OpenFOAM을 이용한 항공기 착빙 현상 해석

Analysis of the Aircraft Icing Phenomenon using OpenFOAM

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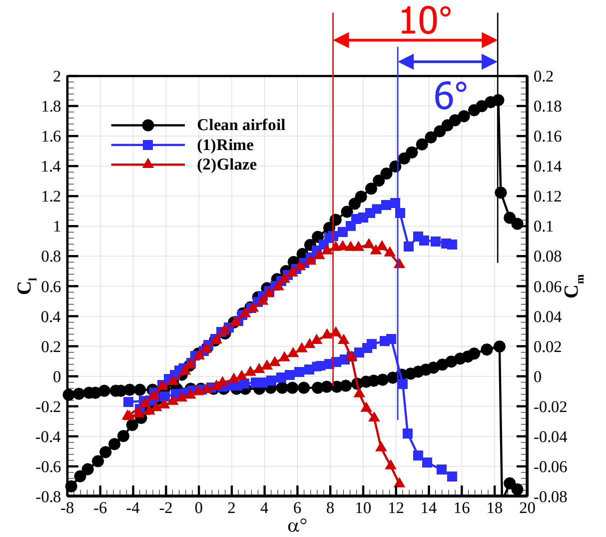
Contents

INTRODUCTION

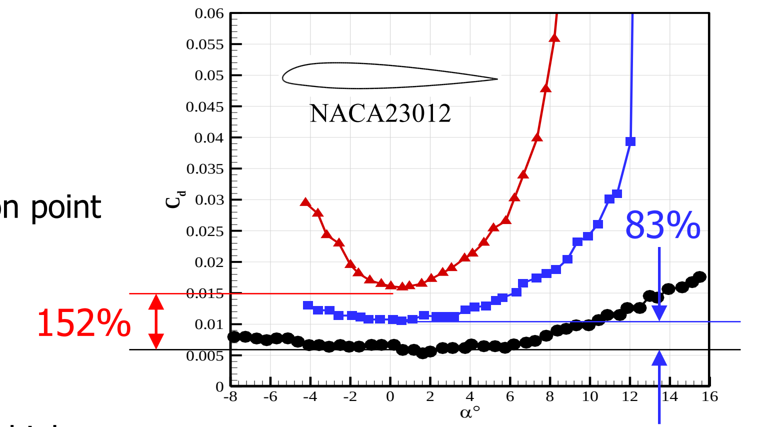
Aircraft icing

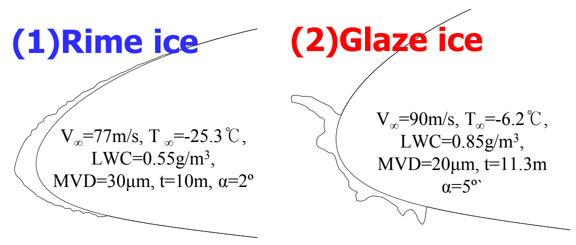
- Super-cooled liquid water droplets impact and freeze on the aircraft surface
- Aircraft and helicopters can encounter the icing conditions in low temperature and high humidity conditions
- Accumulated ice changes surface roughness, and deforms the well designed aerodynamic bodies
    - ✓ Degradation of lift, drag and moment performance, negative to control ability, stall margin, and stall speed



Types of ice shapes

- (1)Rime ice
    - ✓ Rime ice occurs relatively low temperature(under -20℃)
    - ✓ The super cooled droplets immediately freeze at the collision point due to low temperature
    - ✓ Prediction of droplet trajectories is sufficient
    - ✓ The ice shapes are similar to the clean airfoil
- (2)Glaze ice
    - ✓ Rime ice occurs relatively high temperature(0 ~ -15℃) and high humidity conditions
    - ✓ 1)The droplets becomes water film on the surface, then 2) the water flows along the surface, and 3) it freezes at the high heat convection region
    - ✓ Thermodynamic model is required
    - ✓ Ice horn shape is the feature of glace ice





INTRODUCTION

Major cause of aircraft accidents

- Aircraft Owners and Pilots Association(AOPA) report from 1990 to 2000
  - ✓ 3230 accidents are concerned with weather conditions
  - ✓ 388 accidents(12%) are related to aircraft icing phenomenon

CFD approach to predict ice accretion shape and its performance

- Icing wind tunnel test
  - ✓ Expensive in operating and maintain costs of experiment facilities (NASA U.S. and, CIRA Italy)
- Flight test for icing
  - ✓ Specially designed aircraft is required for flight icing tests
  - ✓ Constrained by the weather conditions and safety concerns

▲ Icing wind tunnel test

▲ Flight icing test

INTRODUCTION

Numerical approaches to predict ice accretion shapes and its performance

	1st generation codes	**Limitation of 1st Gen. codes**	**2nd generation codes**
Period	1980~1990s	-	1990s~
Aerodynamic solver	Panel method, Euler equation	(1) Separation flow of high angle of attack, ice horn, cylinder (2) Prediction of aerodynamic force, especially lack of drag prediction	Navier-Stokes equation
Impingement model	Lagrangian approach	No droplet particles in shadow region(flow separation, after ice horn)	Eulerian approach
Thermodynamic mode	2D Messinger model	Sectional approach, axial symmetry problems only	Extended 2D Messinger or 3D water film mode
Representative codes	NASA(LEWICE), ONERA, DRA, CIRA	-	McGill Univ.(FENSAP-ICE), CIRA(ICECREMO)

INTRODUCTION

Scope of topics

- Development of 2nd generation icing code using OpenFOAM
- Validation of the developed code for a 3D fixed wing aircraft
- Representative icing studies

✓ (1) Helicopter fuselage icing

- Check the validity of the isolated fuselage icing research
  - Comparison of ice shapes on isolated rotor and rotor-fuselage interaction cases
- Analyze the aerodynamic effects on fuselage icing with respect to forward flight speed
  - Hovering, low and high speed forward flight

✓ (2) HALE(High-Altitude Long-endurance) aircraft icing

- Whether to operate HALE now ?
- Necessity for the criteria to make a decision based on the performance evaluation under icing conditions
- Meteorological conditions → ice accretion shapes → aerodynamic performance → decision making
  - The quantitative correlation between the meteorological icing parameters and performance degradation

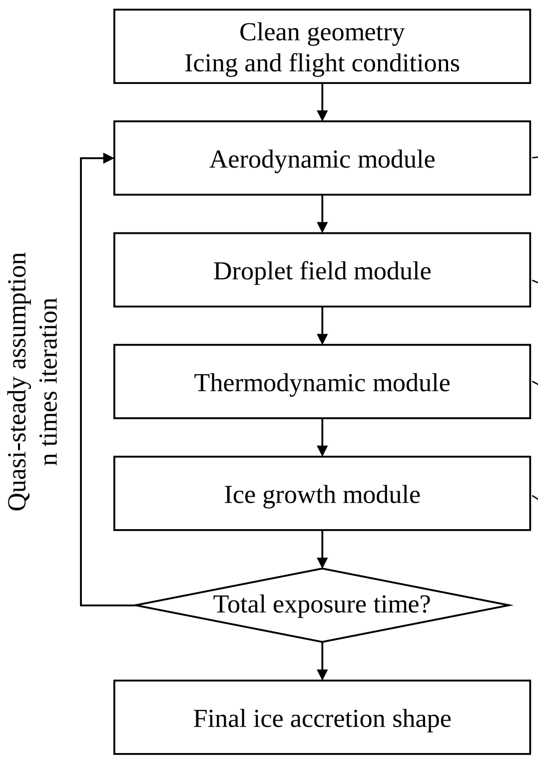
NUMERICAL METHOD

3D ICE ACCRETION CODE

NUMERICAL METHOD

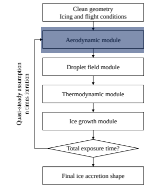
3D icing solver

- 4 separate modules : aerodynamic module, droplet field module, thermodynamic module, ice growth module
- Each module is sequentially progressed under quasi-steady assumption
  - ✓ Each model is assumed to be steady state



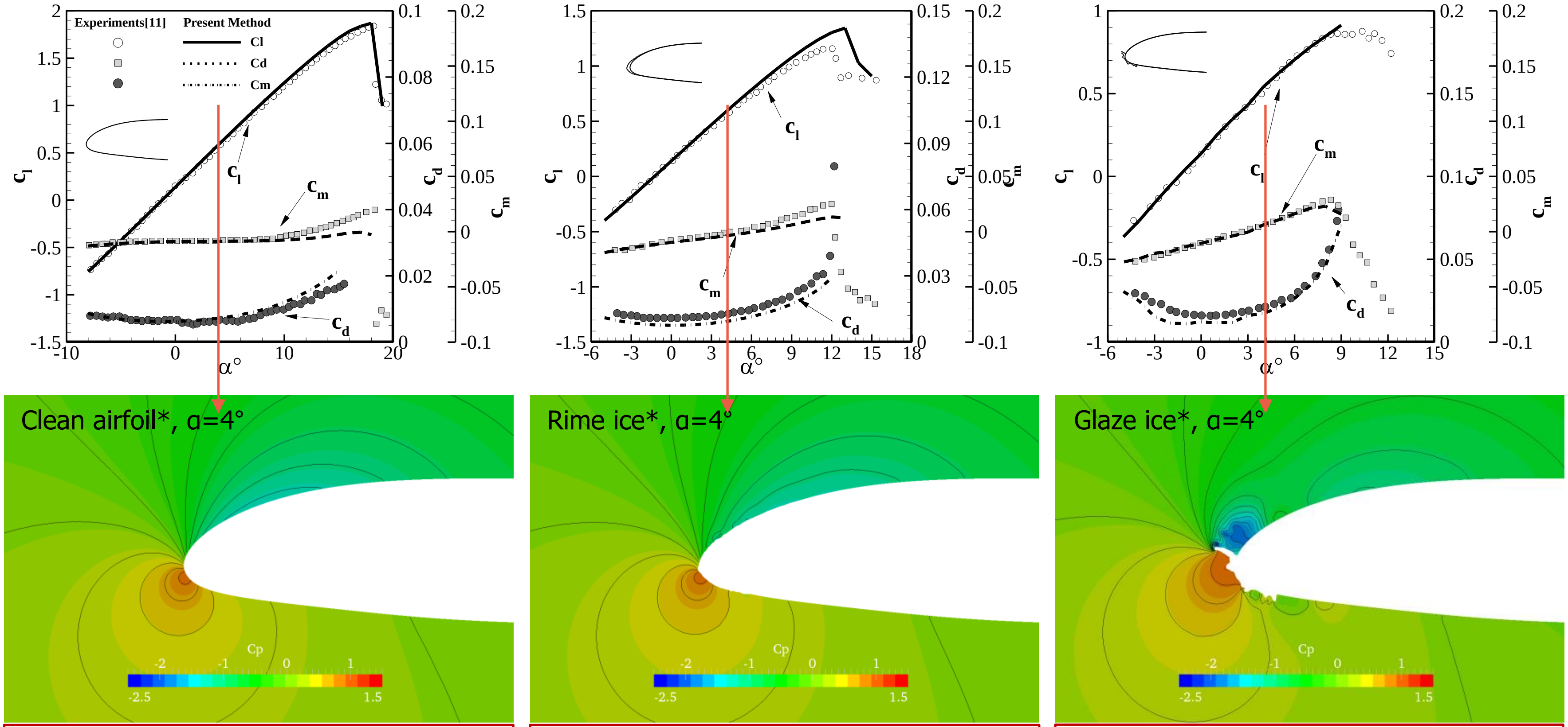
- Fixed wing aircraft
  - ✓ rhoPimpleFOAM(OpenFOAM-2.2.0)
    - Navier-Stokes based solver
    - Unsteady, compressible and turbulent flow
- Helicopter
  - ✓ Advanced actuator surface model coupled with rhoPimpleFOAM(OpenFOAM-2.2.0)
- 3D Eulerian approach
  - ✓ To calculate the droplet trajectories
- 3D water film approach
  - ✓ To calculate the mass of freezing ice
- 3D surface re-meshing

Aerodynamic Module



Fixed wing aircraft solver

- Validation results of aerodynamic solver

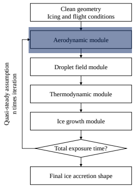


- Flow condition : M_∞=2.0, Re = 15.9 × 10^6, α=4°

- Icing Condition : α=2°, V_∞=77.2m/s, T_∞=-22.2°C, LWC=0.55g/m^3, MVD=30μm, time=10min
- Flow condition : M_∞=0.2, Re = 15.9 × 10^6, α=4°

- Icing Condition : α=5°, V_∞=90m/s, T_∞=-2.2°C, LWC=0.85g/m^3, MVD=20μm, time=11.3min.
- Flow condition : M_∞=0.2, Re = 15.9 × 10^6, α=4°

AERODYNAMIC MODULE

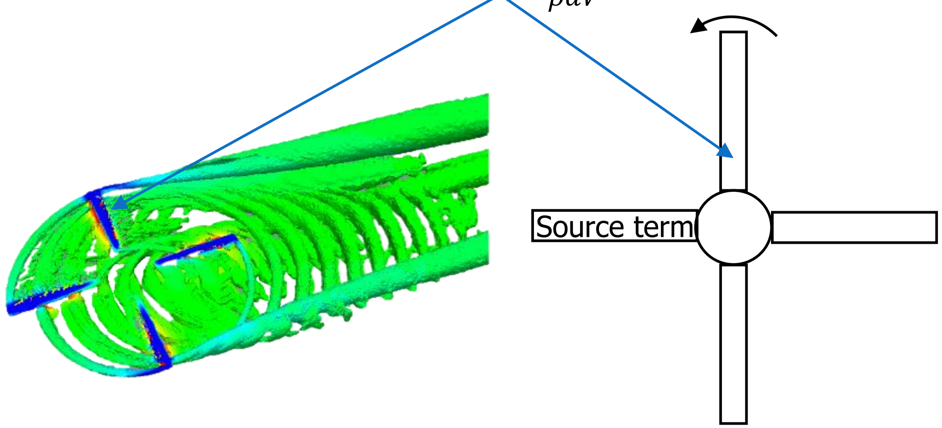


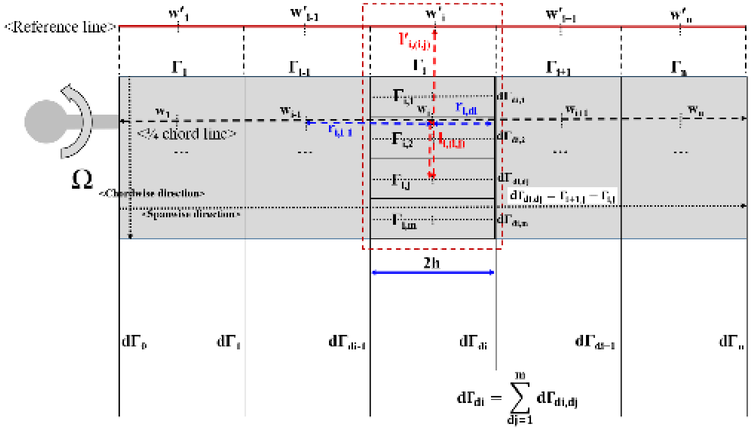
Rotary wing aircraft solver

- Actuator surface model(ASM)
  - ✓ CFD with BET based on improved actuator surface model is employed to solve the flow field and performance of the rotor
  - ✓ ASM treats the blade effects as a source term in the momentum equations
  - ✓ ASM can handle the generation of individual tip vortices and their behavior
  - ✓ The improved ASM based on the lifting line theory has been developed such that new method eliminates the unexpected induced velocity by the circulation, and estimates the spanwise variation of the circulation.

$$\frac{\partial \rho U}{\partial t} + \nabla \cdot (\phi U) - \nabla \cdot (\mu \nabla U) = S - \nabla p$$

$$S = \frac{dT}{\rho dV}$$



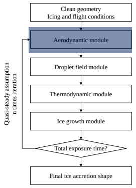


▲ Q criterion of wake for forward flight rotor

▲ Schematic representation of improved ASM method

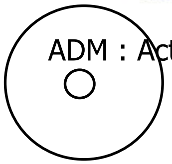
AERODYNAMIC MODULE

NACA0012
rectangular blade
$\mu = 0.15$
$C_T = 0.0063$
$\omega = 221$
$r = 0.86$
$AR = 13$
$\theta_{tw} = -13°$



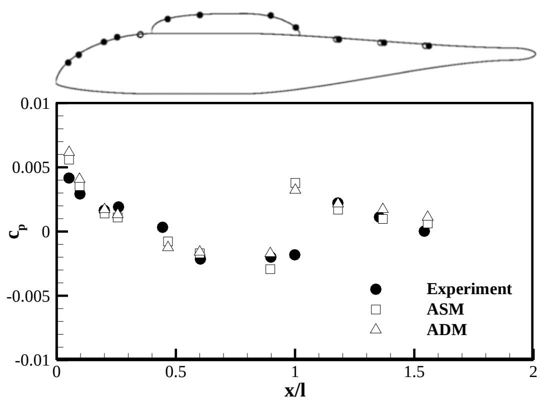
Rotor solver

- Validation results of actuator surface model
  - ✓ ASM shows higher accuracy than ADM due to handling the individual tip vortices and their behavior

