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SLD ICING SIMULATION ON NACA AIRFOIL USING MPS METHOD

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Abstract. *Icing simulations are very important in the development phase of aircraft and jet engines. Currently, icing simulation.s are performed with the grid-based method such as the finite difference method and the finite volume method. However, these methods cannot completely reproduce the characteristics of accreted ice because of the limitation of grid systems which must be used in the simulations. On the other hand, particle-based methods are now popular in industries, because it is a mesh-free method and thus grid generation can be skipped. In addition, it can predict liquid interface sand the large deformation satisfactorily. In the present study, we perform the Super-cooled Large Droplet (SLD) icing simulation on the NACA0012 airfoil using the MPS method which is one of the particle-based method. We expect that the icing simulation by the MPS method might be able to predict the complex ice shapes which cannot be reproduced by the grid-based simulation. The obtained result indicates that the MPS icing simulation can reproduce the ice shape like a feather and the ice thickness reasonably. However, it is confirmed that the ice volume is underestimated due to the improper droplet model and the icing judgement.*

1 INTRODUCTION

The multi-physics phenomena of the jet engine are the ice accretion, sand erosion, deposition, and so on. In the present study, we focus on the ice accretion. Ice accretion is a phenomenon which forms an ice layer on a solid surface due to the collision of supercooled droplets. It is known that the ice accretion on an aircraft causes engine failure and the degradation of the aerodynamic performance. Therefore, various anti-icing and de-icing devices have been developed. However, all of the aircraft accidents due to the icing have not been prevented. In the design phase of an aircraft, an icing wind tunnel, a flight test and a field test are preformed in order to estimate the icing property and the change of the aerodynamic performance due to the accreted ice. However, the experiment is very expensive, and the experimental facilities are limited for the location, because the icing experiment should be conducted in the cold distinction. Therefore, the icing simulation by the computational fluid dynamics (CFD) is desired because of the cost effectiveness.

The icing simulations by grid-based method have been globally conducted. As an example, the two dimensional ice shapes on the airfoil were simulated in the various conditions by Wright et al. [1]. The three dimensional ice shapes were simulated on the aircraft and the rotorcraft by Habashi et al. [2]. The ice shape can approximately be reproduced in the grid-based simulation. However, although the ice shape like a feather is often observed in the experiments and the actual phenomena, the grid-based method cannot reproduce the feather-like ice structure because of the limitation of grid systems. That is, this problem is caused by the difficulty of grid generation to the real ice shape.

In the present study, we perform the Super-cooled Large Droplet (SLD) icing simulations, using the MPS method which is one of particle-based methods. Since the ice growth is very fast in the SLD icing, the pilot tends to overlook the accreted ice, and the SLD icing might lead to serious accidents. However, there has been a few studies on the SLD icing in comparison of the normal icing [3]. It is well known that the splash and the bound phenomenon occur in the SLD icing. The splash phenomenon is that the impingement droplet on a wall is separated into the adhering mass to the wall surface and the rebound mass. On the other hand, the bound phenomenon is that the total mass of the impingement droplet rebounds by perfectly elastic collision. Hence, in the grid-based method, the physical or empirical model of SLD icing is required.

The MPS method developed by Koshizuka et al. [4] is a mesh-free numerical technique. Therefore, the MPS method can clearly treat fluid interfaces and thus it can reproduce the large deformation of fluid. In the past, a number of studies with the MPS method have been performed for various problems [5].

In the present study, as a basic research of the SLD icing simulation with the MPS method, we simulate the SLD icing, making use of the advantage that the reproduction of the splash phenomenon is easy by the MPS method. Furthermore, the icing simulation by the MPS method can be expected to reproduce the ice shape like the feather which cannot be reproduced by the grid-based simulation. Through this study, the promising aspects of the MPS method in the SLD icing simulation are confirmed.

