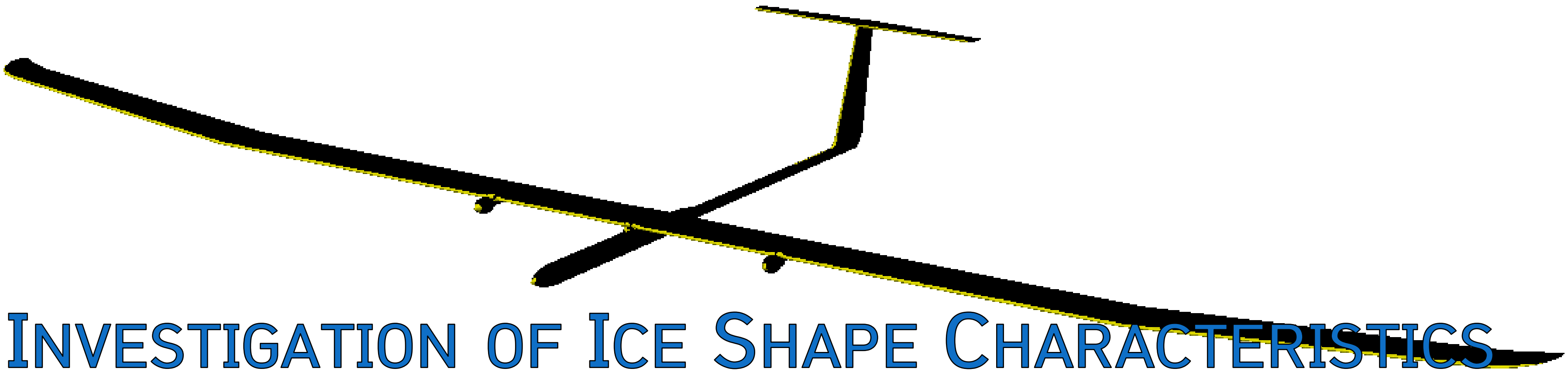

Investigation of Ice Shape Characteristics and Operating Limitation for Low-Speed HALE Aircraft in Icing Conditions

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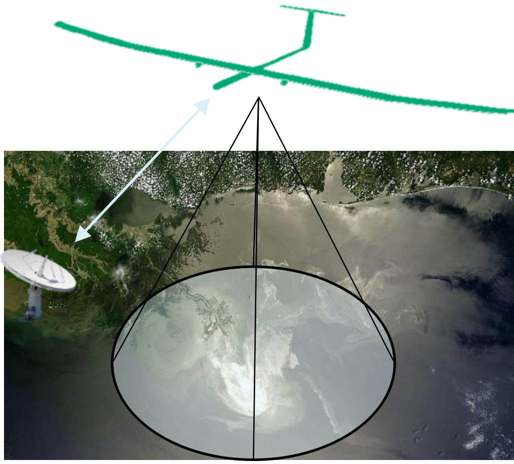
CONTENTS

INTRODUCTION

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

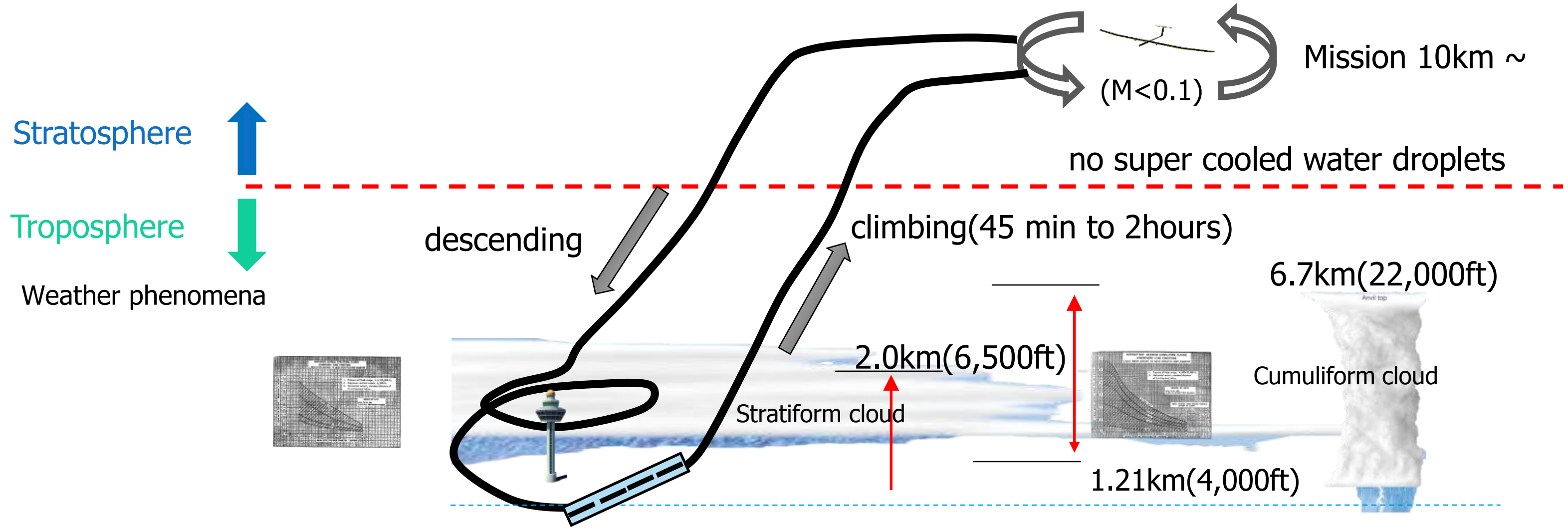
▲ Aircraft manufacturers

▲ 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

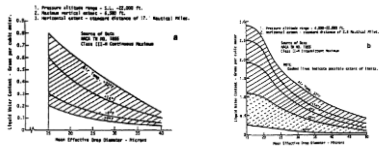
- Aircraft Icing → the major constraint of all-weather capability
  - Icing phenomenon during HALE mission
    - ✓ Typical mission profile of HALE
      - Take off → climbing → mission (over 10km) → descending → landing
        - Stratosphere : No weather phenomena (no water droplets) and low level of 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?'



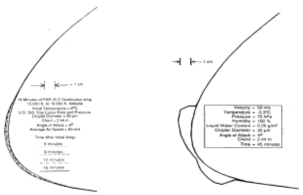
INTRODUCTION

Literature survey on HALE icing

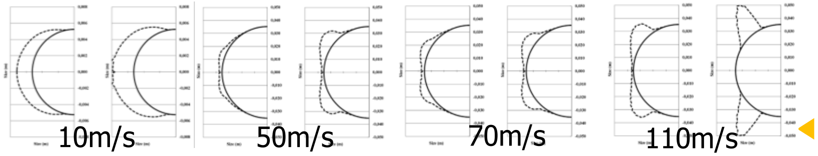
- Different characteristics of HALE compare to convectional aircraft
  - ✓ Low-forward flight speed (M<0.1) to minimize the drag
  - ✓ Long exposure time (45 min to 2hours) due to low rate of climb
  - ✓ No Anti/de-icing devices
- Icing environment study for HALEs
  - ✓ Vogel, G. N.(1988)
    - Explores the characteristics of the icing environment in terms of temperature and cloud structures as related to the HALE mission
    - The icing environment study without the prediction of ice shapes and performance degradation
- Prediction of ice accretion shapes on HALEs
  - ✓ Iya, S. K., and Cook D.E. (1991)
    - Prediction of the ice accretion shapes during climb (45min) using NASA LEWCE 2.0 on the 2D airfoil
    - Estimate the time for sublimating all of the accreted ice → over 100 hours
    - 2D airfoil, lack of performance estimation
  - ✓ Bottyán, Z. (2013)
    - Prediction of the ice accretion shapes by analytic approach because they does not have reliable code
    - High speed (10,50,70,110m/s) with various icing conditions as related to the HALE mission
    - 2D cylinder, short exposure time (under 5 min), and lack of mission profile and performance estimation



▲ Vogel, G. N.(1988)



▲ Iya, S. K., and Cook D.E. (1991)



◀ BOTTYÁN, Z. (2013)

- To assess the flight safety and the mission failure (or success), not only the ice accretion shapes but also its aerodynamic performance should be analyzed

- 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.

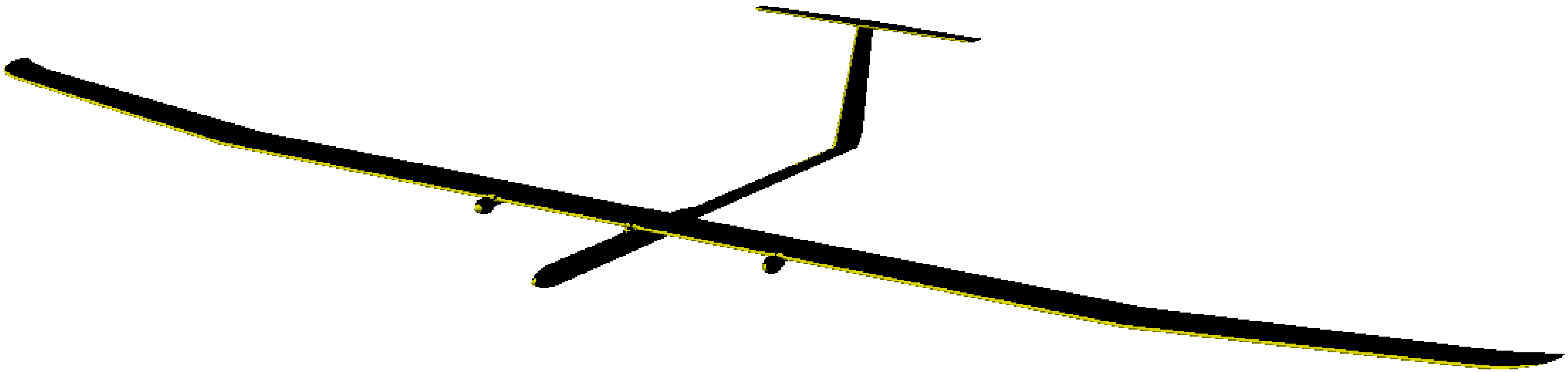
INTRODUCTION

Motivation

- Necessity for the mission failure criteria based on the performance evaluation
  - ✓ Meteorological conditions → ice accretion shapes → aerodynamic performance → decision making
    - Insufficient information from 2D ice shapes to the HALE mission controllers
    - Gathered information is meteorological parameters such as humidity, temperature, and so on
    - The quantitative correlation between the meteorological icing parameters and performance degradation
  - ✓ The prediction of ice accretion shapes and performance degradation considering the mission profile and the design characteristics of HALEs
    - No anti/de-icing devices, long exposure time (45 min to 2hours)

Research scope

- A methodology is suggested 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



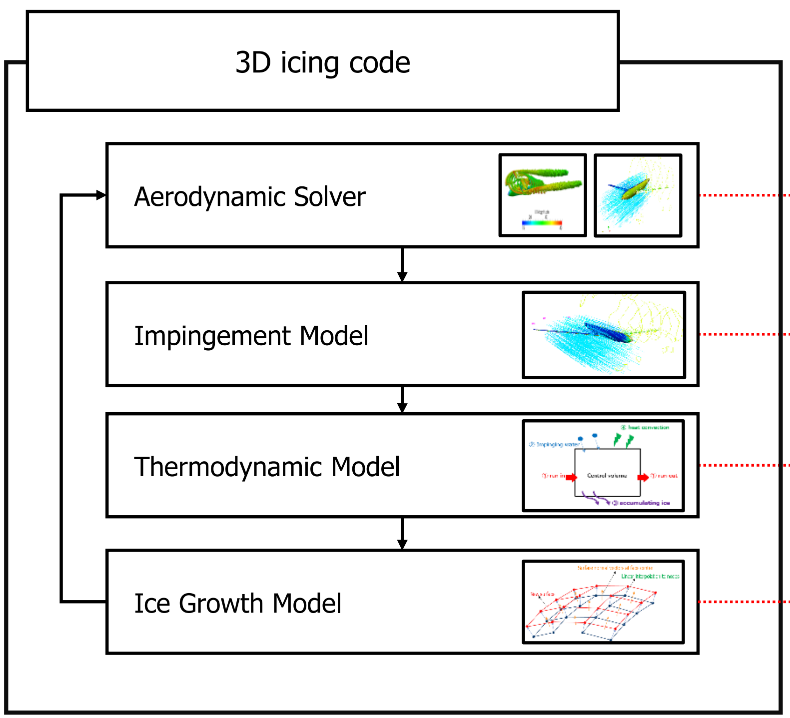
NUMERICAL METHOD

3D ICE ACCRETION CODE

NUMERICAL METHOD

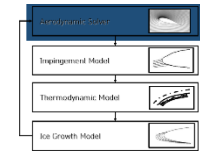
3D icing solver

- 4 models : aerodynamic solver, impingement model, thermodynamic model, ice growth model
- Each model is sequentially progressed by quasi-steady assumption
  - ✓ The converged solution is conveyed to next model
  - ✓ Each model assumed to steady state, and field parts(aerodynamic solver, impingement model) are used local time stepping

