Aerodynamic and propulsive effects of in-flight icing on fixed-wing aircraft and rotorcraft

November 30th Friday, 2018 (9:40~10:20AM)

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Research Center for Aircraft Core Technology

Outline

Introduction of the Research Center for Aircraft Core Technology

In-flight icing and certification of aircraft & rotorcraft

Sensible Use of CFD & icing wind tunnel for in-flight icing

Looking ahead

Aerospace Computational Modeling Laboratory
http://acml.gnu.ac.kr

Research Center for Aircraft Core Technology
(2017-Present) http://actrc.gnu.ac.kr

ACTRC and its vision

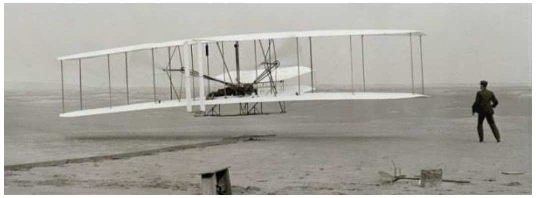
ACTRC aims to revitalize the spirit of “learning by acting (and doing)” in the aeronautics research by tackling directly the crux of unsolved problems in composites and safety-related core systems of aircraft.

ACTRC with annual budget of US$2.7M consists of three core research groups (12 professors from GNU, UNIST, KAIST, SNU; 12 domestic partner companies; 13 foreign partner institutions).

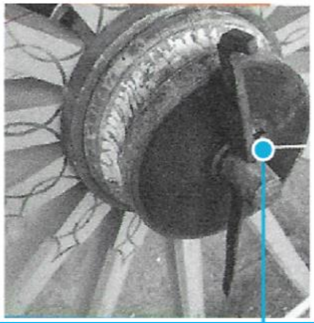
Ultimately, ACTRC envisions the development of the critical linchpin technology upon which the domestic aircraft industry will hinge.

