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# NUMERICAL INVESTIGATION ON FREEZING PROCESS OF SUPER-COOLED DROPLET

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**Abstract.** *Icing is a phenomenon that super-cooled droplets impinge on a solid surface and accrete on it. A lot of researches on the ice accretion have been conducted because the icing phenomenon causes serious problems in various places. In these researches, it is possible to predict the area where the icing takes place, the change of the flow field due to the icing and so on. However, for the reason that there are many unknown physical properties of the super-cooled droplet, the detailed freezing process of super-cooled droplets has not been clarified yet. Tanaka et al. experimentally investigated the freezing process of a super-cooled droplet. However, it is very difficult to investigate the mechanism experimentally because of the small size, and to reproduce the same condition repeatedly. Therefore, in this study, we simulate the freezing process by the numerical simulation using CFD. The obtained results indicate that the simulation code which has been developed in the present study can reasonably reproduce the behavior of the droplet freezing up along the interface between the water and the air.*

## 1 INTRODUCTION

Icing is a phenomenon that super-cooled droplets impinge on a solid surface and accrete on it. Aircraft have serious problems due to the icing. The examples are the degradation of the aerodynamics performance caused by the accreted ice and a mechanical damage due to the ice shed from the wall surface. Therefore, it is important to investigate the effect of icing on the flow field and to predict icing areas in the design phase. Icing wind tunnel tests should be conducted under various weather conditions. However, it is difficult to reproduce the weather conditions by the experiment repeatedly, because icing phenomena depend on various physical factors including the atmospheric temperature, the solid surface temperature on which super-cooled droplets impinge, and the velocity and size of the droplet. Moreover, the icing experiment needs huge cost. Therefore, the numerical investigation using the computational fluid dynamics (CFD) which can reproduce various icing conditions is desirable.

There have been various researches about the icing. For example, Wright et al. [1] compared the predictive performance of the icing simulation codes, which were developed by NASA, ONERA and DRA, with the experiment. Veres et al. [2] simulated the ice accretion which occurs in the compressor of the jet engine with the ice crystals. In our laboratory, we have developed the icing models which can be applied to various conditions, such as the velocity and the temperature of the atmosphere, the droplet diameter, the liquid water content (LWC) and so on [3]. Thus, there have been a lot of researches on the ice growth, the ice area and the ice shape of the main wing, the engine fan and so on. However, the detailed mechanism of the super-cooled droplet freezing has not been clarified yet. Tanaka et al. [4] experimentally investigated the freezing process of a super-cooled droplet. They visualized the temperature of the droplet with two types of luminescent probes. And, they obtained the knowledge that the super-cooled droplet freezes up along the interface between the water and the air. However, it is difficult to reproduce the same physical condition repeatedly and there is the agitation of the luminescent probes such as reflections of the light. Therefore, in the present study, we develop the simulation code which can reproduce the freezing process of a droplet, in order to clarify the temperature change of the droplet and the factor which freezes the droplet.

## 2 SIMULATION METHOD

### 2.1 FLOW FIELD COMPUTATION

In this study, the flow field is treated as two dimensional, incompressible, laminar and three phase flow. As follows, the continuity and the Navier-Stokes equations are used as the governing equations and the MAC method is employed for the pressure computation,

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

$$\frac{\partial \boldsymbol{u}}{\partial t} + \frac{1}{\rho}(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \nu \Delta \boldsymbol{u} + K \tag{2}$$

where $\boldsymbol{u}$ is the velocity, $\rho$ is the density, $t$ is the time, $p$ is the pressure, $\nu$ is the kinetic viscosity and $K$ is the body force. In this study, the body force terms are the gravity and the surface tension. CSF (Continuum Surface Force) model [5] is applied to the surface tension $f_v$,

$$\boldsymbol{f_v} = \sigma \kappa \nabla F \tag{3}$$

where $\sigma$ is the surface tension factor and $\kappa$ is the curvature. The curvature is represented by the following equation with the unit normal vector $\boldsymbol{n}$.

$$\kappa = -\nabla \cdot \boldsymbol{n} \tag{4}$$

For simplicity, in the present study, the surface tension on a flat plate is not considered in CSF model. These governing equations are spatially discretized by Kawamura-Kuwabara third-order upwind scheme [6] for the convection term and the second order central difference scheme for the others. In addition, the four-stage Runge-Kutta method is used for the time marching.