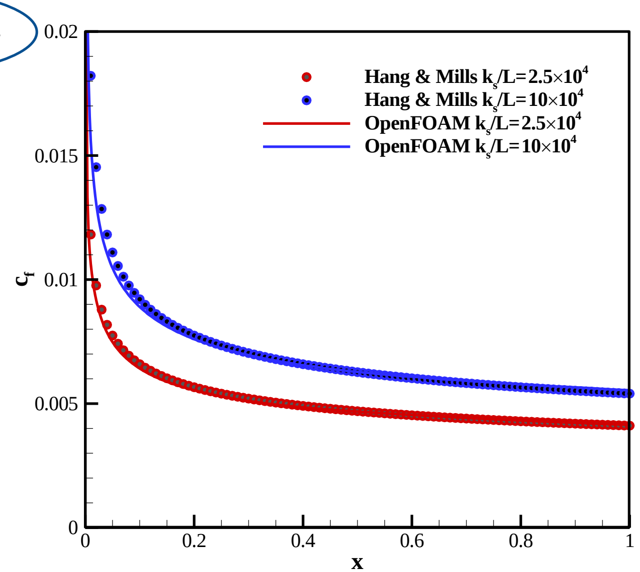


- rhoPimpleFOAM(OpenFOAM-2.2.0)
  - ✓ Navier-Stokes based solver
  - ✓ Unsteady, compressible and turbulent flow
  - ✓ Roughness based S-A model
- 3D Eulerian approach
  - ✓ drag, gravity, and buoyancy forces
- 3D water film approach
  - ✓ FVM method on the surface water film
- 3D surface re-meshing

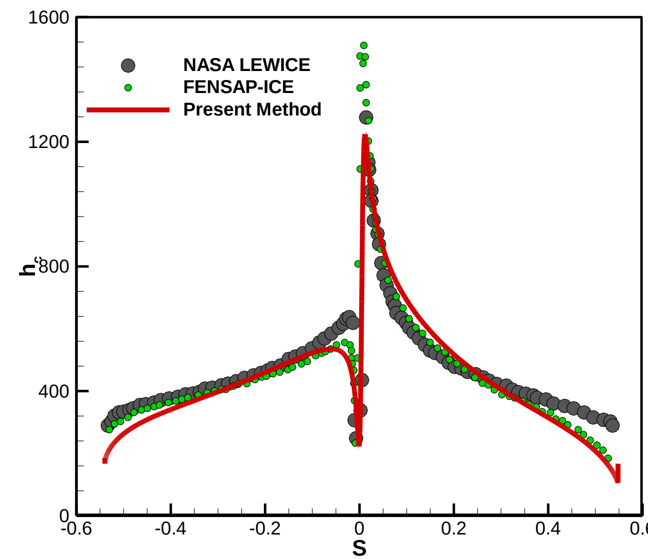
NUMERICAL METHOD



- 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
    - ✓ $d = d_{wall} + 0.03 k_s$
  - Wall boundary
    - ✓ $$\frac{\partial \tilde{\nu}}{\partial n} = \frac{\tilde{\nu}}{d_{new}}$$
  - Heat convection
    - ✓ $$h_c = \frac{-(k_l + k_t)\partial T/\partial n}{T_s - T_\infty}$$
    - ✓ $$k_t = \frac{\mu_t c_p}{Pr_t}$$



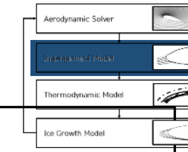
▲ Skin friction coefficient of roughened flat plate



▲ Heat convection coefficient(right) at roughened airfoil

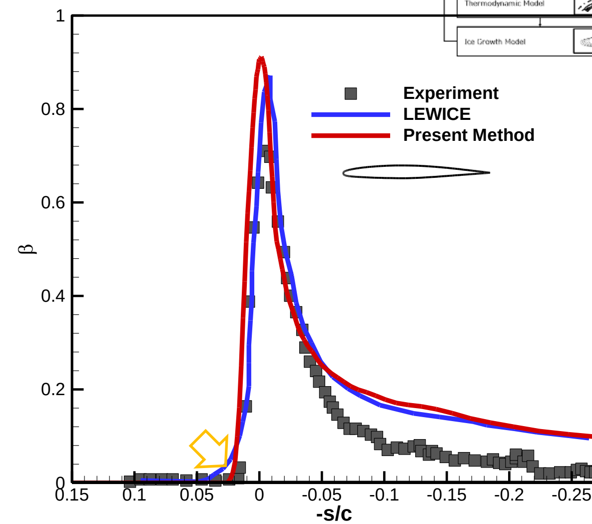
*Ruff, Gary A., and Brian M. Berkowitz. "Users manual for the NASA Lewis ice accretion prediction code (LEWICE)." (1990).

NUMERICAL METHOD



Impingement Model(Eulerian method)

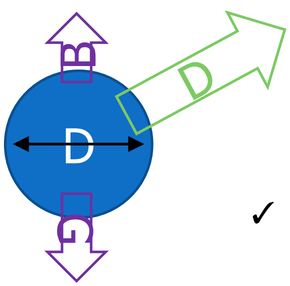
- Eulerian approach is suitable for Finite Volume Method
  - ✓ Shadow region is automatically calculated
- Droplet field is governed by mass and momentum conservation
  - ✓ Mass conservation
    - $\frac{\partial \bar{\rho}_d}{\partial t} + \nabla \cdot (\bar{\rho}_d \vec{u}_d) = 0$
      - $\bar{\rho}_d = \alpha \rho_w$
      - $\bar{\rho}_d$: bulk density, α : volume fraction



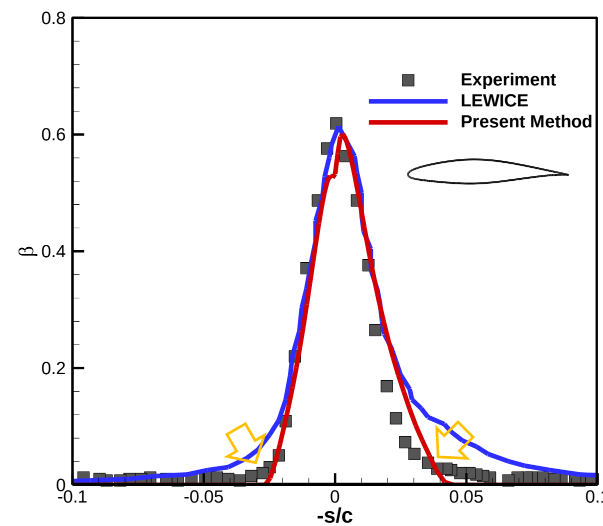
▲ Collection efficiency of GLC305*

  - ✓ Momentum conservation
    - $\frac{\partial \bar{\rho}_d \vec{u}_d}{\partial t} + \nabla \cdot (\bar{\rho}_d \vec{u}_d \vec{u}_d) = \frac{3}{4}\frac{\bar{\rho}_d \mu_a C_D Re_d}{\rho_w MVD^2}(\vec{u}_a - \vec{u}_d) + \bar{\rho}_d \vec{g}\left(1 - \frac{\rho_a}{\rho_w}\right)$

      drag   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
    - $\beta = \frac{\bar{\rho}_d \vec{u}_d \cdot \vec{n}}{LWC \cdot U}, \quad \dot{m}_{com} = \beta \cdot LWC \cdot U \cdot dA \left[\frac{\mathrm{kg}}{\mathrm{m^2 \cdot s}}\right]$



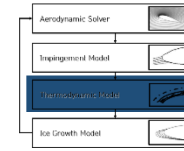
▲ Collection efficiency of NACA64A014*

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

SEOUL NATIONAL UNIVERSITY AEROSPACE VEHICLE DESIGN LABORATORY

*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.

NUMERICAL METHOD



Thermodynamic model

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

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

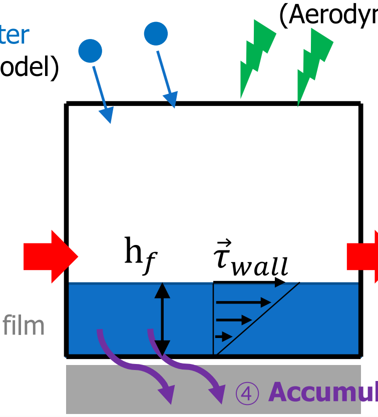
    ① ② ③ ④ ⑤

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

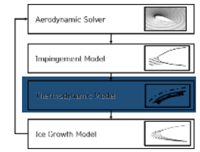
- ✓ $\bar{U}_f = f(\mathrm{h}_f) = \frac{1}{h_f} \int_0^{h_f} u_f dh = \frac{h_f}{2\mu_w} \vec{\tau}_{wall}$

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



NUMERICAL METHOD

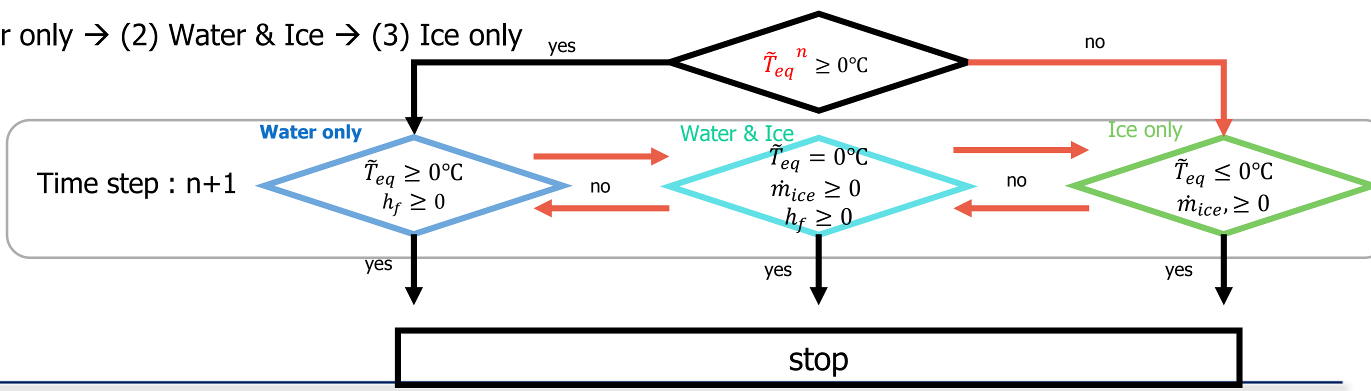


3 compatibility relations

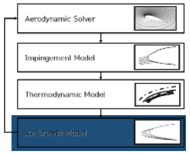
- Compatibility relations are based on physical observations : water freezes at $0°C$

✓ Water only	: $\dot{m}_{ice}, = 0,\ \tilde{T}_{eq} \geq 0°C,\ h_f \geq 0$	Time step : n+1
✓ Water & Ice	: $\dot{m}_{ice}, \geq 0,\ \tilde{T}_{eq} = 0°C,\ h_f \geq 0$	
✓ Ice only	: $\dot{m}_{ice}, \geq 0,\ \tilde{T}_{eq} \leq 0°C,\ h_f = 0$	