Research Center for Aircraft Core Technology

National Research Foundation of Korea

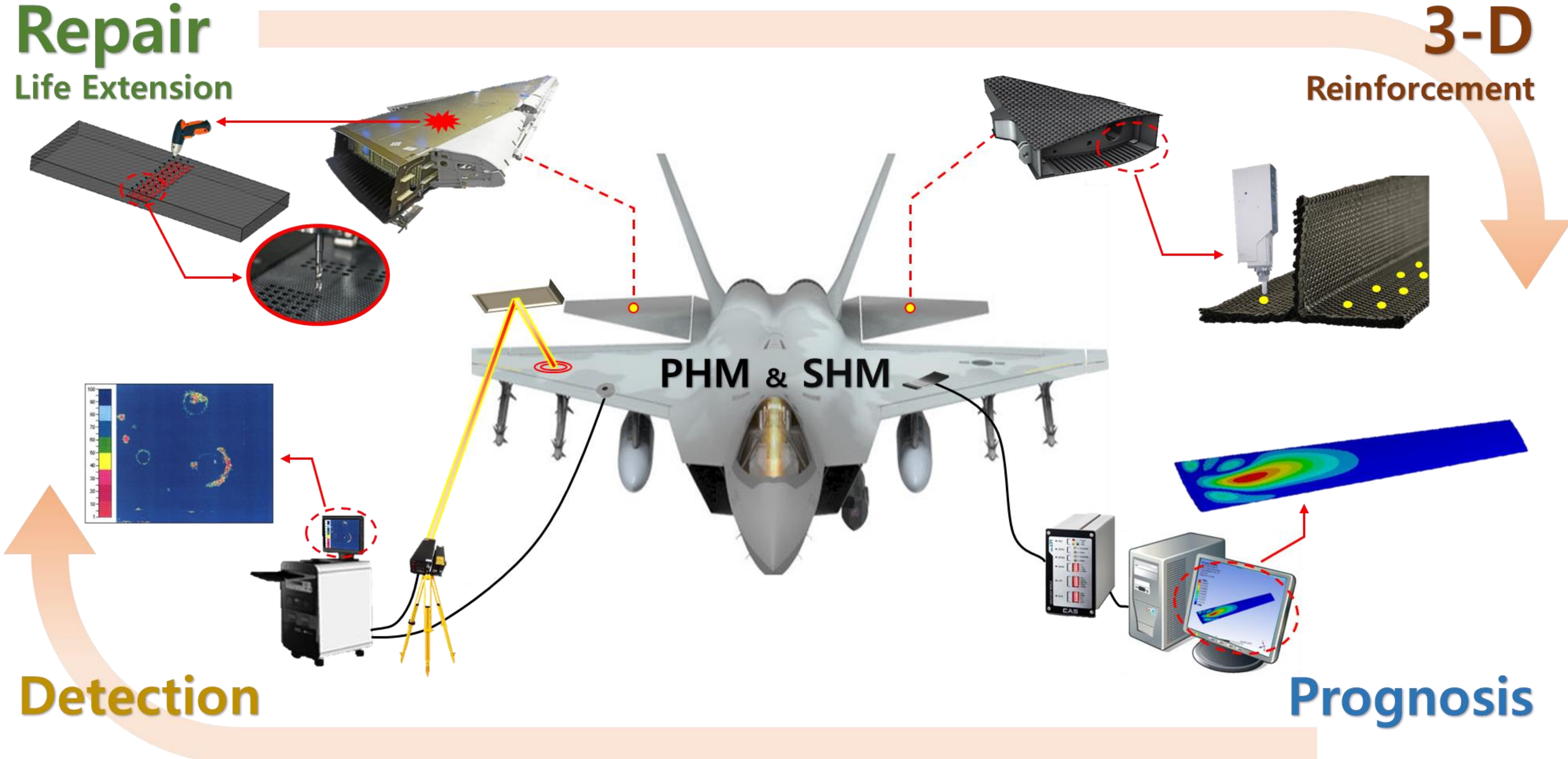


Learning by doing

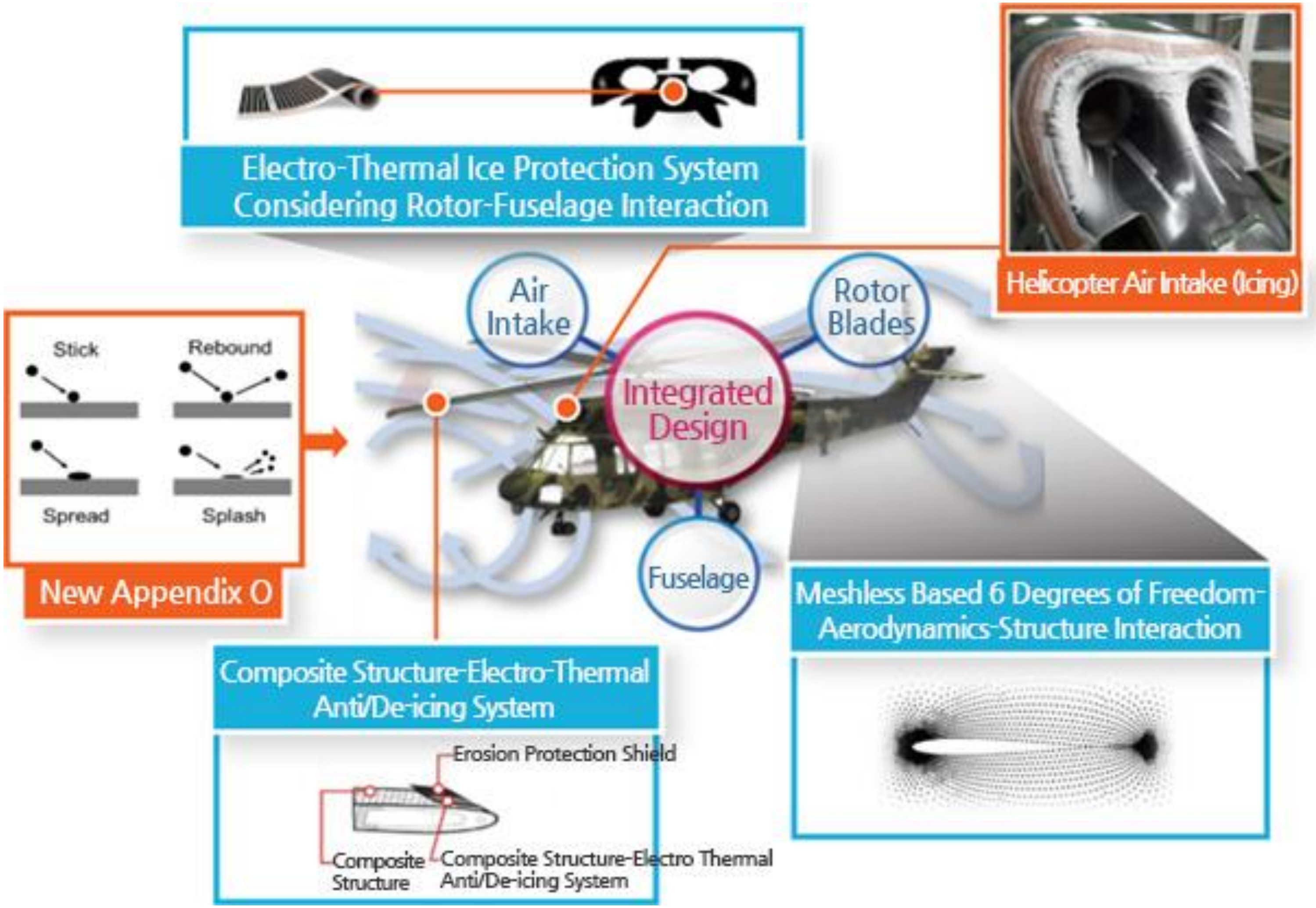


Linchpin

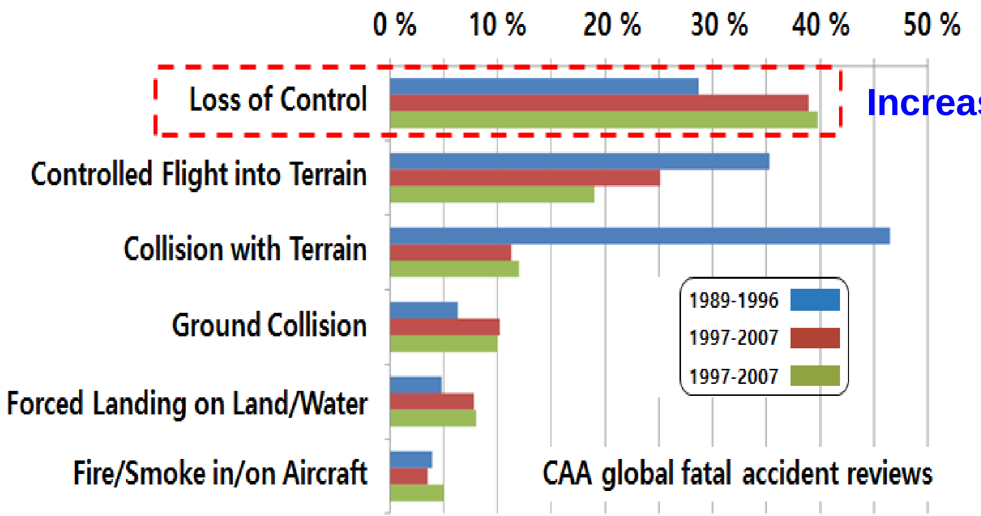
Group I research (tackling de-lamination)

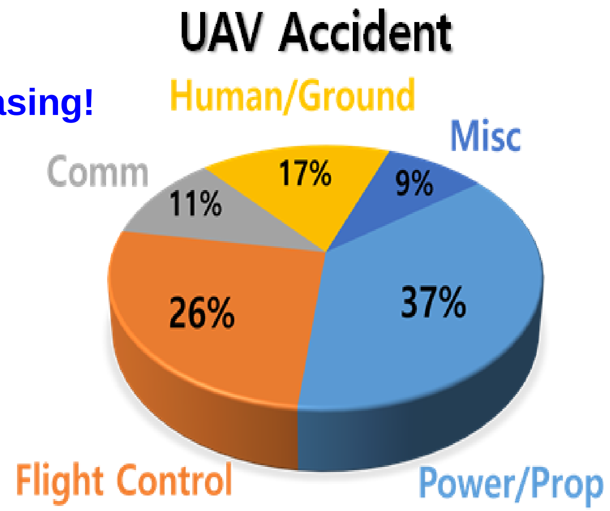


Group II research (tackling icing and certification)



Group III research (tackling upset)





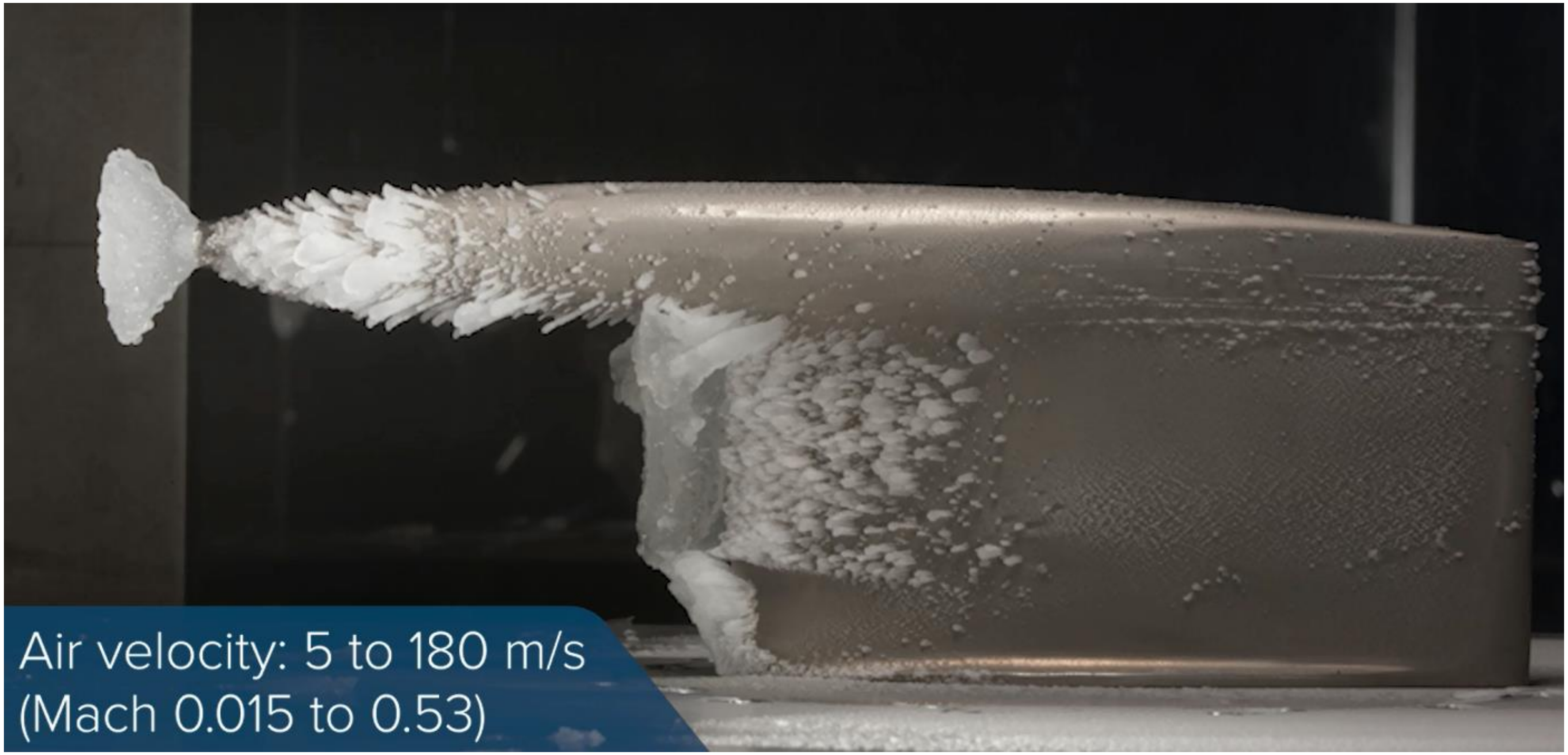
B-2 ADS Malfunction (2008)

ADS: Air Data System

AF447 ADS Malfunction (2009)

Ice accretion on air data probe

Movie: Altitude IWT (National Research Council, Canada)



International collaboration in in-flight icing

International collaboration and **professional course (2010)** in in-flight icing certification

Effective Use of CFD for In-flight Icing Certification

In-flight ice formation on aircraft, rotorcraft, jet engines, UAV, detectors, antennae and optronics surfaces can significantly affect performance, handling qualities and safety. OEM or supplementary certification campaigns, long and tedious, can be greatly helped with modern icing CFD.

"Modern" icing CFD is defined as tools that are an extension of aerodynamic design and analysis technologies. Such an integrated aerodynamic/icing approach is proving itself a cost-effective *aid-to-design-and-to-certification* when made part of a well-structured compliance plan. Using "advanced and realistic" 3D simulations based on modern physical models allows a more comprehensive exploration of the combined aircraft/icing envelopes, optimized ice protection system design, and targeted/focused/reduced icing tunnel and flight tests. The end result is a more cost-effective and safer product that is easier to certificate.

This course presents the *state-of-the-art of icing CFD* by linking theory to applications. It is structured to be of equal interest to aerodynamics, icing, systems and flight simulation engineers, regulators and DERs.

Detailed knowledge of CFD is not essential. The lectures cover the major aspects of in-flight icing simulation: airflow, water impingement, ice accretion, anti-icing and de-icing calculations; handling quality issues; CFD-assisted certification.

The instructors bring a wealth of knowledge, as scientists who have produced codes in current use, practicing engineers who certify aircraft for major manufacturers, and former regulators who have closely monitored certification campaigns and have a deep understanding of safety issues.

Information

Date	October 18 - 22, 2010
Location	Gyeongsang National University Jinju, South Korea
Cost	1,500 US$ + applicable taxes
Registration	Using the registration form enclosed or on NTI web site
E-mail	events@newmerical.com
Web site	www.newmerical.com

Instructors

Mr. Martin AUBÉ
Newmerical Technologies

Mr. John P. DOW, Sr.
Consultant
Former FAA Specialist

Prof. Wagdi G. HABASHI
McGill University

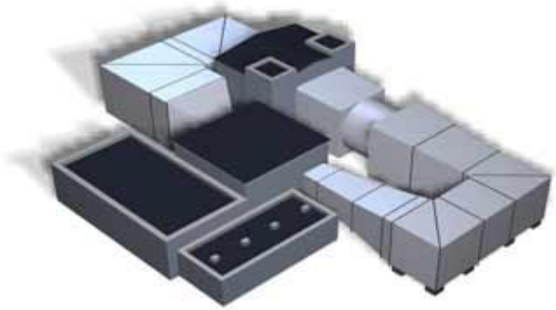
Prof. Rho Shin MYONG
Gyeongsang National University

Dr. Alberto PUEYO
Bombardier Aerospace

GNU Gyeongsang National University | newmerical TECHNOLOGIES INT. | ALTSOFT | McGill

In-flight icing: a critical safety issue

- Icing is an atmospheric phenomenon which deserves adequate protection of aircraft.
- Icing is a **key certification issue** related to **aircraft safety.**
- Need to predict **most critical icing conditions** and the resulting ice shapes within the flight and certification envelopes.
- **Anti-icing** systems: **Prevent** the ice from forming/adhering
- **De-icing** systems: **Remove** the accumulated ice before incurring significant aerodynamic penalties



Effective use of CFD for in-flight icing certification, Professional Development Course, GNU, 2010.