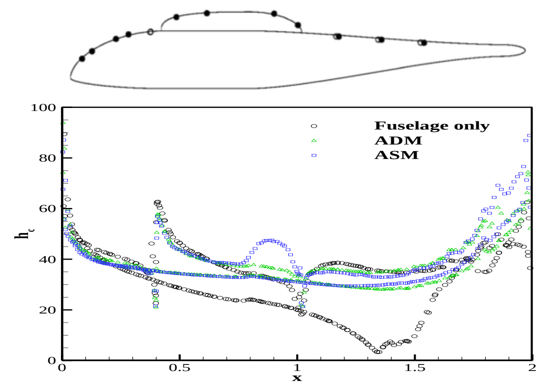


ADM : Actuator disk model

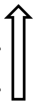
surface properties



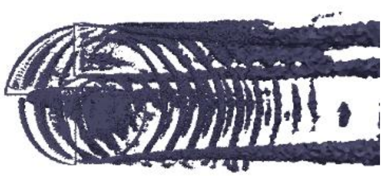
▲ Surface pressure distribution



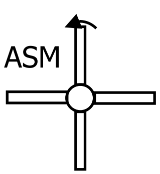
▲ Heat convection coefficient

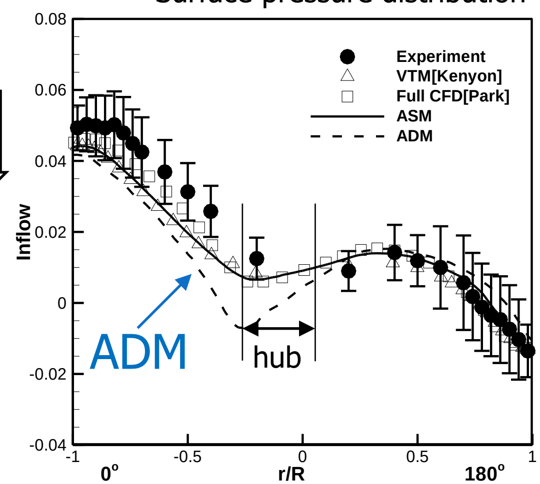


Field Properties

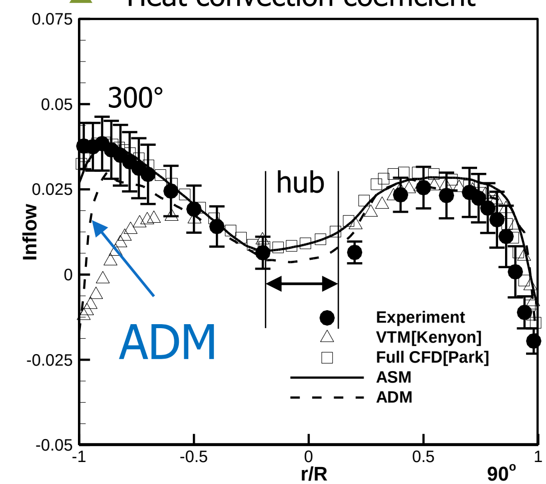


ASM





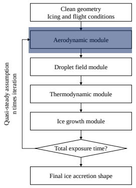
▲ longitudinal inflow distribution



▲ Lateral inflow distribution

Elliot, J., Althoff, S. L., Sailey, R., "Inflow Measurement Made with a Laser Velocimeter on a Helicopter Model in Forward Flight, Vol. 1. Rectangular Planform Blades at an Advance Ratio of 0.15," NASA TM 100541, 1987

AERODYNAMIC MODULE

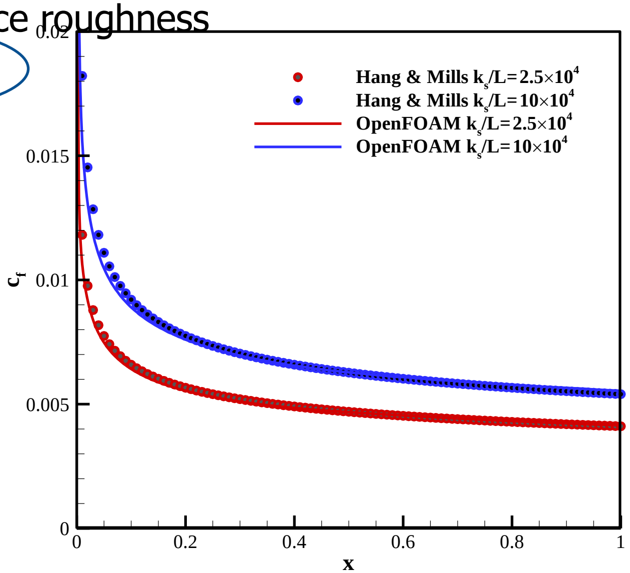


Turbulence model

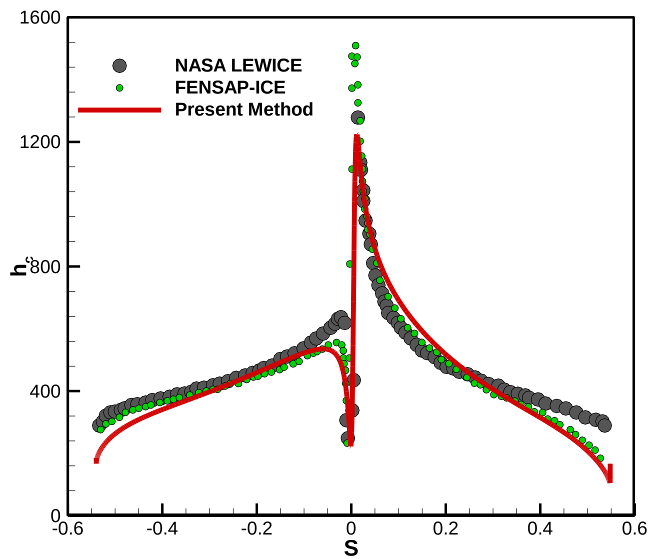
- Ice changes surface roughness(k_s)
  - ✓ Flow transition, skin friction and heat convection characteristics
  - ✓ NASA empirical correlation*, k_s=f(T,V,LWC,MVD)

Modified Spalart-Allmars(SA) for surface roughness

- Original SA model(Present method)
  - ✓ $\frac{\partial\tilde{\nu}}{\partial t} + u_j\frac{\partial\tilde{\nu}}{\partial x_j} = c_{b1}(1-f_{t2})\tilde{S}\tilde{\nu} - \left[c_{w1}f_w - \frac{c_{b1}}{\kappa^2}\right]\left(\frac{\tilde{\nu}}{d}\right)^2 + \frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}\left((\nu+\tilde{\nu})\frac{\partial\tilde{\nu}}{\partial x_j}\right) + c_{b2}\frac{\partial\tilde{\nu}}{\partial x_i}\frac{\partial\tilde{\nu}}{\partial x_i}\right]$
- Current Model : Surface roughness
  - ✓ $d = d_{wall} + 0.03k_s$
- Wall boundary
  - ✓ $\frac{\partial\tilde{\nu}}{\partial n} = \frac{\tilde{\nu}}{d_{new}}$
- Heat convection
  - ✓ $h_c = \frac{-(k_l+k_t)\partial T/\partial n}{T_s - T_\infty}$
  - ✓ $k_t = \frac{\mu_t c_p}{Pr_t}$



▲ Skin friction coefficient of roughened flat plate



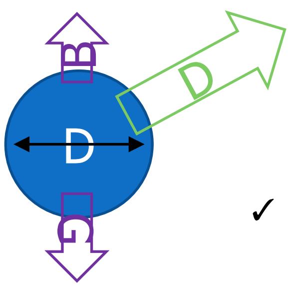
▲ Heat convection coefficient(right) at roughened airfoil

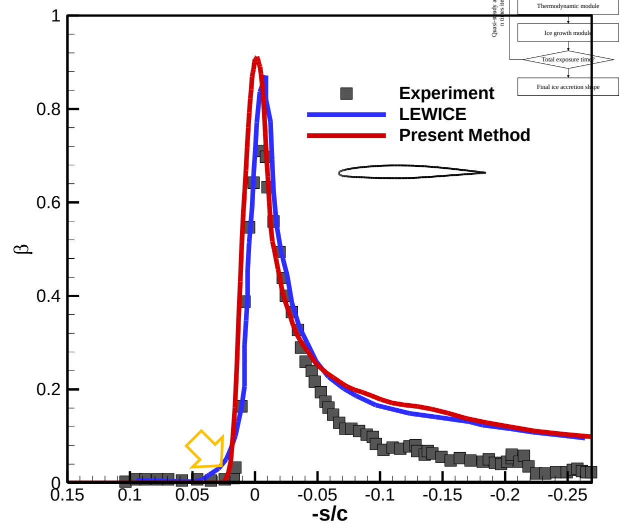
*Ruff, Gary A., and Brian M. Berkowitz. "Users manual for the NASA Lewis ice accretion prediction code (LEWICE)." (1990).

DROPLET FIELD MODULE

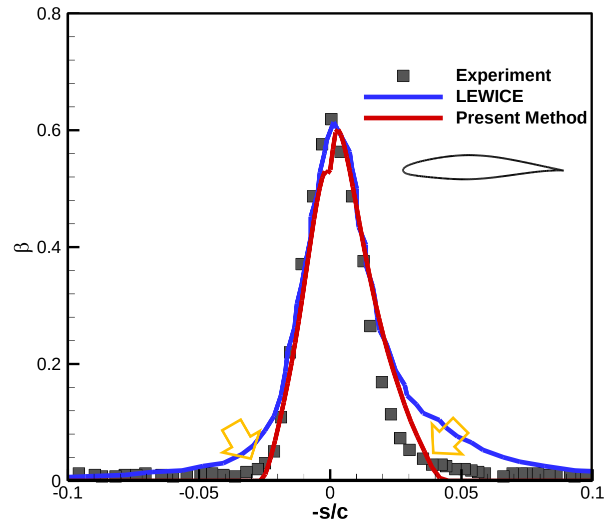
Eulerian method

- Eulerian approach is suitable for FVM(Finite Volume Method)
  - ✓ Same grid with aerodynamic solver
  - ✓ Shadow region is automatically calculated
- Droplet field is governed by mass and momentum conservation
  - ✓ Mass conservation
    - $\frac{\partial \bar{\rho}_d}{\partial t} + \nabla \cdot (\bar{\rho}_d \vec{u}_d) = 0$
      - $\bar{\rho}_d = \alpha \rho_w$
      - $\bar{\rho}_d$: bulk density, α : volume fraction
  - ✓ Momentum conservation
    - $\frac{\partial \bar{\rho}_d \vec{u}_d}{\partial t} + \nabla \cdot (\bar{\rho}_d \vec{u}_d \vec{u}_d) = \underbrace{\frac{3}{4}\frac{\bar{\rho}_d \mu_a C_D Re_d}{\rho_w MVD^2}(\vec{u}_a - \vec{u}_d)}_{\text{drag}} + \underbrace{\bar{\rho}_d \vec{g}\left(1 - \frac{\rho_a}{\rho_w}\right)}_{\text{gravity, and buoyancy}}$
    - $C_D = 24/Re_d\left(1 + 0.197 Re_d^{\,0.63} + 2.6 \times 10^{-4} Re_d^{\,1.38}\right)$
  - ✓ Collection efficiency
    - Nondimensional parameter how many droplet particles impinging to the surface
    - $\beta = \frac{\bar{\rho}_d \vec{u}_d \cdot \vec{n}}{LWC \cdot U}, \quad \dot{m}_{com} = \beta \cdot LWC \cdot U \cdot dA \left[\frac{\text{kg}}{\text{m}^2 \cdot \text{s}}\right]$





▲ Collection efficiency of GLC305*

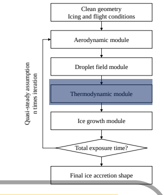


▲ Collection efficiency of NACA64A014*

*MVD : Mean Volumetric droplet Diameter *LWC : Liquid Water Contents

*Papadakis, M., Hung, K. E., Vu, G. T., Yeong, H. W., Bidwell, C. S., Breer, M. D., and Bencic, T. J., *Experimental Investigation of Water Droplet Impingement on Airfoils, Finite Wings, and an S-Duct Engine Inlet*, NASA Technical Memorandum, 2002.

THERMODYNAMIC MODULE



Water film model with phase change

- Mass conservation ---------- 2 Unknowns : $h_f, \dot{m}_{ice}$
  - ✓ ① Water film, ② Run in and out(runback water), ③ Impinging water, ④ Accumulating ice
  - ✓ $\rho_w \left[\int \frac{\partial h_f}{\partial t} dV + \int \nabla \cdot (h_f \bar{U}_f) dV \right] = \dot{m}_{com} - \dot{m}_{ice}$

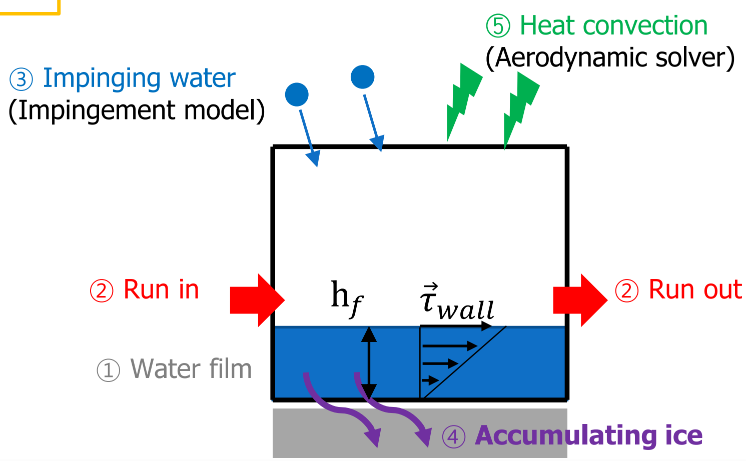
    ① ② ③ ④

- Energy conservation ---------- 3 Unknowns : $h_f, \dot{m}_{ice}, \tilde{T}_{eq}$
  - ✓ ① Water film, ② run in and out(runback water), ③ Impinging water, ④ Accumulating ice, ⑤ Heat convection
  - ✓ $\rho_w \left[\int \frac{\partial h_f c_{p,w} \tilde{T}_{eq}}{\partial t} dV + \int \nabla \cdot (h_f c_{p,w} \tilde{T}_{eq} \bar{U}_f) dV \right] = \dot{m}_{com} \left[c_{p,w} \tilde{T}_{d,\infty} + \frac{1}{2} U_d^2 \right] + \dot{m}_{ice} \left[L_{fus} - c_{p,i} \tilde{T}_{eq} \right] + h_c (T_{eq} - T_\infty)$

    ① ② ③ ④ ⑤

→ Momentum conservation ---------- $\bar{U}_f = f(h_f)$

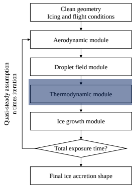
- ✓ $\bar{U}_f = f(h_f) = \frac{1}{h_f} \int_0^{h_f} u_f dh = \frac{h_f}{2\mu_w} \vec{\tau}_{wall}$



Compatibility relations

- Unknowns : h_f, $\tilde{T}_{eq}$, $\dot{m}_{ice}$
- 2 Equations : Mass and energy conservation
  - ✓ Not enough to determine the unknowns
  - ✓ **Additional compatibility relations** are required

THERMODYNAMIC MODULE



3 compatibility relations

- Compatibility relations are based on physical observations : water freezes at 0°C

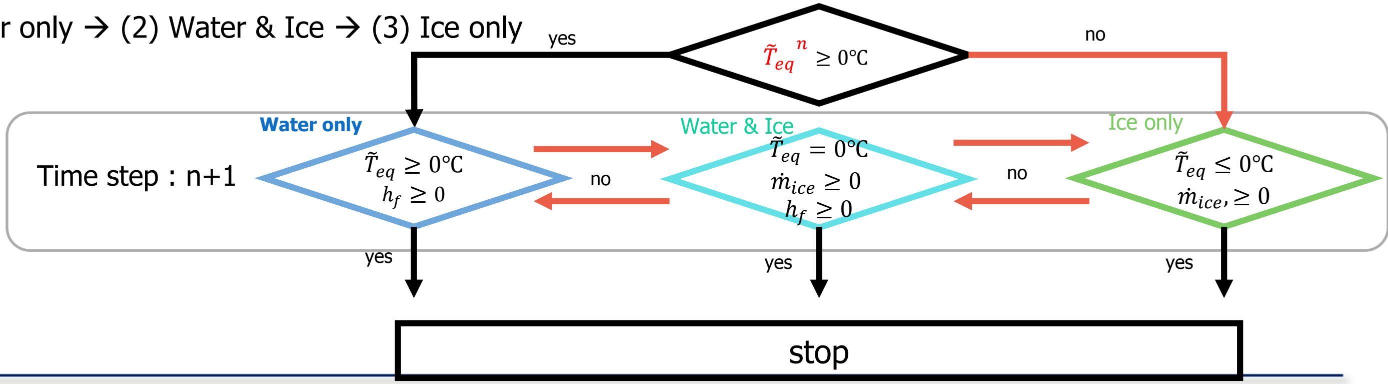
✓ Water only : $\dot{m}_{ice'} = 0,\ \tilde{T}_{eq} \geq 0°C,\ h_f \geq 0$

✓ Water & Ice : $\dot{m}_{ice'} \geq 0,\ \tilde{T}_{eq} = 0°C,\ h_f \geq 0$

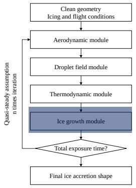
✓ Ice only : $\dot{m}_{ice'} \geq 0,\ \tilde{T}_{eq} \leq 0°C,\ h_f = 0$

Time step : n+1

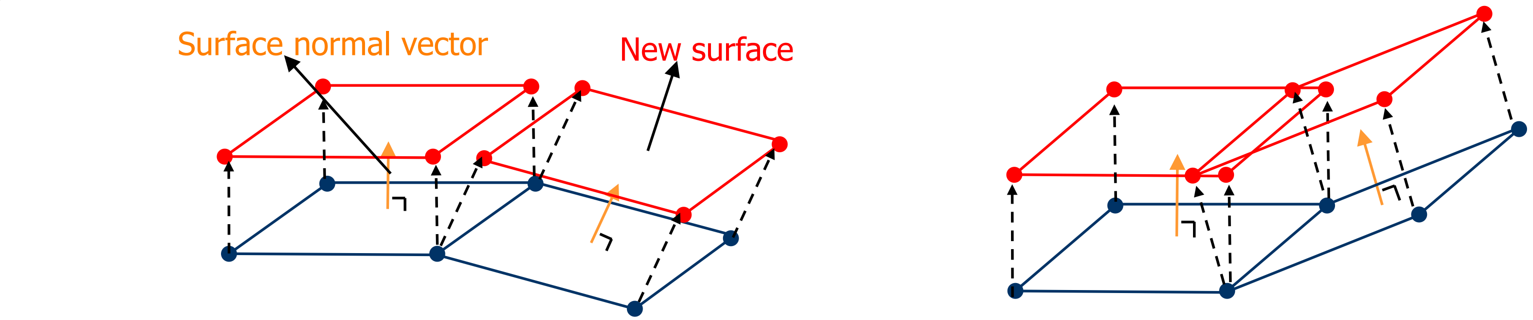
- 1 unknown determined → the other 2 unknowns explicitly calculated
- Apply each surface condition at each surface cell and check the compatibility relations
- From the surface temperature of previous time step($\hat{T}_{eq}{}^{n}$), application order is determined
  - ✓ If $\tilde{T}_{eq}{}^{n} < 0°C$
    - (3) Ice only → (2) Water & Ice → (1) Water only
  - ✓ Else if $\tilde{T}_{eq}{}^{n} \geq 0°C$
    - (1) Water only → (2) Water & Ice → (3) Ice only