2 COMPUTATIONAL TECHNIQUE

2.1 MPS Method and Interparticle Interaction Model

In the SLD icing, super-cooled large droplets impinge to a wall. The droplets are assumed to be incompressible, and the rotation, the merging and the breaking out of the droplet are not taken into account for simplicity. The governing equations which consist of the Navier-Stokes equation and the continuity equation are given as follows,

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\mathbf{u} + \mathbf{g} + \frac{1}{\rho}\sigma\kappa\delta\mathbf{n} \tag{2}$$

where t is the time, ρ is the density, ν is the kinematic viscosity, $\boldsymbol{u}$ is the velocity vector, $\boldsymbol{g}$ is the gravity vector, P is the pressure, σ is the surface tension coefficient, κ is the interface curvature, δ is the delta function which limits the surface tension to the surface particles, $\boldsymbol{n}$ is the unit normal vector of the interface. In the MPS method, fluid is expressed by a number of small particles. The governing equations are descretized by the particles. The particle interaction model in the MPS method is applied to the weighting function w_{ij} defined by the following equation.

$$w_{ij} = \begin{cases} \left(1-\left|\mathbf{r}_{ij}\right|/r_e\right)^2 & \left|\mathbf{r}_{ij}\right| < r_e \\ 0 & \left|\mathbf{r}_{ij}\right| \geq r_e \end{cases} \tag{3}$$

where $\mathbf{r}_{ij}$ is the distance between particle i and j, r_e is the influence radius of particle i. Finally, the governing equations are discretized by the following Gradient Laplacian model.

$$\nabla\phi = \frac{d}{n^0}\sum_j \frac{\phi_j - \phi_i}{\left|\mathbf{r}_{ij}\right|^2}\mathbf{r}_{ij} w_{ij} \tag{4}$$

$$\nabla^2\phi = \frac{2d}{\lambda n^0}\sum_j \left(\phi_j - \phi_i\right) w_{ij} \tag{5}$$

where ϕ is the physical quantity, d is the number of dimensions, n^0 is the initial particle number density, λ is the coefficient used in order to match an increase in statistical variance of the distribution to the analytical solution, λ is given by the following equation.

$$\lambda = \frac{\sum_{j \neq i} \left|\mathbf{r}_{ij}\right|^2 w_{ij}}{\sum_{j \neq i} w_{ij}} \tag{6}$$

The particle number density n_i is obtained by the following equation.

$$n_i = \sum_j w_{ij} \tag{7}$$

The algorithm of the MPS method uses the semi-implicit procedure. First, we solve the terms without the pressure term by the explicit method, and then solve the pressure term by the implicit method.

2.2 Icing Judgment Condition

We judge the icing, based on the following assumptions.

- The interparticle distance between the liquid particle and the solid particle (or the wall particles) is 0.9 times less than the particle diameter.
- The particle number density which is obtained from the weighting function of solid-phase particles and wall particles is more than 0.7.

If these two assumptions are satisfied simultaneously, the liquid-phase particle changes into the solid-phase particle. Conversely, if these assumptions do not satisfied, we treat the particle as a liquid-phase. The liquid particle which changes into the solid phase is treated as the same way as the wall particle. Note that the icing judgement described above is for rime ice condition.

3 COMPUTATIONAL CONDITION

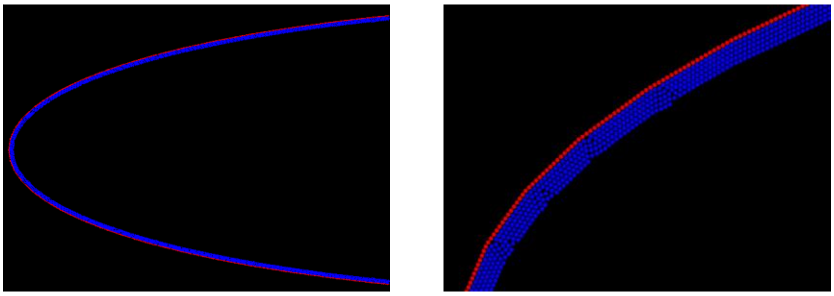
In the present study, as the basic research of the SLD icing simulation with the MPS method, the MPS simulation is performed under the rime ice condition. The rime ice condition is that super-cooled droplets instantly freeze on the collision wall due to the low temperature of the environment. The computational target is a NACA0012 airfoil, because a lot of literatures on this airfoil are available. The computational conditions are listed in Table 1, where LWC is the liquid water content, and MVD is the median volume diameter.

