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[4-B-04] Numerical Simulation of SLD Icing under Glaze Ice Conditions by Coupling Scheme of Grid- and Particle-Based Method Introducing Purcell Approximation

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Keywords: Aircraft icing, Glaze Icing, Purcell approximation, Coupling scheme

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Numerical Simulation of SLD Icing under Glaze Ice Conditions by Coupling Scheme of Grid- and Particle-Based Method Introducing Parcel Approximation

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Abstract: Numerical simulations of aircraft icing by supercooled large droplets (SLD) under glaze ice conditions were performed using the coupling scheme of the grid- and particle-based methods. The computation of airflow around an airfoil and droplet trajectory was done using the grid-based method, while droplet behavior in the vicinity of the airfoil surface, including the solidification, was computed by using the particle-based method. The switching between these methods is determined by the droplet location, and the grid-based method is switched to the particle-based method when the droplet approaches a surface of the wall, ice, or waterfilm on the airfoil. Moreover, the Parcel approximation, which increases the droplet diameter for the particle-based method, was employed to reduce the computational cost. To reproduce the droplet-impinging behavior under the Parcel approximation, we performed simulations in which three types of non-dimensional parameters were individually fixed. As a result, the overestimation of splash rate, which is the mass rate between impinged droplets and splashed water, decreased. A non-dimensional parameter based on conserving the particle Reynolds number is effective in using the Parcel approximation for SLD icing simulation.

Keywords: Numerical Simulation, Aircraft Icing, Coupling Scheme, Moving Particle Method, Grid-based method, Parcel approximation.

1 Introduction

Ice accretion is a phenomenon that forms an ice layer on a solid surface when supercooled droplets or ice particles in the atmosphere impinge there. Ice accretion on an aircraft threatens navigation safety because it changes the wing shapes and reduces aerodynamic performance. Hence, it is a significant technical issue to predict the icing during the design phase of an aircraft. In the glaze ice conditions, where the ambient temperature is about −10 to −3 °C, the impinging supercooled droplets do not freeze instantly after the impingement but runback along the wing surface as a liquid film, forming complex ice shapes such as horns [1]. In addition, splashing and rebounding occur, which generate secondary droplets when supercooled large droplets (SLD) whose diameters are over 40 µm impinge on an aircraft surface. Due to these secondary droplets, very complex ice shapes are formed in SLD icing conditions. Therefore, the prediction of SLD icing under glaze ice conditions is a challenging issue in terms of the complexity of physics.

SLD Icing simulations on aircraft have been widely studied by using the grid-based method [2]. The numerical procedure of general SLD icing simulation consists of grid generation, airflow computation, computation of droplet trajectory and collision to the airfoil surface, and thermodynamics computation based on the extended Messinger model [3]. However, reproducing the SLD ice shape is still difficult because of the very complex multi-physics and formed ice shape. Recently, the authors have developed a coupling scheme of grid- and particle-based methods to reproduce the complex ice shapes [4, 5]. As a result, the simulation reasonably reproduced the ice height near the stagnation point compared to the experimental data. However, the icing limit position, where the ice accretion occurred on the most downstream, did not correspond to the experiment result [1]. In addition, due to the high computational cost, a cost-reduction method with high accuracy should be proposed.

In the present study, the icing simulation by the coupling scheme of grid- and particle-based methods introducing Parcel approximation was conducted to reduce the computational cost with acceptable accuracy of ice shape prediction. In the grid-based method, droplet size is computed as the actual scale, while the Parcel approximation, which increases the droplet diameter, was introduced in the particle-based method. To reproduce the droplet collision behavior, three different methods of substituting velocity from the grid-based method to the particle-based method were investigated, and the accuracy of the computations was verified for each method.

2 Numerical Procedure

A coupling scheme of grid-based and particle-based methods was employed [4, 5]. The grid-based method simulates the airflow and the trajectory of the SLD around an airfoil, and the particle method computes the behavior of the droplet impingement and liquid film in the vicinity of the blade surface and the solidification process. The flow field of the airflow is assumed to be a steady flow, while other computations consisting of droplet trajectory, collision behavior, and thermodynamics are treated as unsteady computations.

For the grid-based method, the overset grid method was employed to simulate the airflow around a NACA0012 airfoil. The governing equations are Favre averaged continuity, Navier–Stokes, and energy equations. The flow is assumed to be two-dimensional turbulence, and the Kato–Launder k-ε model [6] was adopted. For the spatial discretization, the second-order central difference method was applied to the viscous terms, and the second-order upwind TVD scheme [7] was applied to the inviscid terms. As the boundary conditions, total temperature and pressure were fixed; and the Mach number was extrapolated at the inflow boundary, while static pressure was fixed at the outflow boundary. The droplet trajectory was simulated in a Lagrangian manner using the simplified Basset–Boussinesq–Oseen (BBO) equation, which considers the fluid drag from the surrounding air and the gravity of the droplet. Here, one-way coupling was assumed in which the airflow affects the droplet trajectory, but the droplet trajectory does not affect the airflow. In addition, the individual droplet diameter was set to the actual scale (about 20 μm to 70 μm).

