An improved splashing model for supercooled large droplets based on minimum mass loss ratio

Honglin Ma 1, Weibin Li 1,2, *, Yuejun Wang 1, Fan Zhao 1 and Yingyu Wang 1

1 Computation Aerodynamics Institute, China Aerodynamics Research and Development Center, Mianyang 621000, China
2 State Key Laboratory of Aerodynamics, China Aerodynamics Research and Development Center, Mianyang 621000, China

*Corresponding author e-mail: weibinli@cardc.cn

Abstract. Supercooled large droplets widely exist in clouds, which have poor aerodynamic follow-up and strong dynamic characteristics, making the relevant experiments and numerical simulation more difficult. Splash is the main influencing factor of droplet collection efficiency, and it is easier to be recorded and quantified. In the LEWICE model, little or no splash happened around stagnation point. Focus on this problem, an improved large droplet splashing model is proposed based on the idea of minimum mass loss ratio. In the numerical simulation part, the advantages and disadvantages of the proposed model are analyzed by comparing with several classical splashing models and experimental data. Based on the experimental data of airfoil MS317, the validity of the model is verified. Moreover, airfoil NACA23012 and ARJ cruise configuration are chosen to obtain the droplet collection efficiency, which shows the feasibility of the proposed model.

1. Introduction
Supercooled large droplets (SLD) icing was first found in the US Eagle ATR-72-212 flight accident [1], and it often occurs in freezing rain, freezing drizzle and other icing weather conditions. Differing from small droplet, SLD has a larger size and its aerodynamic following performance is worse, which causes a larger area and more serious condition of icing. Meanwhile, SLD is more significant on dynamic behavior and often appears deformation, breakage, rebound and splash, which makes the icing process more complex and the research of SLD icing test, numerical simulation and anti-/de-icing more difficult.

SLD splash is the main influencing factor of droplet collection efficiency and is easier to be recorded and quantified, thus splash is the breakthrough of SLD icing research. Based on the wind tunnel experimental data, Lee [2], Mundo [3], Trujillo [4] and others proposed a variety of semi empirical models of SLD fragmentation and splashing. In these models, the judgment rules of SLD dynamic behavior and quantitative information about the velocity, quantity and mass of sub droplets are all determined. At the same period, the famous software such as LEWICE, FENSAP-ICE and Star CCM+ have added the SLD dynamic models and achieved great results.

Nowadays, SLD experiments are still carried out to provide strong support for improving the dynamic model. These studies mainly include the deformation and breaking behavior catching using high-speed photography system, and the dynamic behavior and influence laws of droplet on different
surfaces and icing conditions. In order to check the effectiveness of SLD dynamic models, numerical simulations about droplet collection efficiency, icing shape calculation, similarity laws are also presented [5-9]. These researches on SLD have improved the accuracy of numerical simulation. However, NASA pointed out in the icing development prospect that the dynamic model of SLD still needs to be developed [10].

In this paper, the mass loss ratio of the LEWICE splashing model on the incident angle and impact parameters is analyzed. It shows that little or even no splash happened around the stagnation point. Focus on this problem, an improved SLD splashing model is proposed based on the idea of minimum loss ratio. In the numerical simulation part, the proposed model is compared with many classical models and experimental results, and the advantages and disadvantages of the method are analyzed. Moreover, airfoil NACA 23012 and ARJ cruise configuration are selected to verify the effectiveness and applicability of the proposed splashing model.

2. SLD splashing model

Based on the splashing model summarized in the experiment, the basic idea is to determine the relevant parameters and the splashing judgment criterion, and then give the quantitative information of the splashing droplet through the formulas. In this paper, the mass loss ratio of the droplet is mainly considered.

2.1. Mundo model [3]

When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. Should authors use tables or figures from other Publications, they must ask the corresponding publishers to grant them the right to publish this material in their paper.

According to the experimental data, Mundo et al. proposed the following parameter to characterize the impact energy of droplets

\[ K = O_h^{1/2} \cdot W_e^{5/2} = \left( \frac{\rho^3 d^3 v^5}{\sigma^2 \mu} \right)^{1/2} \]  

(1)

Where \( O_h \) and \( W_e \) are the dimensionless Ohnesorge number and Weber number, respectively. \( \rho \), \( d \), \( v \), and \( \mu \) are the density, the average size, the normal velocity and the dynamic viscosity of the droplet, respectively. And \( \sigma \) is the surface tension coefficient.