## 2.2 VOF METHOD

We use the VOF (Volume of Fluid) method [7] to simulate the free interface between the water and the air. In the VOF method, the free-interface movement is determined by solving an advection equation of the liquid filling rate *F*,

$$\frac{\partial F}{\partial t}+u\frac{\partial F}{\partial x}+v\frac{\partial F}{\partial y}=0 \tag{5}$$

where *u* is the velocity of the *x* direction, *v* is he velocity of the *y* direction and *t* is the time. The advection equation is discretized by the K-K scheme. By the liquid filling rate *F*, the computational cells are classified into three categories as follows.

- $F=0$ : Gas cell
- $F=1$ : Liquid cell
- $0<F<1$ : Gas-Liquid cell

Using the liquid filling rate *F*, the density $\rho$ and the viscosity $\mu$ in each computational cell are given as follows,

$$\rho=\rho_G(1-F)+\rho_L F \tag{6}$$

$$\mu=\mu_G(1-F)+\mu_L F \tag{7}$$

where index *G* and *L* mean the gas phase and the liquid phase, respectively.

## 2.3 HEAT CONDUCTIVE COMPUTATION

As follows, the heat conductive equation is used for the temperature computation,

$$\rho C_p\left(\frac{\partial T}{\partial t}+\boldsymbol{u}\cdot\nabla T\right)=k\Delta T \tag{8}$$

where *T* is the temperature, $C_p$ is the specific heat and *k* is the thermal conductivity. Moreover, at the interface of the solid phase, the liquid phase and the gas phase, the convection heat transfer $Q_c$ and the latent heat $Q_l$ are computed and added to the heat equation of Eq. (8),

$$Q_C=h(T_{sur}-T_{gas}) \tag{9}$$

$$Q_L=\rho_{ice}L_f\frac{\partial B}{\partial t} \tag{10}$$

where *h* is the heat transfer coefficient, $T_{sur}$ is the interface temperature, $T_{gas}$ is the gas temperature, $\rho_{ice}$ is the ice density, $L_f$ is the latent heat and *B* is ice thickness. The latent heat $Q_l$ is divided into each cell by the weight function obtained from the temperature gradient between the frozen cell and the neighboring cells. In this study, the evaporation of the droplet and the heat loss caused by the radiation are not considered, because these are smaller enough than the heat conduction and the heat transfer. In addition, the heat transfer with the wall surface is not taken into account because the wall is assumed to be adiabatic.

## 2.4 FREEZING JUDGEMENT

In this study, the liquid phase is judged as freezing up when the temperature is ascended to 273.15 K (i.e. freezing point) by the heat conduction computation. It is assumed that the temperature of a frozen cell is fixed to be 273.15 K.

## 3 COMPUTATIONAL CONDITION

In this study, we simulate the behaviour, the temperature distribution and the freezing process of the super-cooled droplet which is dropped to the flat plate as shown in Fig. 1. The heat conduction computation is conducted after the super-cooled droplet becomes a static state. In order to investigate the freezing process of a super-cooled droplet, in this study, a nucleus of the ice is given on the top of the interface as the freezing trigger. The computational conditions are summarized in Table 1. Because the phenomenon is symmetric, the computation domain is half which is surrounded in the frame in Fig. 2. On the wall, the no-slip condition is imposed.

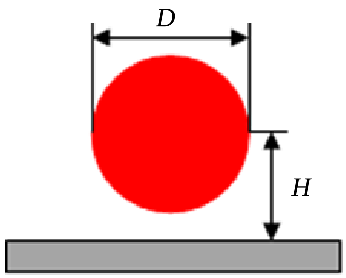


**Figure 1**: Computational Configuration

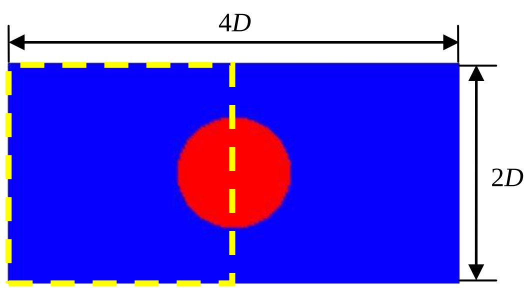


**Figure 2**: Computational Domain

**Table 1**: Computational Condition

| | | |
|---|---|---|
| Initial Temperature of Gas Phase $T_G$ | [K] | 253.15 |
| Initial Temperature of Liquid Phase $T_L$ | [K] | 265.15 |
| Initial Heght of Droplet $H$ | [mm] | 4 |
| Initial Diameter of Droplet $D$ | [mm] | 4 |
| Latent Heat of Solidification $L_f$ | [J/Kg] | $3.344 \times 10^5$ |
| Heat Transfer Coefficient $h$ | [W/(m$^2$·K)] | 10.0 |
| Surface Tension Coefficient$\sigma$ | [N/m] | 0.0756 |