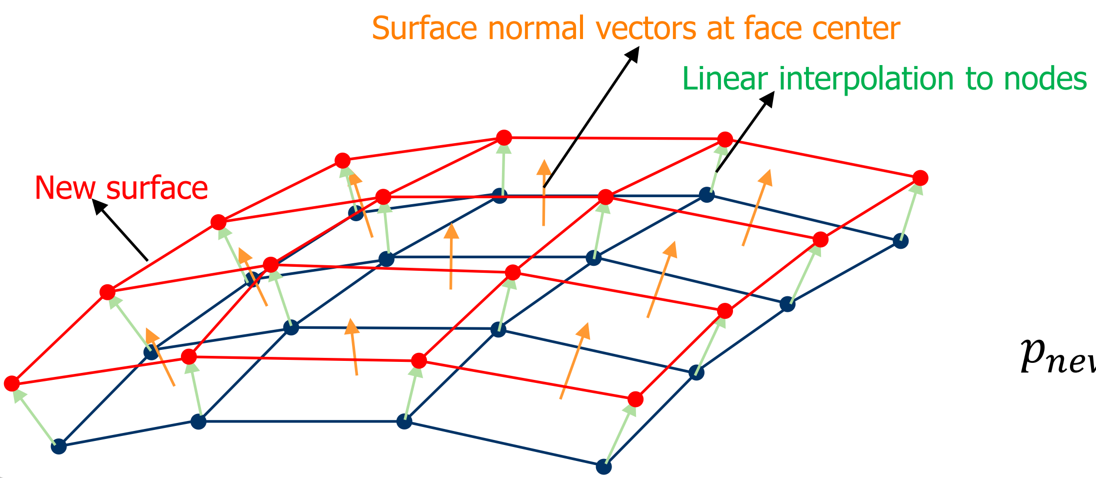


ICE GROWTH MODULE



- 3D grid generation
  - Linear interpolation from face to point
    - ✓ Face values : ice thickness, surface normal vector
  - Update surface geometry and re-meshing





$$h_t = \frac{\dot{m}_{ice}\Delta t}{\rho_{ice} A_{sur}}$$

$$p_{new}(x,y,z) = p(x,y,z) + h_t \vec{n}$$

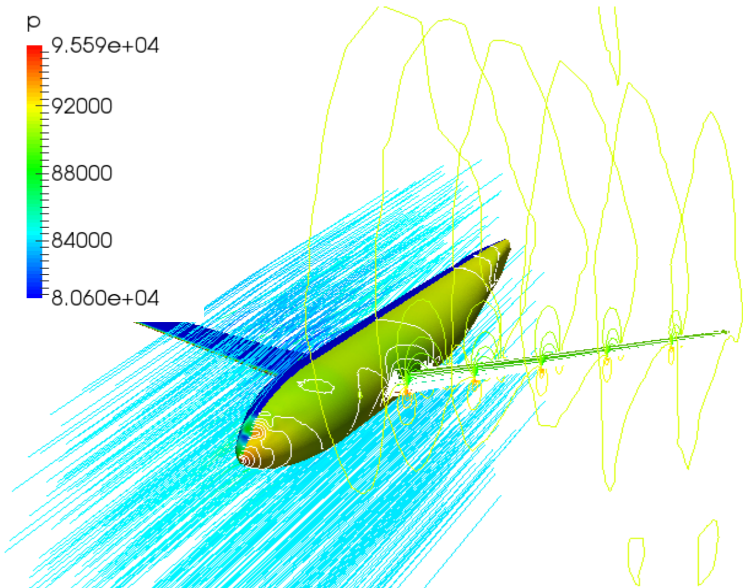
VALIDATION

3D AIRCRAFT : WING + FUSELAGE

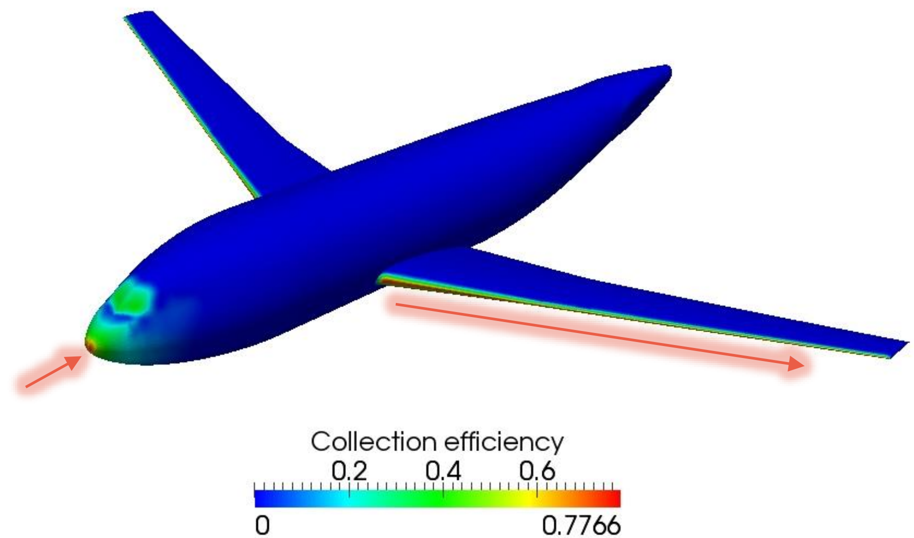
VALIDATION : FIXED WING AIRCRAFT

DLR-F6 Wing + Fuselage

- Aerodynamic solver
  - ✓ Surface pressure and pressure contour



- Impingement model
  - ✓ Collection efficiency and droplet trajectory

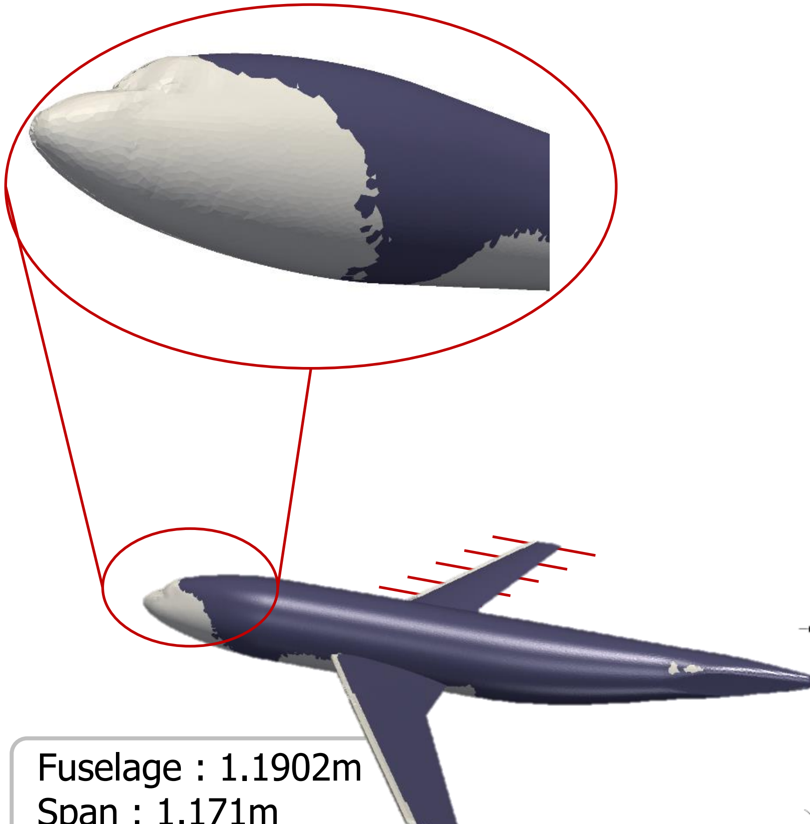


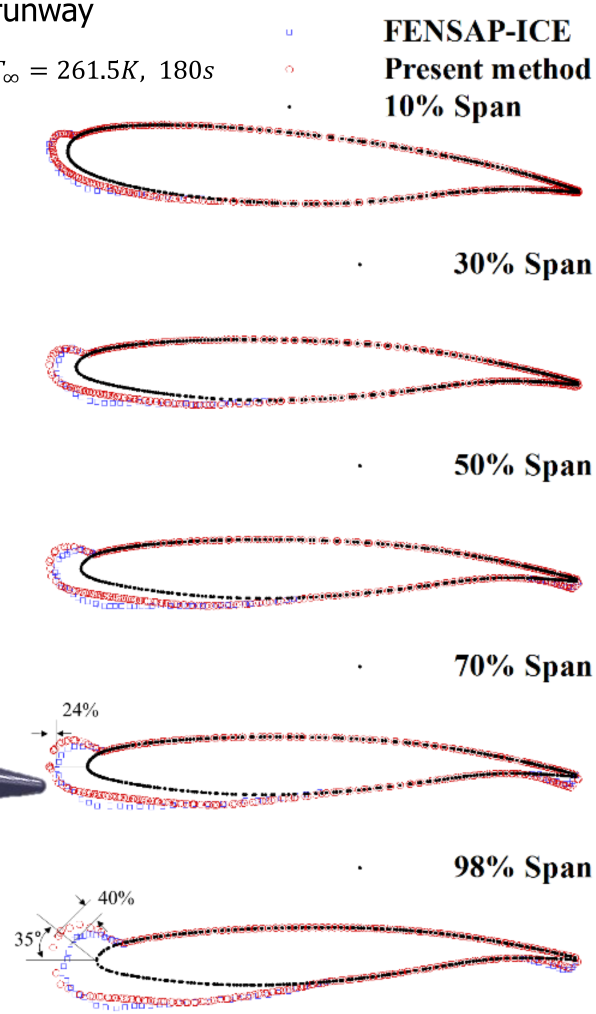
- Glaze ice conditions with approaching speed
  - ✓ $\alpha = 6, M_\infty = 0.235, LWC = 1.0\frac{g}{m^3}, T_\infty = 261.5K, 180s$
- Maximum location of collection efficiency
  - ✓ Nose of fuselage and leading edge of wing root
  - ✓ Along the leading edge, high value of collection efficiency
- $0 < \beta < 0.78$: The rage of collection efficiency in general airfoils

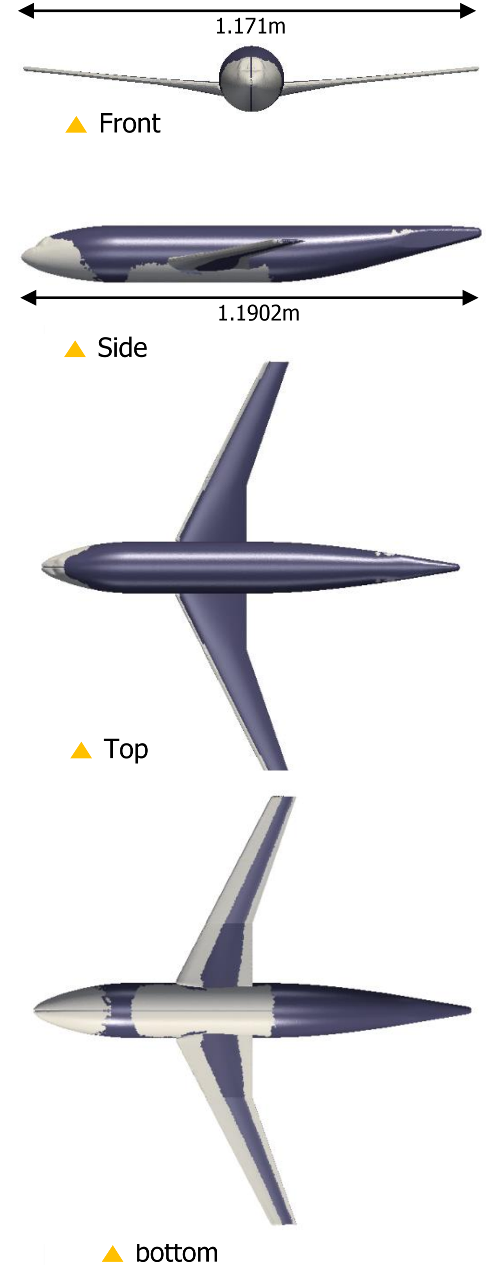
VALIDATION : FIXED WING AIRCRAFT

DLRF6 : Wing + Fuselage

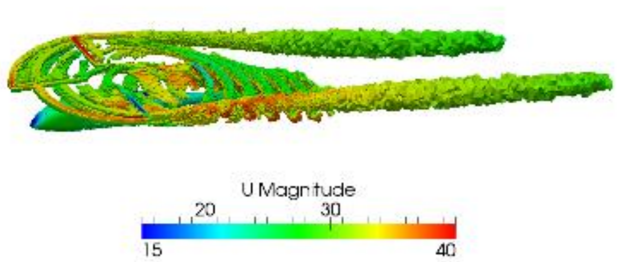
- Assume the approaching stage to the runway
  - ✓ $\alpha = 6°,\ M_\infty = 0.235,\ LWC = 1.0\frac{g}{m^3},\ T_\infty = 261.5K,\ 180s$

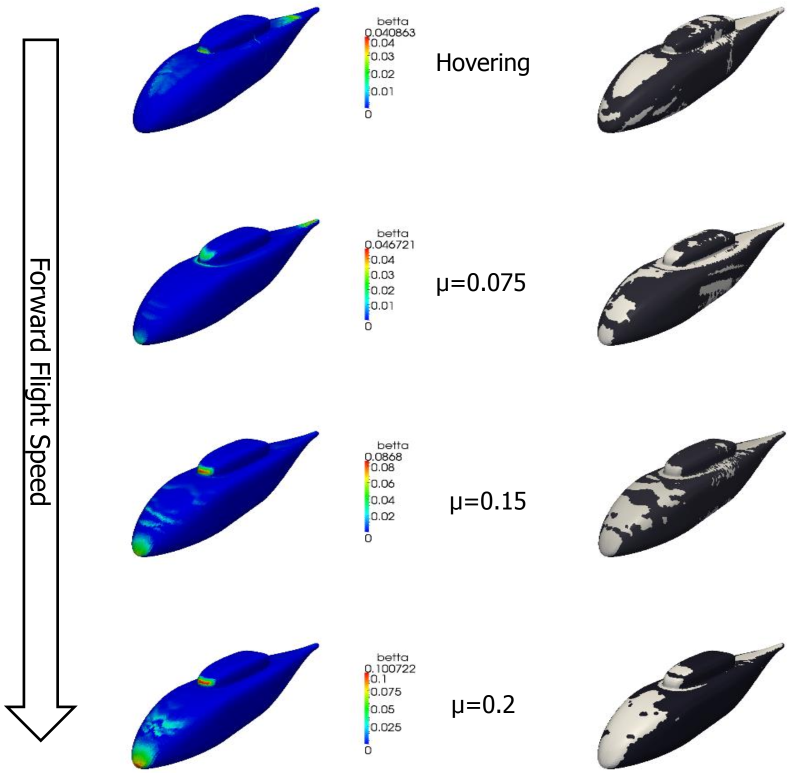






Fuselage : 1.1902m
Span : 1.171m
Icing Time : 180s
Total ice mass : 87.2g





REPRESENTATIVE APPLICATIONS

1. HELICOPTER FUSELAGE ICING

2. HALE(HIGH-ALTITUDE LONG-ENDURANCE) ICING

1. Helicopter Fuselage Icing

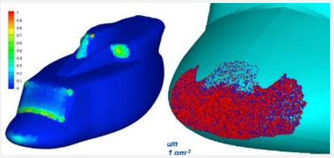
Motivation

- Numerical and experimental studies have been conducted without rotor effects for the fuselage icing
  - ✓ Numerical studies : Both reliable rotor and icing solvers are required
  - ✓ Experiment : including rotor for the icing analysis is technically difficult
- Previous studies maily focus on the high forward flight speed (μ>0.15)
  - ✓ Hover and low forward flight speed condition require efficient flow solver

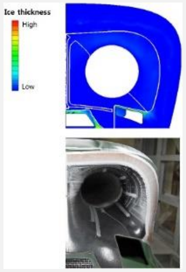
Goals of this study

- Check the validity of the isolated fuselage icing research
  - ✓ Comparison of ice shapes on isolated rotor and rotor-fuselage interaction cases
- Analyze various forward flight speed effects on fuselage icing
  - ✓ Hovering, low and high speed forward flight

[Fuselage only]

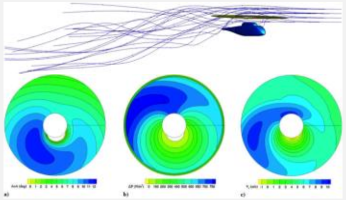


▲ Szilder, K(2007)



▲ Ahn, G. B. (2015)

[High forward flight speed]



▲ Fouladi, H.(2013)

Szilder, K., "Numerical Simulation of Ice Formation on a Helicopter Fuselage," SAE Technical Paper 2007-01-3308, 2007, doi:10.4271/2007-01-3308.
Ahn, G. B., et al. "Numerical and Experimental Investigation of Ice Accretion on Rotorcraft Engine Air Intake." *Journal of Aircraft* 52.3 (2015): 903-909.
Fouladi, H., Habashi, W. G., and Ozcer, I. A., "Quasi-Steady Modeling of Ice Accretion on a Helicopter Fuselage in Forward Flight," Journal of Aircraft, vol. 50, Jun. 2013, pp. 1169–1178.