- 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

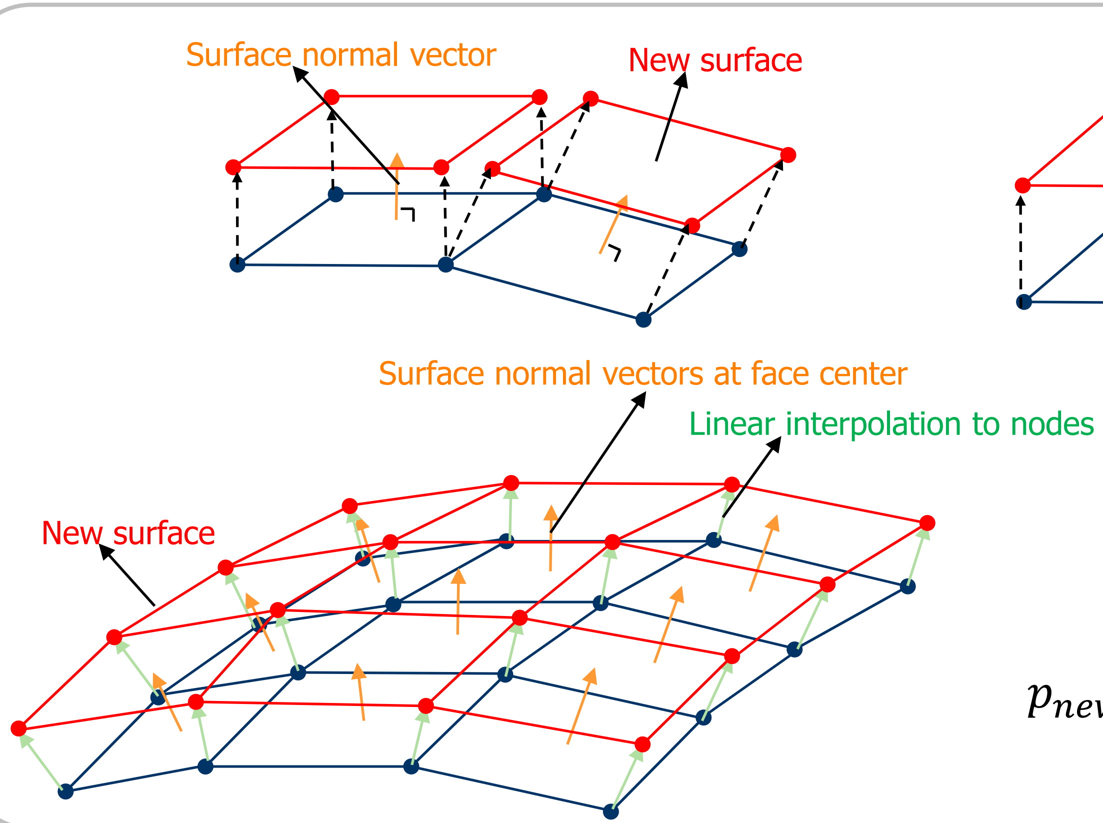


NUMERICAL METHOD



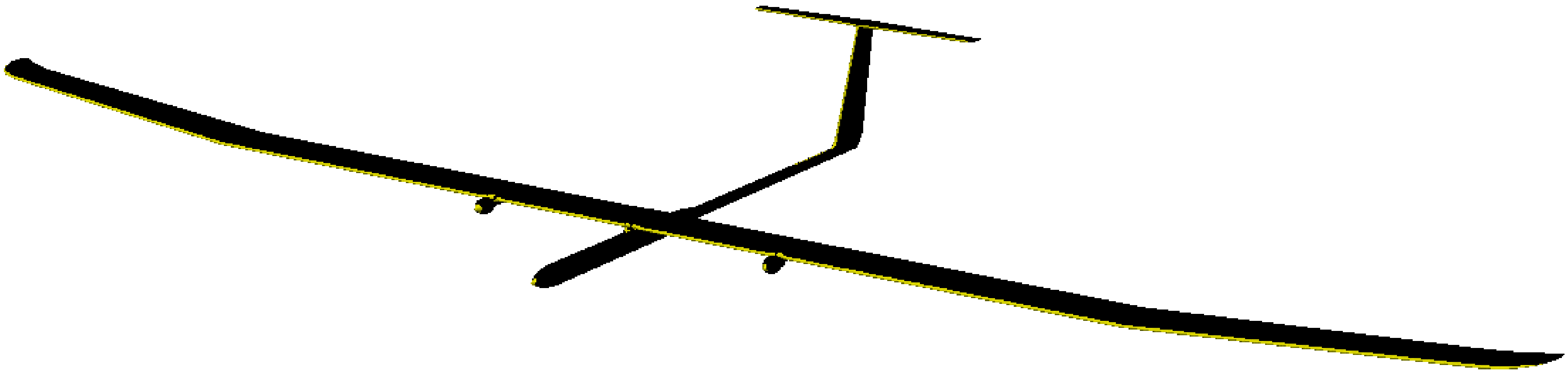
3D Grid generation

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



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

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



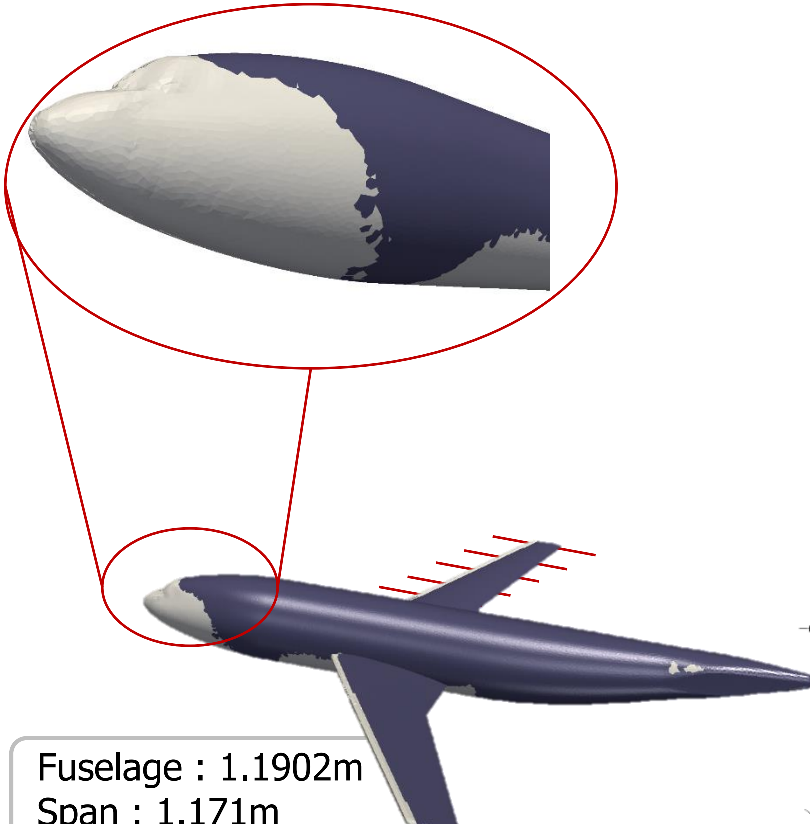
VALIDATION

3D AIRCRAFT

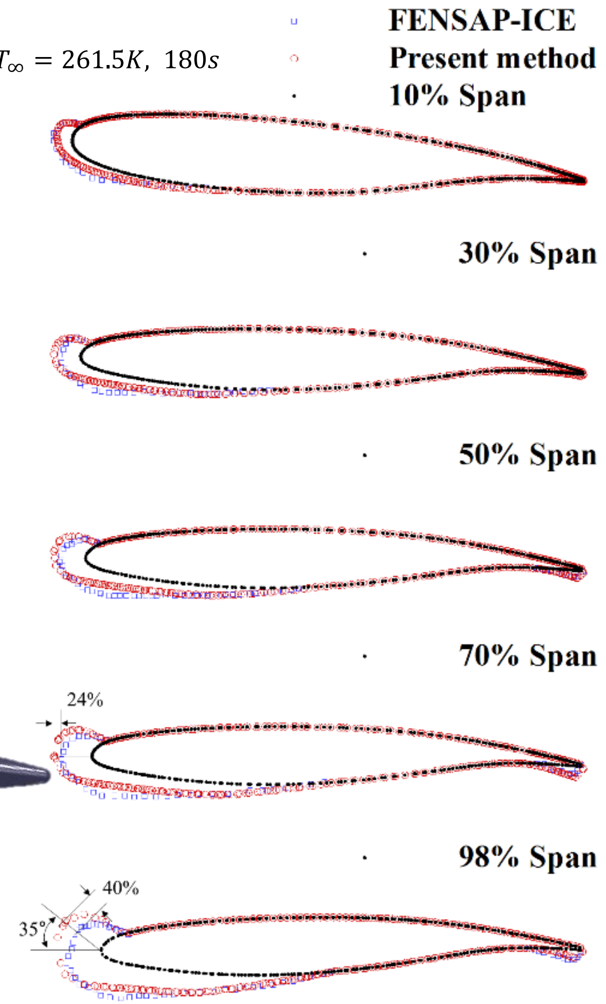
VALIDATION : FIXED WING AIRCRAFT

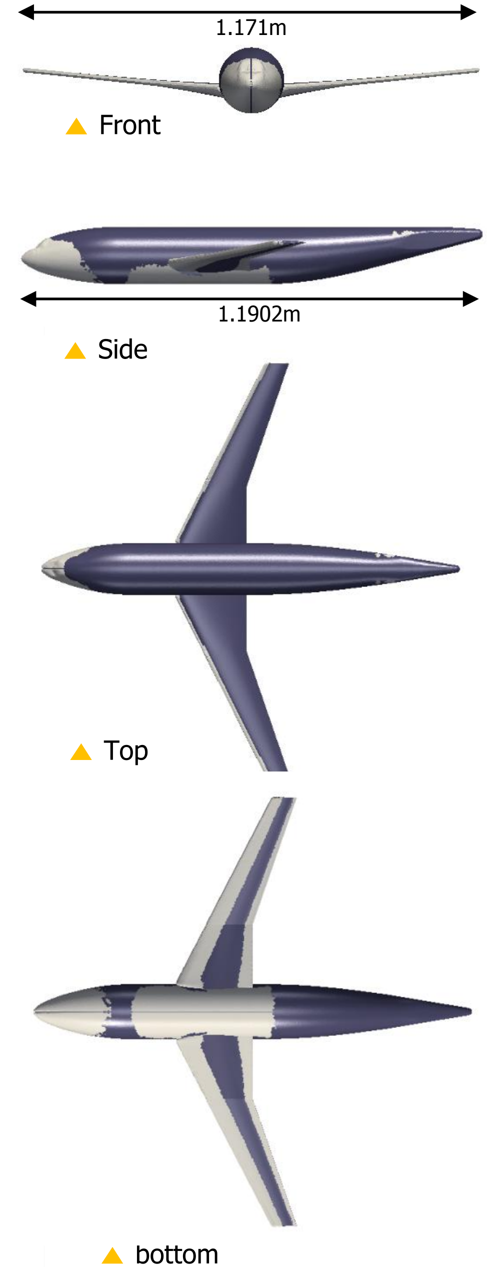
DLRF6 Wing + Fuselage

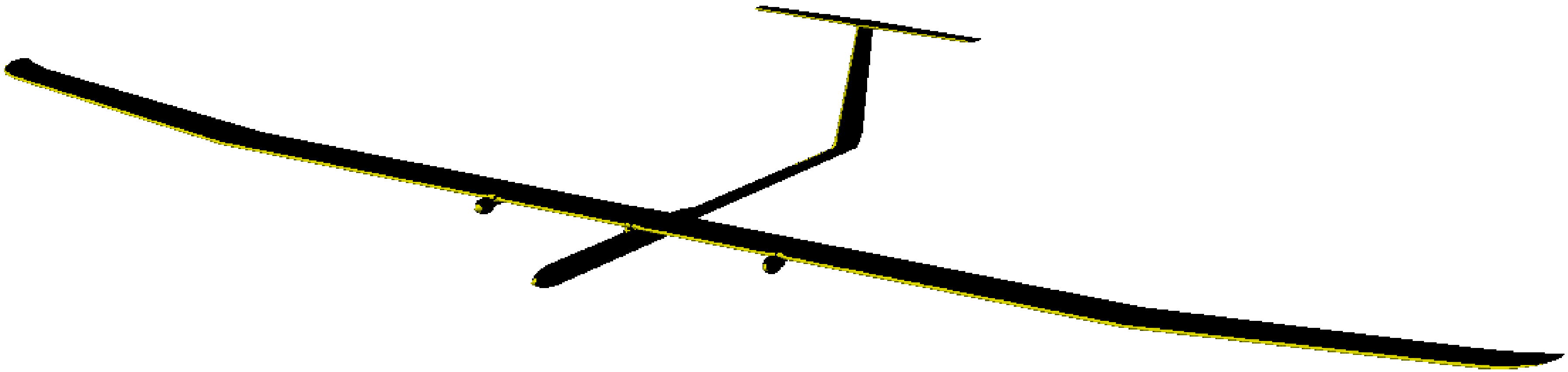
- Assumption of the descending stage
  - ✓ $\alpha = 6°,\ M_\infty = 0.235,\ LWC = 1.0\frac{g}{m^3},\ T_\infty = 261.5K,\ 180s$



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







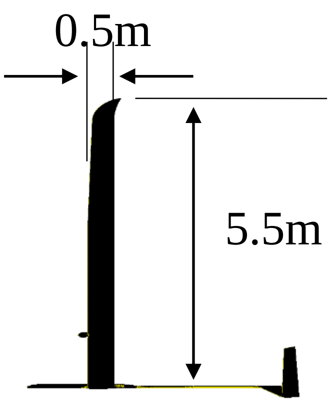
RESULTS AND DISCUSSION

TO IDENTIFY THE ICING CONDITIONS WHICH THE HALE MISSION IS SUCCESSFULLY PERFORMED

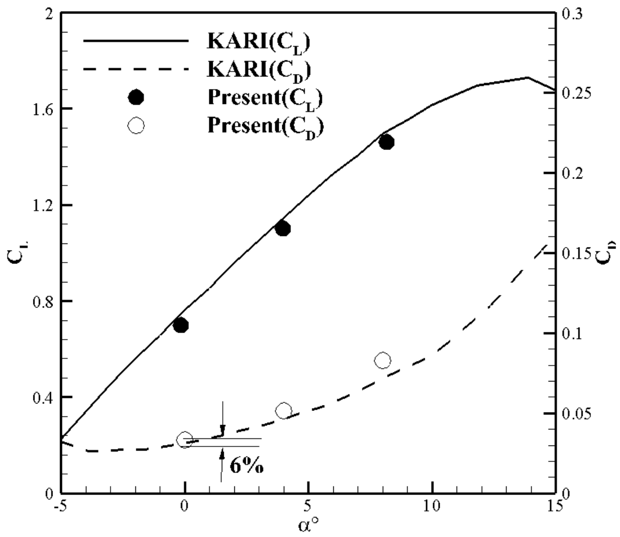
RESULTS AND DISCUSSION

STEP1 : Set up the calculation conditions

- 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
    - Solar cell
    - Span : 11m
    - Chord : 0.5m
    - Maximum takeoff weight : 20kg
    - Empty Weight : 13kg
    - Operating altitude : 10km
    - Rate of climb = 1m/s
    - Battery : 3kWh



