}/d_0<3/2> &= 2.84 + 0.013 \text{We} - 2.18 \times 10^{-4} \text{We}^2
\end{align*}
\]  

(5)

Figure 9. The relationship between dimensionless breaking time and We number
4. Conclusion

In this paper, the phenomenon of acceleration, deformation and fragmentation of droplets after secondary atomization is experimentally studied and analyzed, and the characteristics of droplets with liquid as water after secondary atomization are studied. The critical We number for the secondary water atomization was obtained. The relationship between the factors affecting the secondary atomization characteristics and the We number in the mixed crushing mode is analyzed. In the mixed crushing mode, as the We number increases, the crushing angle decreases first and then increases, and in the range of 45 < We < 60, the crushing angle is less than the average level; the instantaneous crushing speed decreases and decreases. However, the overall trend is decreasing; the dimensionless crushing time decreases as the We number increases; the instantaneous crushing speed generally decreases as the We number increases. These factors all affect the various characteristics of the droplet after secondary atomization, and determine the effect of atomization.

5. Acknowledge

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6. References

[1] Hsiang LP and Faeth GM 1995 Drop deformation and breakup due to shock wave and steady disturbances International Journal of Multiphase Flow 21(4) pp 545-560
[2] Hsiang LP and Faeth GM, 1993 Drop properties after secondary breakup International Journal of Multiphase Flow 19(5) pp 721-735
[3] Reitz RD 1982 Mechanism of atomization of a liquid jet Physics of Fluids 25(10) p 1730
[4] Zhao H, Liu HF and Cao XK 2011 Breakup characteristics of liquid drops in bag regime by a continuous and uniform air jet flow International Journal of Multiphase Flow 37(5) pp 530-534
[5] Transition Weber number between surfactant-laden drop bag breakup and shear breakup of secondary atomization Fuel 2018 221 pp 138-143
[6] Flock AK, Guildenbecher DR and Chen J 2012 Experimental statistics of droplet trajectory and air flow during aerodynamic fragmentation of liquid drops International Journal of Multiphase Flow 47 pp 37-49
[7] LEE, CH and REITZ 2000 An experimental study of the effect of gas density on the distortion and breakup mechanism of drops in high speed gas stream International Journal of Multiphase Flow 26(2) pp 229-244
[8] Brodkey RS and Talbot L 1969 The Phenomena of Fluid Motions Physics Today 22(9) pp 85-85
[9] Pilch M and Erdman CA 1987 Use of breakup time data and velocity history data to predict the maximum size of stable fragments for acceleration-induced breakup of a liquid drop International Journal of Multiphase Flow 13(6) pp 741-757