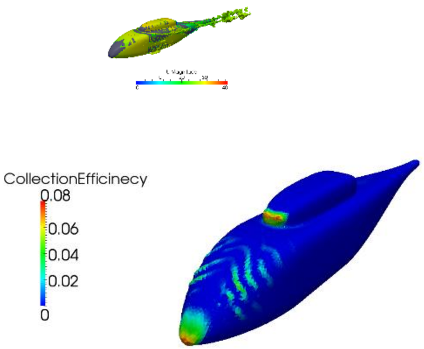
1. Helicopter Fuselage Icing

Helicopter fuselage icing

- $\mu = 0.15, U_{\infty} = 27m/s, LWC = 0.6g/m^3, MVD = 20\mu m, T_{\infty} = -10°C$, 30min, ROBIN(2m)
- Comparison of collection efficiency and ice accretion shapes with and without rotor
  - ✓ Total mass of ice and ice distribution are different between ◀Fuselage only and Rotor+fuselage▶ case

◀Fuselage only

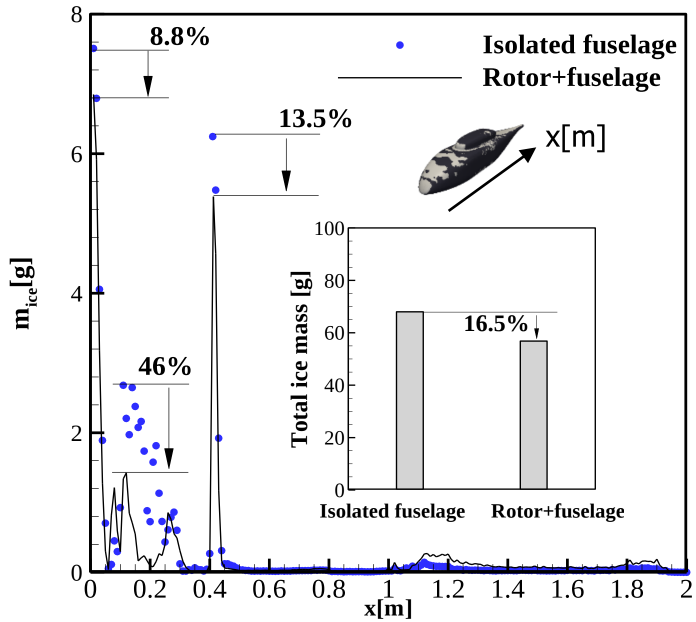
Rotor+fuselage▶



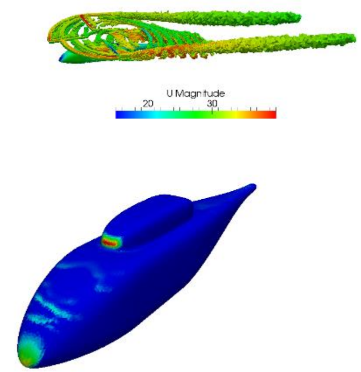
▲ Collection efficiency

▲ Ice shape

Ice mass : 68.0 g



▲ Mass distribution



▲ Collection efficiency

▲ Ice shape

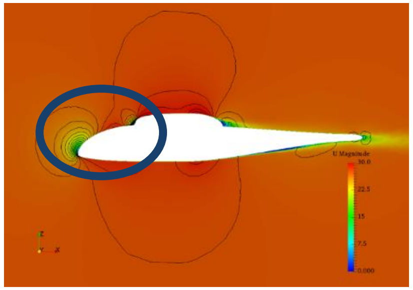
Ice mass : 56.8 g (16.5%↓)

1. HELICOPTER FUSELAGE ICING

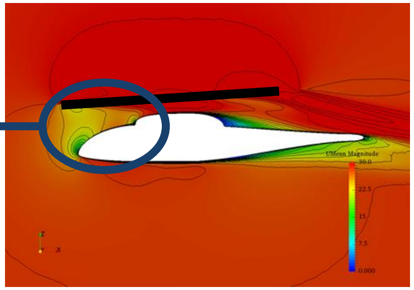
Droplet behavior

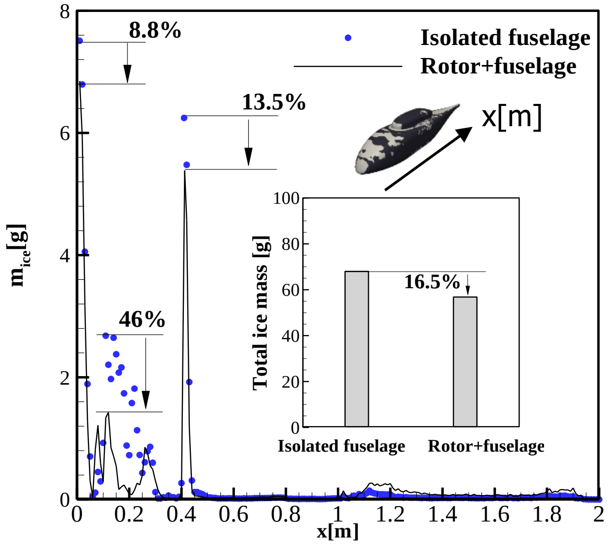
- Why is the isolated fuselage case heavier than rotor+fuselage case?
- $K = \frac{\rho_w V_\infty MVD^2}{18\mu c}$: Droplet inertia parameter
  - ✓ $K\downarrow$: $V_{air}\downarrow$, $MVD\downarrow$, $c\uparrow$
    - Low velocity region is generated by the rotor between the rotor and fuselage
      - Rotor + fuselage : 12~17m/s
      - Fuselage only : 22m/s
    - Low-inertia particles avoid the fuselage like streamline of air
- The amount of ice accumulated on the overall fuselage with the rotor-fuselage interaction is less than that on isolated fuselage
- In full scale helicopter($c\uparrow$), the difference between isolated fuselage and rotor+fuselage cases because of low droplet inertia parameter ($K\downarrow$)
- Rotor wake effects should be considered in low-speed forward flight, a small droplet size, and full scale helicopter

Fuselage only ▶



Rotor+fuselage ▶



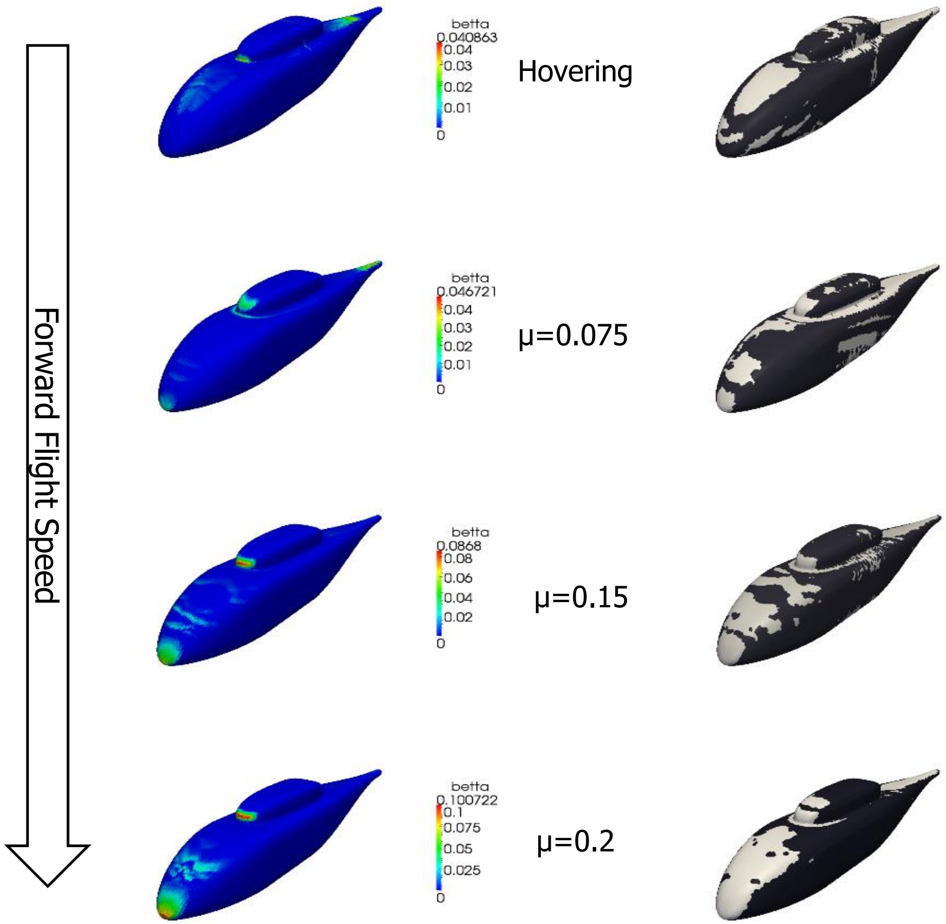


▲ Mass distribution

1. Helicopter Fuselage Icing

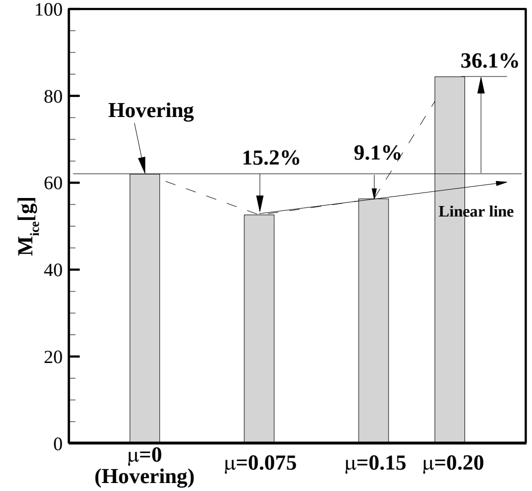
Effects of forward flight speed

- $LWC = 0.6g/m^3, MVD = 20\mu m, T_\infty = -10°C$, 30min, ROBIN(2m)

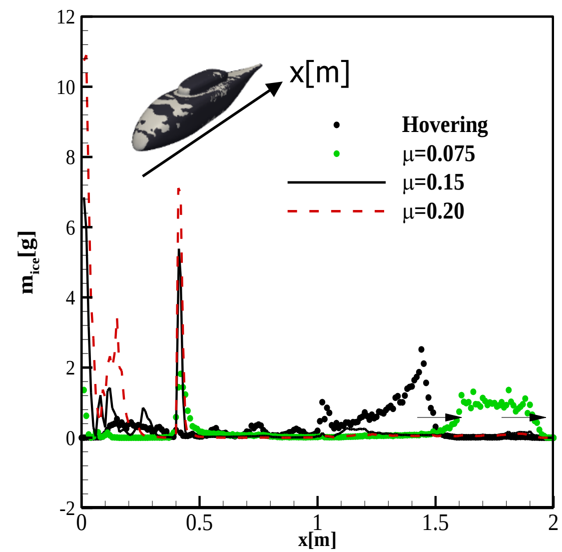


▲ Collection efficiency

▲ Ice accretion shapes



▲ Total mass of ice

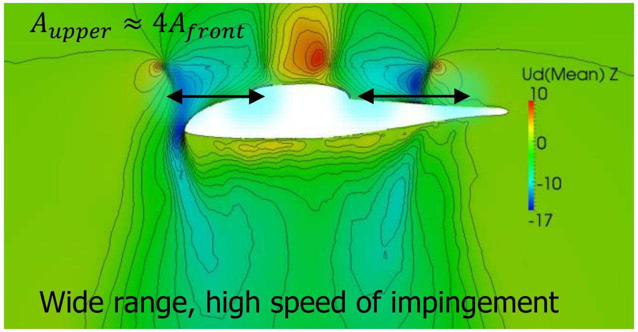


▲ Mass distribution

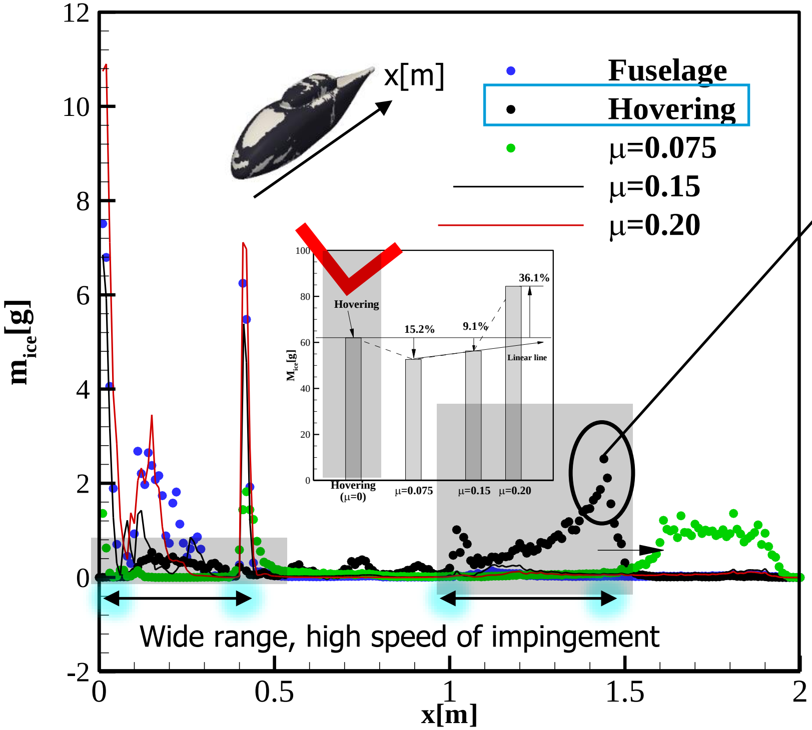
1. HELICOPTER FUSELAGE ICING

Hovering

- The 2nd largest ice accumulation in hover
  - ✓ Wide range and high speed of impingement
    - Area : $A_{upper} \approx 4A_{front}$
    - Impinging speed of droplet ≈ forward flight speed at μ=0.075
- Maximum ice at tip vortex and fuselage interaction point

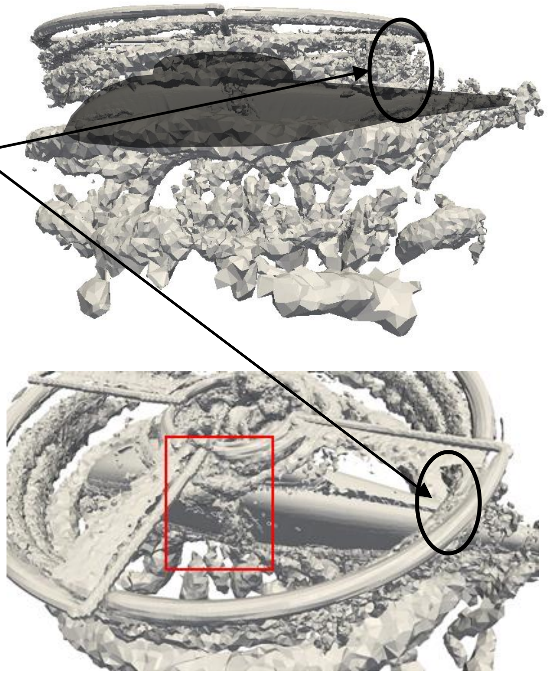


▲ Droplet field velocity



▲ Mass distribution

Tip vortex and fuselage interaction

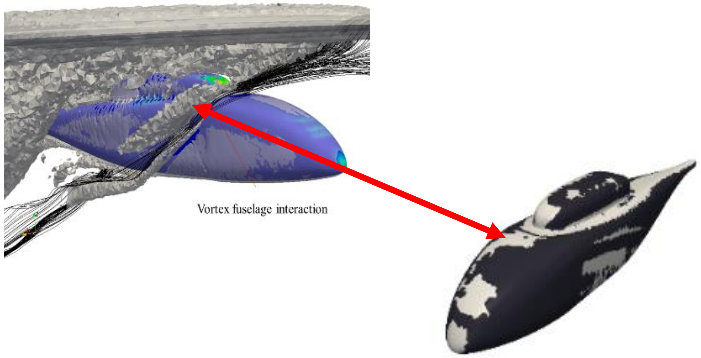


▲ Q = 1000 for hovering

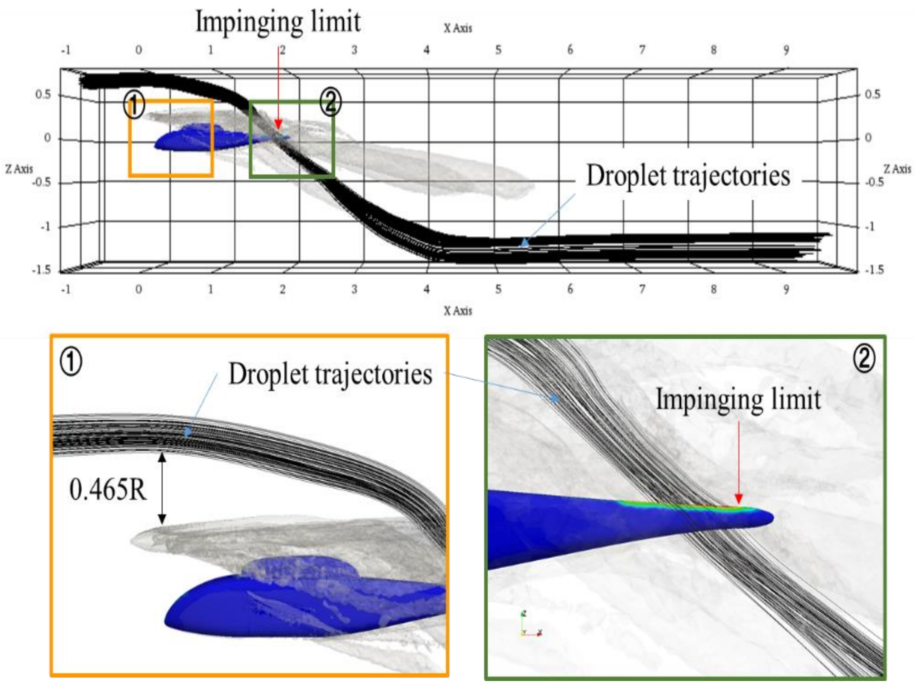
$LWC = 0.6g/m^3$, $MVD = 20\mu m$, $T_\infty = -10°C$, 30min, ROBIN(2m)