In-flight icing: aerodynamic & propulsive effects

- **Loss of aerodynamic performance & degradation of handling qualities**
  - Decrease of C_{Lmax} and lift (thrust in case of rotorcraft)
  - Increased drag due to roughness and flow separation
  - Reduced stall margin (lower AoA to stall)
  - Increased weight and shifted center of gravity
  - Stability and control problems from asymmetrical roughness
- **Blocking engine inlets and internal ducts** (if ingested, it can damage components and cause power fluctuations, thrust loss, rollback, flameout and loss of transient capability.)
- **Engine damage by ice crystals** at cruising altitude
- **Incorrect readings** for instrumentation (ex. air data system)
- **Visibility problems** for windshield
- **Ice shedding**

Key difference with aerodynamics:
Effect of icing like C_{Lmax} reduction, **not itself** (less interested in the exact ice shape)

Atmospheric icing fundamentals

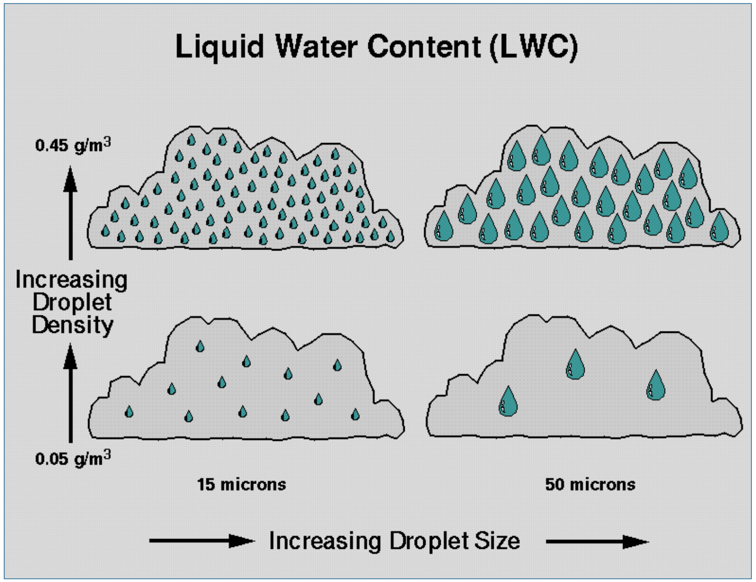
Atmospheric ice accretion depends on

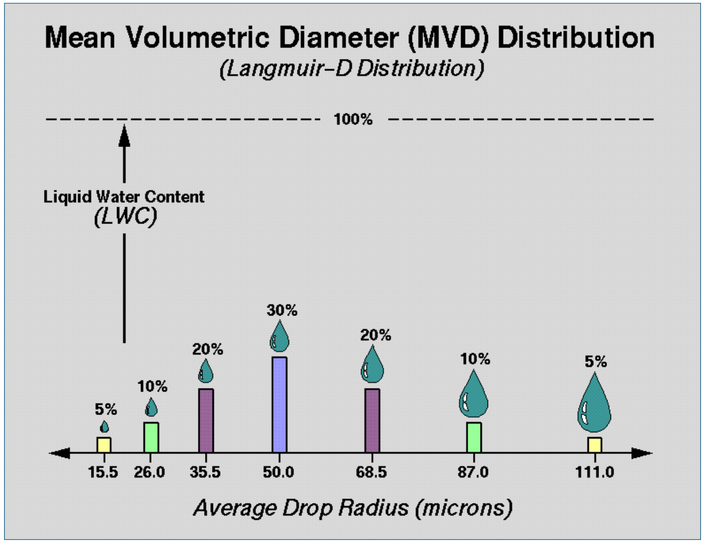
Point of operation (location, altitude etc.)
Geometry of aircraft
Relative **velocity**
Atmospheric **temperature**
Droplet diameter **size**
Liquid water content (LWC)

Cf. The LWC is defined as the mass of water (contained in liquid cloud droplets) within a unit volume of cloud, usually given in grams of water per cubic meter of air, g/m^3 (0.2~3.0 in typical icing).

Key difference with aerodynamics:

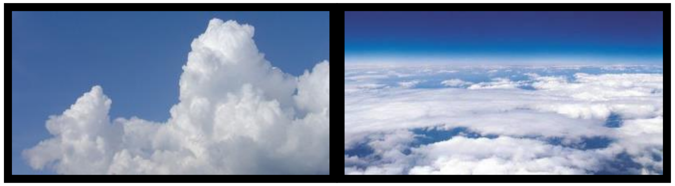
Involvement of droplet with surface tension & evaporation/freezing possibility

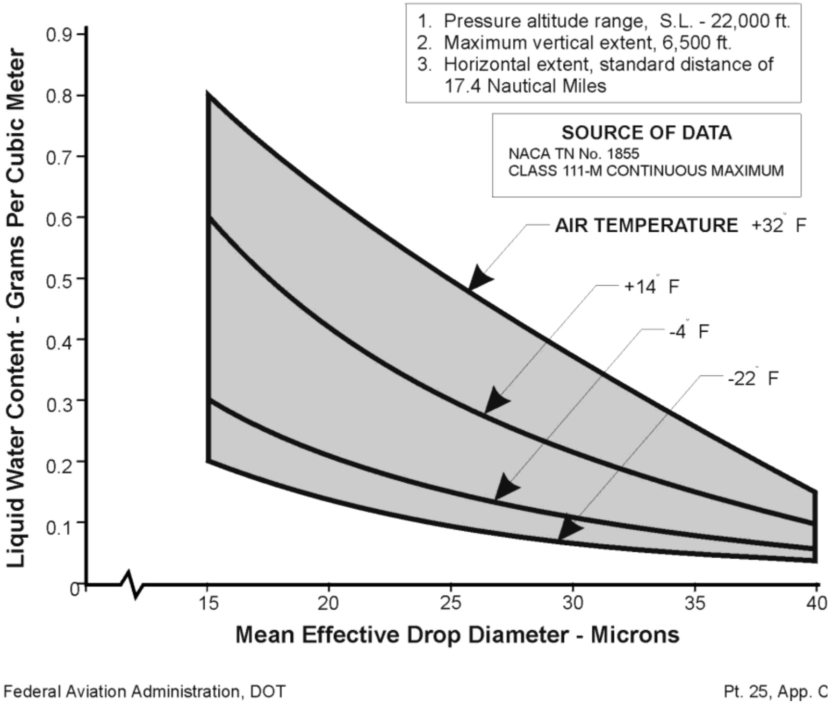




Aircraft Icing: certification envelope

- For demonstration of an aircraft safe flight in icing conditions, an icing certification envelope must be defined. (45, 30, 22.5 mins)
- Data gathered during the 1940's and 1950's on icing clouds led to the creation of FAR 25 and 29 Appendix C, still used to this day.
- Appendix C icing conditions are envelopes of maximum severity icing that occur in winter cumuliform and stratiform clouds.

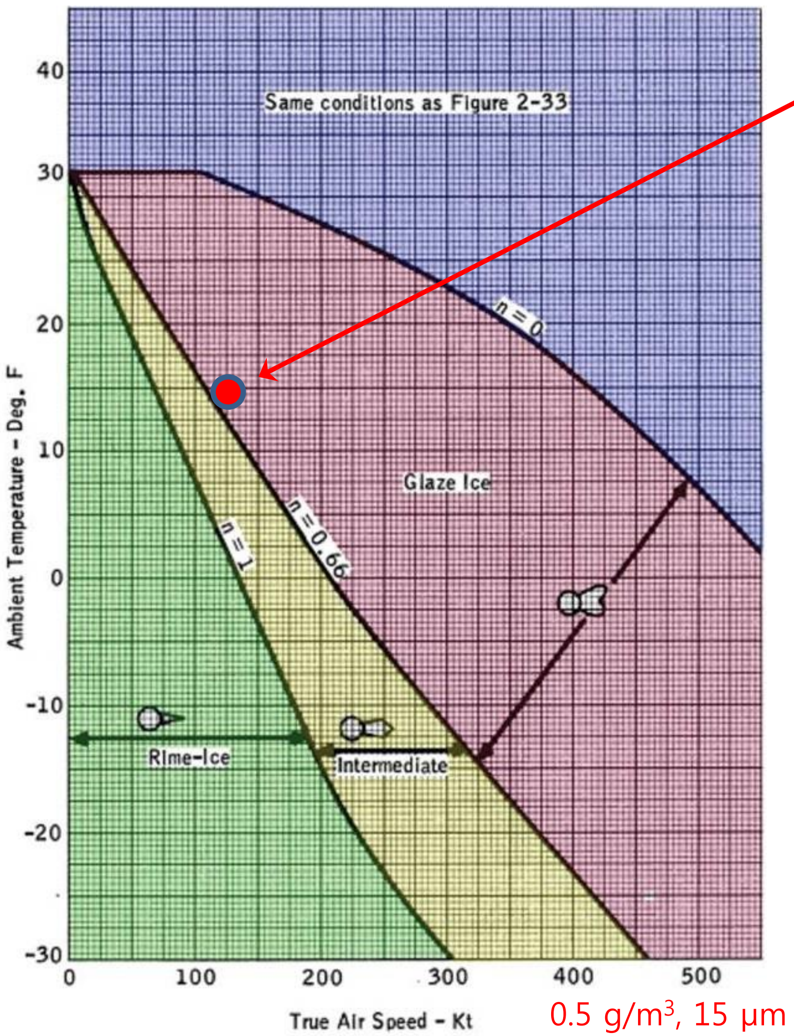




Appendix C comprises 3 sets of curves:

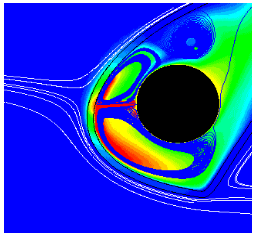
- Curves relating droplet size to temperature & LWC
- Altitude vs temperature envelope
- A curve relating LWC to cloud horizontal extent

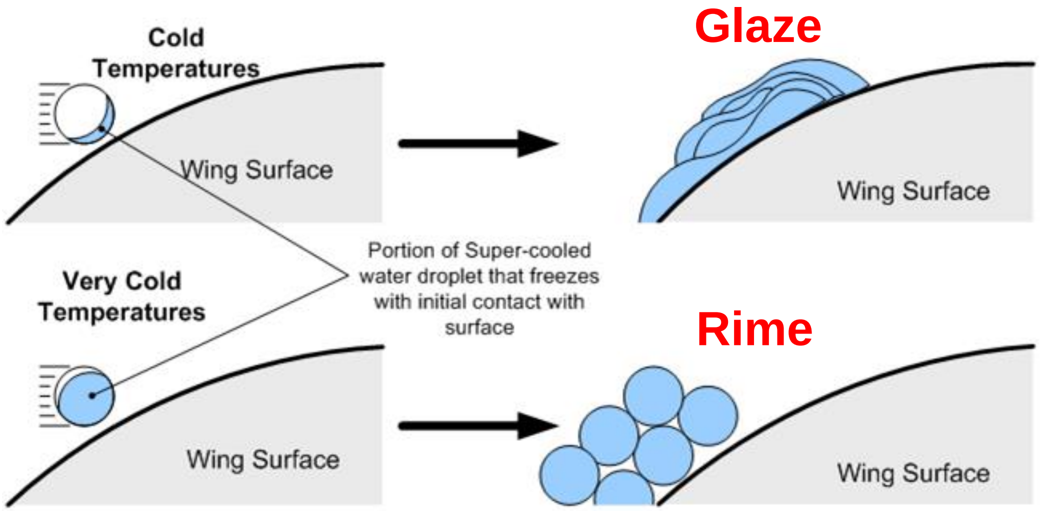
Ice shape type as a function of icing conditions



65 m/s = 126 Kt; 263 K = 14 F
0.6 g/m^3, 20 μm

Classified as glaze ice!





$$T_{\text{Stagnation}} = (1 + 0.2M^2)T_{\text{Freestream}}$$

Key difference with aerodynamics: High uncertainties in ice density & roughness

Dickey, T. A., "An Analysis of the Effects of Certain Variables in Determining the Form of an Ice Accretion," AEL 1206, Naval Air Experimental Station, 1952.

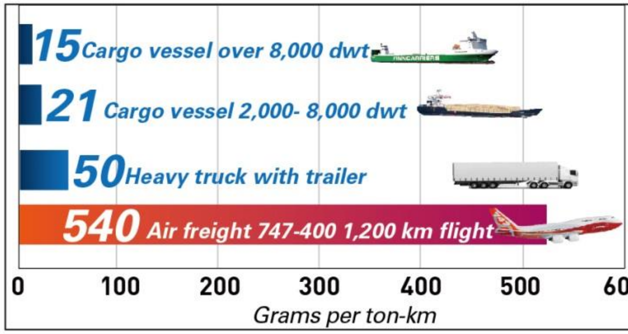
Icing wind tunnel (US NASA Glenn IRT & China)

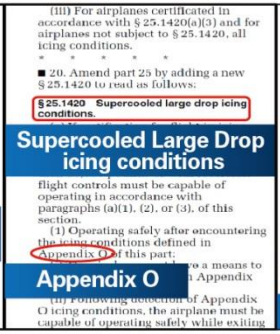
- Airspeeds 50-400 miles/h with 6'x9'x20' test section
- Temperatures as low as -40F and controllable within 1F
- Droplet sprays of sizes 15-40 micrometer
- LWC 0.5-2.5 g/m^3

- Icing tunnels not capable of reproducing the entire Appendix C
- Most icing tunnels not capable of simulating altitude effects
- Icing scaling laws necessary to achieve the same catch rates and water distributions (including for the internal flow related to ice protection systems), but very complicated, which is a key difference with aerodynamics.

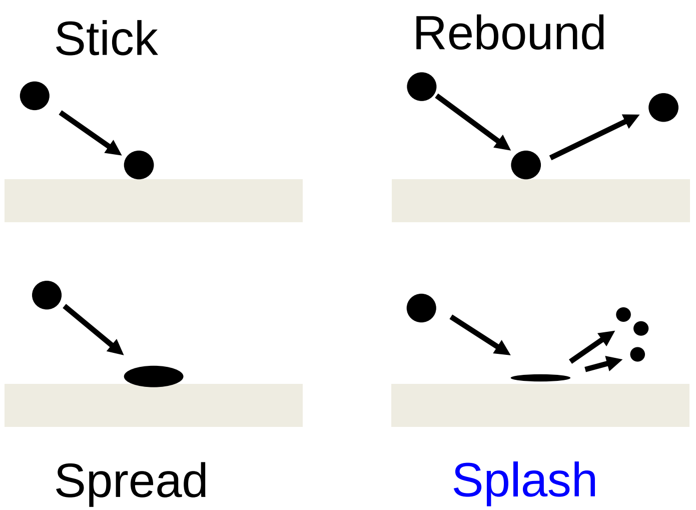
Movie: Recent IWT (CARDC, Mianyang, China)

Aircraft in-flight icing: critical role of certification



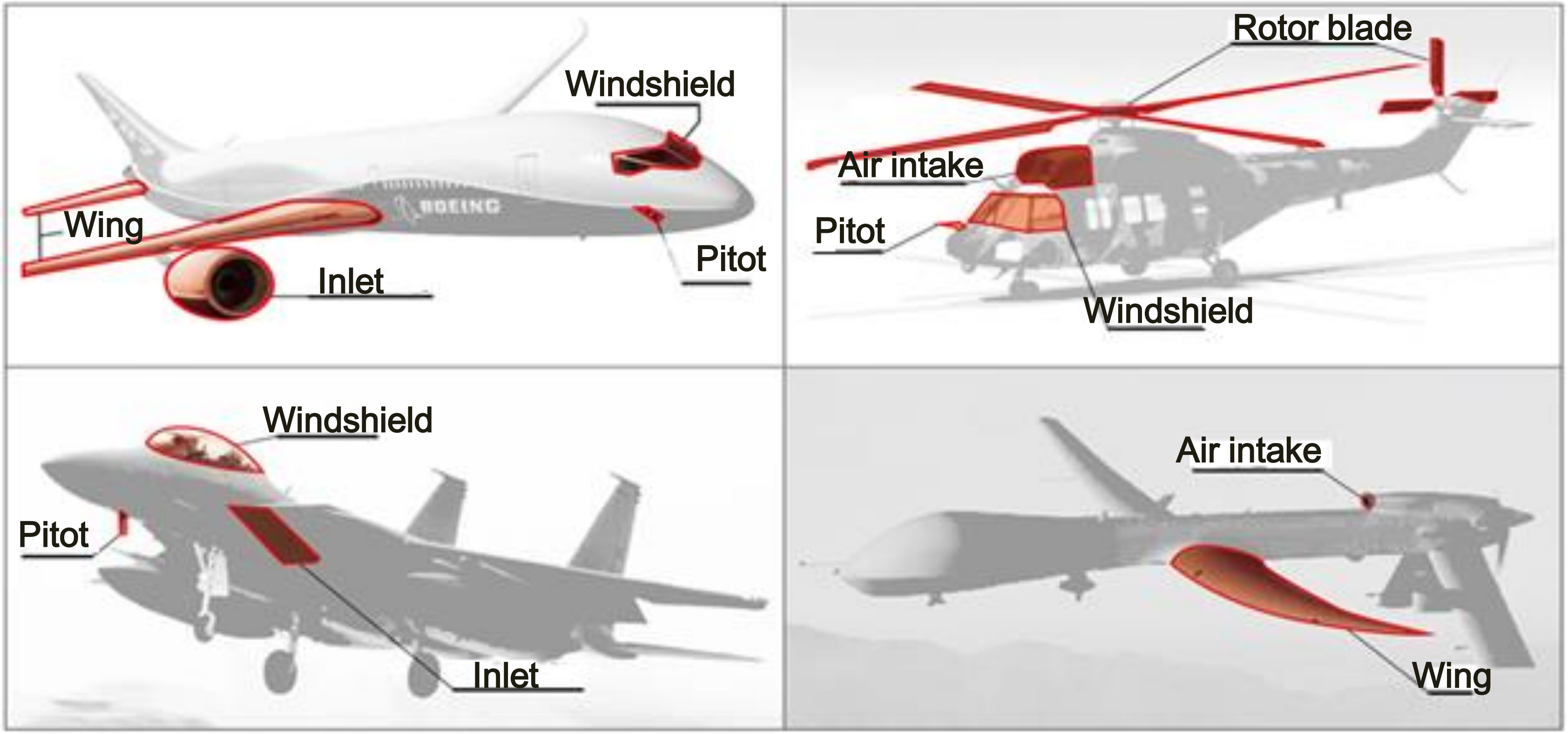


FAA Appendix O (Nov, 2014) for FAR 25:
SLD (Supercooled Large Droplet)