## 4 NUMERICAL RESULTS AND DISCUSSION

## 4.1 BEHAVIOUR OF FREE FALLING DROPLET

We show the behavior of the droplet when the droplet freely falls on the flat plate in Fig. 3 (a)-(i). The droplet oscillates up and down after impinges on the plate in about 0.020 seconds. Generally, in the interface between a gas and a liquid phase, the droplet easily keeps the stable condition when the interfacial surface is small enough. Since the shape that the surface area is the smallest in the same volume is a sphere, the surface tension acts to keep a droplet spherical. Then, the surface tension and the gravity force lead the droplet to oscillate up and down like Fig. 3. This trend is same as the experiment by Tanaka et al. [4]. In addition, we show the graph of the temporal change of the maximum interface height in Fig. 4. It indicates that the maximum interface height completely converges at 0.4 s later. From the above, the surface tension and the gravity force are in balance, and the droplet can be confirmed in the static state. Accordingly, in this study, we judge that the droplet at 0.4 s later has converged and the heat conduction computation was carried out from this converged state of the droplet. The results are shown in next section.

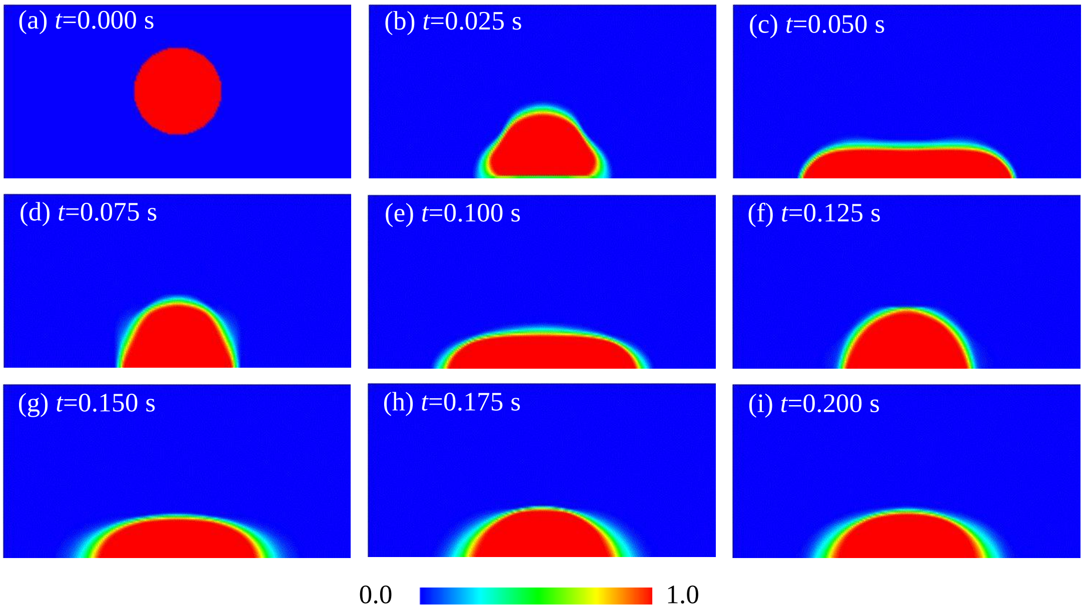


**Figure 3**: Behavior of Free Fall Droplet (Liquid Filling Rate)

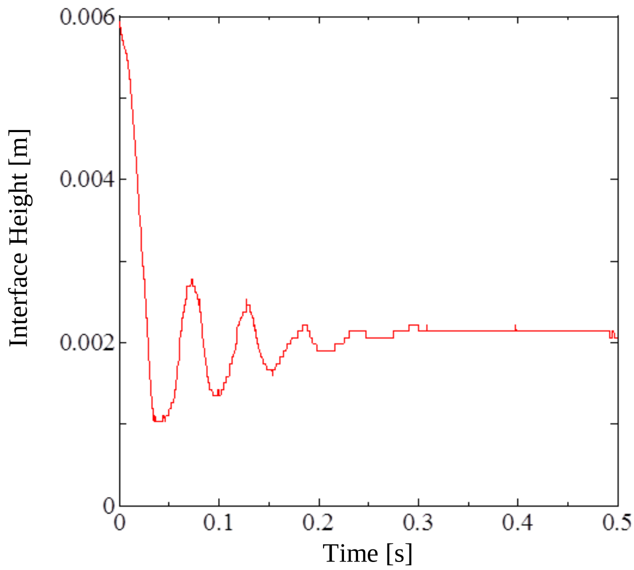


**Figure 4**: Temporal Change of Max. Interface Height

## 4.2 FREEZING PROCESS OF DROPLET

We show the freezing process of the droplet in a static state in Fig. 5 (a)-(i). The cell which has frozen up is expressed by coloring with white. Figure 5 (a) is the initial condition which has been given a nucleus of the ice on the top of the droplet. The temperature rises from the center of