In Mundo model, the splashing judgment criterion is \( K \geq 57.7 \), and the mass loss ratio is as follows:

\[ f_m = n_s \left( \frac{d_f}{d_o} \right)^3 \]  

(2)

Where \( n_s \) is the number of sub droplets, and \( \frac{d_f}{d_o} \) is the diameter ratio of droplets before and after splashing. They have the following expressions

\[
\begin{align*}
    n_s &= \min \left\{ 1.676 \times 10^{-2} K^{2.539}, 1000 \right\}, \\
    \frac{d_f}{d_o} &= \max \left\{ \min \left\{ 8.72 e^{-0.0281 K}, 1 \right\}, 0 \right\}.
\end{align*}
\]  

(3)

2.2. LEWICE model [11]

In LEWICE model, a new parameter is proposed based on the parameter \( K \) in Eq. (1) as follows:

\[ K_L = \frac{d^{3/8} \Lambda^{-3/8}}{(\sin \theta)^{1/2}} \]  

(4)
Where $\theta$ is the angle between the droplet impact orientation and the surface. $\Lambda$ is the incident frequency with the form $\Lambda = 1.5 \left( \frac{LWC}{\rho} \right)^{1/3}$, where $LWC$ is the liquid water content.

The splashing judgment criterion of LEWICE model is $K_c \geq 200$, and the mass loss ratio is as follows:

$$f_m = 0.7(1 - \sin \theta) \left[ 1 - e^{-0.0092(K_c - 200)} \right]$$  \hspace{1cm} (5)

### 2.3. Trujillo model [4]

Based on the impact parameters $K$, the Trujillo model present a new one as

$$K_c = K^3 = \left( \frac{\rho^3 d^3 v^5}{\sigma^2 \mu} \right)^{2/5}$$  \hspace{1cm} (6)

The influence of surface roughness is considered in the splashing judgment criterion as follows

$$K_c > K_p$$  \hspace{1cm} (7)

Where the threshold value is $K_p = 540 \left( \frac{R_s/d_0}{d_0} \right)^{0.35}$, $R_s$ is the surface roughness.

The mass loss ratio is as follows:

$$f_m = \frac{3.8}{\sqrt{\Lambda^{-3/8} K}} \left( 1 - e^{-\Lambda^{-3/8}(K_p - K_c)} \right)$$  \hspace{1cm} (8)

### 3. Improved splashing model

Fig. 1 shows the distribution contour map of mass loss ratio given in Eq. (5) under different incident angles $\theta$ and parameters $K_c$. It can be seen that the mass loss ratio increases with the increase of the parameters $K_c$ for a given incident angle. And it also shows that the loss ratio $f_m < 0.05$ when the incident angle $\theta > 70^\circ$, which causes that there is almost no loss of mass around the stagnation point ($\theta \approx 90^\circ$). In other words, the LEWICE model considers that there is actually no splashing in a certain range when the splashing judgment criterion satisfied.

![Figure 1](image)

**Figure 1.** Distribution of mass loss ratio for LEWICE model.

Aiming at the problem mentioned above, the minimum mass loss ratio which we choose as 0.2 is presented. This means that at least 20% mass of the droplet is not collected on the surface when splashing happened. Therefore, the mass loss ratio of our improved splashing model is as follows:

$$f_m = \max \{0.7(1 - \sin \theta) \left[ 1 - e^{-0.0092(K_c - 200)} \right], 0.2\}$$  \hspace{1cm} (9)
By using the proposed model, the droplet collection efficiency around stagnation point ($\theta \approx 90^\circ$) will be reduced.

4. Model validation

In order to test the proposed model, airfoil MS317 is selected and the simulation conditions are shown in Table 1.

**Table 1. Simulation conditions.**

| Case | Airfoil | AOA/° | Speed/m s$^{-1}$ | MVD/μm |
|------|---------|-------|------------------|--------|
| 1    | MS317   | 0     | 78              | 92     |

Under Case 1, the proposed model is compared with several classical SLD splashing models. The comparison results are shown in Fig. 2. It is clear that the result of Mundo model is larger than the others. The performance of Trujillo model is similar as that of the proposed model around the stagnation point, but it is larger at the upper and lower surface of airfoil. Moreover, the LEWICE model fits not so well to the experimental data around the stagnation point. In contrast, the proposed model has better accuracy.