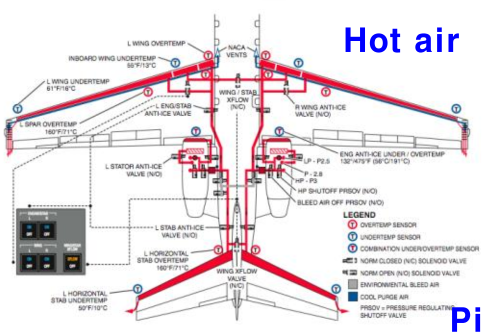


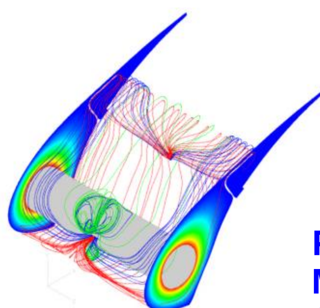
American Eagle 4184 Accident

Aircraft in-flight icing: IPS (Ice Protection System)



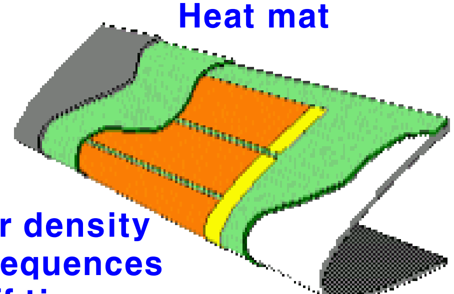
Hot air





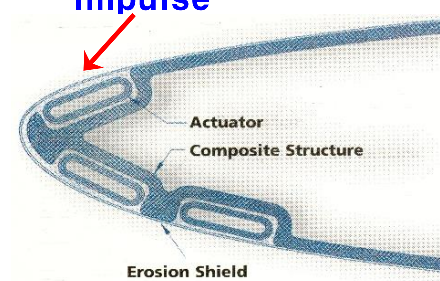
Piccolo tube

Heat mat



Power density
Mat sequences
On/off times

Impulse



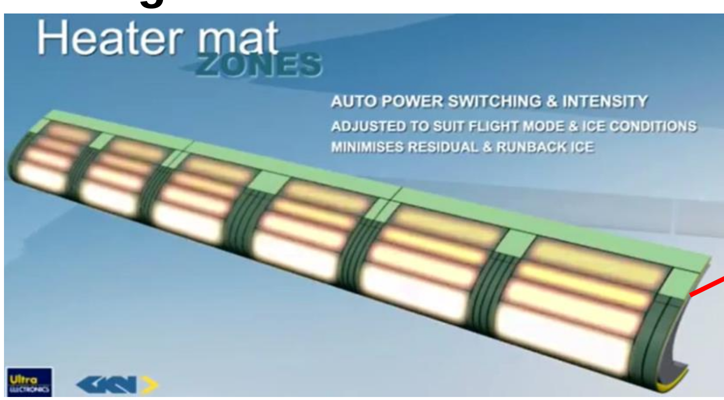
Ice Protection System: bleed air vs electro-thermal

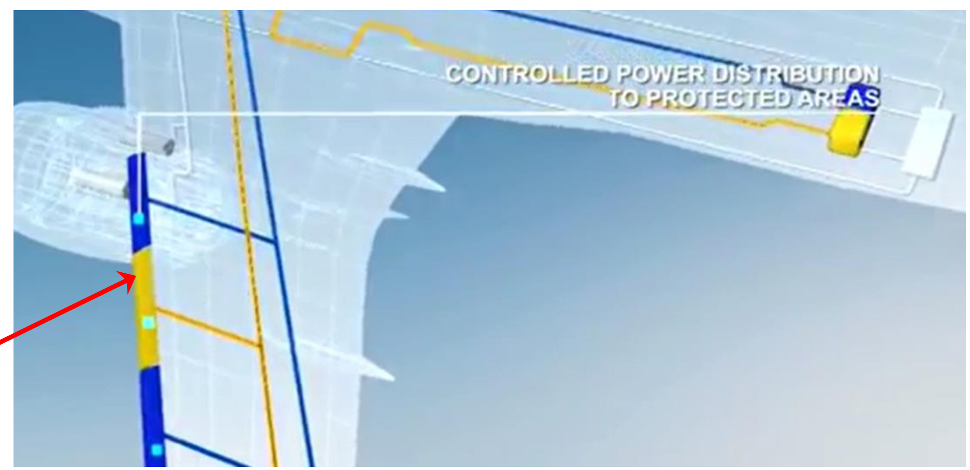
Hot air IPS

Most of transport airplanes

Electro-thermal IPS

Boeing 787





Korean Utility Helicopter program 2015-2018

Movie: Korean Surion Helicopter

Pitot-type air intake and anti-icing system

- The **Pitot-type air intake** (with good total pressure recovery) **requires** an (electro-thermal) **anti-icing** system.

EC 725 Super Puma: Pitot intake

Bell 430: side mounted intake

Agusta A109: flush side intake

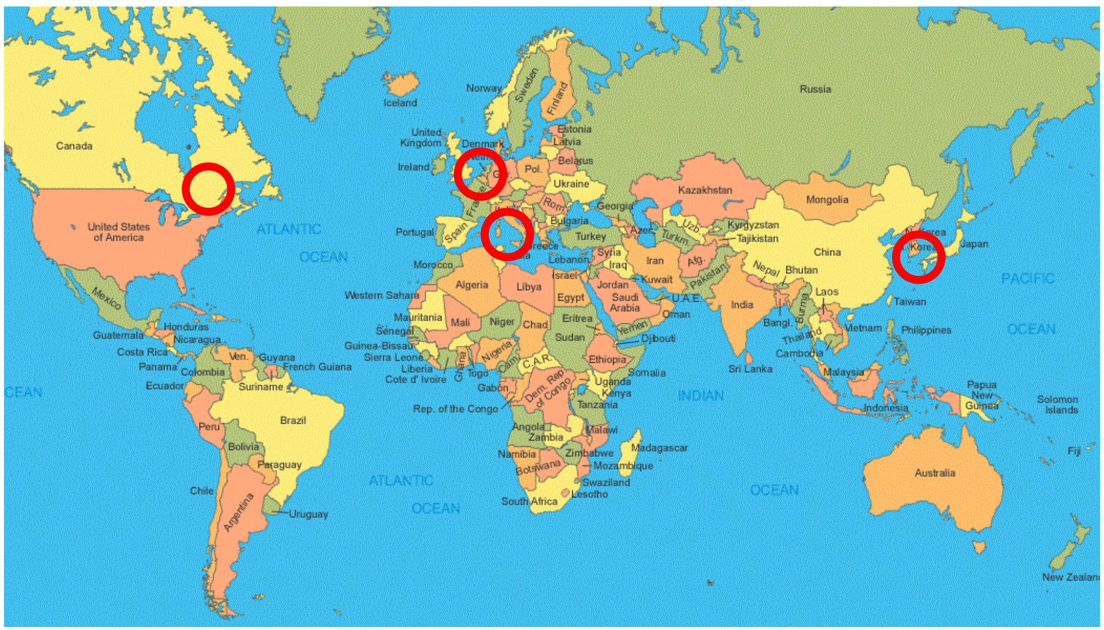
Mill Mi 24: radial inflow intake

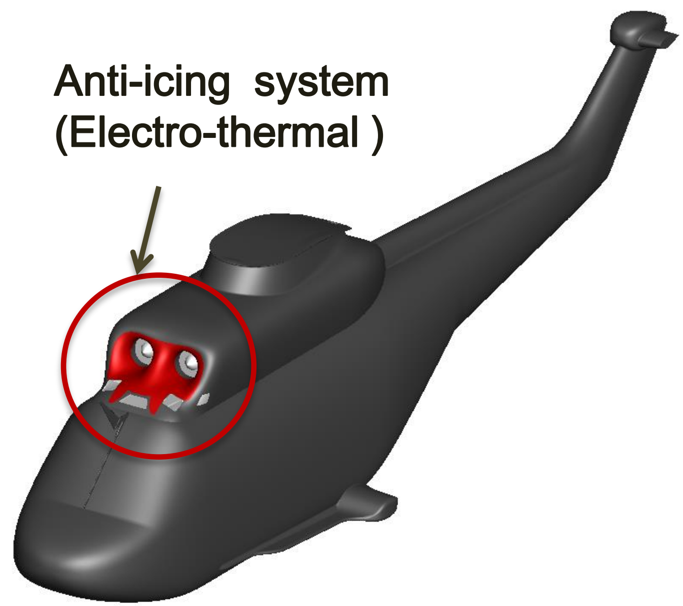
Total pressure recovery
Distortion
Foreign object impact

Icing (**ice ingestion 130 g for 2 minutes**)

