APCOM & ISCM
11-14th December, 2013, Singapore

Numerical and Fundamental Study on Ice Growth of Ice Crystal Accretion

***Koharu Furuta[1] and Makoto Yamamoto[2]**

[1]Graduate School of Mechanical Engineering, Tokyo University of Science
6-3-1 Niijyuku, Katsushika-ku, Tokyo, Japan
[2]Department of Mechanical Engineering, Tokyo University of Science

*Corresponding author: j4513645@ed.tus.ac.jp

Abstract

This paper discusses a fundamental study on the ice crystal accretion. Ice accretion is a phenomenon to form ice layer on a body due to impingement of super-cooled water droplets. In recently years, it is known that ice accretion occurs in the engine core such as the low pressure compressor and the first stage of the high pressure compressor, where the temperature is about 30 degree C. The ice accretion in the engine core is called as "ice crystal accretion". It differs from rime and glaze ice accretion because these ice accretions occur under the temperature of the water freezing point. Some scenarios are given as a factor of the ice crystal accretion, but the mechanism has not been sufficiently clarified yet. Moreover, the current icing model is not available in the environment where the temperature is above the freezing point. In this paper, we present a new icing model which is applicable to a warm environment. The new icing model consists of four computations for turbulent flow, droplet/ice trajectory, thermodynamics of icing, and heat conduction within a wall, and is applied to for a flat plate instead of compressor blades as a basic study of the ice crystal accretion. The simulation results by use of the new model indicate that ice accretion occurs in the condition of the temperature even above the freezing point.

Keywords: Multi-physics CFD, Engine inner icing, Ice crystal accretion, Super-cooled water droplet

Introduction

Ice accretion is a phenomenon that super-cooled water droplets in the atmosphere impinge on a body and form ice layer. When it occurs in a jet engine, the shape change of iced blades makes aerodynamic performance worse, and ingestion of shedding ice flakes causes serious mechanical damages to the fan and the compressor components. Since there is the risk to lead to the serious accidents such as crashes by an ice accretion on a jet engine as well as an aircraft, the prediction of ice accretion is necessary. Experimental investigations have been carried out to estimate the ice accretion, but it is too difficult to set actual icing condition. Therefore, computational fluid dynamics (CFD) is useful to predict the ice accretion. Engine components such as splitter, nose cone, fan blades and fan exit guide vane have been considered as icing area in a jet engine. However, it came to be confirmed that icing area expands to the low pressure compressor and the first grade of the high pressure compressor in the engine core [1]. The ice accretion in the engine core is called as ice crystal accretion. It causes the flame out of the engine because ice flakes shed from the compressor components flow into the combustor. There is a hypothesis that ice crystal accretion occurs mainly when the engine ingests ice particles. In addition to ice particles, super-cooled water droplets and mixture of ice particles and super-cooled water droplets have been advanced for ice crystal accretion. These three scenarios are given as a factor of ice crystal accretion, but the mechanism of ice crystal accretion is not clarified. It occurs in the environment where the ambient static temperature is at about 30 degree C, but the current icing model is unavailable in the environment where the temperature is above the freezing point. Therefore, a new icing model which can be applied to such a warm environment is needed to find out the mechanism of the ice crystal accretion.

In this paper, as a basic study of the ice crystal accretion, we develop a new icing model which is applicable to the environment where the flow static temperature is above the freezing point. We simulate ice crystal accretion phenomena and predict the icing area and the icing mass by computing super-cooled water droplet impingements on an aluminum flat plate which has a high thermal conductivity. It comes out that the wall temperature of the flat plate can fall to the freezing point by interaction of the cooling with the super-cooled water droplets and the heat conduction in the flat plate. In addition, it becomes clear that ice accretion starts and grows where the wall temperature falls to the freezing point.

Computational Approach

Fig. 1 shows the flow chart of the simulation procedure in this study. First, a flow field around a flat plate is computed. Then, properties of droplet trajectory, such as collision position and mass, are caught by a Lagrangian method. At last, temporal change of the plate temperature and the icing mass are computed by thermodynamic calculation. These computation approaches used in this study are described in detail below.