The airfoil surface is formed by the fixed wall particles, as shown in Fig. 1. The wall boundary condition is imposed on all of the wall particles in the MPS method. In this study, for the reduction of the computational cost, the computational domain is limited to around the leading edge. In Fig. 1, the red particle is the outer wall particle for which we perform the pressure computation, and the blue particle is the inner wall particle for which we do not perform the pressure computation. If the particle number density is low, the area might be judged as the free interface. Therefore, the blue inner wall particles are arranged over five layers so as to satisfy the influence radius (i.e. kernel). About 150 droplets are ingested from the upstream boundary, as shown in Fig. 2. The droplets are randomly put into the upstream with the distribution obtained from the LWC.

The droplet velocity is same as that of the flow. We treat only droplet behavior without the interference between the droplets and the flow field, since the SLD has sufficiently large inertia. The particle trajectory which is simulated using the splash model based on the grid-method (Isobe et al., [6]) is shown in Fig. 3. The bouncing particle trajectry in the Fig. 3 indicates the splash occurrence. Moreover, the inlet droplets fly straightly without the effect of the flow field. Therefore, using the above assumption is reasonable.

Table 1: Computational Conditions

Exposure Time	[s]	300
Inflow Velocity	[m/s]	15.0
Particle Diameter	[mm]	0.2
MVD	[mm]	2.0
LWC	[g/m^3]	1.2
Chord Length	[m]	0.53
Angle of Attack	[deg.]	4.0