Icing wind tunnel model design of engine intake

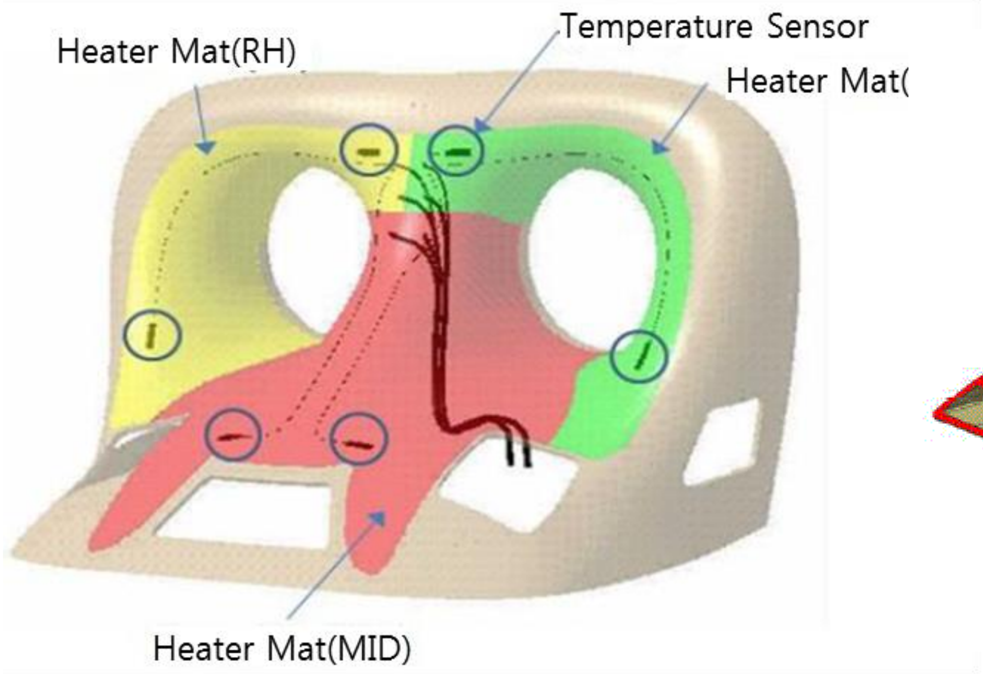
- **Korean Utility Helicopter** program (through Korea Aerospace Industries Ltd.).
- Also in association with National Aerospace Laboratory of the Netherlands (NLR; icing wind tunnel model design).

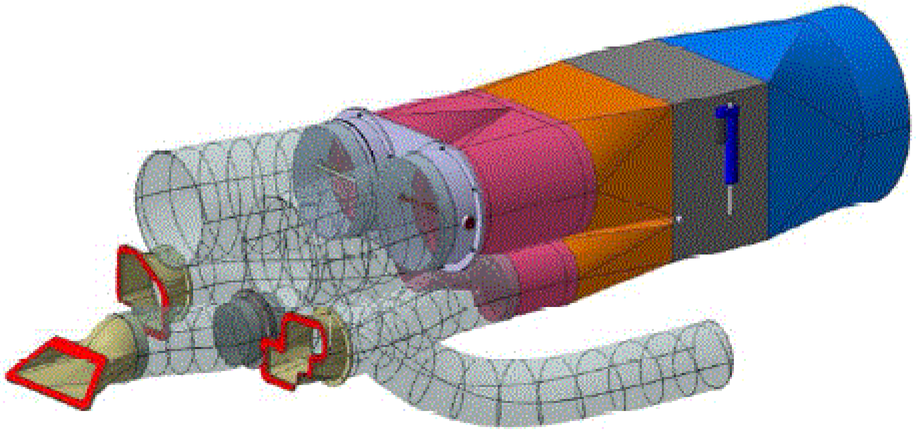




Test model of electro-thermal anti-ice system

National Aerospace Laboratory of the Netherlands

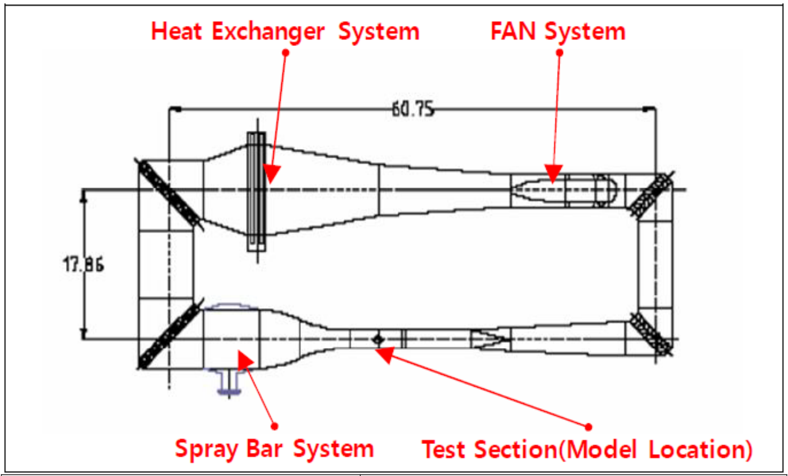




[Flow Suction System]

Courtesy of Korea Aerospace Industries LTD (KAI) (2011)

Icing wind tunnel testing



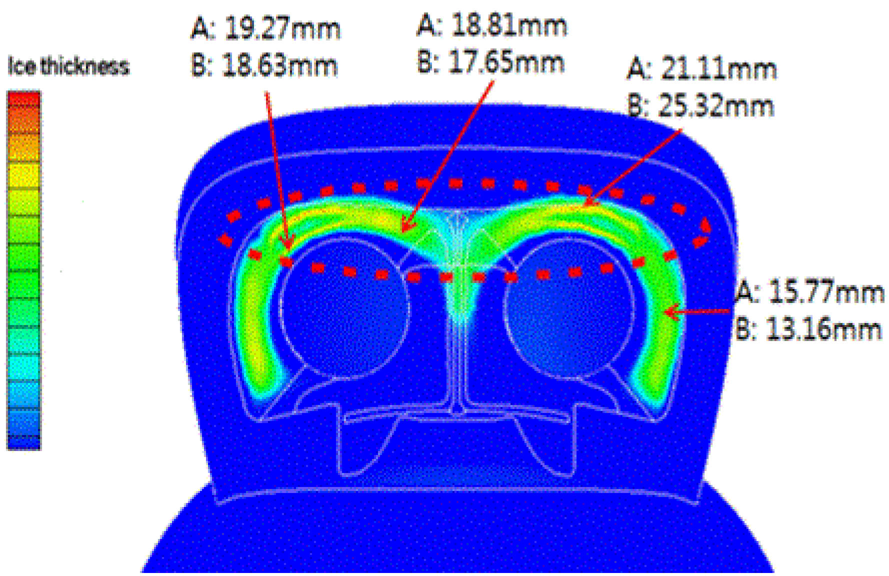
Item	Specification
Test Section Size	2.35 m (H) x 3.6 m (W) x 8.30 m (L)
Tunnel Type	Closed Circuit
Power	4.0 MW
Maximum Velocity	80 m/s (155.5 kts)
Mach Range	0.25
Temperature	-32 ℃
Pressure Altitude	7000 m (22,965 ft)

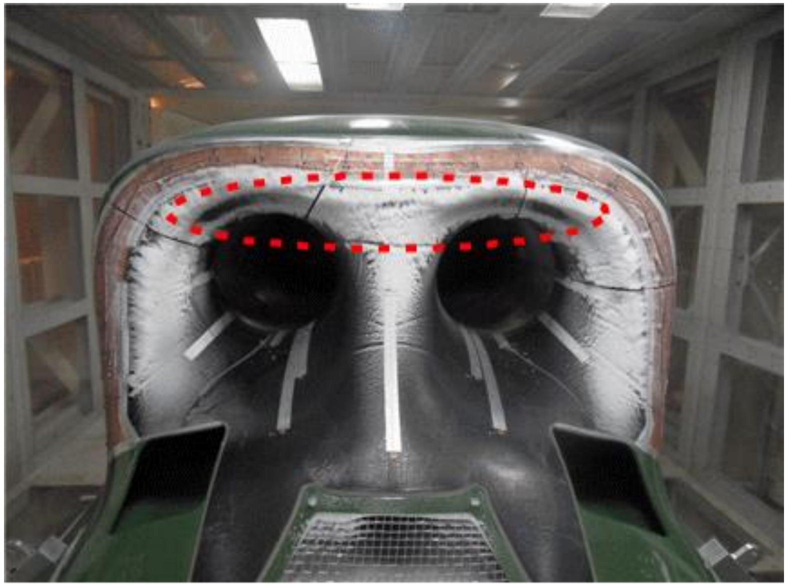
CIRA (Italian Aerospace Research Centre), CAPUA, Italy
1~2 cases / day; each case costing five digits $ (December, 2011)

Courtesy of Korea Aerospace Industries LTD (KAI) (2018)

Icing computational simulation

- Validation of icing CFD (FENSAP-ICE) prediction (heat-off mode)





The upper parts of intake with largest ice accretion.
Narrow region with small ice accretion between these parts.