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

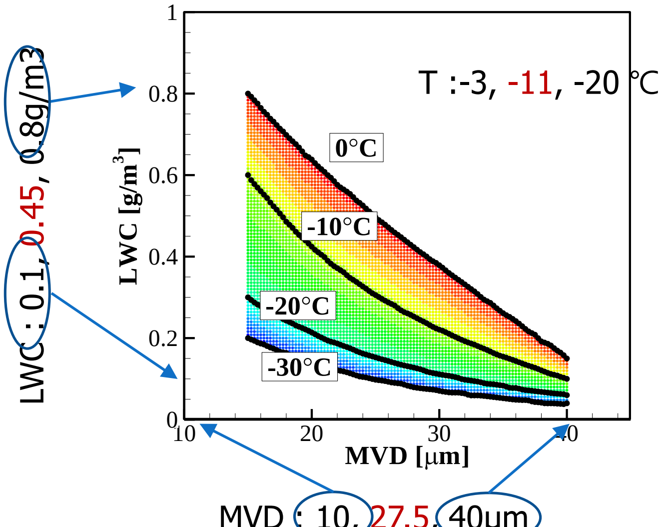


▲Validation results of C_L and C_D

RESULTS AND DISCUSSION

STEP1 : Set up the calculation conditions

- FAR PART 25, Appendix C conditions
  - ✓ Appendix C provides the observed icing conditions for the airworthiness certification
  - ✓ 7 cases for the parametric study and construction of RSM using the boundary values of Appendix C
    - Cf.) The temperature range -20 ℃ ≤ T ≤ -3 ℃
      - No ice at T=0 ℃, and -20≥T ℃ does not change the ice shapes given LWC
- Other inputs are obtained based on the mission profile of HALE
  - ✓ Exposure time = 2 hours, Rate of climb = 1m/s, water droplet exist 7.2km
  - ✓ Target altitude is 10km but the ambient parameters is adopted at 5km
- One shot method
  - ✓ To reduce the calculation time without the grid update on the ice shapes

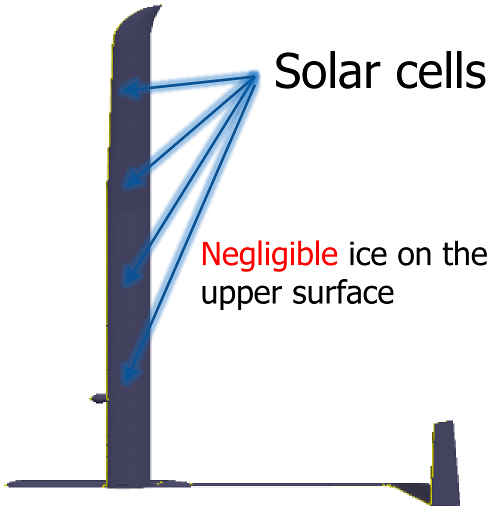


No	Case name	LWC[g/㎥]	MVD[μm]	T[℃]
1	Reference	0.45	27.5	-11
2	LWC↑	0.8	27.5	-11
3	LWC↓	0.1	27.5	-11
4	MVD↑	0.45	40	-11
5	MVD↓	0.45	10	-11
6	T↑	0.45	27.5	-3
7	T↓	0.45	27.5	-20

RESULTS AND DISCUSSION

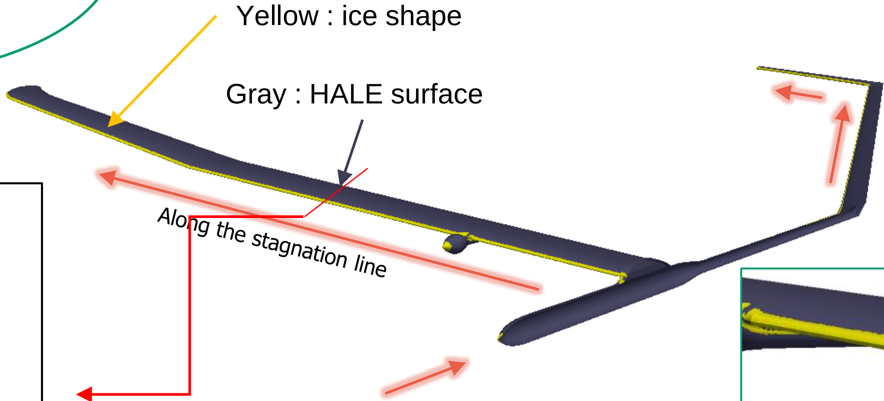
STEP2 : Ice accretion shapes

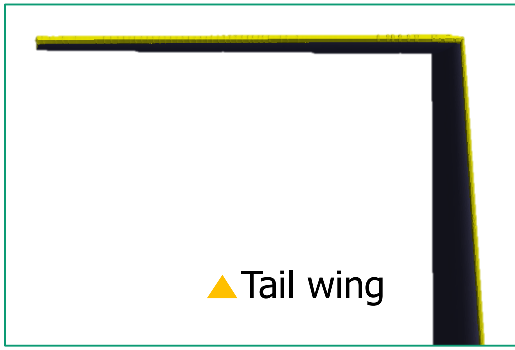
- Accreted ice shapes at reference condition
  - ✓ $U_\infty = 6.7m/s, LWC = 0.45g/m^3, MVD = 20\mu m, T_\infty = -11℃,\ 7200s$
  - ✓ Ice accretion occurs along the stagnation line
    - Fuselage nose, leading edge of main and tail wings
  - ✓ Negligible ice on the upper and lower surface of the wings
    - The decrease of solar cell efficiency is negligible



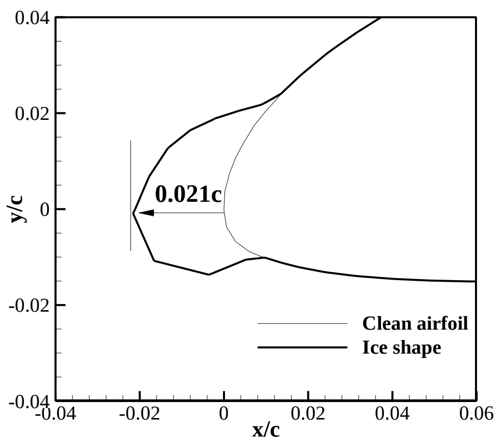
Top view

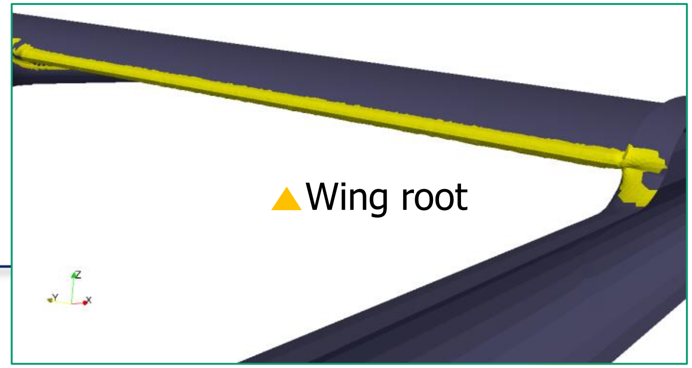
Wing tip





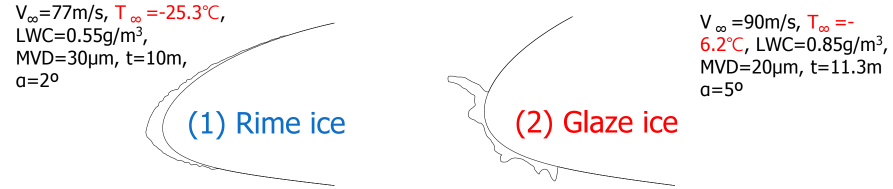
Tail wing





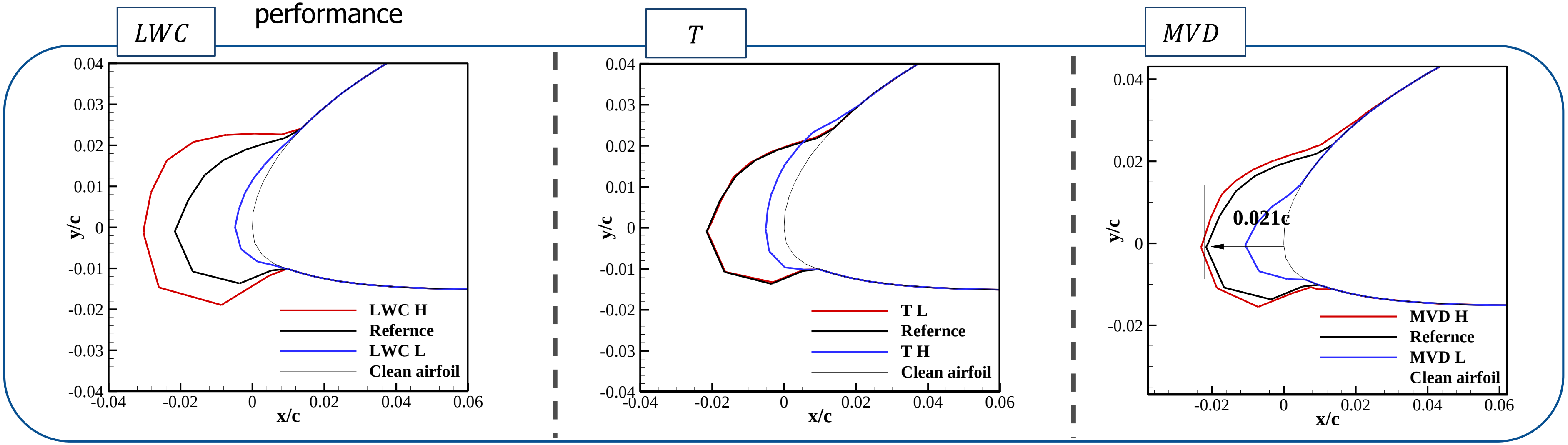
Wing root

RESULTS AND DISCUSSION

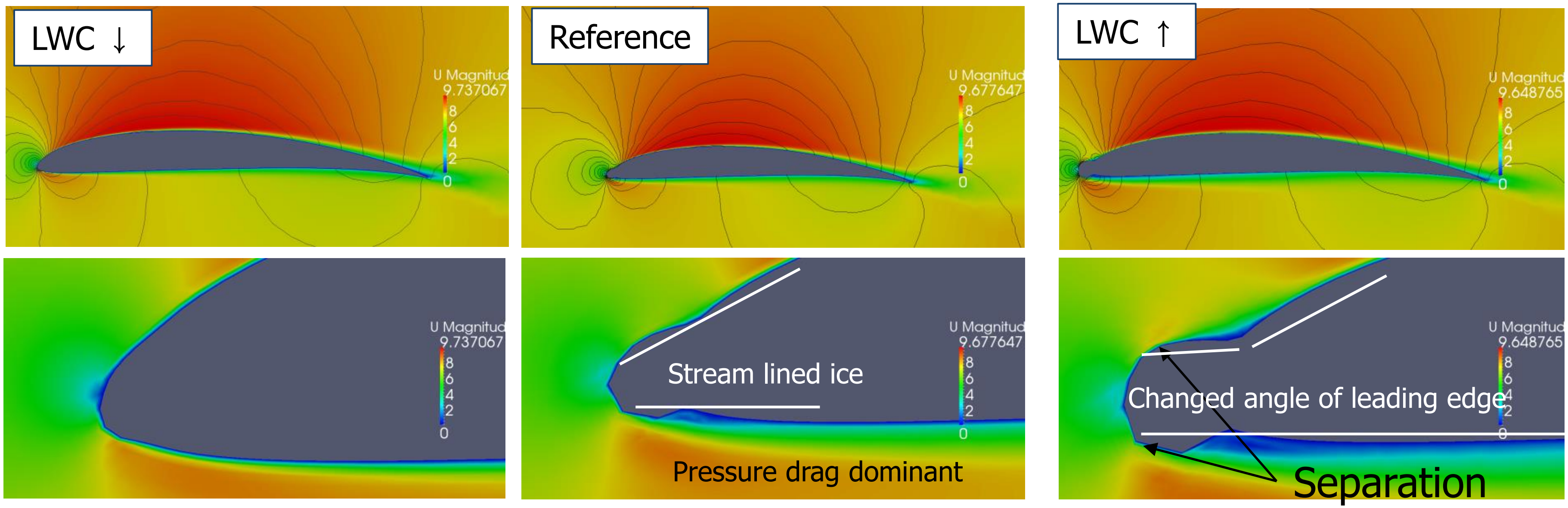


SETP2 : Ice accretion shapes

- Rime ice shapes in all cases (not ice hon shapes)
  - ✓ Even in high temperature (-3℃) case, runback water occurs but the ice horn does not appear
    - Due to insufficient heat transfer to freeze the whole runback water
- MVD
  - ✓ Low inertia ($K = \frac{\rho_w V_\infty MVD^2}{18\mu c}$) of droplet does not make the significant change of ice accretion shapes
    - In low K, the trajectories similar to stream line of air, and in high K, the thickness slightly changed maintaining the shapes
- LWC and T are the key parameters
  - ✓ Maximum thickness depends on the LWC and T
  - ✓ The worst case can be expected in low temperature and high LWC condition for the aerodynamic performance



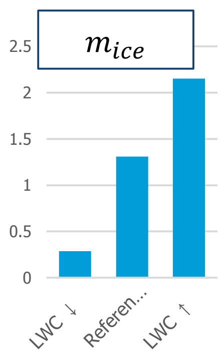
RESULTS AND DISCUSSION

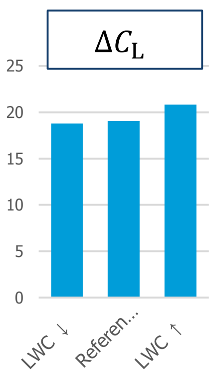


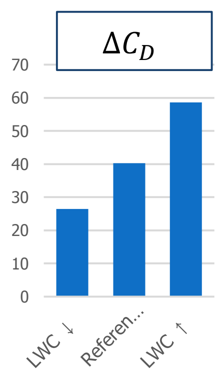
$U_\infty = 6.7m/s, LWC = 0.1g/m^3, MVD = 27.5\mu m, T_\infty = -11°C$