1. Helicopter Fuselage Icing

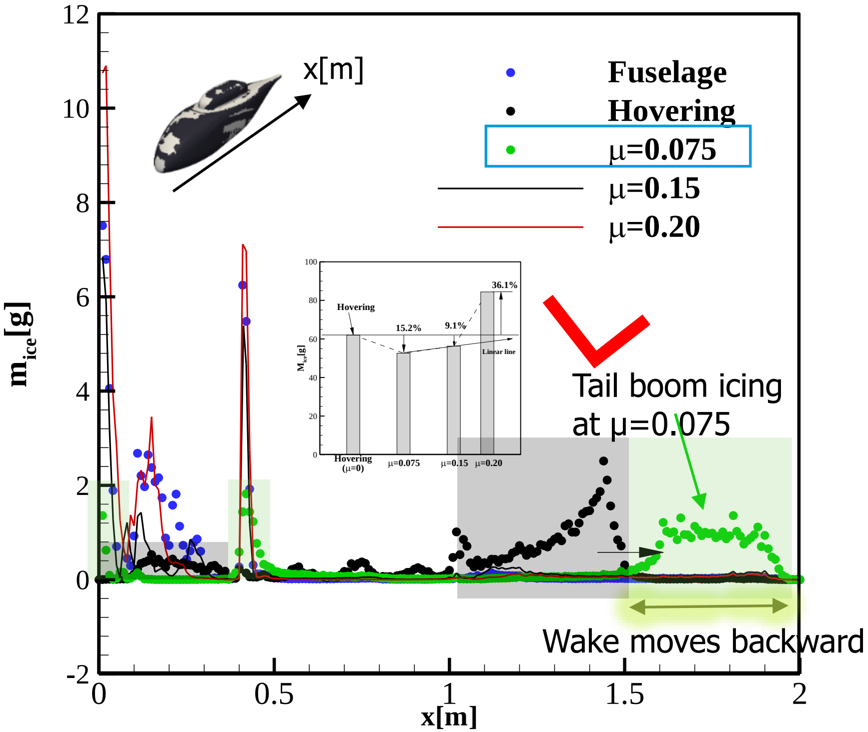
- Low speed forward flight(μ=0.075)
  - Most ice is accumulated on the tail boom icing because wake moves backward
  - Due to the tip vortex and fuselage interaction, asymmetric icing occurs in front of engine intake



▲ Fuselage and tip vortex interaction



▲ Droplet trajectories under rotor wake effects

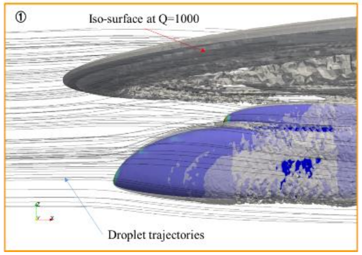


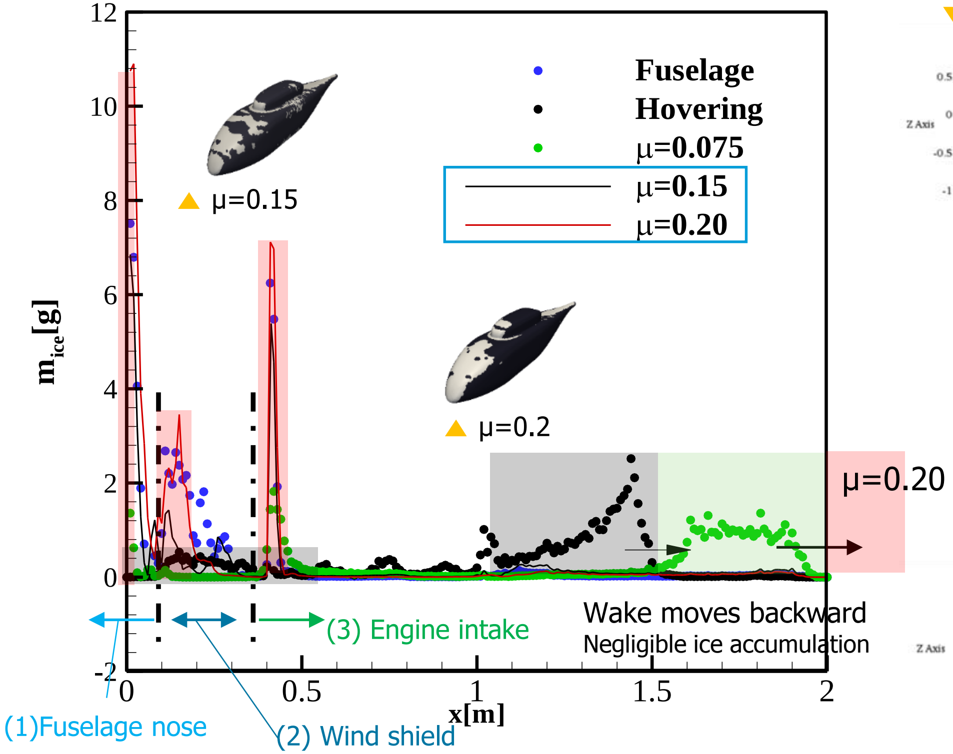
$LWC = 0.6g/m^3, MVD = 20\mu m, T_\infty = -10°C$, 30min, ROBIN(2m)

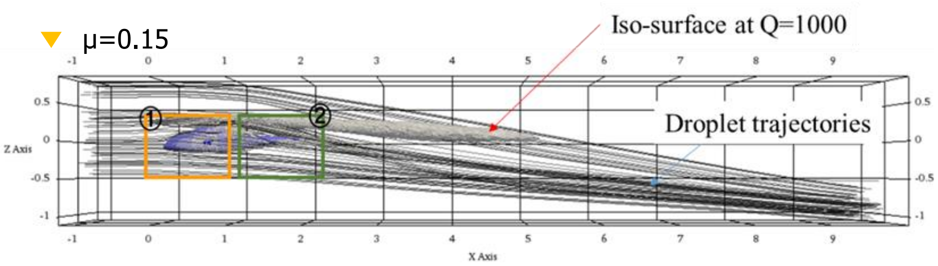
1. HELICOPTER FUSELAGE ICING

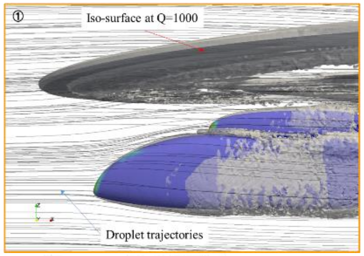
High speed forward flight(μ=0.15, μ=0.20)

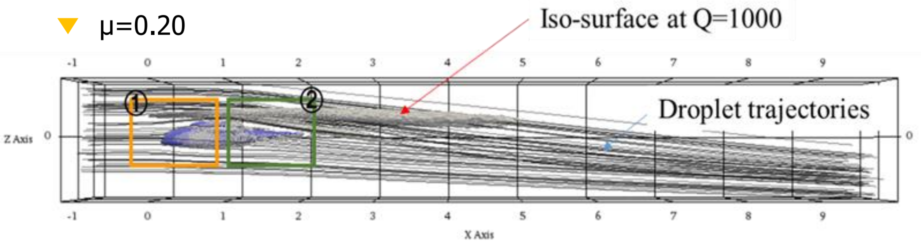
- In high speed forward flight, fuselage and wake contraction is negligible
  - ✓ The wake moves backward → Negligible ice accumulation on the tail boom
  - ✓ Particle path lines are parallel to the fuselage after the rotor hub
- Most of the particles impact on the front of fuselage
  - ✓ (1) Fuselage nose, (2) Wind shield, (3) Engine intake











$LWC = 0.6g/m^3, MVD = 20\mu m, T_\infty = -10°C$, 30min, ROBIN(2m)

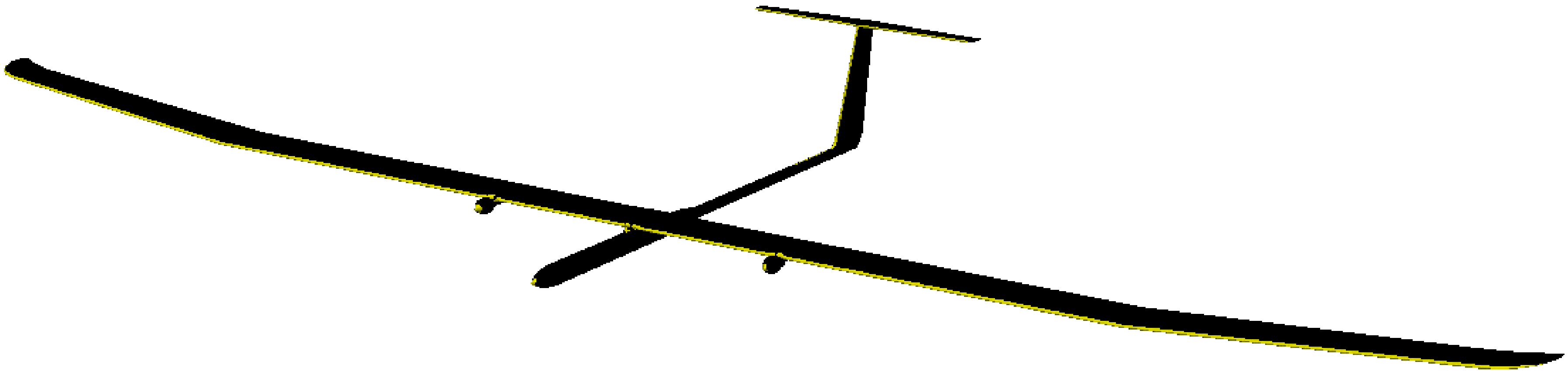
SUMMARY OF HELICOPTER FUSELAGE ICING

Check the validity of the isolated fuselage icing research

- Comparison of helicopter fuselage icing with and without rotor
  - ✓ Total ice mass and ice distribution vary with respect to the existence of rotor-body interation
  - ✓ The rotor produced high pressure and low velocity region where the drag force on droplets declined. Consequently, droplets avoided the fuselage which reduced the mass of freezing ice in the rotor-fuselage interaction case

Forward flight speed effects on fuselage icing shapes

- Total ice mass and ice distribution are different with respect to the forward flight speed
  - ✓ Hovering, low-speed forward flight
    - Massive ice accumulated on the tail boom due to inflow
  - ✓ High speed forward flight
    - Fuselage nose, engine intake and wind shield icing due to forward flight speed
  - ✓ The 2nd largest ice accumulation in the hovering
    - To estimate the required power for anti/de-icing devices, hovering condition should be considered



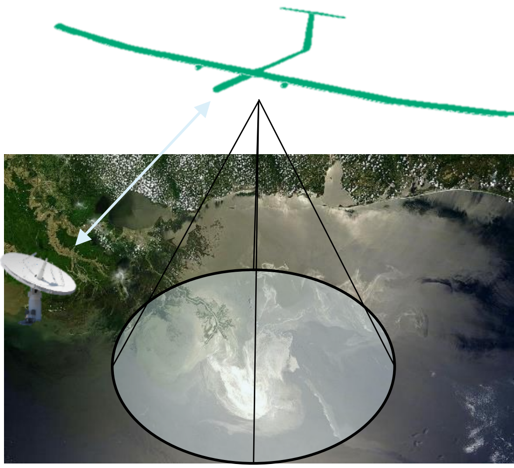
REPRESENTATIVE APPLICATIONS

1. HELICOPTER FUSELAGE ICING
2. HALE(HIGH-ALTITUDE LONG-ENDURANCE) ICING

INTRODUCTION OF HALE ICING

HALE(High-Altitude Long Endurance) aircraft

- Definition of HALE
  - ✓ 'High-Altitude' means that a UAV can climb above 10km
  - ✓ 'Long Endurance' can be airborne for 24 hours or longer
- Main merits of HALE
  - ✓ High mission capabilities
    - Broadcasting service
    - Real-time disaster observation
    - Intelligence collection
    - Communications links (cell phone/internet/broadcasting)
  - ✓ Lower acquisition and operating cost than satellites
    - Research agencies, and aircraft manufacturers + IT companies
      - Research agencies : NASA(Helios), QinetiQ(Zephyr)
      - Manufacturer : Boeing(phantom eye), Northrop Grumman(Global Hawk)
      - IT company : Facebook, Google
- The renewed interest in the development and operation of HALEs



▲ Application example of HALE at oil leakage accident

▲ Research agencies

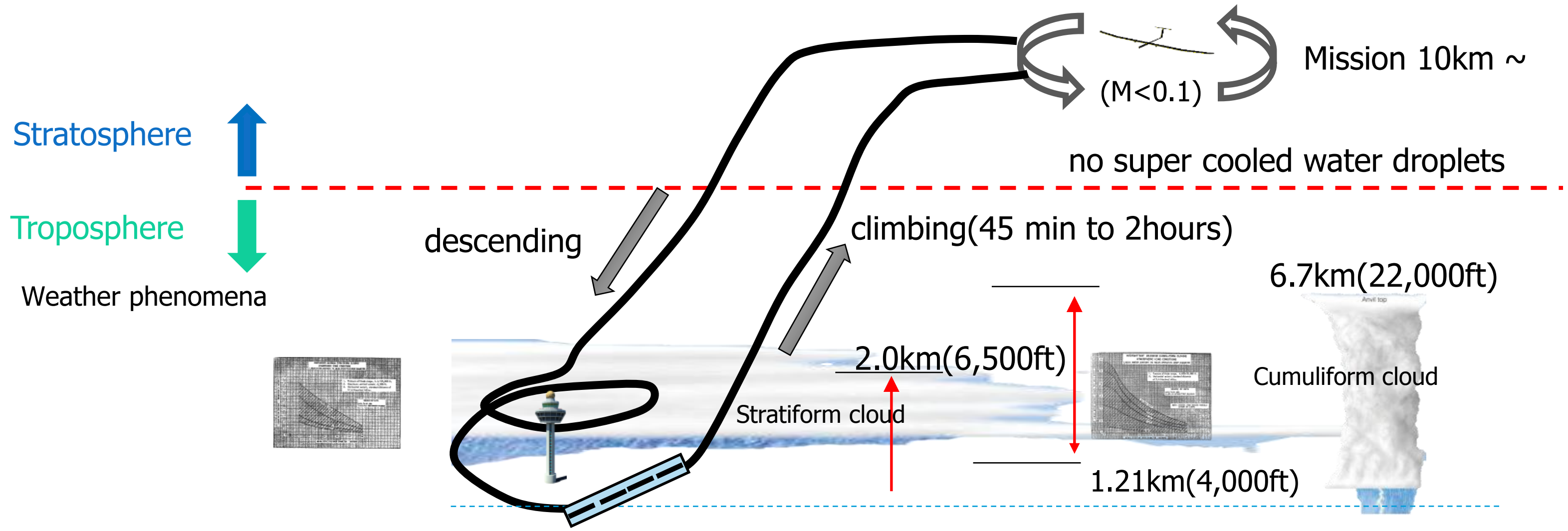
▲ Aircraft manufacturers

▲ IT company

*Peck, Lindamae, Charles C. Ryerson, and Courtland James Martel. *Army aircraft icing*. No. ERDC/CRREL-TR-02-13. ENGINEER RESEARCH AND DEVELOPMENT CENTER HANOVER NH COLD REGIONS RESEARCH AND ENGINEERING LAB, 2002.

INTRODUCTION OF HALE ICING

- Aircraft Icing → the major constraint of all-weather capability
  - Icing phenomenon during HALE mission
    - ✓ Typical mission profile of HALE
      - Take off → climbing → mission (over 10km) → descending → landing
        - Stratosphere : No weather phenomena (no water droplets) and low level of turbulence
        - Troposphere : HALE can encounter icing conditions in climbing and descending stage
  - Technical Issues related with HALE icing
    - ✓ Long exposure time in icing conditions without anti/de-icing devices
      - Low rate of climb and ultra-light design
    - ✓ Once accretes → Endurance ↓, stability ↓, propulsion efficiency ↓, mass ↑, improper radio communications
  - The major issue of the HALE operator, 'Whether to operate now or wait?'



2. HALE(HIGH-ALTITUDE LONG-ENDURANCE) ICING

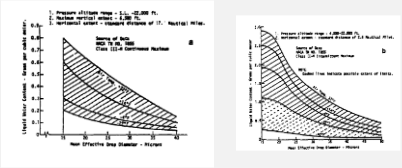
Motivation

- Necessity for the criteria based on the performance evaluation under icing conditions; whether the HALE can perform the mission or not
  - ✓ Meteorological conditions → ice accretion shapes → aerodynamic performance → decision making
    - Gathered information is meteorological parameters such as humidity, temperature, and so on
    - Previous HALE icing studies focused on the prediction of ice accretion shapes
    - The quantitative correlation between the meteorological icing parameters and performance degradation

Goals

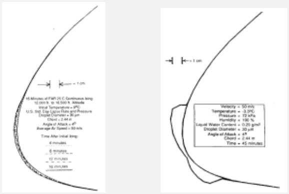
- Suggestion of methodology to identify the icing conditions which the HALE mission is successfully performed
  - ✓ STEP1 : Set up the icing conditions based on the typical mission profile of HALE
  - ✓ STEP2 : Predict the 3D ice accretion shapes on the HALE and its performance
  - ✓ STEP3 : Construct the regression analysis model (meteorological conditions ←→ aerodynamic performance)
  - ✓ STEP4 : Evaluate the aerodynamic performance and the success or failure of the mission

[Investigation of meteorological conditions]

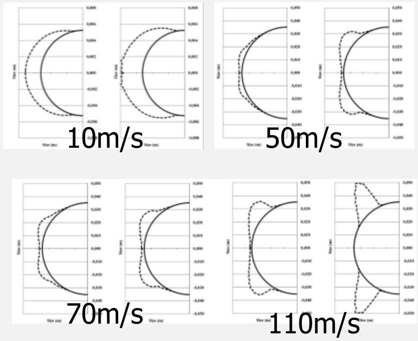


▲ Vogel, G. N.(1988)

[prediction of ice accretion shapes]



▲ Iya, S. K., and Cook D.E. (1991)



▲ BOTTYÁN, Z. (2013)

Hall, D. W., Fortenbach, C.D., Dimiceli, E.V., and Parks, R.W., "A Preliminary Study of Solar Powered Aircraft and Associated Power Trains," NASA CR-3699, December 1983.

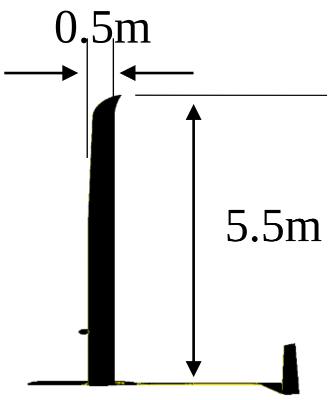
Vogel, Gerard N. Icing Considerations for HALE (High Altitude, Long Endurance) Aircraft. No. NEPRF-TR-88-11. NAVAL ENVIRONMENTAL PREDICTION RESEARCH FACILITY MONTEREY CA, 1988.