The droplet in the vicinity of the surface of the airfoil body, including formed ice or water film on the airfoil, is introduced into the particle-based simulation to compute the impinging behavior, including the splashing phenomena and the solidification. The governing equation is incompressible continuity, Navier–Stokes, and energy equations by using explicit moving particle simulation (E-MPS) method [8]. The potential model is adopted to treat the surface tension force, and the solidification is estimated based on the enthalpy of the droplet particle where the supercooled state was released just after the droplet collision [5]. To reduce the computational cost, the particle method employs the Parcel approximation, in which multiple particles are treated together as a single droplet by using the droplet diameter being larger than those used in the trajectory calculations impact on the surface. To reproduce the collision behavior, the droplet velocity V used in the particle-based method was modified to preserve dimensionless numbers: Weber number We, particle Reynolds number Re, or splashing parameter-K [9]. When these values are conserved, the droplet diameter D and velocity have the following relationship.

$$\mathrm{We}: D_g^{0.5} V_g = D_p^{0.5} V_p,$$

$$\mathrm{Re}: D_g V_g = D_p V_p,$$

$$K: D_g^{0.6} V_g = D_p^{0.6} V_p,$$

where, the subscripts g and p denote the respective values for the grid-based and particle-based methods, respectively. This sequential process was repeated until a specified exposure time with multi-shot simulations accompanying the numerical grid update along the formed ice surface. Target icing conditions were set based on the previous experiment [10, 11], as shown in Table 1.

Table 1: Computational condition.

Condition	Case 1 [10] non-SLD	Case 2 [11] SLD
Exposure time [s]	120	318
Chord length [m]	0.53	0.356
Inflow velocity [m/s]	58.1	62.0
Angle of attack [deg.]	4.0	0.0
Ambient temperature [°C]	-8.0	-6.8
Liquid water content (LWC) []	2.1	0.95
Droplet diameter in grid-based method [μm]	20.0	68.0
Droplet diameter in particle-based method [μm]	1000	
Computational particle diameter [μm]	100	

3 Results and Discussion

Figure 1 shows the comparison of ice shapes by experiment [10] and the simulations. In Figure 1, the black line represents the experimental result, and green, blue, yellow, and red plots indicate the simulated results of We-, Re-, and *K*-based modifications and our previous results [5] without modification, respectively. According to Figure 1, the ice heights around the stagnation point in all cases were close to the experiment. Moreover, the icing limit positions at the pressure side were overestimated in all cases. Comparing the simulated cases, the We-based modification case was the closest icing limit position to the experiment. All cases in the present study improved the prediction accuracy of the icing limit position compared to the previous result.

Table 2 shows the splash rates computed in the present simulations and the grid-based method using the splash model proposed by Wright [12]. The splash rate is the ratio of the mass remaining on the airfoil surface to the mass of the impinged droplets. According to Table 1, the splash rates in We- and *K*-based modifications were overestimated compared to the grid-based method, while that in Re-based modification was underestimated in SLD conditions. By tuning these parameters, such as droplet velocity and diameter, the icing simulation using the Parcel approximation will reproduce the ice shape more precisely. However, the splashed water droplets tend to spread widely by Parcel approximation; therefore Re-based modification was considered effective in the present conditions.

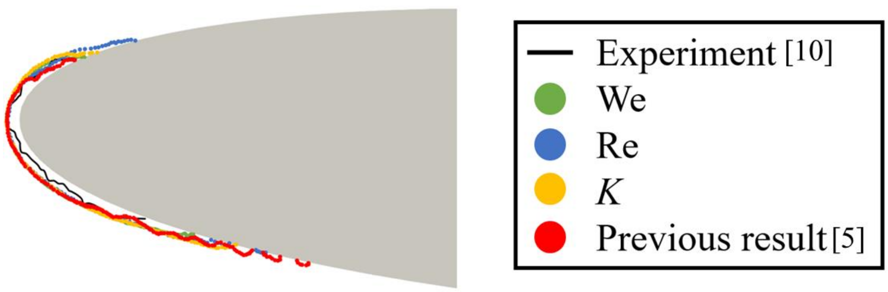

Figure 1: Comparison of ice shape. The angle of attack is set to be 4 deg.

Table 1: Splash rate in SLD condition.

Conserved parameter	SLD (D_g = 68 μm) [11]
We-based	78.4 %
Re-based	12.4 %
K-based	56.4 %
Grid-based method [12]	29.2 %

3 Conclusion and Future Work

SLD icing simulations were performed using a coupling scheme of grid- and particle-based methods with Parcel approximation. Three kinds of non-dimensional parameters were examined to conserve in terms of reproducing the droplet behavior at the collision to the surface of an airfoil, ice, or waterfilm. Droplets were less likely to impinge on the trailing edge, and the icing limit position was shifted to the leading edge by computing the droplet trajectory using actual scale droplets. Ice thickness reproduced reasonably well near the stagnation point. Moreover, the velocity modification based on conserving the non-dimensional parameter works effectively to reproduce the SLD icing with Parcel approximation. As for future work, the non-dimensional parameter and solidification time scale should be adjusted to reproduce the ice shape more precisely due to the Parcel approximation.

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