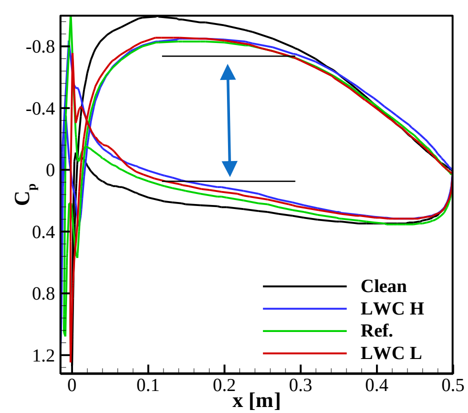
$U_\infty = 6.7m/s, LWC = 0.45g/m^3, MVD = 27.5\mu m, T_\infty = -11°C$

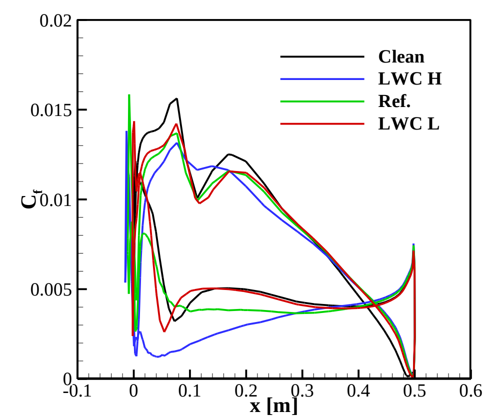
$U_\infty = 6.7m/s, LWC = 0.8g/m^3, MVD = 27.5\mu m, T_\infty = -11°C$











RESULTS AND DISCUSSION

STEP3 : RSM(Response Surface Methodology)

- To efficiently analyze the correlation between meteorological parameters and aerodynamic performance
- As a 1st attempt, the 1st order equation is constructed in this study, due to huge computation required to construct higher order model
- $y_i = \beta_0 + \beta_0 x_1 + \beta_2 x_2 + \beta_3 x_3$

R^2	0.90	y_1	$\Delta M = \frac{m_{ice}}{MTOW}$ (%)
	0.84	y_2	$\Delta C_L = \frac{(C_{L,clean} - C_{L,ice})}{C_{L,clean}}$ (%)
	0.75	y_3	$\Delta C_D = \frac{(C_{D,clean} - C_{D,ice})}{C_{D,clean}}$ (%)

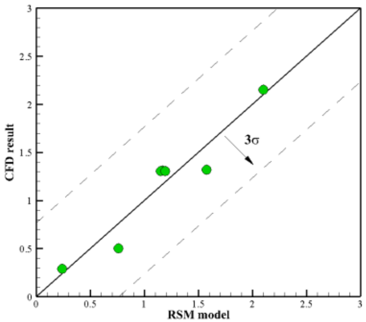
x_1	x_2	x_3
LWC[g/m³]	MVD[μm]	T[k]

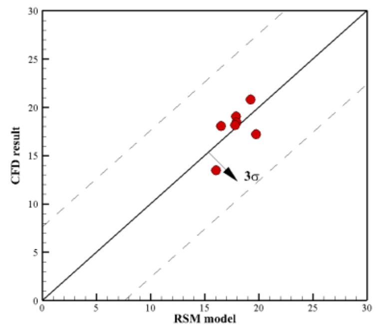
	Mice[kg]	ΔC_L (%)	ΔC_d (%)
β_0	11.93148	29.88058	117.8446
β_1	2.65858	2.12089	45.9686
β_2	-0.00151	-0.10204	-0.13271
β_3	-0.04546	-0.04252	-0.36459

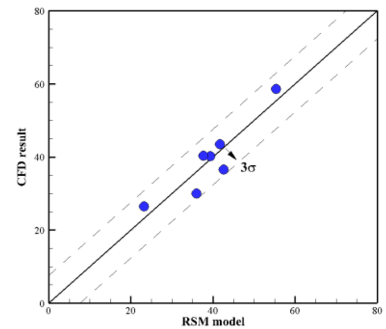
$$\Delta M = \frac{m_{ice}}{MTOW} \ (\%)$$

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

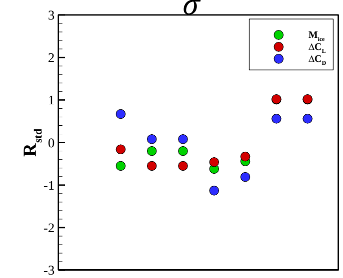
$$\Delta C_D = \frac{|C_{D,clean} - C_{D,ice}|}{C_{D,clean}} \ (\%)$$







$$R_{std} = \frac{e}{\sigma}$$



Within 3σ, $\sigma = standard\ deviation$

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

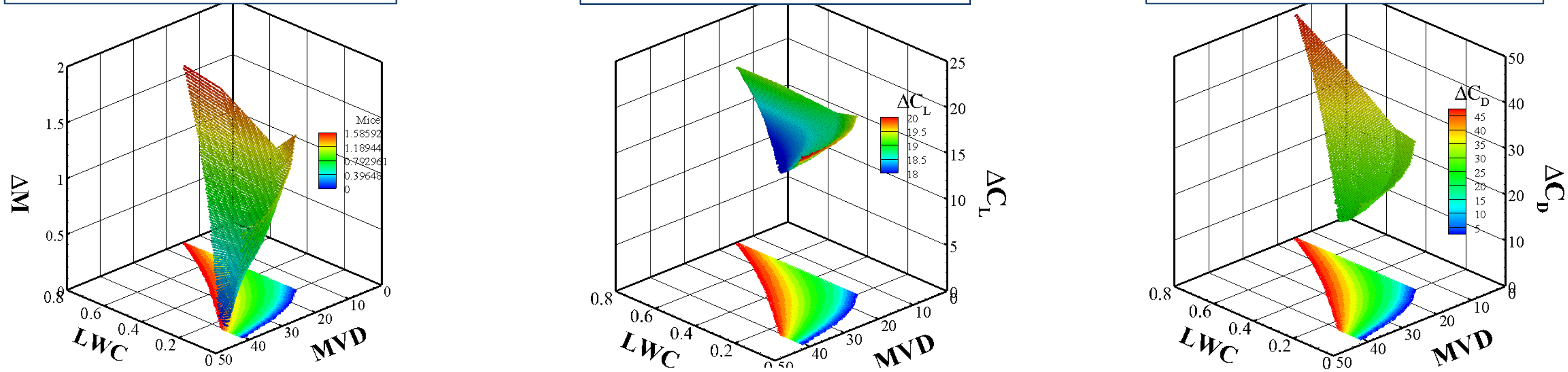
RESULTS AND DISCUSSION

STEP3 : RSM(Response Surface Methodology)

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

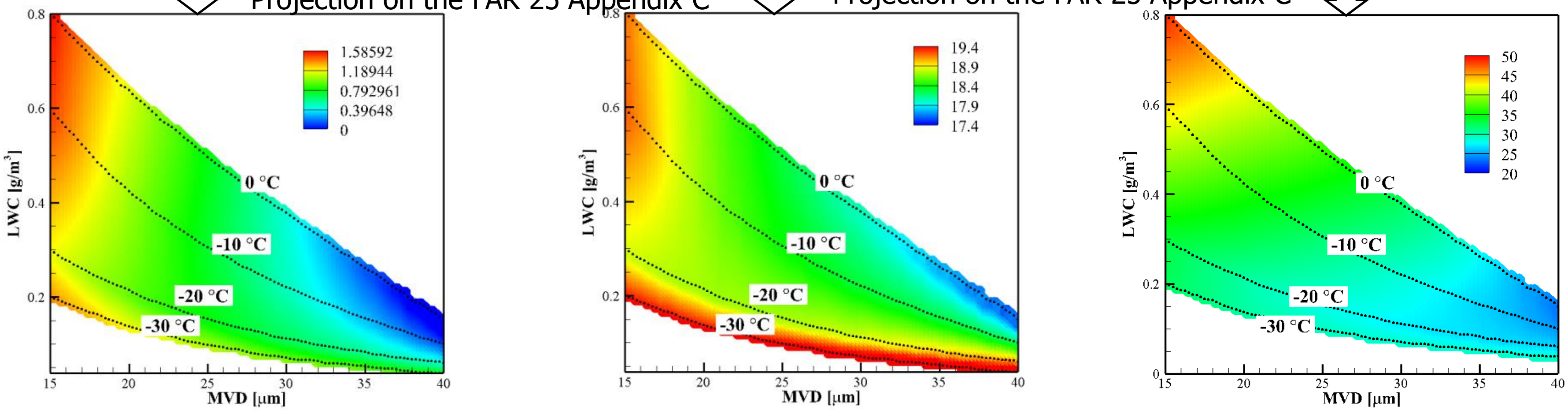
$$\Delta C_L = \frac{|C_{L,clean} - C_{L,ice}|}{C_{L,clean}}\ (\%)$$

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



Projection on the FAR 25 Appendix C

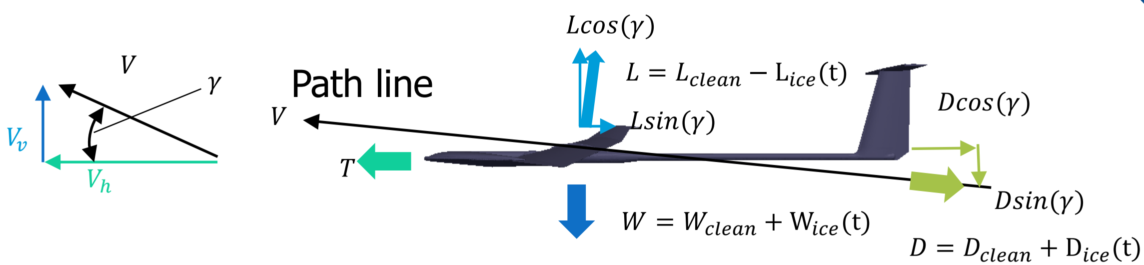
Projection on the FAR 25 Appendix C



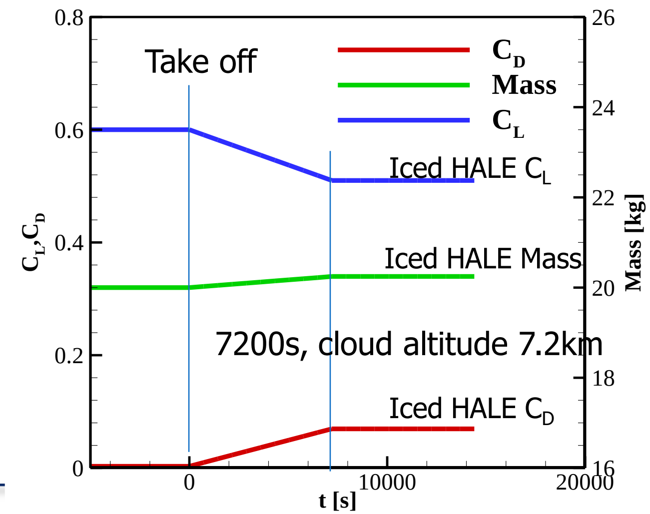
RESULTS AND DISCUSSION

STEP4 : Performance of HALE

- The capacity of battery → Whether the HALE can perform the mission or not
  - ✓ If the HALE can climb up to the target altitude using 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
  - ✓ 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
      - $\eta_{battery} = 90\%,\ \eta_{propeller} = 60\%,\ \eta_{motor} = 88\%,\ \eta_{control} = 95\%$



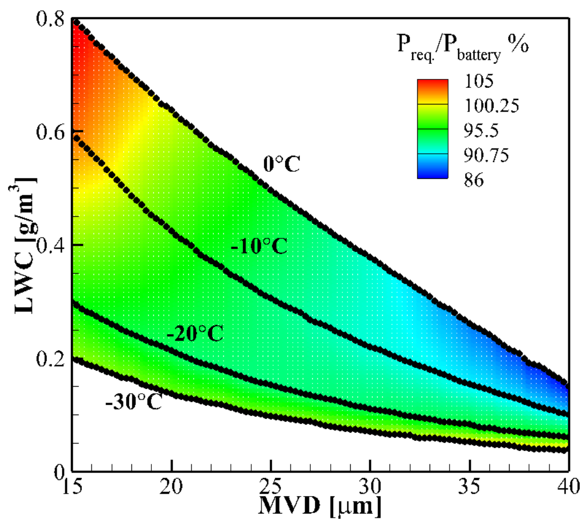
$$Lcos(\gamma) = W + Dsin(\gamma)$$
$$T = Dcos(\gamma) + Lsin(\gamma)$$
$$P = TV/(\eta_{battery} \cdot \eta_{propeller} \cdot \eta_{motor} \cdot \eta_{control})$$