Flow Field

It is supposed that flow field is two-dimensional, compressive and turbulent. Favre-averaged mass, momentum and energy conservation equations are used as governing equations. Non-viscous terms and viscous terms in these equations are discretized by Yee-Harten's second-order upwind difference TVD scheme [2] and second-order central-difference scheme, respectively. Then, time integration is computed by LU-ADI method [3], turbulence is estimated by k-ε model with Kato-Launder modification [4].

Droplet Trajectory

Droplet trajectory computation based on a Lagrangian method is conducted to get properties of the droplet impingement on a flat plate. Force acting on droplets is only drag, and the other forces are not taken account. Also, droplet-droplet collision, evaporation, merge and break-up are ignored. It is supposed that droplets are complete sphere and do not make any effect on flow field (One-Way Coupling). The following B-B-O equation, which is simplified, is used as the governing equation:

$$\frac{d\vec{U}_w}{dt} = \frac{3}{4} C_D \frac{\rho_f}{\rho_w} \frac{1}{d_w} \vec{U}_r \left| \vec{U}_r \right| \tag{1}$$

where U_w is droplet velocity, U_r is relative velocity of gas and droplet, d_w is droplet diameter, ρ_f is density of gas, and ρ_w is density of droplet. C_D is drag coefficient and calculated from following formula. Then, Re_w is Reynolds number of a droplet.

$$C_D = \frac{24}{\mathrm{Re}_w}\left(1 + 0.15\,\mathrm{Re}_w^{\ 0.687}\right) \tag{2}$$

Ice Accretion

Extended Messinger model [5] based on the Stefan problem is used for the ice accretion calculation. This model is governed by four equations; heat conduction equations in ice and water layers, a mass balance equation in the ice and water, and a phase change condition at the ice/water interface:

$$\frac{\partial T_i}{\partial t} = \frac{k_i}{\rho_i C_{pi}} \frac{\partial^2 T_i}{\partial {y_w}^2} \tag{3}$$

$$\frac{\partial T_w}{\partial t} = \frac{k_w}{\rho_w C_{pw}} \frac{\partial^2 T_w}{\partial {y_w}^2} \tag{4}$$

$$\rho_i \frac{\partial B_i}{\partial t} + \rho_w \frac{\partial B_w}{\partial t} = m_{im} + m_{in} - m_{e,s} \tag{5}$$

$$\rho_i L_F \frac{\partial B_i}{\partial t} = k_i \frac{\partial T_i}{\partial y_w} - k_w \frac{\partial T_w}{\partial y_w} \tag{6}$$

where T_i and T_w are the temperatures, B_i and B_w are the thicknesses, k_i and k_w are the thermal conductivities, and C_{pi} and C_{pw} are the specific heats of ice and water, respectively. In Eq. (5), m_{im}, m_{in} and $m_{e,s}$ are impinging, runback and evaporating (or sublimating) water mass flow rates for a control volume, respectively. In Eq. (6), ρ_i is density of ice, L_F is latent heat by solidification and y_w is distance from the wall. In Eqs. (3)-(6) are integrated on time by the fourth phase Runge-Kutta method. Each parameter used in upper equations is shown in Table 1.

Heat Transfer

In order to estimate the temporal change of temperature within a flat plate, the heat conduction equation is employed:

$$\frac{\partial T_{in}}{\partial t} = a\left(\frac{\partial^2 T_{in}}{\partial x^2} + \frac{\partial^2 T_{in}}{\partial y^2} \right) \tag{7}$$

where T_{in} is temperature in a flat plate, a is thermal conductivity of a flat plate, x and y are horizontal and vertical coordinate in a flat plate, respectively. The material of plate used in this study is aluminum which has a high thermal conductivity.