S.K. Lya, and D.E. Cook, Icing Characteristics of a High-Altitude Long-Endurance Aircraft Wing Airfoil, AIAA 91-0562, 29th Aerospace Science Meeting, Jan. 7-10, 1911/Reno, Nevada

Z. BOTTYÁN, In-Flight Icing Characteristics of Unmanned Aerial Vehicles during Special Atmospheric Condition over the Carpathian-Basin, Landscape & Environment 7 (2) 2013. 74-80.

2. HALE ICING

STEP1 : Set up the calculation conditions

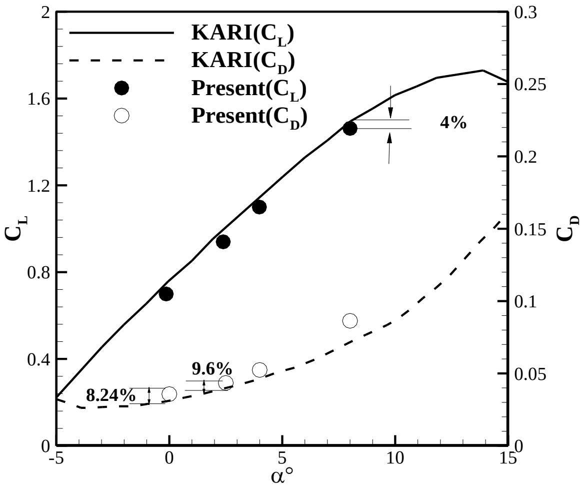


- Target HALE : EVA-2H+
  - ✓ Developed by KARI(Korean Aerospace Research Institute)
  - ✓ On September 5th , 2014
    - EVA-2H+ reached at operating altitude (10km) for 3 hours, and stayed 4 hours
  - ✓ Specification

MTOW	20kg
Empty weight	13kg
Main wing	Airfoil : SG6043, span : 11m, chord : 0.5m
Horizontal tail	NACA0010, Area : 0.4m²
Vertical tail	NACA0012, Area : 0.386m²
ROC	1m/s
Battery capacity	3kWh
C_L	1.0
C_D	0.033
V_∞	7.6m/s at ground, 13.13m/s at 10km

KARI 한국항공우주연구원 Korea Aerospace Research Institute

- Validation
  - ✓ $Re=2.78 \times 10^5$, $V_\infty = 6.7$m/s
  - ✓ Comparison with other numerical results
    - No wind tunnel data (22m span)
    - KARI (FLUENT) results and OpenFOAM(rhoPimpleFoam)

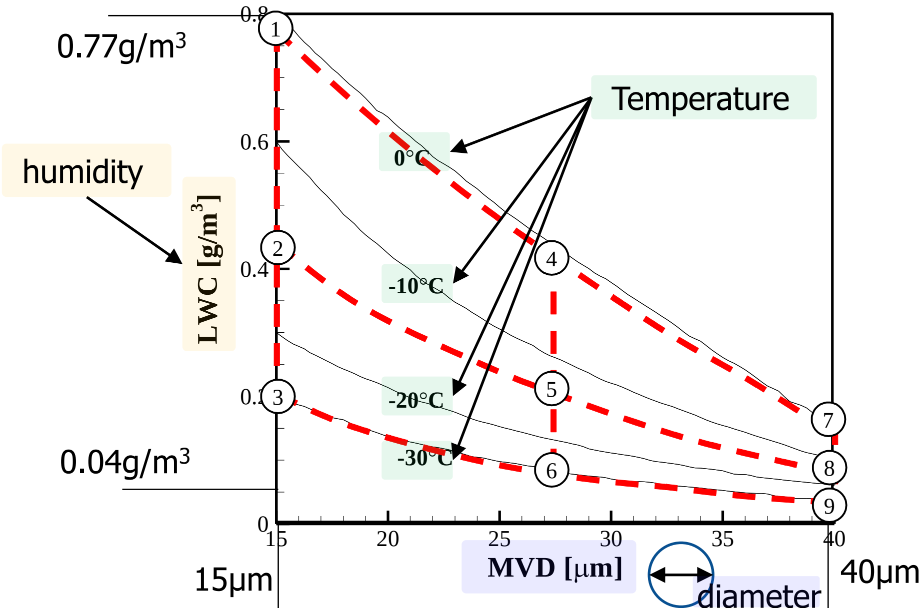


▲Validation results of C_L and C_D

2. HALE ICING

STEP1 : Set up the calculation conditions

- FAR PART 25, Appendix C conditions
  - ✓ Appendix C provides the observed icing conditions for the airworthiness certification
  - ✓ 9 cases for the parametric study and construction of RSM using the boundary values of Appendix C
    - Cf.) The temperature range -30 ℃ ≤ T ≤ -1.3 ℃
      - No ice at T=0 ℃, total temperature is followed by NASA Icing wind tunnel tests
- Other inputs are obtained based on the mission profile of HALE
  - ✓ Exposure time = 1.86 hours, rate of climb = 1m/s, water droplet exist 6.7km



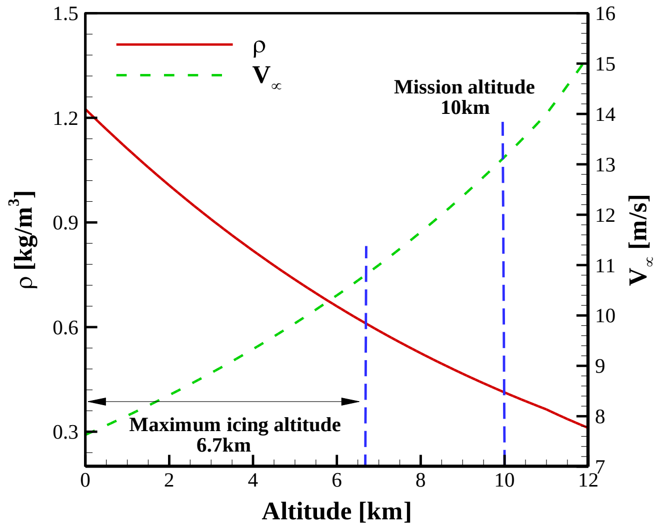
▲ FAR PART 25, Appendix C

Case No.	LWC[g/m³]	T[℃]	MVD[μm]
1	0.77	-1.4	15
2	0.456	-14.25	15
3	0.2	-30	15
4	0.41	-1.4	27.5
5	0.21	-14.25	27.5
6	0.083	-30	27.5
7	0.144	-1.4	40
8	0.08	-14.25	40
9	0.04	-30	40
Common values			
ρ[kg/m³]	0.878436 at 3.35km		
Time[h]	1.86 until 6.7km		

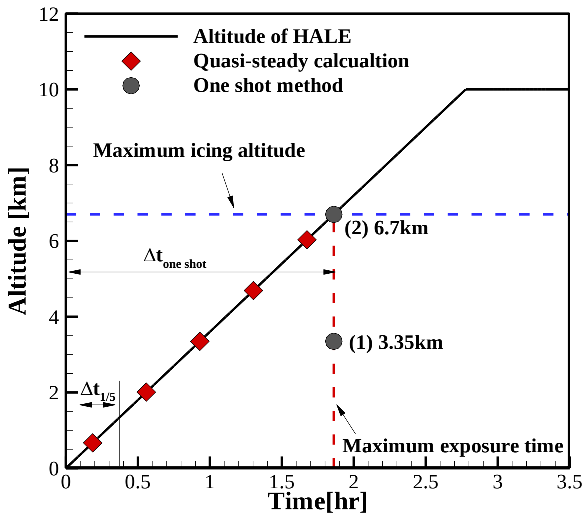
2. HALE ICING

STEP1 : Set up the calculation conditions

- Altitude changes during climbing stage
  - ✓ With the growth of altitude, density decreases and forward flight speed increases to keep the constant lift
- One shot method
  - ✓ Unsteady 3D icing analysis is almost impossible considering the available computational resources
  - ✓ The feasibility of one shot method on HALE airfoil
    - ① 5 step quasi-steady calculation
    - ② 3.35km : Average condition between ground and the maximum icing altitude(6.7km)
    - ③ 6.70km : The maximum icing altitude



▲ Density and velocity according to altitude

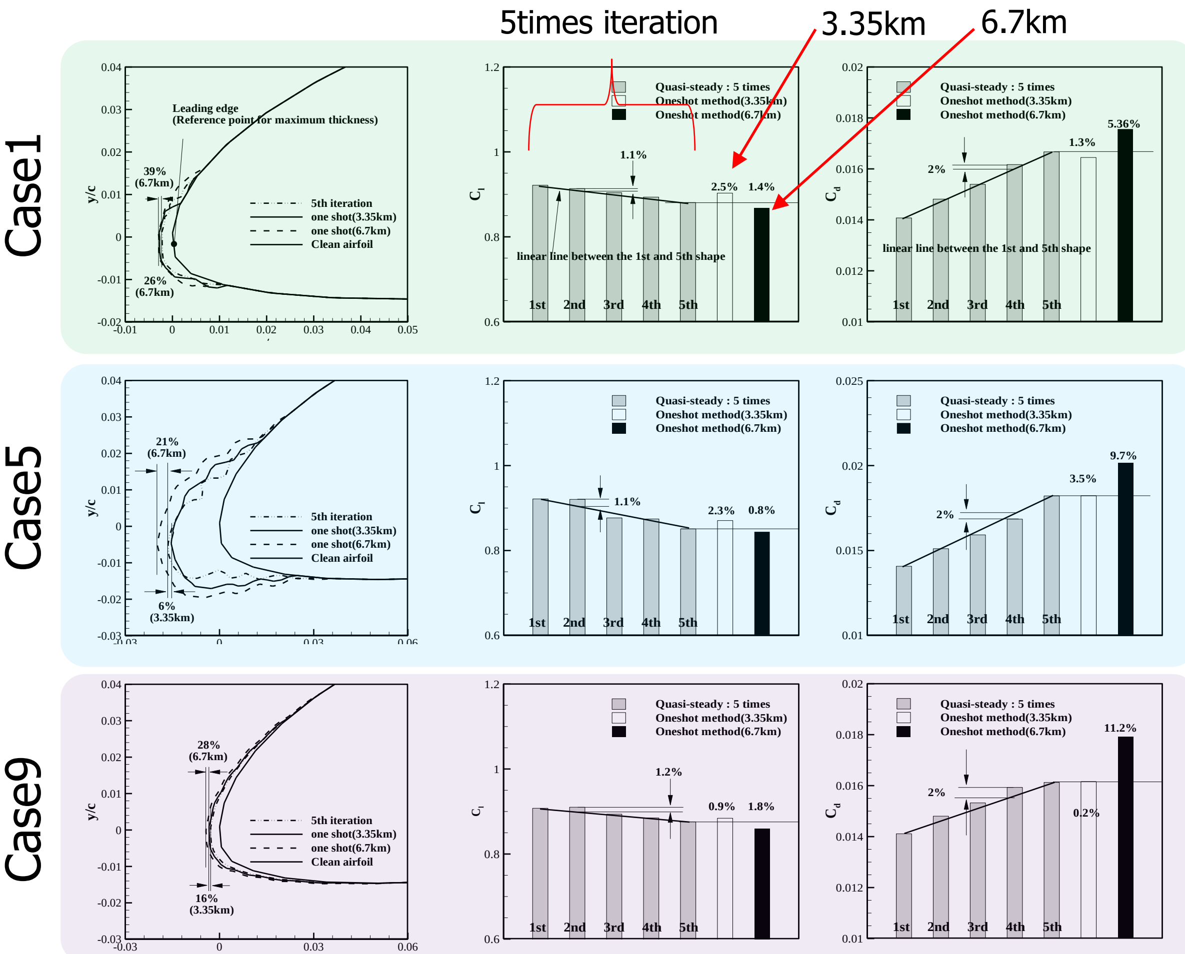


▲ The feasibility study of one shot method

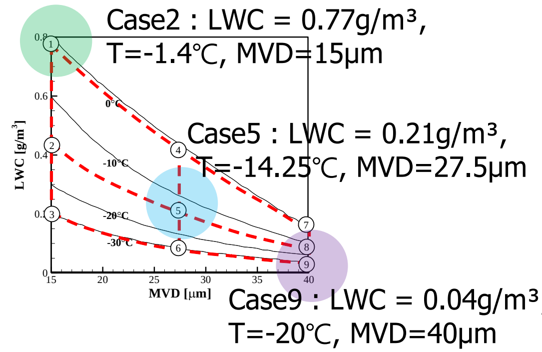
2. HALE ICING

STEP1 : Set up the calculation conditions

- The feasibility of one shot method on HALE airfoil (2D)



▲ Ice shapes ▲ C_L ▲ C_D



Ice accretion shapes

- 3.35km condition is more similar to the 5 times iteration results
- Maximum thickness form the leading edge under 26%

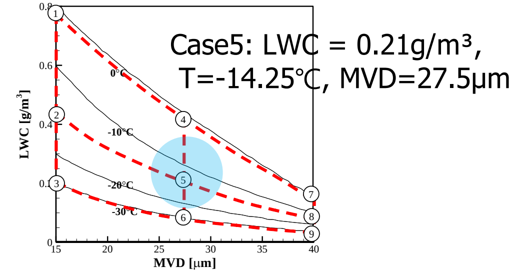
Lift and drag coefficient

- 3.35km condition shows under 2.5% of lift coefficient, and under 3.5% of drag coefficient compared to the 5 step quasi-steady calculation

Density and velocity

- The averaged altitude(3.35km) condition is used for one shot method

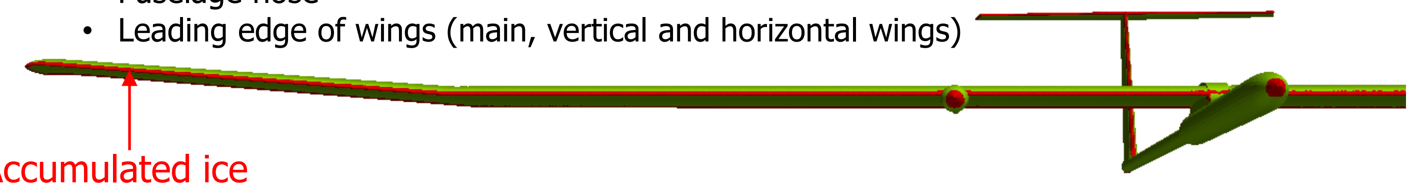
2. HALE ICING

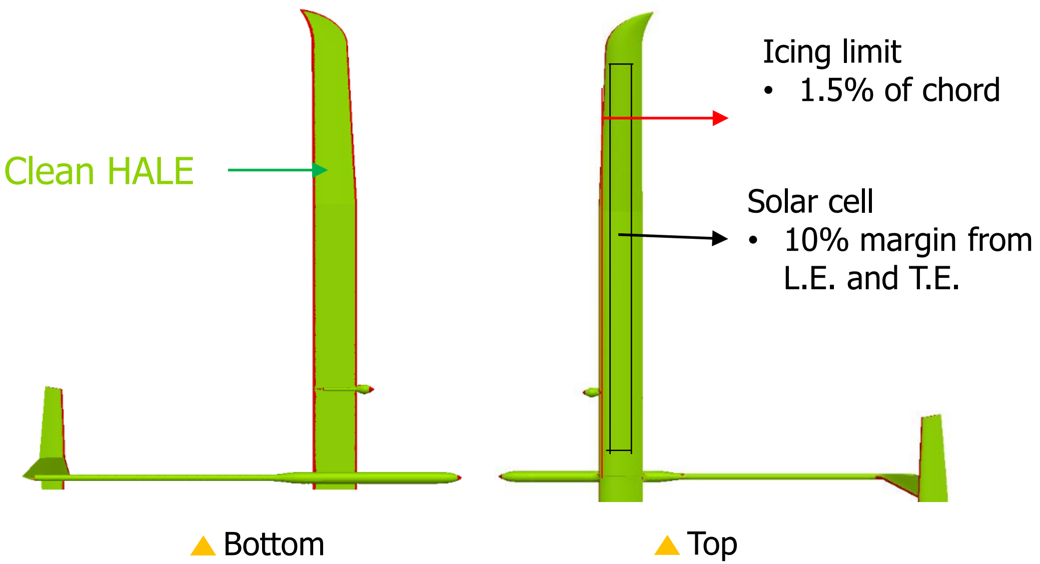


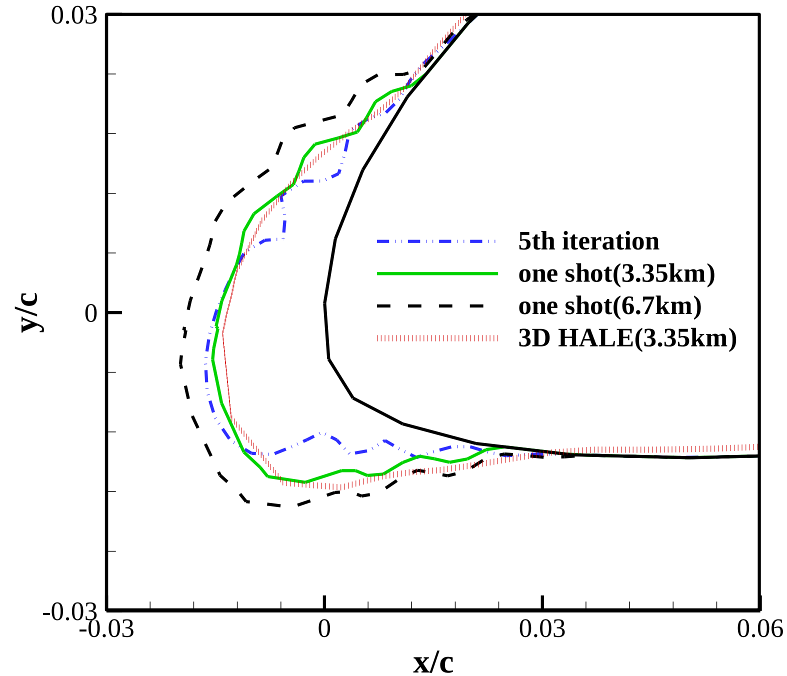
SETP2 : Ice accretion shapes (3D HALE)

- Massive ice accretion case (Case5)
  - ✓ Negligible drop in solar cell efficiency
  - ✓ The averaged altitude(3.35km) for 3D HALE also follows the 5th iteration of 2D case

Ice accretion occurs
- Fuselage nose
- Leading edge of wings (main, vertical and horizontal wings)