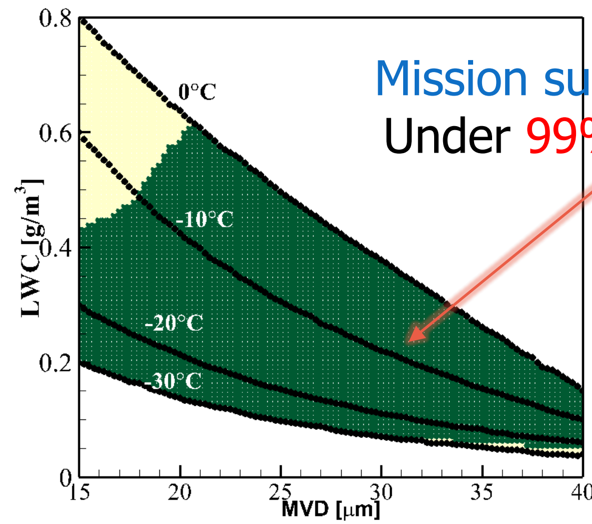
RESULTS AND DISCUSSION

STEP 4: Performance of HALE

- Ice accretion requires more power than clean HALE to reach to the mission altitude
  - ✓ Clean HALE : 74% of battery power for 2.78 hours to 10km altitude by 1m/s of ROC
  - ✓ Minimum required power of ice HALE : 86.2%
  - ✓ Maximum required power of ice HALE : 106%
- There is mission failure area where the HALE can not reach to the mission altitude
  - ✓ High LWC (over 0.4 g/m3)and high temperature (over -15 ℃) region

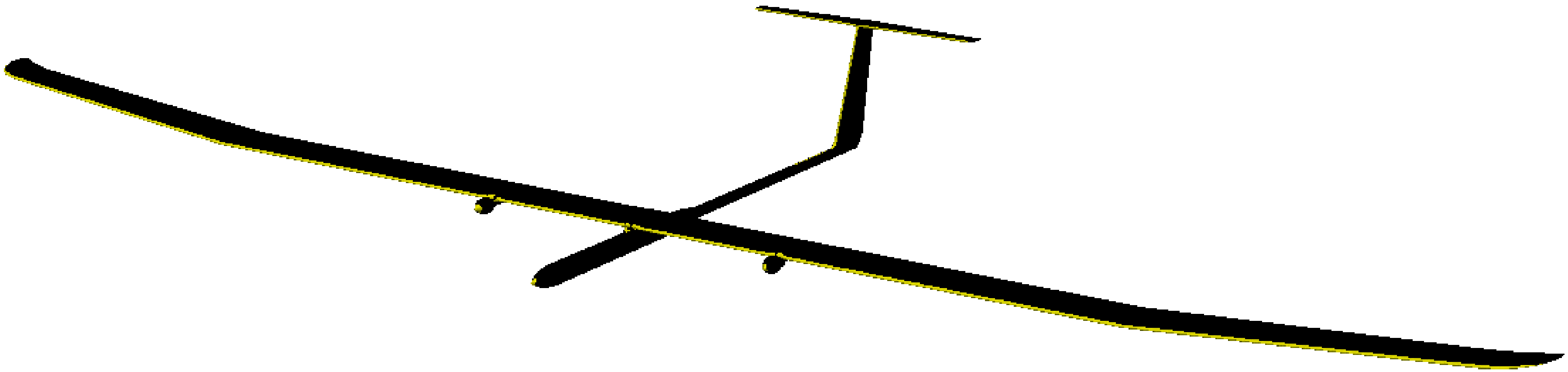


▲Required power



Mission success region
Under 99% of battery

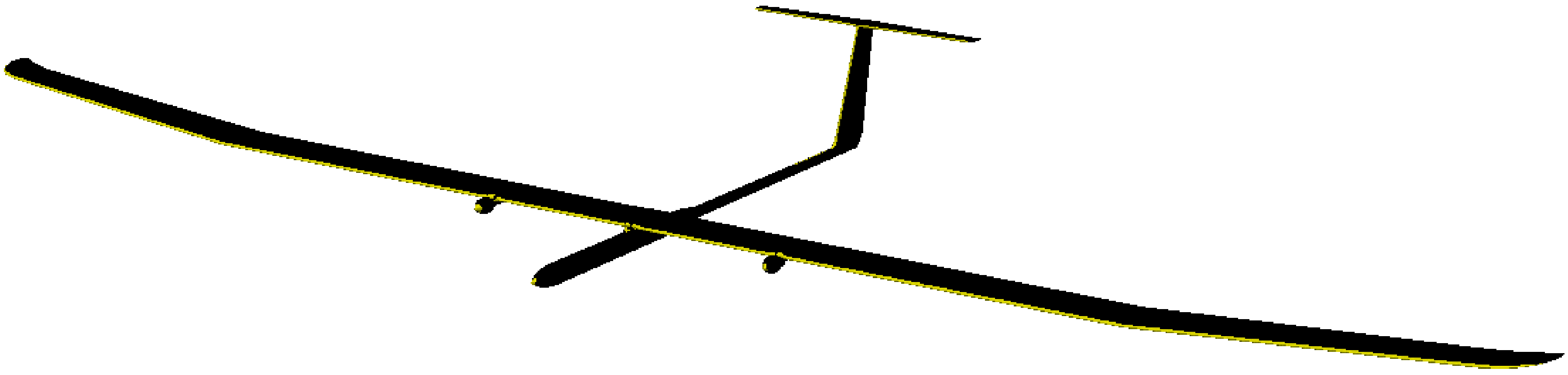
▲Required power[kWh]



CONCLUSIONS

CONCLUSIONS

- Development of 3D Ice Accretion Code Based on Eulerian approach
  - Generic 3D problems : DLR-F4(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
- LWC and T are the key parameters to the ice accretion shapes
    - ✓ Maximum thickness depends on the LWC and T
    - ✓ The effects of MVD are negligible due to low inertia of droplet (K)
- The methodology is suggested to identify the icing conditions under which the given HALE mission is successfully performed
  - From the gathered meteorological parameters, the HALE operators could make a decision from the estimation of required power
  - The linear RSM shows limitation for the prediction of lift and drag, thus, the higher order RSM is required
- The EAV-2H+ has the successful mission area where the HALE can ignore the degradation of performance
    - ✓ Low humidity (under 0.4g/m^3), low temperature (under -15 ℃) conditions regardless of temperature and MVD

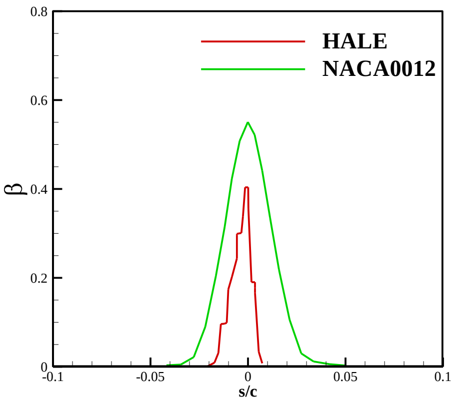


THANK YOU FOR YOUR ATTENTION.

RESULTS AND DISCUSSION

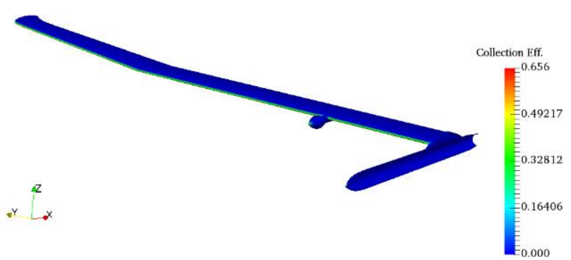
Effects of velocity

- 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

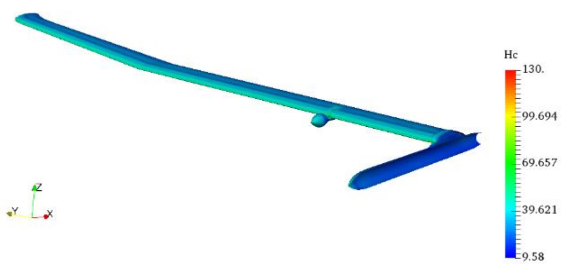


▲ Collection efficiency

- 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



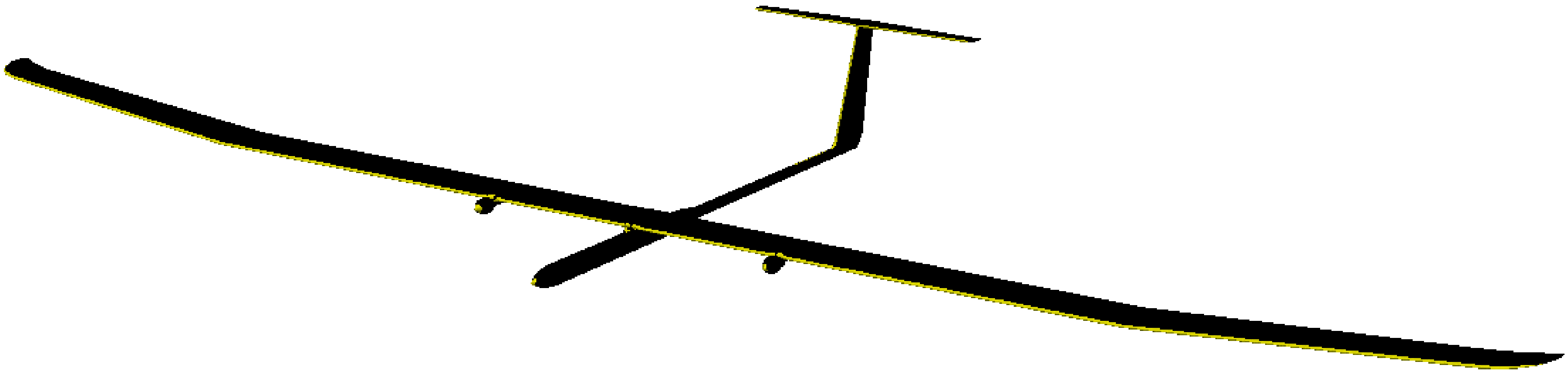
▲ Heat convection coefficient

INTRODUCTION

Development of 3D Ice Accretion Code

- Expensive to operating and maintain costs of experiment

	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)

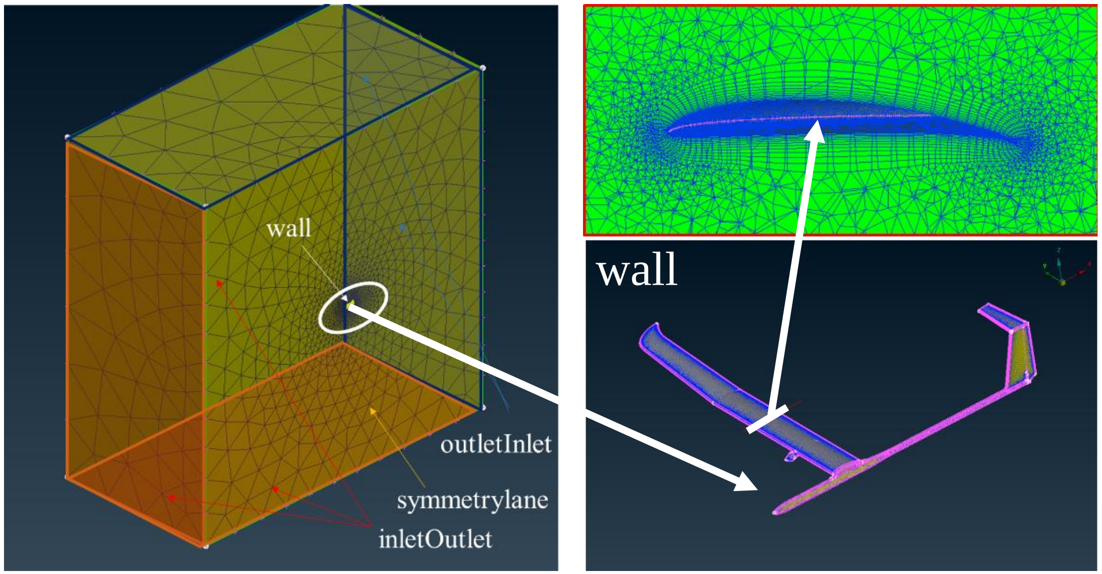


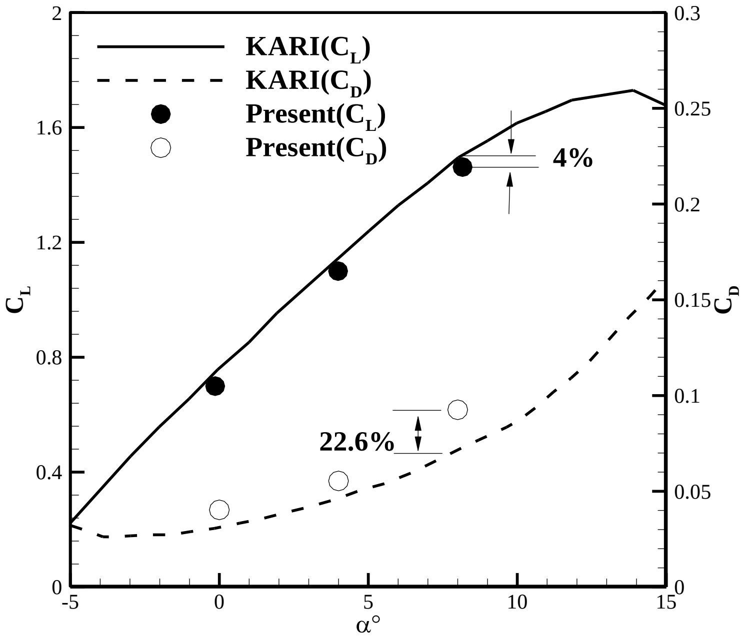
VALIDATION OF ICE ACCRETION SHAPES

2D AIRFOIL

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;