**Figure 2.** Comparisons of droplet collection efficiency among several splash models under Case 1.

5. Application examples

5.1. Airfoil NACA23012

**Table 2. Simulation conditions.**

| Case | Chord length/m | AOA/° | Speed/m s$^{-1}$ | MVD/μm |
|------|----------------|-------|------------------|--------|
| 2    | 0.9144         | 2.5   | 78.23            | 20     |
| 3    | 0.9144         | 2.5   | 78.23            | 52     |
| 4    | 0.9144         | 2.5   | 78.23            | 111    |
| 5    | 0.9144         | 2.5   | 78.23            | 154    |

Fig. 3 shows the simulation results of the droplet collection efficiency corresponding to the conditions in Table 2. It can be seen that although the mass losing under each Case, the law that the collection efficiency and the range of icing increase as the MVD increasing still holds. The simulation results show good agreement with the experimental data on the upper and lower surface of airfoil. However, the results around the stagnation point are slightly deficient under some conditions.
5.2. ARJ cruise configuration

The complex ARJ cruise configuration is selected in this sub-section, where the engine is simplified without considering the influence of internal flow. The simulation conditions are shown in Table 3. In Fig. 4, the distribution of droplet collection efficiency on the whole aircraft surface under Case 6 is given. It can be seen that the windward nose part and leading edge parts of wing, flat tail and vertical tail have greater droplet collection efficiency. In addition, the droplet collection efficiency at section z=9m is higher than that at z=3m away from the symmetrical plane. This is because that the escaping part of droplets from impact surface follows the airflow to spread around, resulting a low LWC around the fuselage.

### Table 3. Simulation conditions.

| Case | AOA/° | Speed/m·s⁻¹ | MVD/µm |
|------|-------|--------------|--------|
| 6    | 6     | 78           | 52     |
| 7    | 6     | 78           | 154    |
6. Conclusion
In order to improve the simulation accuracy of SLD splashing model, an improved splashing model based on the idea of minimum loss ratio is proposed. The simulation results compared with several classical models and experimental data shows that the proposed has an efficient performance. Moreover, the applicability of the proposed model is verified through the numerical examples on airfoil NACA 23012 and the ARJ cruise configuration.

From the numerical simulation results of airfoil NACA 23012, the setting of the minimum mass loss ratio may not be perfect. In the future, the effect of MVD on minimum mass loss ratio should be added to improve the simulation accuracy of the splashing model.

Acknowledgments
This work was supported by the National Natural Science Foundation of China under grant no 11802327 and the National Numerical Windtunnel project.
References

[1] Pereira M. Status of NTSB aircraft icing certification-related safety recommendations issued as a result of the 1994 ATR-72 accident at Roselawn [R]. AIAA-1997-0401, 1997.

[2] Lee S H, Ryou H S. Development of a new model and heat transfer analysis of impinging diesel sprays on a wall [J]. Atomization and Sprays, 2001, 11: 85-105.

[3] Mundo C, Tropea C, Sommerfeld M. Numerical and experimental investigation of spray characteristics in the vicinity of a rigid wall [J]. Experimental thermal and fluid science, 1997, 15(3): 228-237.

[4] Trujillo M F, Matthews W S, Lee C F, et al. Modeling and experiment of impingement and atomization of a liquid spray on a wall [J]. International Journal of Engine Research, 2000, 1(1): 87-104.

[5] Colin S, Bidwell C S. Super cooled large droplet analysis of several geometries using LEWICE3D Version 3 [R]. AIAA-2010-7675, 2010.

[6] Villedieu P, Trontin P, Guffond D, et al. SLD Lagrangian modeling and capability assessment in the frame of ONERA 3D icing suite [C]//New Orleans, Louisiana: 4th AIAA Atmospheric and Space Environments Conference, 2012: 3132.

[7] Anttho A M, Mohiudeen A, Kara K. Determination of water droplet collection efficiency: an empirical model [C]// Grapevine, Texas: AIAA Atmospheric Flight Mechanics Conference, 2017.

[8] Weimin Sang, Yang Cai, Tian Lu. Effect of deformation and breakup characteristic on supercooled large droplet icing process [J]. Journal of Aerospace Power, 2017, 32(07): 1537-1544. (in Chinese)

[9] Weihao Li, Xian Yi, Weibin Li, et al. Influence factors on deformation and breakup of supercooled large droplets [J]. Acta Aeronautica et Astronautica Sinica, 2018, 39(12): 122243. (in Chinese)

[10] Qiao Wang, Xianli Zhao, Senyun Liu, et al. Effects of roughness on splashing characteristics of water droplet [J]. Acta Aerodynamica Sinica, 2019, 37(1): 147-152. (in Chinese)

[11] Wright W. Further refinement of the LEWICE SLD model [C]. Reno, Nevada: 44th AIAA Aerospace Sciences Meeting and Exhibit, 2006: 464.