Numerical and experimental investigation of ice accretion on a rotorcraft engine air intake, *Journal of Aircraft*, Vol. 52, No. 3, pp. 903-909, 2015

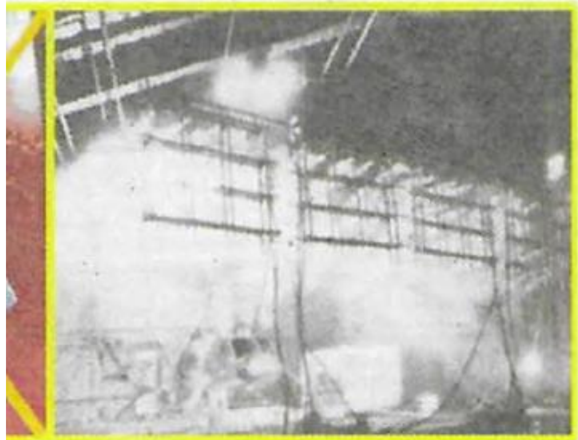
Icing certification campaign (rotorcraft case)

Icing certification requires 3+ seasons of testing

	Winters
UH-60	3
AH-64	2
AS-332	7
EH101	3
V22	3
M214ST	1
S92	1.5

(*) M214ST certified to CAA North Sea Operations
S92 certified to AC29-2C 10Kft limited icing

McKinley Lab



HISS

(Helicopter Icing Spray System)

R. Aubert, Bell Helicopter, 2013

McKinley Lab (Model)	McKinley (AC)	HISS (AC)
$400K (3 weeks + 2)	$400K (3 weeks + 2)	$700K (30 days / 20 hrs)
Full Aircraft ~ $1,050K	Full Aircraft ~ $1,050K	Full Aircraft + Chase ~ $1,050K

Icing certification campaign (Korea Surion case)

Natural & HISS tests
Two seasons (2015-16 & 2017-18)
Michigan, US

Courtesy of Korea Aerospace Industries LTD (KAI) (2018)

Icing certification campaign: failure & 2nd full effort

A critical redesign of IPS

Season 2015-16

Higher surface temperature
More time for evaporation
Longer distance for evaporation

Season 2017-18

Removing runback ice on intake

Clearance of ice shedding of windshield & wiper

Courtesy of Korea Aerospace Industries LTD (KAI) (2018)

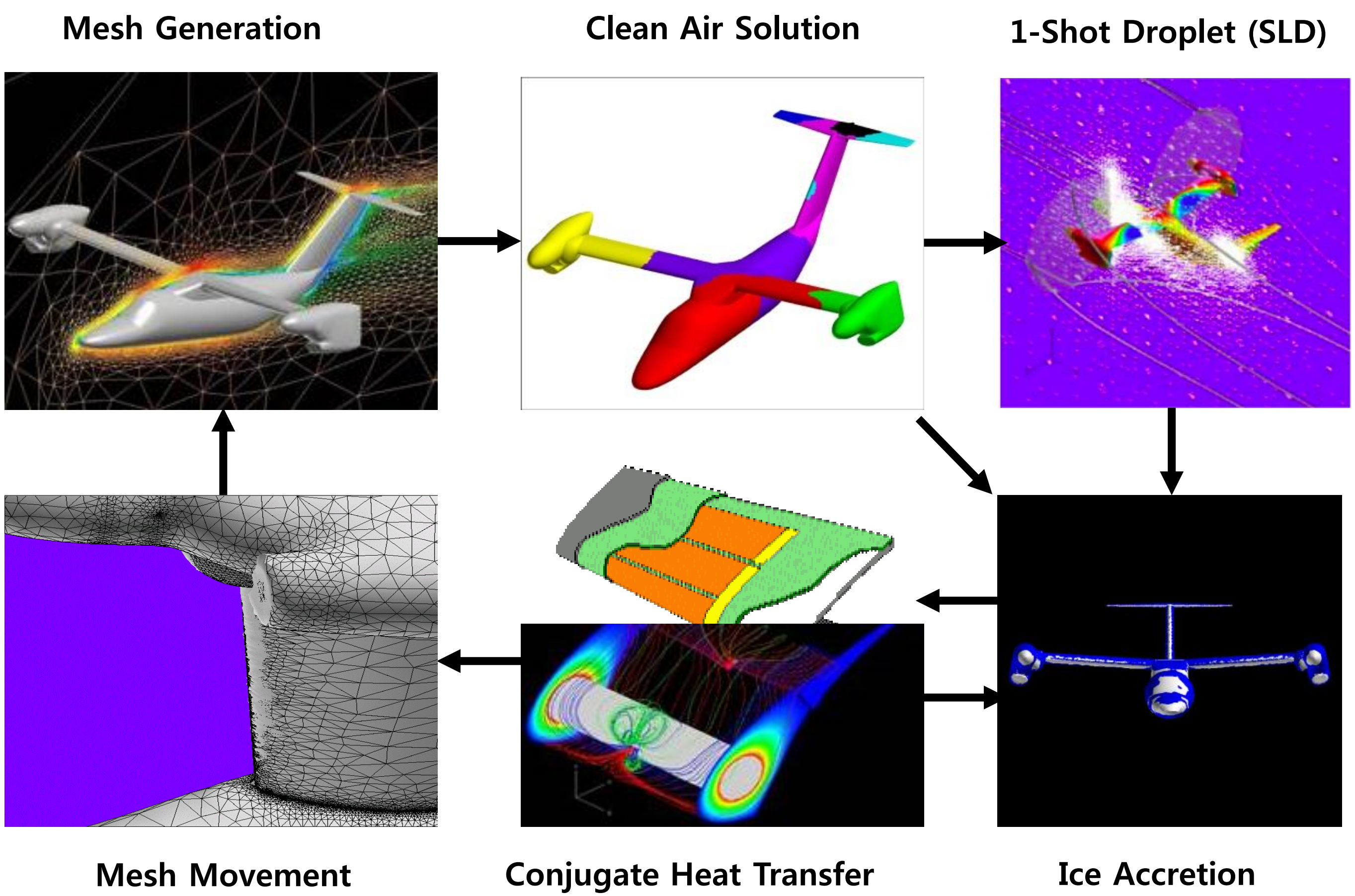
Icing certification campaign: lessons learned

- Sensitivity of impingement limits to MVD in engine intake
- In rotor, time-scheduling of de-icing critical
- Large variation of temperature sensor (in order of 10 C)
- Importance of HISS (limitation of IWT by lack of engine heat transfer)
- Challenges of computational icing prediction (previous experimental data tailored to NASA-LEWICE, lack of thermal property of complex composite material)

Ex. MVD 20 vs 30 μm
LWC 0.6 g/m^3
Temp -10°C

Courtesy of Korea Aerospace Industries LTD (KAI) (2018)

Structure of GNU unified solvers based on FVM



Effective use of CFD for in-flight icing certification, Professional Development Course, GNU, 2010.

Mathematical equations for multi-disciplinary physics

Equations for clean air

Shear stress
Heat flux

$$\begin{bmatrix}\rho_g\\ \rho_g\mathbf{u}_g\\ E\end{bmatrix}_t + \nabla\cdot\begin{bmatrix}\rho_g\mathbf{u}_g\\ \rho_g\mathbf{u}_g\mathbf{u}_g+p\mathbf{I}\\ (E+p)\mathbf{u}_g\end{bmatrix} = \nabla\cdot\begin{bmatrix}0\\ \boldsymbol{\tau}\\ \boldsymbol{\tau}\cdot\mathbf{u}_g+\mathbf{Q}\end{bmatrix},\qquad \boldsymbol{\tau}=2\mu\left[\nabla\mathbf{u}_g\right]^{(2)},\quad \mathbf{Q}=k\nabla T$$

Equations for droplets

Droplet impact velocity
Collection efficiency

$$\begin{bmatrix}\rho\\ \rho\mathbf{u}\end{bmatrix}_t + \nabla\cdot\begin{bmatrix}\rho\mathbf{u}\\ \rho\mathbf{u}\mathbf{u}+\rho g d\mathbf{I}\end{bmatrix} = \begin{bmatrix}0\\ \mathbf{S}_D+\mathbf{S}_G+\mathbf{S}_S\end{bmatrix}$$

Equations for ice accretion

$$\begin{bmatrix}h_f\\ h_f T_{equi}\end{bmatrix}_t + \nabla\cdot\begin{bmatrix}\dfrac{h_f^2}{2\mu_w}\tau_{wall}\\ \dfrac{h_f^2 T_{equi}}{2\mu_w}\tau_{wall}\end{bmatrix} = \begin{bmatrix}\dfrac{S_M}{\rho_w}\\ \dfrac{S_E}{\rho_w Cp_{,w}}+\dfrac{T_c S_M}{\rho_w}\end{bmatrix}$$

$$S_M = U_\infty LWC_\infty \beta - \dot{m}_{evap} - \dot{m}_{ice}$$

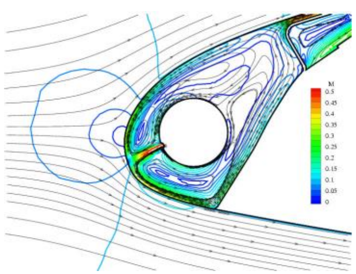
$$S_E = \left[Cp_{,w}\tilde{T}_{d,\infty} + \frac{\left\|\vec{u}_d\right\|^2}{2}\right]\times U_\infty LWC_\infty\beta - L_{evap}\dot{m}_{evap}$$

$$+\dot{m}_{ice}\left[L_{fus} - Cp_{,ice}T_{equi}\right] + h_c\left(T_{equi}-T_\infty\right) + \sigma_o\varepsilon\left[T_{equi}^4 - T_\infty^{\ 4}\right]$$

$$h_f \ge 0,\ \dot{m}_{ice}\ge 0,\ h_f T_{equi} \ge h_f T_C,\ \dot{m}_{ice}T_{equi} \le \dot{m}_{ice}T_C$$

A unified solver for clean air, droplet impingement, ice accretion, and aerodynamic analysis of ice effects were developed based on an unstructured upwind finite volume method.