Computational Condition

Computational Target and Grid

Computational domain in this study is shown in Fig. 2. Computational grid system has a sub grid based on the overset grid method to analyze the flow around the flat plate as indicated in Fig.3. The total number of the grid points is about 10,000.

Computational Condition

Computational conditions used in the ice accretion calculation are exhibited in Table 2. 100,000 droplets whose median volume diameter is 20μm are put in the inlet flow. Then, collision mass on the wall is computed and the ice accretion calculation for 15 sec. is performed.

In the inlet boundary, the total temperature and the total pressure are fixed and the Mach number is extrapolated. In the outlet boundary, the static pressure is fixed, other variables are extrapolated. The top and the bottom boundaries are periodic. The wall of the flat plate is under no-slip, wall function and adiabatic conditions. The inflow turbulent kinetic energy is assumed by the 0.1 % turbulence of the free stream. The temperature boundary condition at the wall in heat transfer calculation is adopted by Newton’s law of cooling.

Result and Consideration

Flow Field

Static temperature and stream line are seen in Fig. 4 (a) and (b), respectively. The static temperature increases to about 309 K, around the stagnation point. Since ice accretion occurs on the windward wall of the plate, it is apparent that the plate wake does not have any remarkable influence on the icing phenomena.

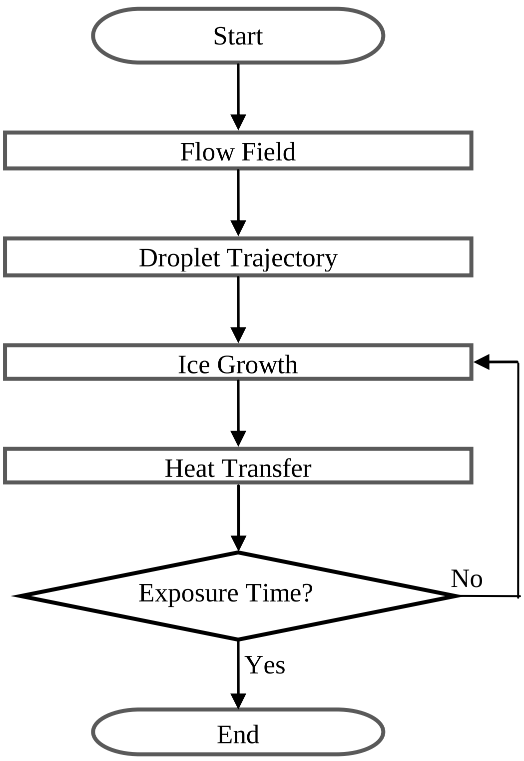


Figure 1. Algorithm of Icing Simulation

Table 1. Parameter of Icing Model

Specific Heat of Ice C_{pi}	2,050 J/kg K
Specific Heat of Water C_{pw}	4,218 J/kg K
Thermal Conductivity of Ice k_i	2.18 W/m K
Thermal Conductivity of Water k_w	0.571 W/m K
Latent Heat of Solidification L_F	3.344×10^{5} J/kg
Density of Glaze Ice ρ_i	917.0 kg/m
Density of Water ρ_w	1,000 kg/m
Heat Conductivity a	9.73×10^{-5} m^2/s

Table 2. Computational Conditions

Inlet Mach Number	0.3
Inlet Total Pressure	0.1149 MPa
Inlet total Temperature	308.60 K
LWC (Liquid Water Content)	1.0 g/m^3
Inlet Droplet Temperature	-20.0 °C
MVD (Median Volume Diameter)	20.0 μm
Plate Size	5.0 mm×40.0 mm
Exposure Time	15.0 sec.