(a) Over View (b) Enlarged View

Figure 1: Airfoil Shape around Leading Edge

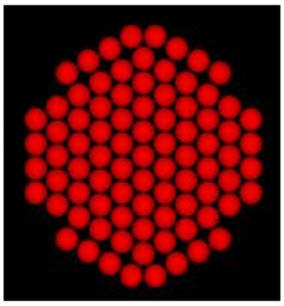


Figure 2: Computational Droplet

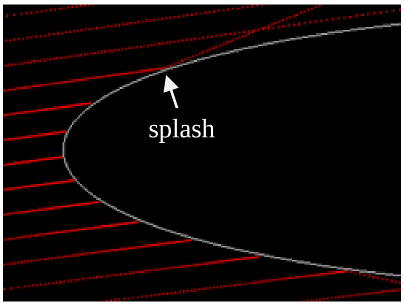


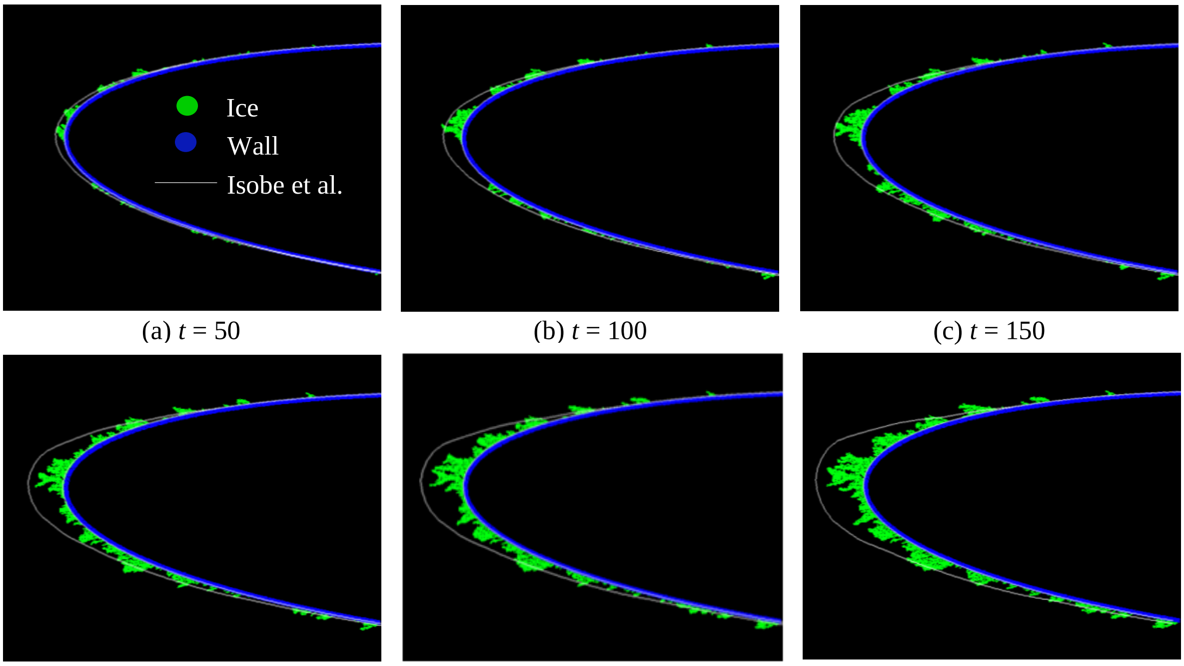
Figure 3: Droplet Trajectory

4 RESULTS AND DISCUSSION

The ice shapes every 50.0 seconds are shown in Figs. 4 (a)-(f). Since there are no experimental results in the computational conditions of this study, we make a comparison with the simulation of the grid-based method by Isobe et al. [6]. The white line in Fig. 4 is the result of the simulation by the grid-based method. According to Isobe et.al., their simulation contains the 15% error of the icing area. In Fig. 4, it is seen that the MPS method developed in the present study can reproduce the typical ice shape like the feather. As described above, this ice shape cannot be reproduced by any grid-based simulations. In addition, since the ice shape like the feather contains many irregularities, they might greatly affect the performance degradation of the airfoil during the icing process. Therefore, the ice shape like the feather is important for icing simulations. Accordingly, the reproduction of the ice shape by the MPS method in the present study is a huge first step of the icing simulation with the complex ice shapes.

The maximum thickness of the ice layer is in relatively good agreement with the result of the grid-based method. However, it is apparent that the icing simulation by the MPS method tends to underestimate the ice volume as the whole in comparison with the simulation by the grid-based method. The snap shot when the droplet collides with the leading edge surafce is shown in Fig. 5, in order to explain the cause of this underestimation. We can find that, although the droplets adhere on the leading edge without splash in the grid-based simulation, the droplets in the MPS method cause a certain amount of splash mass. In addition, as shown in Fig. 2, the computational droplet is assumed to be a perfect sphere. The volume of the water is underestimated by the gap formed between the particles. It is considered that these two factors are the main causes of the underestimation of the icing volume.

In the icing simulation by the MPS method, the ice accretion which is beyond the maximum icing limit area of the grid-based simulation is confirmed. Since the influence of the flow field on the particle trajectory is neglected, the extend of the icing area is not due to the assumption ignoring the flow field. To understand the mechanism of ice growth beyond the icing limit area, one snap shot of a droplet impact is exhibited in Fig. 6. The ice projections are generated at first (green particles on the wall). Then, the subsequent particle collides with the projections, and the ice locally grows. In the area beyond the icing limit, the droplets collide concentrates on the accrreted ice, and this causes droplets not to collide with the other wall surface. Therefore, the ice tends to grow on the adhered particles and not to adhere on the other area where the initial droplets do not collide. This icing property that the ice grows over the limited icing area cannot be predicted by the grid-based method. Therefore, in the present study, we can simulate the new icing properties which has not been confirmed by the grid-based method.