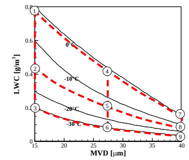






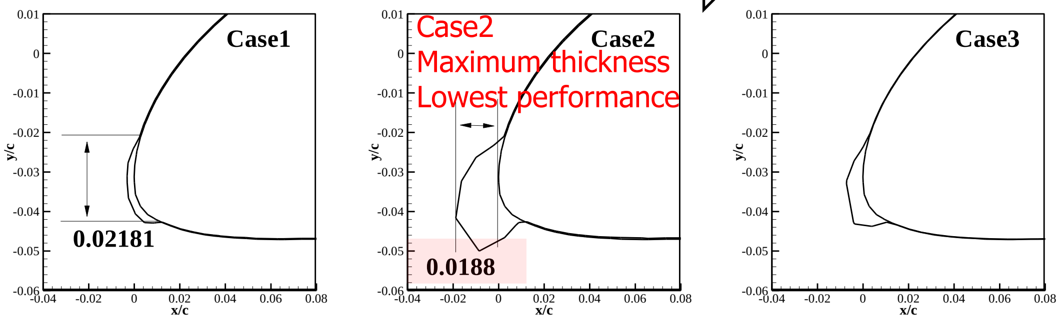
2. HALE ICING

SETP2 : Ice accretion shapes

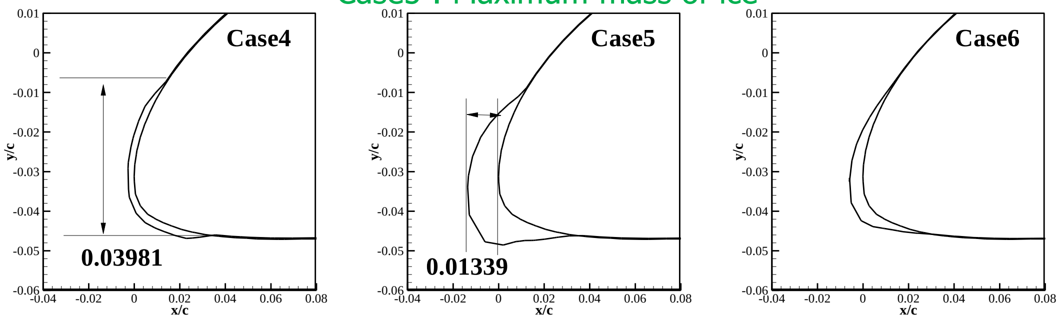


LWC ↓ , T ↓

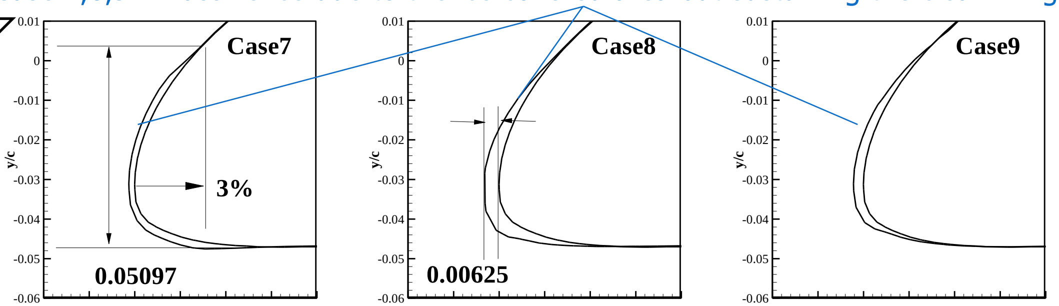
MVD ↑



Case5 : Maximum mass of ice

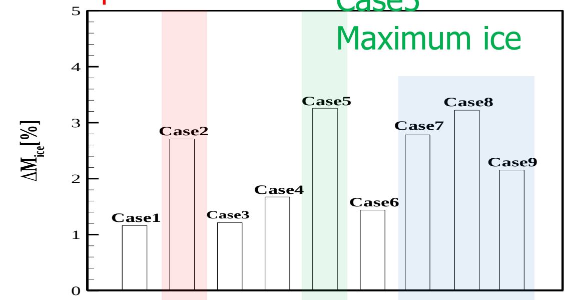


Case 7,8,9 : Massive ice due to the ice covered area but sustaining the clean wing shapes



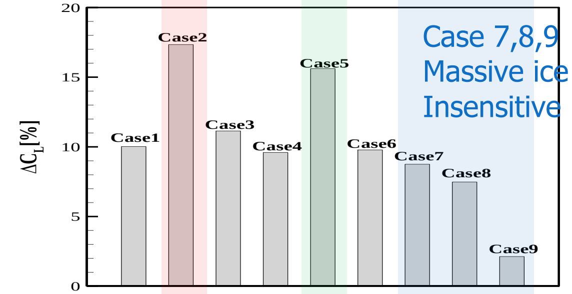
Case2
Maximum thickness
Lowest performance

Case5
Maximum ice

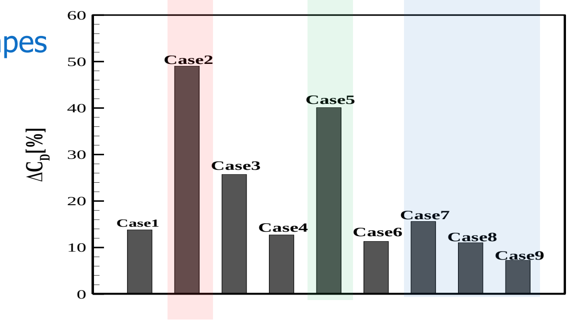


▲ Mass of ice

Case 7,8,9
Massive ice at MVD ↑
Insensitive performance



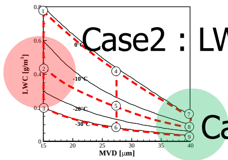
▲ Degradation of lift



▲ Growth of drag

2. HALE ICING

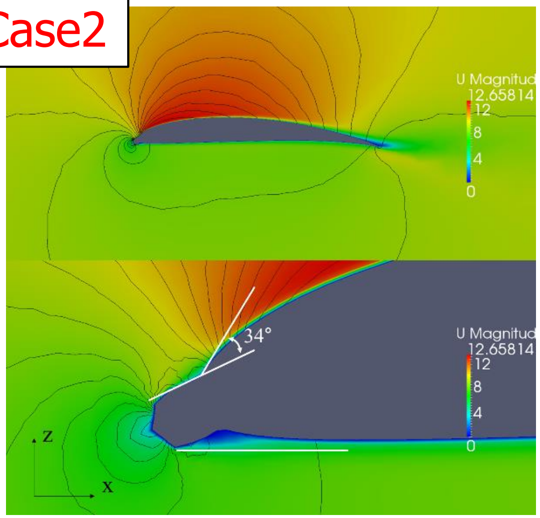
SETP2 : Aerodynamic performance



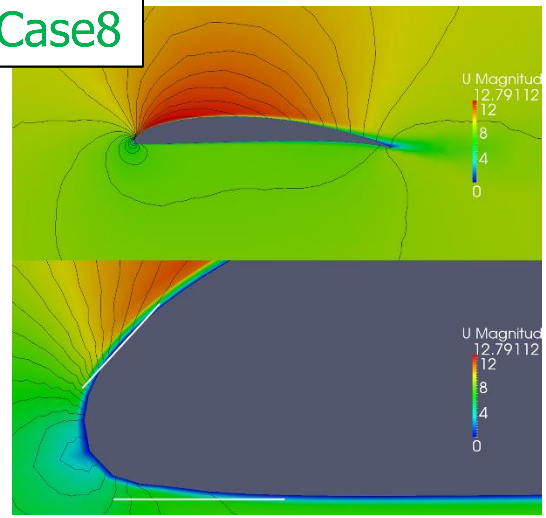
Case2 : LWC = 0.456g/m³, T=-14.25℃, MVD=15μm

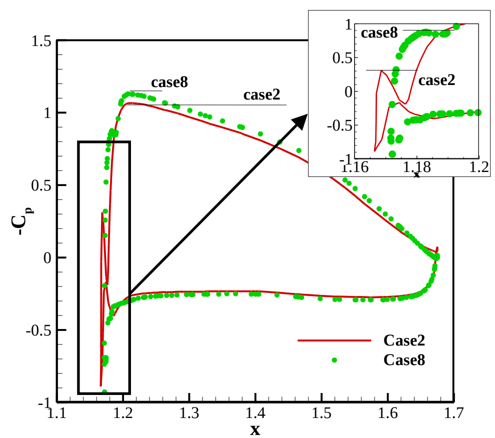
Case8 : LWC = 0.08g/m³, T=-14.25℃, MVD=40μm

Case2

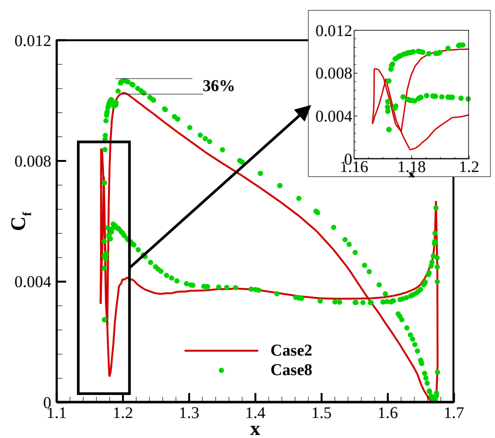


Case8





▲ C_p



▲ C_f

Maximum thickness

- Maximum thickness determines the aerodynamic performance
- No strong correlaton between the total mass of ice and the aerodynamic performance
- High maximum thickness occurs LWC↑, T↓, MVD↓

Flow separation

- As the ice thickness grows, the angle increases between the clean airfoil and ice shapes
- Leading edge ice induces leading edge separation and reattachment
- Due to separation, boundary layer(↑), and total pressure(↓) overall surface

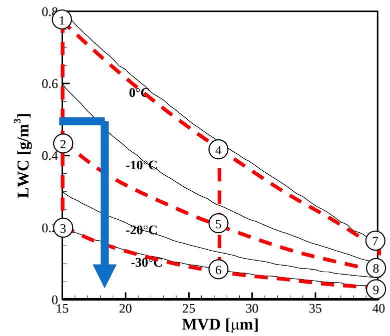
2. HALE ICING

STEP3 : RSM(Response Surface Methodology)

- To quantitatively analyze the correlation between meteorological parameters and aerodynamic performance
- The 2nd order polynomial is used as a RS model
  - ✓ $y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} {x_1}^2 + \beta_{12} x_1 x_2 + \beta_{22} {x_2}^2$
- $MVD = f(LWC, T)$, LWC and T have easy accessibility to the operators

R^2	0.86	y_1	$\Delta M = \frac{m_{ice}}{MTOW}$ (%)
	0.81	y_2	$\Delta C_L = \frac{(C_{L,clean} - C_{L,ice})}{C_{L,clean}}$(%)
	0.88	y_3	$\Delta C_D = \frac{(C_{D,clean} - C_{D,ice})}{C_{D,clean}}$(%)

x_1	x_2
LWC[g/m³]	T[k]

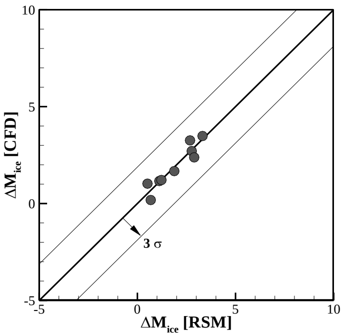


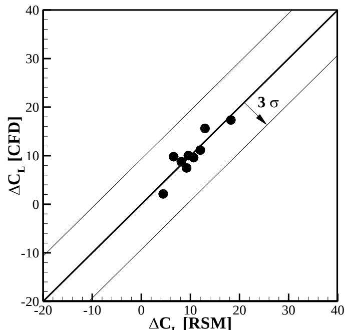
$$\Delta M = \frac{m_{ice}}{MTOW} (\%)$$

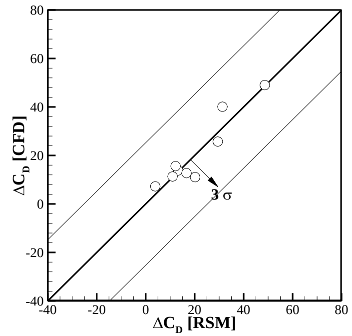
$$\Delta C_L = \frac{|C_{L,clean} - C_{L,ice}|}{C_{L,clean}} (\%)$$

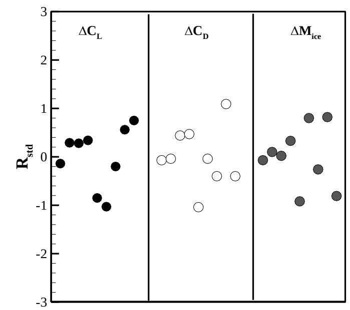
$$\Delta C_D = \frac{|C_{D,clean} - C_{D,ice}|}{C_{D,clean}} (\%)$$

$$-3 < R_{std} < 3$$









Within 3σ, $\sigma = standard\ deviation$ $\quad R_{std} = \frac{e}{\sigma}$

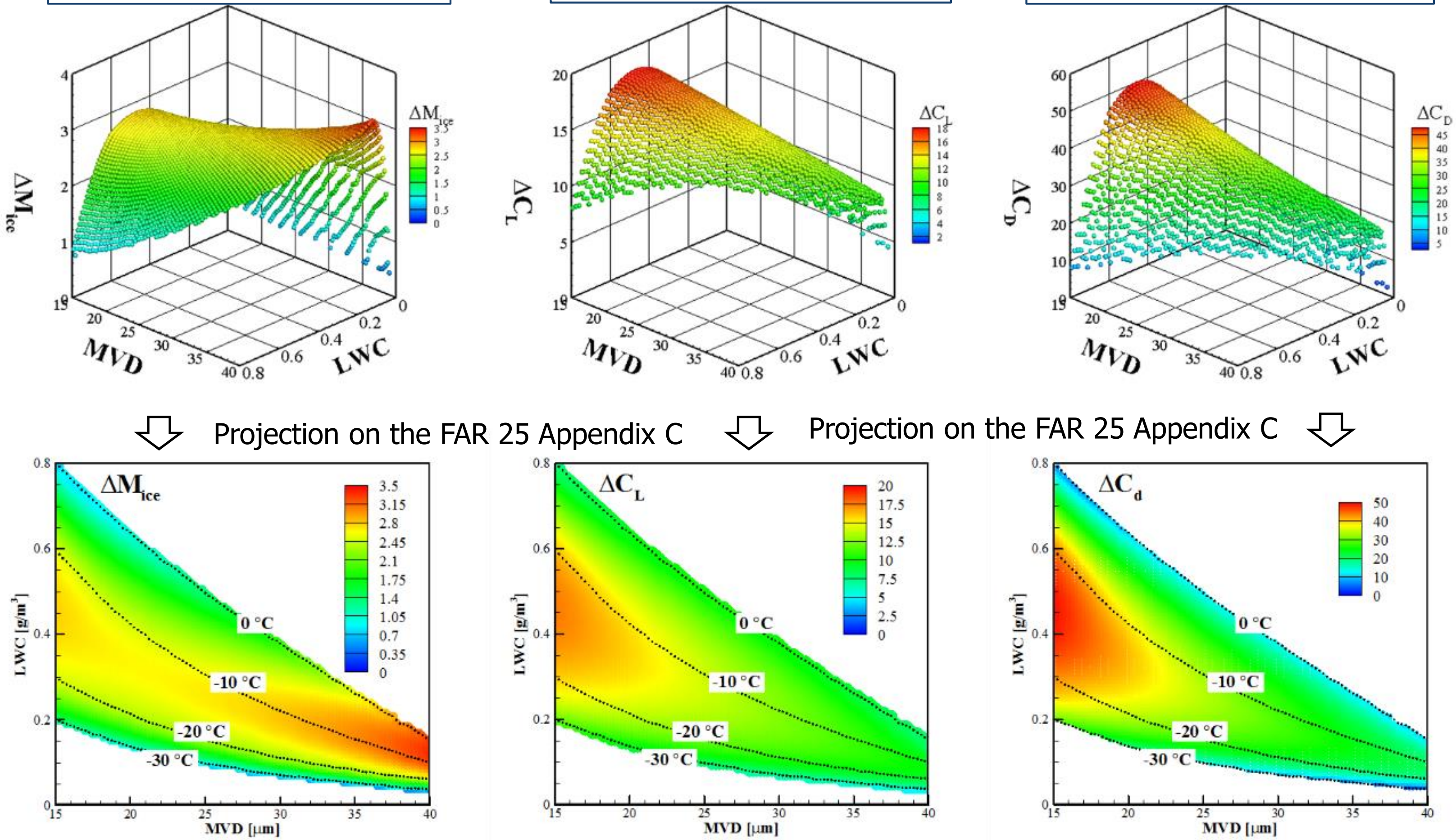
2. HALE ICING

STEP3 : RSM(Response Surface Methodology)

$$\Delta M = \frac{m_{ice}}{MTOW} \ (\%)$$

$$\Delta C_L = \frac{|C_{L,clean} - C_{L,ice}|}{C_{L,clean}} \ (\%)$$

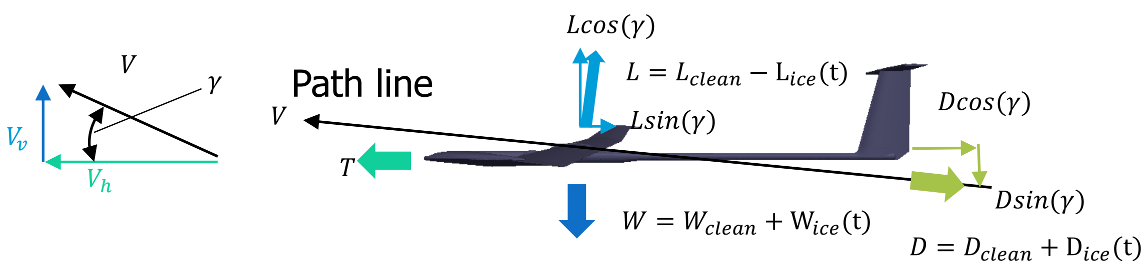
$$\Delta C_D = \frac{|C_{D,clean} - C_{D,ice}|}{C_{D,clean}} \ (\%)$$