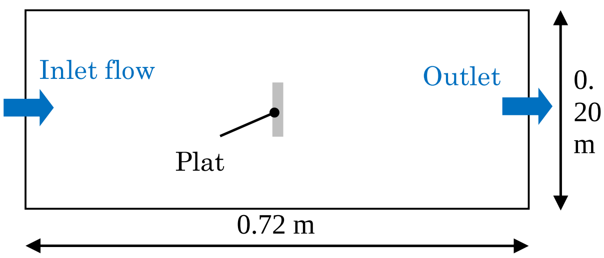


Figure 2. Computational Domain and Size

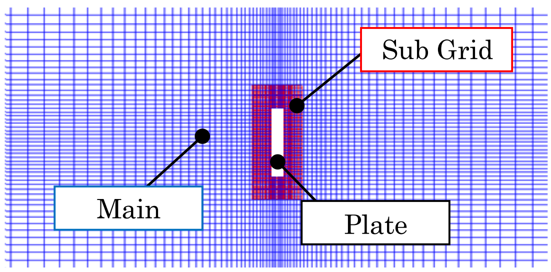
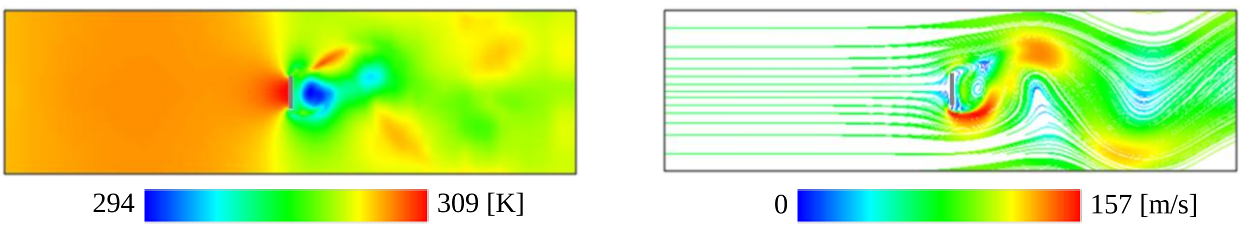


Figure 3. Computational Grid



(a) Static Temperature

(b) Stream Line

Figure 4. Flow Field

Collection Efficiency

Collection efficiency on the plate is shown in Fig. 5. The collection efficiency is smaller at the stagnation point, because droplets tend to follow the flow streamline. Since droplets flow along the free stream, many droplets are collected near the edge of the plate.

Mechanism of Ice Crystal Accretion

Temporal changes of the plate temperature are presented in Fig. 6. At first, temperature at the stagnation point of the wall is higher than the other area on the collision wall, but it is stable near 0 degree C as time passes. Then, temporal change of the ice thickness is exhibited in Fig. 7. The vertical axis in this figure represents the plate position, which is non-dimensionalized by the plate length. As Figs. 6 and 7, it is clear that ice accretion starts and grows around the region where the wall temperature fell to the freezing point. Ice accretion is related to not only collection efficiency but also wall temperature. With an existing icing model, ice accretion does not occur where the ambient fluid temperature is higher than the freezing point. Instead, with the new icing model developed in this study, ice accretion is observed around the region where the wall temperature falls to the freezing point due to heat transfer. Therefore, it is clear that the heat transfer computation in the plate and ice accretion calculation work each other.