(a) *t* = 50 (b) *t* = 100 (c) *t* = 150

(d) *t* = 200 (e) *t* = 250 (f) *t* = 300

Figure 4: Predicted Ice Shapes using MPS Method

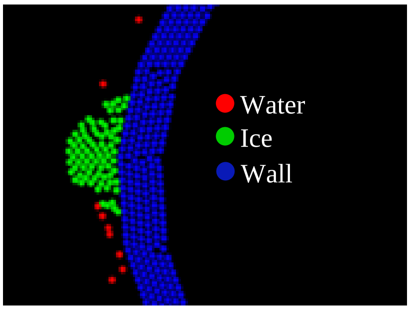


Figure 5: Droplet Collision to Wall

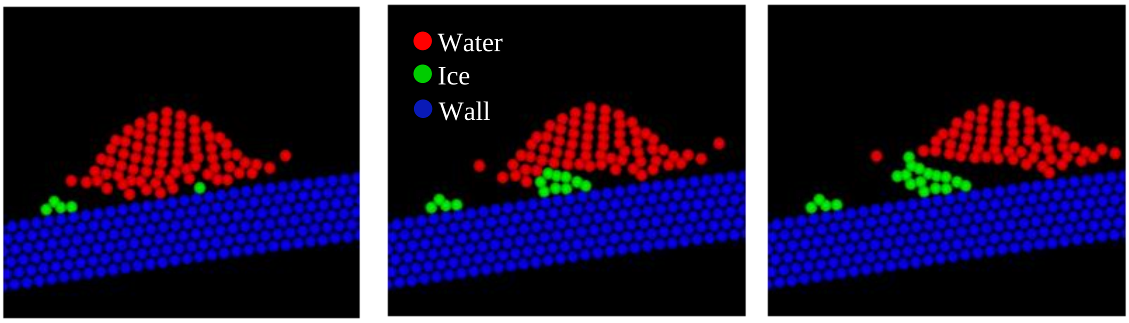


Figure 6: Ice Growth Mechanism beyond the Maximum Icing Limit Area

5 CONCLUSION

Super-cooled Large Droplet (SLD) icing simulations were carried out with the MPS method which is one of particle-based techniques. A NACA0012 airfoil was simulated under rime ice condition. We obtained the following knowledge through the present investigation.

- We can reproduce the ice shape like a feather which has not been predicted by the grid-based simulations.
- The MPS icing simulation caputures the ice thickness, but it tends to underestimate the icing volume due to the insufficient droplet model and the icing condition.
- The icing which grows beyond the limited icing area of the grid-based method is reproduced by the MPS method.
- We confirmed that the MPS method is promising to improve the icing simulations.

In our future work, we are planning to simulate the three-dimensional icing with the MPS method.

REFERENCES

[1] W. B. Wright, R. W.Gent and D. Guffond, DRA/NASA/ONERA Collaboration on Icing Research, *NASA CR 202349* (1997), pp. 32-52.

[2] W. G. Habashi, M. Aubé, G. Baruzzi, F. Morency and P. Tran, FENSAP-ICE: a fully-3d in-flight icing simulation system for aircraft, rotorcraft and UAVS, *Proceeding of 24th International Congress of the Aeronautical Sciences* (2004).

[3] D. N. Anderson and J. C. Tsao, Additional Results of Ice-Accretion Scaling at SLD Conditions, *NASA CR 213850* (2005), pp. 1-11.

[4] S. Koshizuka, H. Tamako and Y. Oka, A particle method for incompressible viscous flow with fluid fragmentation, *Journal of Computational Fluid Dynamics* (1995), Vol. 4, pp. 29-46

[5] J. Arai and S. Koshizuka, Numerical Analysis of Droplet Impingement on Pipe Inner Surface Using a Particle Method, *Journal of Power and Energy Systems* (2009), Vol. 3, No. 1.

[6] K. Isobe and M. Yamamoto, Numerical Simulation of Ice Accretion on the Rotor Blade of a Jet Engine Considering Splash and Bounce, *Proceeding of SAE 2013-01-2209* (2013), pp. 1-8