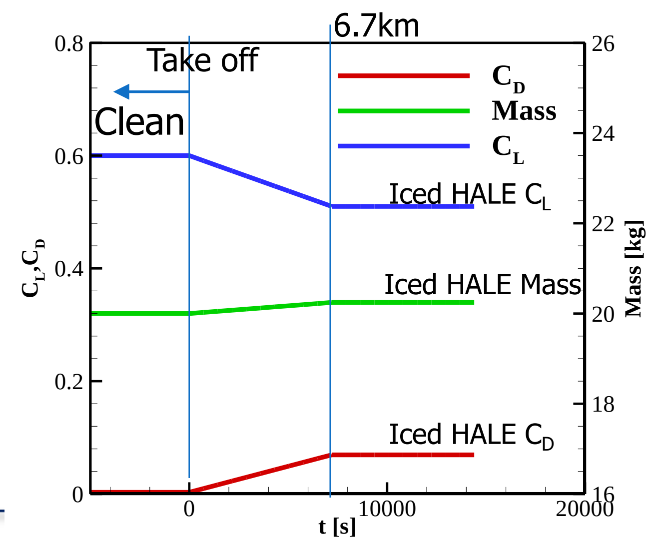
2. HALE ICING

STEP4 : Performance of HALE

- Required power
  - ✓ Whether the HALE could finish mission or not
  - ✓ If the HALE can climb up to the target altitude with given battery capacity, the HALE can successfully perform the mission
    - HALE recovers the performance at the mission altitude by the sublimation of ice
    - The decrease of solar cell efficiency is negligible because of negligible upper surface ice accretion
  - ✓ Assumptions
    - Fixed ROC(Rate of Climb) as 1m/s
    - Velocity is increased to compensate the reduced lift and increased weight(secure the stall speed and stall margin)
    - Mass, drag, and lift are linearly changed form clean to iced conditions
    - Efficiencies of battery, propeller, motor, and motor controller are set to clean condition
      - $\eta_{battery} = 90\%,\ \eta_{propeller} = 60\%,\ \eta_{motor} = 88\%,\ \eta_{control} = 95\%$



$$Lcos(\gamma) = W + Dsin(\gamma)$$
$$T = Dcos(\gamma) + Lsin(\gamma)$$
$$P = TV/(\eta_{battery} \cdot \eta_{propeller} \cdot \eta_{motor} \cdot \eta_{control})$$



2. HALE ICING

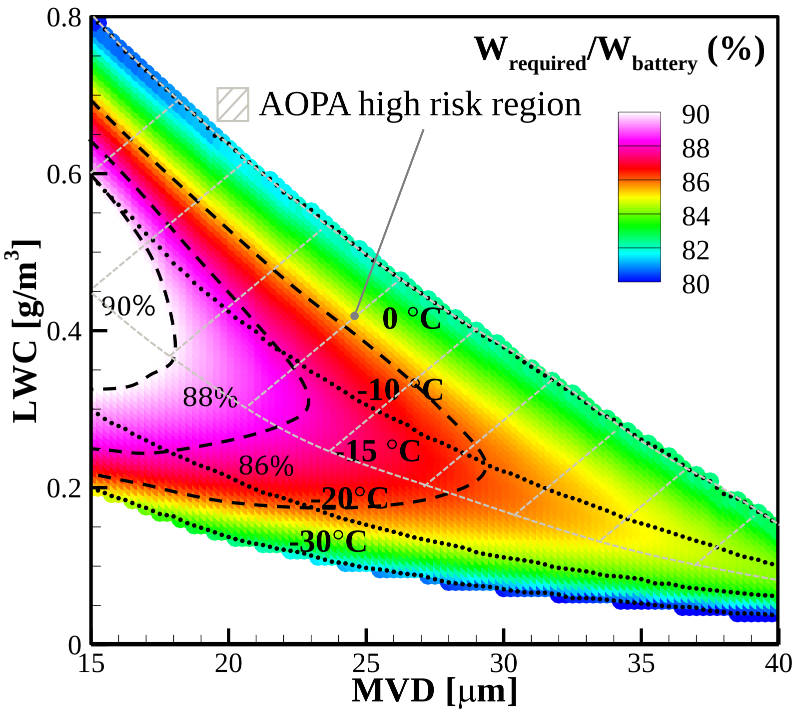
STEP4: Performance evaluation

- Ice accretion requires more power than clean HALE to reach he mission altitude
  - ✓ Battery margin
    - Clean HALE : 40%
    - Maximum of iced HALE : 20%
    - Minimum of iced HALE : 9%
- Mission failure area where the HALE can not reach the mission altitude
  - ✓ Under 10% battery margin region
    - LWC : 0.3~0.6 g/m^3
    - T : -10~-20℃
    - MVD < 17.5μm
- The icing risk region of HALE is different from the convectional aircraft
  - ✓ Convectional aircraft : T>-15℃
    - Wider than HALE icing risk region
    - Ice horn due to high heat convection and high rate of impinging water
  - ✓ HALE
    - Not Ice horn, but sustaining the clean wing shapes

Icing Risk

Cumulus Clouds		Stratiform Clouds		Rain and Drizzle
0° to -20°C 32° to -4°F	High	0° to -15°C 32° to 5°F	High	0°C and below 32°F and below
-20° to -40°C -4° to -40°F	Med.	-15° to -30°C 5° to -22°F	Med.	
< than -40°C <than -40°F	Low	< than -30°C <than -22°F	Low	

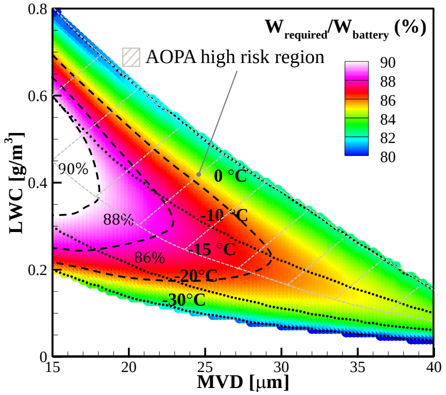
▲ Aircraft Owners and Pilots Association(AOPA) Report



▲ Required power for the climbing stage

2. Summary of HALE Icing

- The methodology is suggested to identify the mission failure icing conditions for HALE
  - Using the quantitative correlation between meteorological parameters and the required power to reach the mission altitude
    - ✓ Applying the quantitative correlation to FAR Part 25 Appendix C
    - ✓ The mission failure icing conditions : under 10% battery margin
      - LWC : 0.3~0.6 g/m³
      - T : -10~-20℃
      - MVD < 17.5μm



- One shot method
  - For the density and velocity, the averaged altitude(3.35km) yields better accuracy than the maximum droplet altitude(6.7km)
    - ✓ Lift coefficient under 2.5% and drag coefficient under 3.5% compared with the 5 times iteration results

- Maximum thickness
  - Maximum thickness is the major ice shape parameter that determines the degradation of aerodynamic performance
  - As growing the thickness of ice, flow separation and reattachment occurs at the leading edge
  - No strong tendency between the total mass of ice and the aerodynamic performance

CONCLUSIONS

CONCLUSIONS

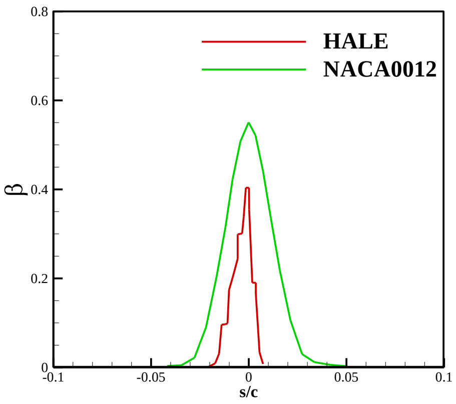
- Development of 3D ice accretion code based on Eulerian approach and water film model
  - Generic 3D problems : DLR-F6(wing and fuselage) cases
    - ✓ Ice heading direction, and maximum thickness are well predicted
    - ✓ Predict not only the ice accretion shapes, but also its the aerodynamic performance because of N-S solver
- Using the developed 3D icing code, various icing problems could be treated
  - 1. Helicopter fuselage icing
    - ✓ Rotor wake effects on the fuselage icing
      - Rotor wake effects should be considers to obtain the ice accretion shapes on helicopter fuselage
    - ✓ Forward flight speed effects on ice distribution
      - Designing the anti/de-icing devices, the flight conditions (hover, low and high forward flight) should be considered
  - 2. HALE icing
    - ✓ Icing risk region
      - The methodology is suggested to identify the mission failure icing conditions for HALE based on the quantitative correlation between icing parameters and aerodynamic performance
    - ✓ One-shot method
      - For the density and velocity, the averaged altitude(3.35km) yields better accuracy than the maximum droplet altitude(6.7km)

THANK YOU FOR YOUR ATTENTION.

RESULTS AND DISCUSSION

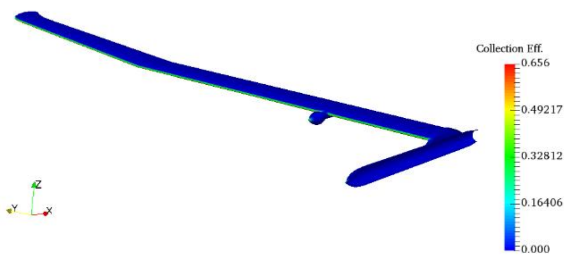
Effects of velocity

- Collection efficiency : non-dimensional parameter (commonly 0.0 – 1.0)
  - ✓ How many water droplets impinge against the local surface
  - ✓ $\beta = \frac{\overline{\rho}_d \vec{u}_d \cdot \vec{n}}{LWC \cdot U}$, $\dot{m}_{com} = \beta \cdot LWC \cdot U \cdot dA$
    - HALE : $\beta \approx 0.4$
      - V=6.7m/s, LWC=0.45g/m3, MVD=27.5μm
    - NACA0012 : $\beta \approx 0.6\text{-}0.8$
      - V=129.46m/s, LWC=0.5g/m3, MVD=20μm

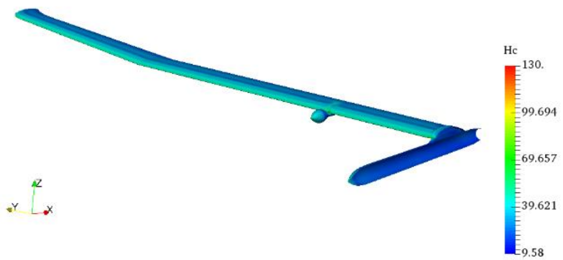


▲ Collection efficiency

- Heat convection coefficient
  - ✓ $h_c = \frac{-k\left(\frac{\partial T}{\partial n}\right)_{wall}}{T_{wall} - T_{\infty}}$
    - HALE : $h_c = 54W/m^2 \cdot K$
      - V=6.7m/s, LWC=0.45g/m3, MVD=27.5μm, T=-11℃
    - Airfoil : $h_c = 1500W/m^2 \cdot K$
      - V=129.46m/s, LWC=0.5g/m3, MVD=20μm, T=-12.6℃
- Less impinging water and low convective cooling make rime ice shapes



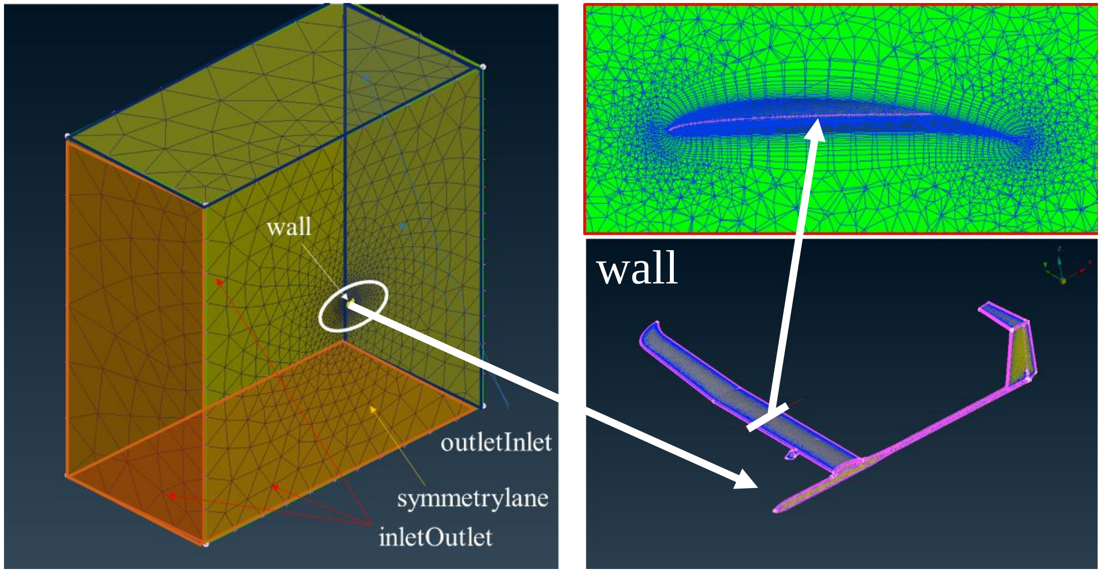
▲ Collection efficiency

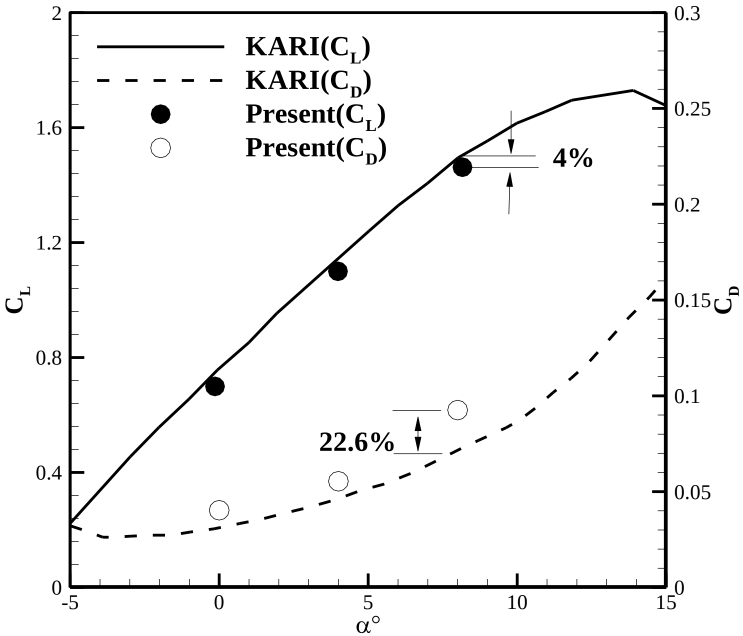


▲ Heat convection coefficient

RESULTS AND DISCUSSION

Grid and Boundary condition





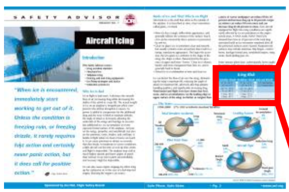
- Number of cells ≈ 6,000,000
- y+ ≤ 15 and 15 prism layers with growth ratio of 1.2
- ddtSchemes
  - ✓ CoEuler;
- divSchemes
  - ✓ Div(phi,U) Gauss linearUpwindV grad(U);
  - ✓ Div(phi,*) Gauss upwind;
  - ✓ Div(second order) Gauss linear;

- Re=2.78 × 10^5, Ma = 0.022
- No wind tunnel data (22m span)
- Comparison with other numerical results
  - ✓ KARI (FLUENT) results and OpenFOAM(rhoPimpleFoma)

RESULTS AND DISCUSSION

Effects of velocity

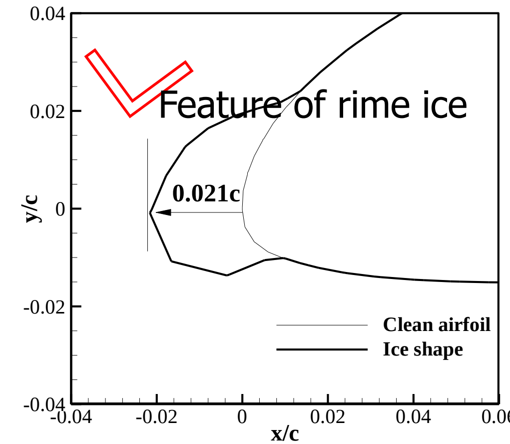
- AOPA(Aircraft Owners and Pilots Association) Report and NASA IRT tests results
  - ✓ The icing risk is categorized by temperature and cloud types
  - ✓ AOPA report is well correspond with IRT test results (glace ice horn)



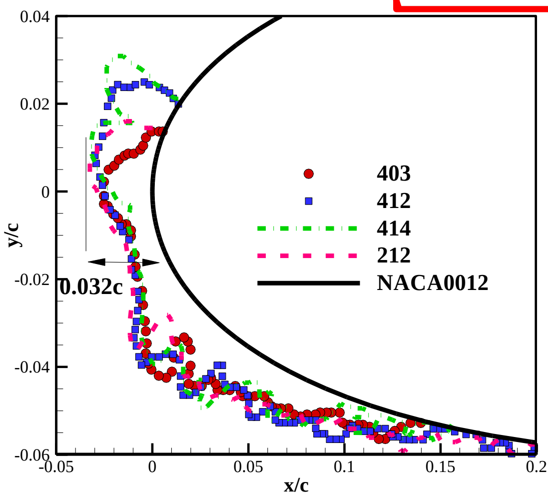
▲AOPA Report

Icing Risk

Risk	Cumulus Clouds	Stratiform Clouds	Rain and Drizzle
High	0° to -20°C 32° to -4°F	0° to -15°C 32° to 5°F	0°C and below 32°F and below
Med.	-20° to -40°C -4° to -40°F	-15° to -30°C 5° to -22°F	
Low	< than -40°C <than -40°F	< than -30°C <than -22°F	



▲HALE results



▲IRT results

Case name	LWC[g/㎥] (difference%)	MVD[μm] (difference%)	T[K] (difference%)	V[m/s] (difference%)	Time[s] (difference%)
403	0.55 (22%)	20 (27.3%)	262.0 (0.042%)	102.8 (1253%)	420 (94.2%)
412	0.47 (9.1%)	30 (9.1%)	261.54 (0.23%)	102.8 (1253%)	492 (93.2%)
414	0.55 (22%)	25 (9.1%)	262.04 (0.042%)	102.8 (1253%)	420 (94.2%)
212	0.44 (2.2%)	30 (9.1%)	262.04 (0.042%)	102.8 (1253%)	525 (92.7%)