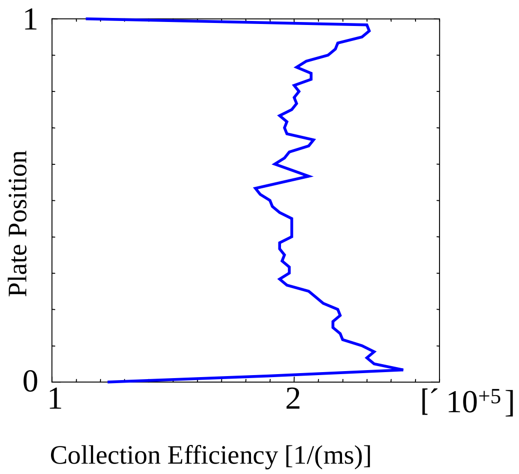


Figure 5. Droplet Collection Property

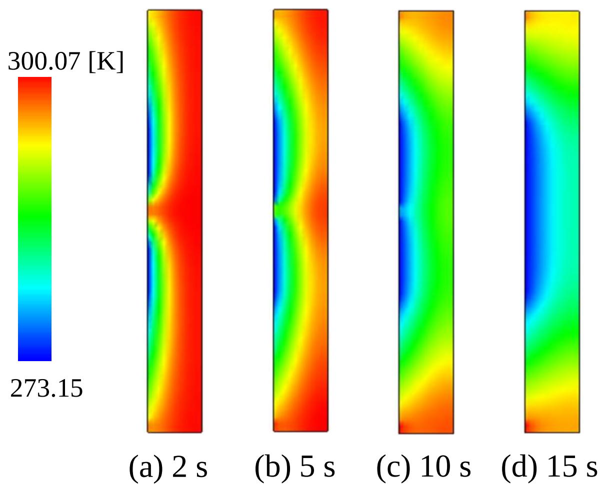


Figure 6. Temporal Change of Plate Temperature

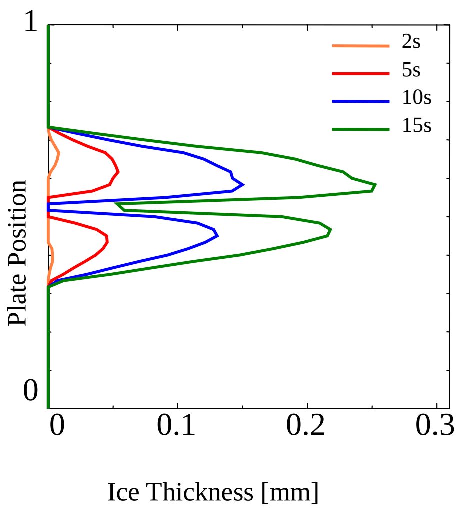


Figure 7. Temporal Evolution of Ice Thickness

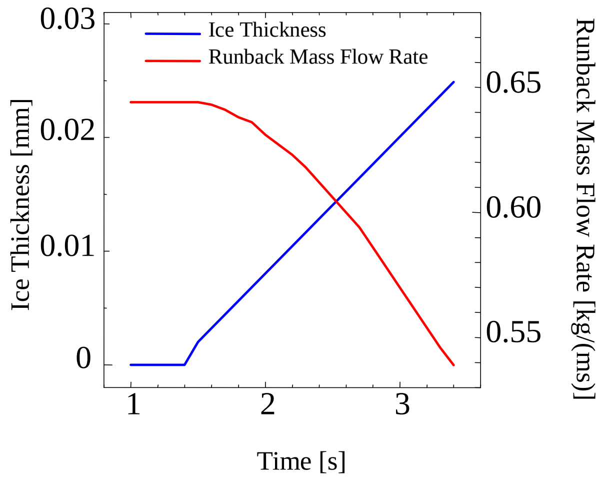


Figure 8. Ice Thickness and Runback Mass Flow Rate

Ice thickness and runback mass flow rate where ice accretion occurs for the first time are shown in Fig. 8. The collision wall certainly has water film, because the ambient static temperature is above the freezing point. Then, water film flows to the edge of the plate along the plate surface. When water film does not change to ice, the runback mass flow rate is constant even if time passes. However, from Fig.8, the runback mass flow rate decreases as ice thickness increases. Therefore, the runback mass changes into ice mass. In fact, ice accretes near the stagnation point rather than the icing area, because a part of water film which streams from the center of the plate changes to ice. Therefore, position of the maximum ice thickness approaches toward the stagnation point.

Influence of Droplet Temperature

Icing area and time history of the plate temperature are shown in Figs. 9 and 10, respectively. The droplet temperature is changed from -40 to -2 degree C, every 1 degree C, exposure time is 60 sec. and the other computational conditions are not changed. As indicated in Fig. 9, the icing area increases as droplet temperature is lower. Also, the area of the temperature 0 degree C on the wall expands while droplet temperature is lower as seen in Fig. 10. The icing area increases when droplet temperature is lower, but the plate temperature is stable near the freezing point and no longer decreases. This is why most of energy droplets have is used for the ice growth.