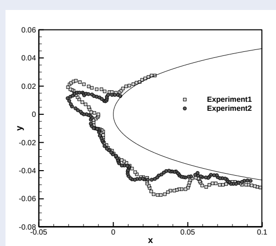
- Re=2.78 × 10^5, Ma = 0.022
- No wind tunnel data (22m span)
- Comparison with other numerical results
  - ✓ KARI (FLUENT) results and OpenFOAM(rhoPimpleFoma)

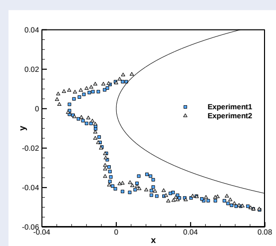
RESULTS AND DISCUSSION

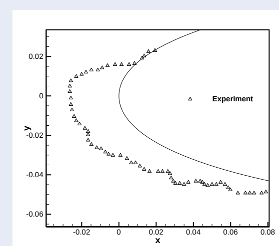
- Case study(2D ice accretion shapes)
  - NASA Icing wind tunnel tests*

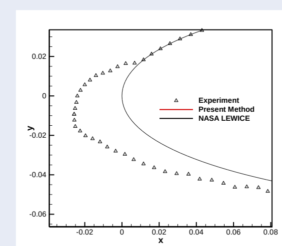
IRT case #	308	403	404	405
Airfoil	NACA0012			
$\alpha[\ ^\circ]$	4			
$V_\infty[m/s]$	102.8	102.8	102.8	102.8
T_∞[K]	262.04	262.04	256.49	250.3
LWC$[g/m^3]$	1.0	0.55	0.55	0.55
MVD$[\mu m]$	20	20	20	20
Time$[s]$	231	420	420	420
Description	Ice horn case	Mixture condition	Mixture condition	Rime ice

IRT shapes



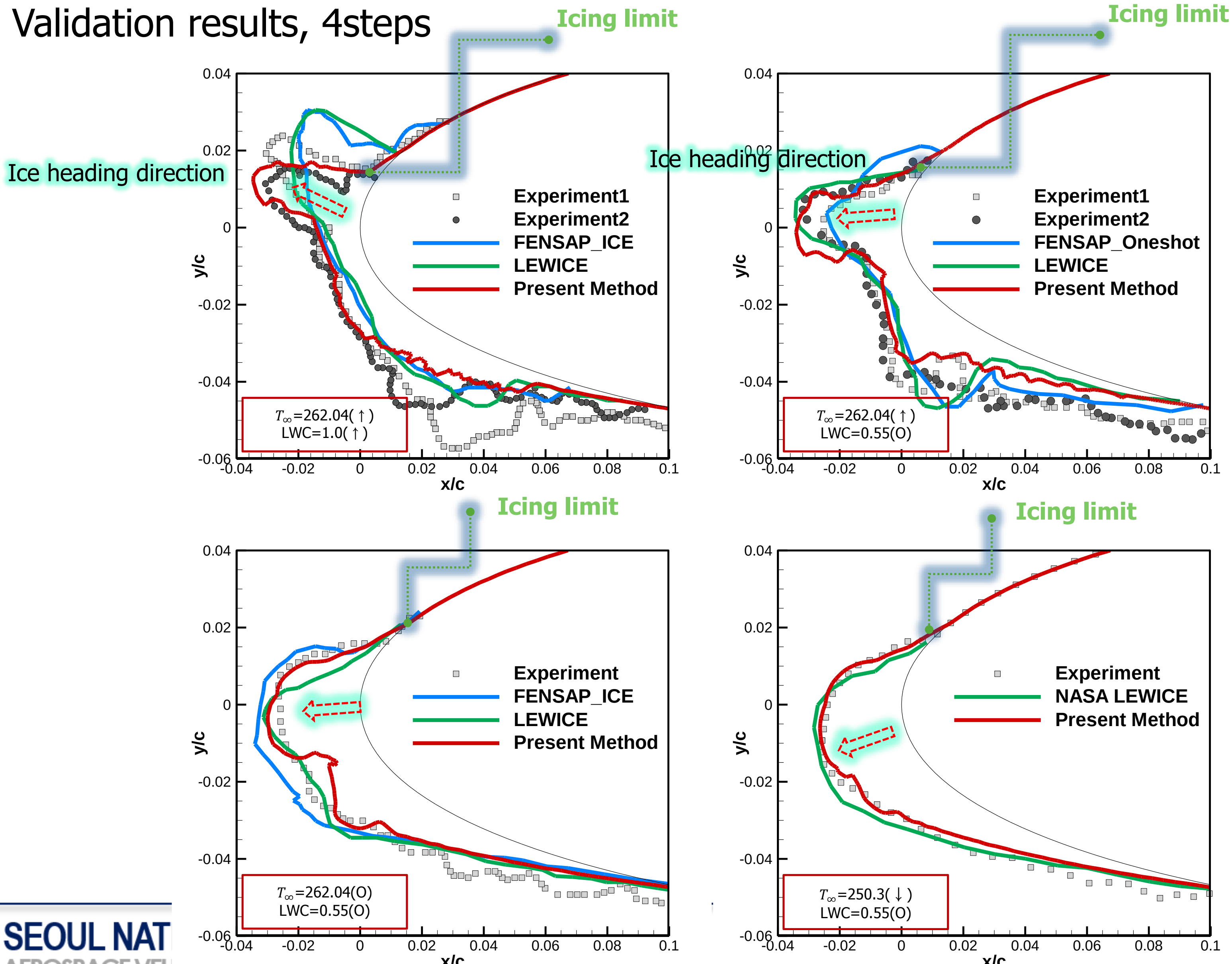






Results and Discussion

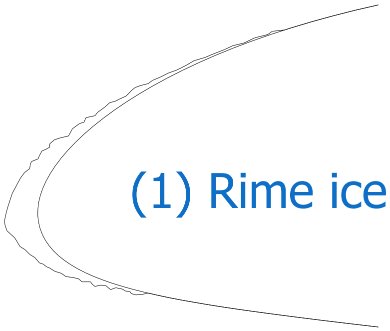
- Validation results, 4steps



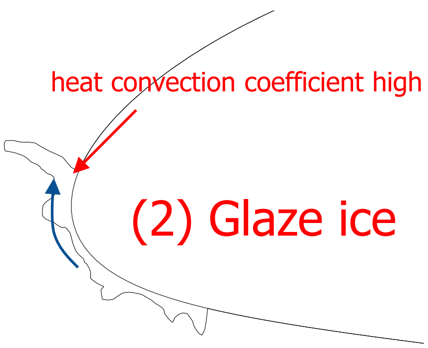
RESULTS AND DISCUSSION

Aircraft icing

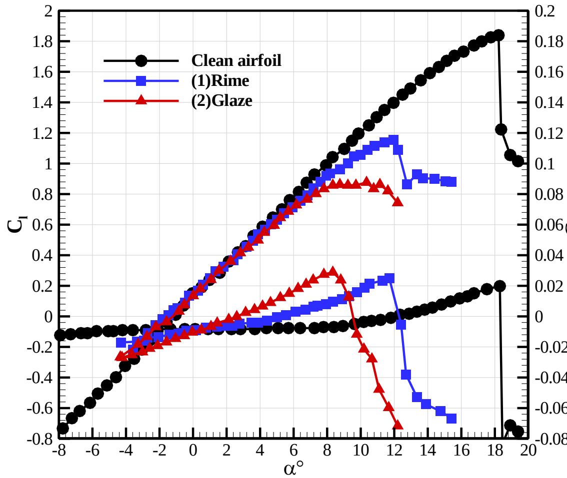
- Super cooled liquid water droplets freeze on the HALE surface
- (1) Rime ice
  - ✓ Super cooled liquid water droplets immediately freeze on the surface
- (2) Glaze ice
  - ✓ The collided super cooled liquid water droplets flow along the surface
  - ✓ The flowing water freezes where the heat convection coefficient high
- Problems : HALE is vulnerable system to icing conditions
  - ✓ Ultra-light design : can't afford to equip the anti/de-icing devices
  - ✓ Endurance ↓ , stability ↓ , propulsion efficiency ↓ , improper radio communications

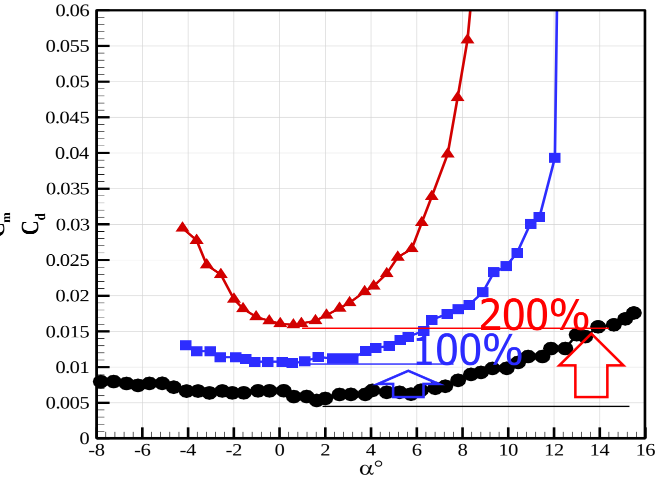


Icing condition : V_∞=77m/s, T_∞=-25.3℃, LWC=0.55g/m³, MVD=30μm, t=10m, α=2º



Icing condition :V_∞ =90m/s, T_∞ =-6.2℃, LWC=0.85g/m³, MVD=20μm, t=11.3m α=5º





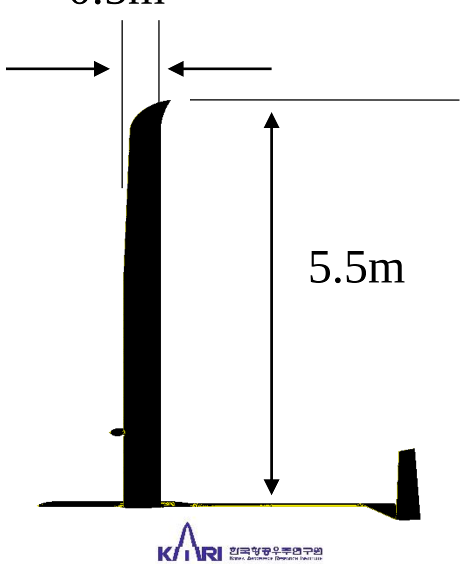
✓ *Broeren, P. A. et al, "Effect of High Fidelity Ice-Accretion Simulations on Full-Scale Airfoil Performance", J. of Aircraft, Vil.47, No.1, 2010, pp.240-254.

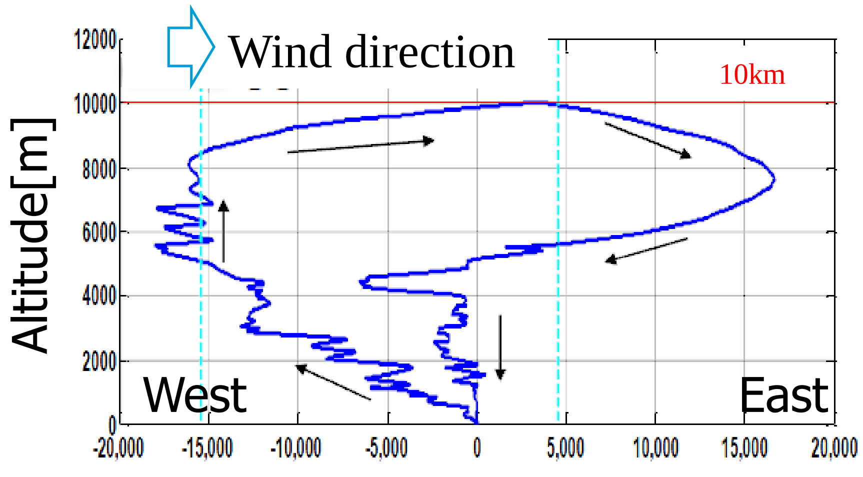
RESULTS AND DISCUSSION

Introduction of EVA-2H+

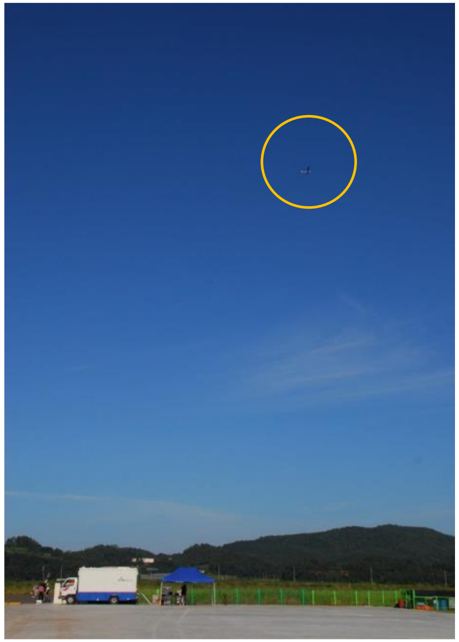
- Developed by Korean Aerospace Research Institute
  - ✓ Solar cell
  - ✓ Span : 11m, Chord : 0.5m, Maximum takeoff weight : 20kg, Empty Weight : 13kg
  - ✓ Operating altitude : 10km
  - ✓ Main wing section : SG6043
- On September 5, 2014
  - ✓ EVA-2H+ reached at operating altitude (10km) for 7 hrs.