the ice nucleus. This is caused by the latent heat, which is generated by the phase change from the water to the ice. Moreover, the ice area spreads along an interface between the liquid and the gas phase. On the interface between the liquid and the gas phase, the temperature falls due to the heat transfer. Hence, on the droplet interface, the temperature gradient is larger in comparison with the droplet inside. It is considered that the interface has higher temperature potential due to the latent heat since the energy flows into the direction for the lager gradient. Therefore, the ice grows up along the interface. In addition, the tendency that the super-cooled droplet freezes along the interface is similar to the experiment by Tanaka et al. again.

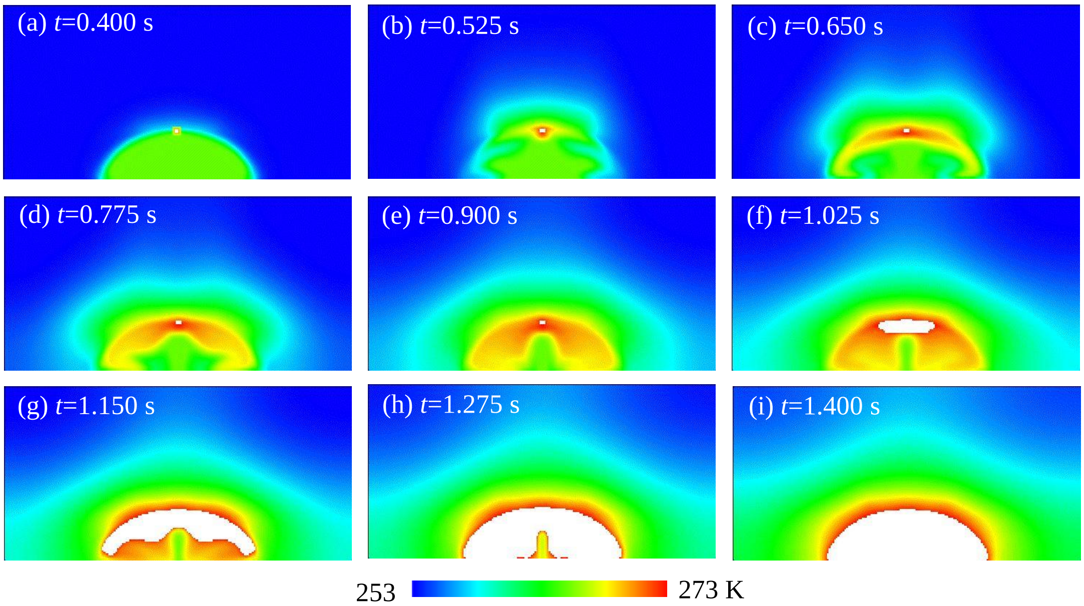


**Figure 5**: Freezing Process of Super-cooled Droplet

## 5 CONCLUSION

We conducted two simulations in the present study, which are the behaviour of a super-cooled droplet when the droplet freely falls on a flat plate and the temperature change on the freezing process of the super-cooled droplet in a static state. The knowledge that this study provided is as follows.

- We succeeded the simulation that the droplet oscillates up and down after impinges on the plate.
- The super-cooled droplet freezes up along an interface between the liquid and the gas phase.
- The latent heat and the temperature gradient are important factors to freeze the droplet.

In our future work, we take into account the heat transfer and the surface tension between the droplet and the plate which were neglected in this study. Moreover, we will reproduce a phenomenon that the droplet freezes up by the energy that a droplet impinges on the plate.

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