Conclusion

The research on the mechanism of ice crystal accretion is numerically performed. Insights obtained in this study are below.

(1) Ice accretion occurs in the environment where the ambient static temperature is at 30 degree C when the wall temperature falls to the freezing point.
(2) Ice grows where ice has accreted once, and the runback phenomenon becomes hard to occur in this area.
(3) Icing wall temperature is stable near the freezing point and no more decreases.
(4) The droplet temperature has an influence on the ice crystal accretion.

The future prospects include that the material and shape of the computational target should be changed from the aluminum flat plate to an actual compressor blade. In addition, the ingestion of not only super-cooled water droplets but also ice particles is taken into account. And a temporal change of the super-cooled droplet temperature will be computed in a jet engine core.

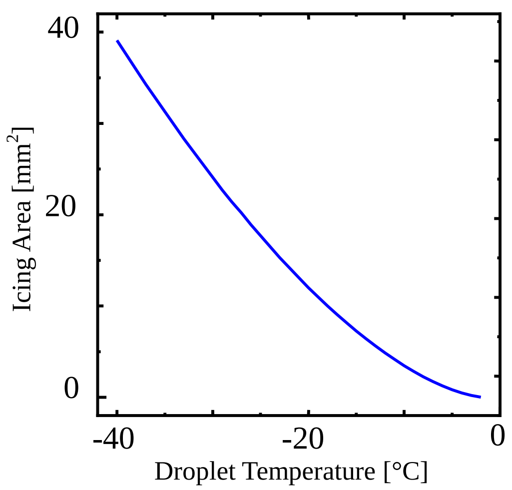
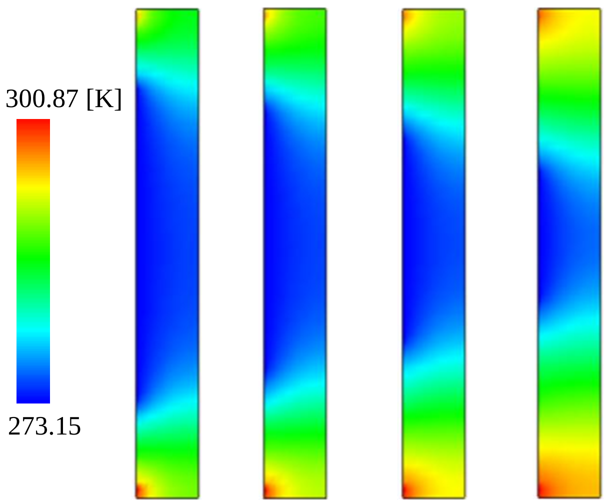


Figure 9. Influence of Droplet Temperature



(a) -40 °C (b) -30 °C (c) -20 °C (d) -10 °C

Figure 10. Influence of Droplet Temperature on Plate Temperature

References

[1] Jeanne G. Mason, J. Walter Strapp, Philip Chow, (2006), The Ice Particle Threat to Engines in Flight," 44th AIAA Aerospace Sciences Meeting and Exhibit, *AIAA* 2006-206.

[2] Yee H. C., (1987), Upwind and symmetric Shock-Capturing Schemes, *NASA TM* 89464.

[3] Fujii K. and Obayashi S., (1987), Practical application of improved LU-ADI scheme for the three-dimensional Navier-Stokes computations of transonic viscous flows, *AIAA Paper*, 86-0513.

[4] Kato M., Launder B. E., (1993), The modeling of turbulent flow around stationary and vibrating square cylinder, *Proceedings of 8th Symposium on Turbulent Shear Flows,* 10-4-1-10-4-6.

[5] Ozgen S., Canibek M., (2009), Ice accretion simulation on multi-element airfoils using extended Messinger model, *Heat and Mass Transfer*, Vol. 45, pp. 305-322.