▲Take off





▲Vertical flight path line

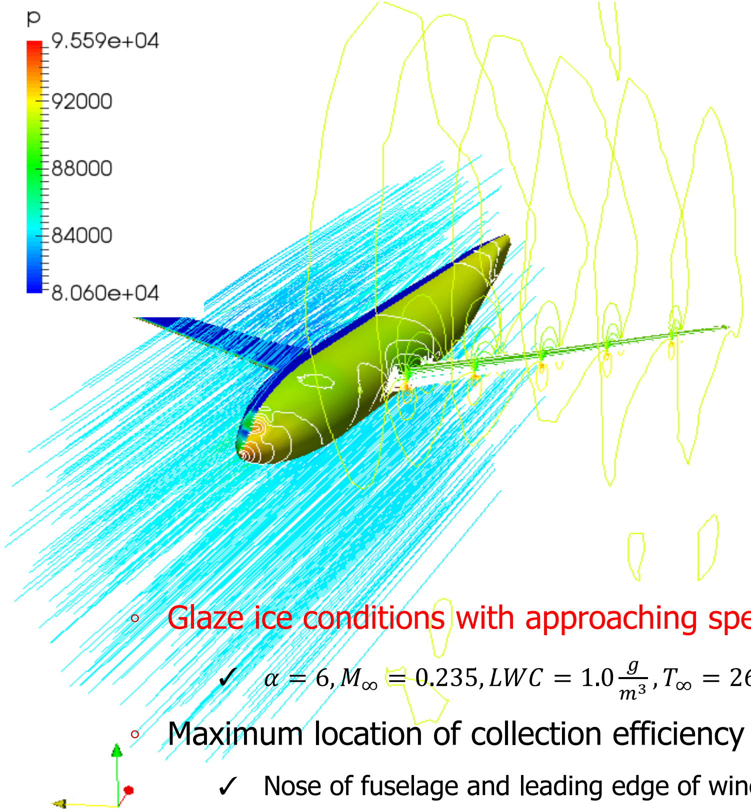


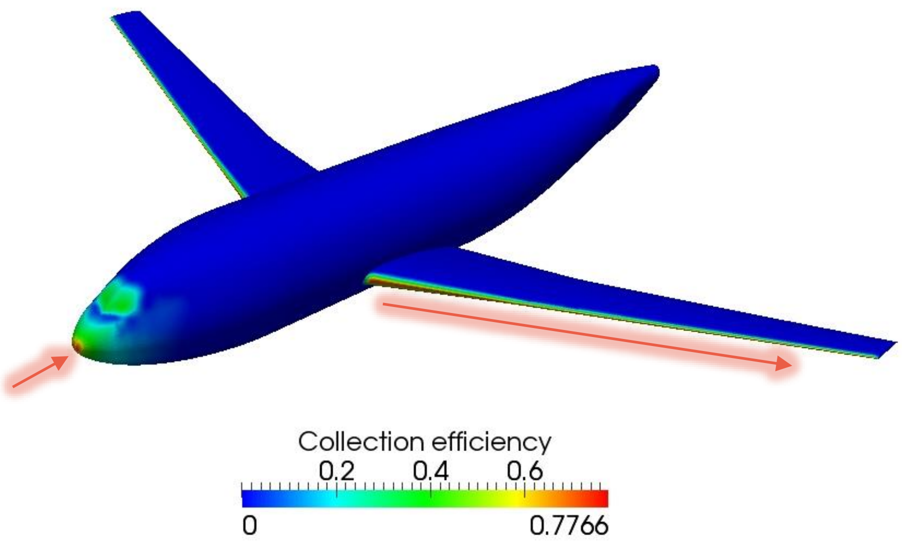
▲Climbing stage

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

RESULTS AND DISCUSSION

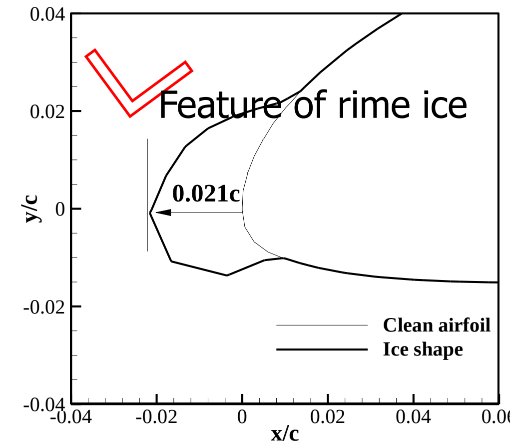
Effects of velocity

- 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)

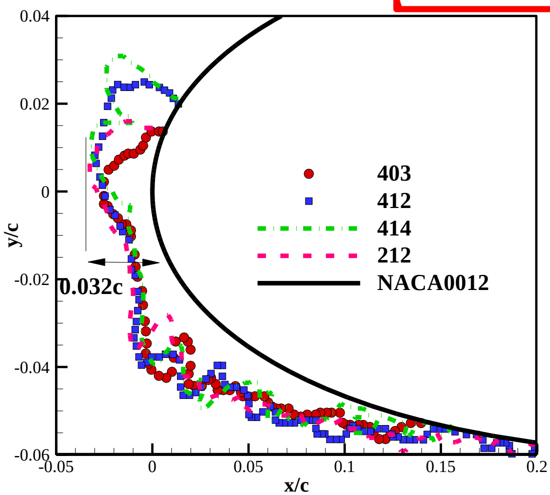
▲AOPA Report

Icing Risk

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	



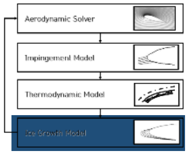
▲HALE results



▲IRT results

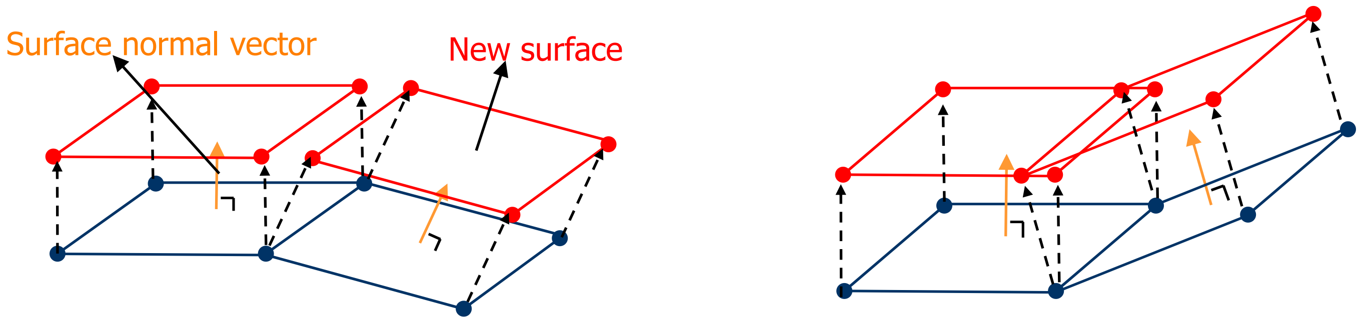
Case name	LWC[g/㎥] (difference%)	MVD[μm] (difference%)	T[K] (difference%)	V[m/s] (difference%)	Time[s] (difference%)
403	0.55 (22%)	20 (27.3%)	262.0 (0.042%)	102.8 (1253%)	420 (94.2%)
412	0.47 (9.1%)	30 (9.1%)	261.54 (0.23%)	102.8 (1253%)	492 (93.2%)
414	0.55 (22%)	25 (9.1%)	262.04 (0.042%)	102.8 (1253%)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

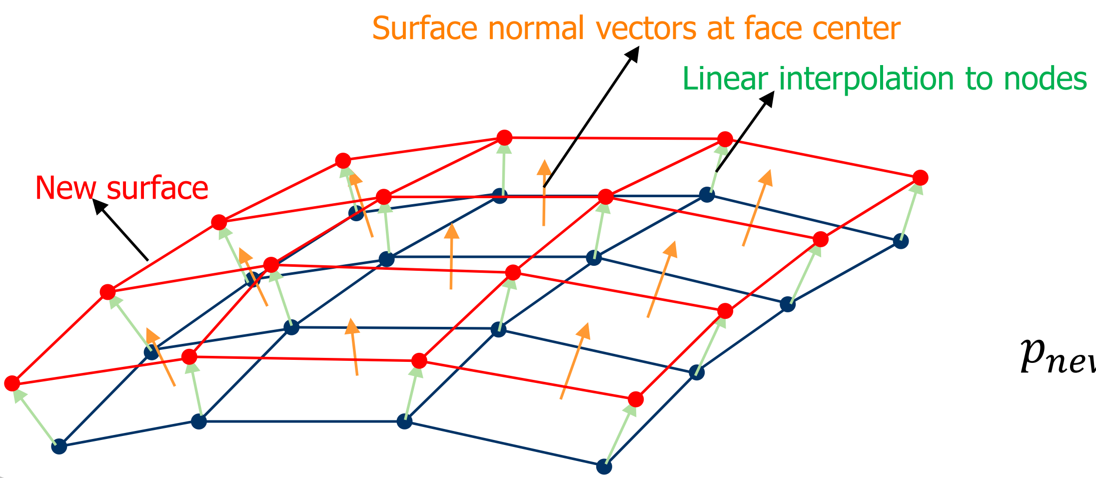
NUMERICAL METHOD



3D Grid generation

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





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

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

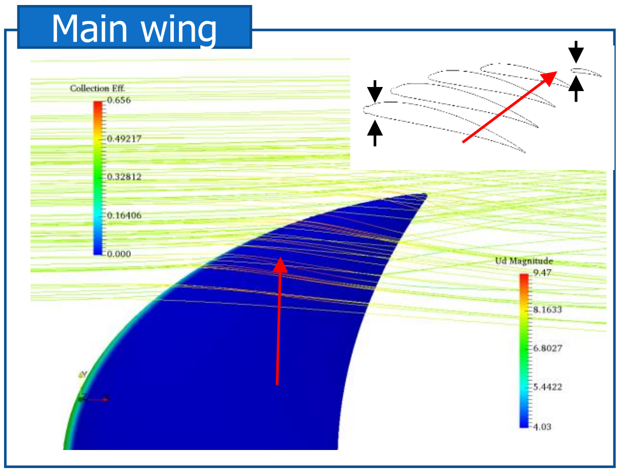
RESULTS AND DISCUSSION

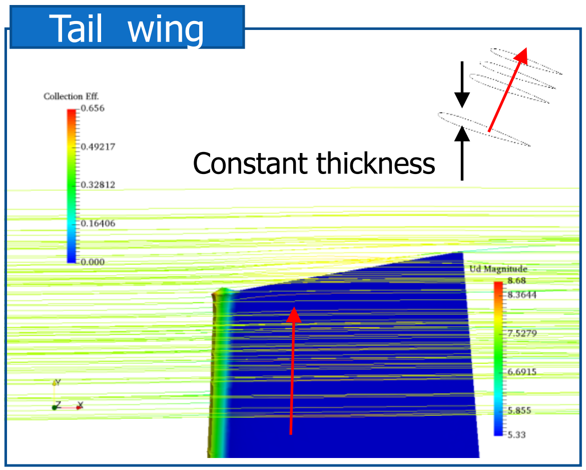
▲ Airbus 350 XWB

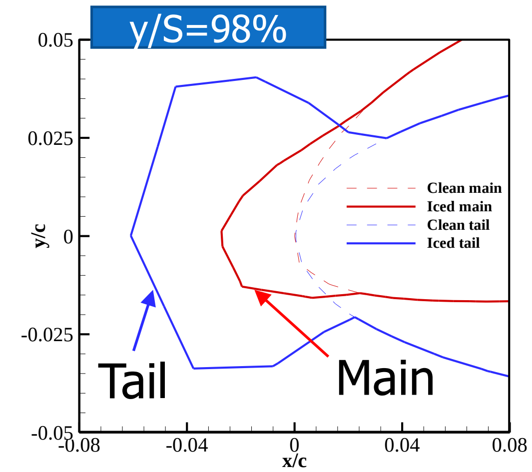
▲ Boing-787

Raked wing tip shape

- Aerodynamic efficiency
  - ✓ The reduced strength of the wing tip vortex and shortened dissipation length
  - ✓ The recent aircraft developed by Boing-787 and Airbus 350 XWB adopt the raked wing tip shape
  - ✓ The 2.2% less drag is also predicted in raked wing tip shape than elliptic planform in HALE platform
- Ice reduction effects of the raked wing tip
  - ✓ Thickness (frontal area) gradually decrease form the root to tip region
- Raked wing tip shape has aerodynamic efficiency with less ice accretion
  - ✓ At tail wing tip, maximum collection efficiency (0,61) and heat convection (163 W/m^2·K)







R. Babigian, and S. Hayashibara, "Computational Study of the Vortex Wake Generated by a Three - Dimensional Wing with Dihedral, Taper, and Sweep," AIAA Paper 2009- 4107, Jun. 2009.
Wonjin Jin, Yung-Gyo Lee, "Drag Reduction Design for a Long-endurance Electric Powered UAV," Int'l J. of Aeronautical & Space Sci. 16(2), 311–324 (2015)