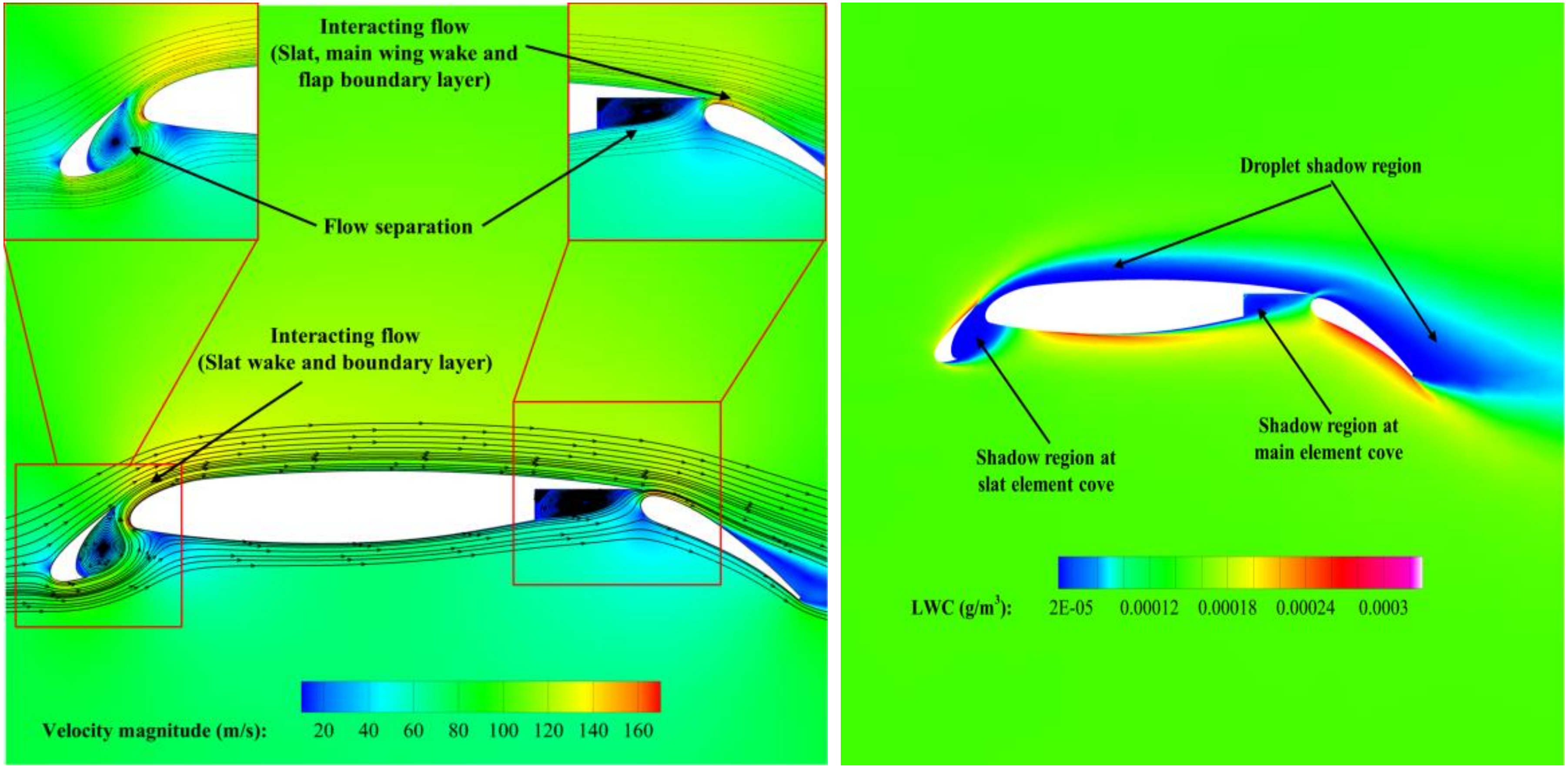
Conjugate (convection-conduction-convection) heat transfer



Equations for conductive heat transfer

$$\rho_s C_p(\Delta T)_t = \nabla\cdot\mathbf{Q} - \rho_s(\Delta H/\Delta T),\quad \mathbf{Q}=k_s\nabla(\Delta T)$$

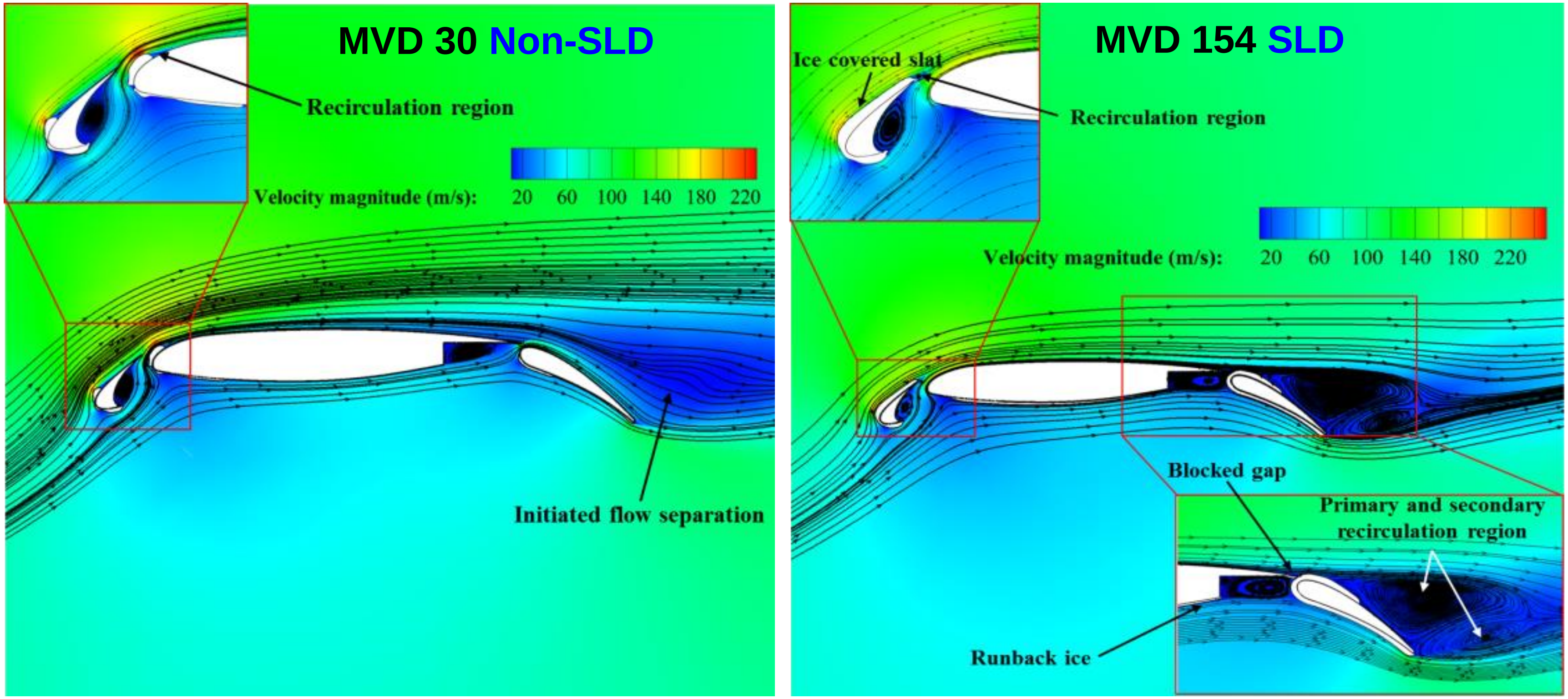
Air flow and droplet fields on a multi-element airfoil



Very complicated flow-fields: Improper modeling of droplet could easily result in a numerical break-down due to the strong circulation and flow separations on the slat and the main element cove.

Substantial difference between air streamlines and droplet trajectories

Ice accretion on a multi-element airfoil (SLD)



No leading edge ice formed on the suction side of the main element for the SLD condition, leading to a significant reduction in loss of performance. This runs **counter to previous studies on iced single element airfoils**, in which the aerodynamic performance loss was higher for SLD icing conditions.

Future research topics

- Further study on icing physics (ice density, evaporation, roughness, runback ice, SLD, ice break-up, ice-shedding etc.)
- Full 3D ice accretion and unsteady anti-icing simulation
- Integrated high-fidelity simulation (rotor + fuselage + intake)
- Thermal DB of complex material
- New fundamental experimental study using IWT for validation of prediction tools (Tailored to modern CFD code, SLD, oscillating airfoil, etc.)
- Innovative IPS & ID and extension to UAV & wind turbine
- More accurate IWT method (scaling method)
- International collaborative exploration on aircraft icing

Aircraft icing vs wind turbine icing

	Aircraft	*Wind turbine*
General	Sudden, fatal, short, expensive	Unavoidable, gradual, long, remote
Cloud	0~12km Supercooled large droplet, ice crystal Uniform freestream	0~250m from the ground Freezing rain & drizzle Turbulent shear boundary layer
Iced area	Leading edge	Leading edge and other areas
Ice sensor	Non-shadow region	Tip of blade (not nacelle)
Exposed time	45, 30, 45/2 minutes	Hours/days
Anti/de-ice	Hot-air, boot, electro-thermal Retrofittable	Hot-air, boot, electro-thermal Natural (using centrifugal force)
Surface ice	Instability due to asymmetric roughness	Fatigue
Instrument	Pitot tube malfunction	Anemometer/wane vane malfunction
Life time	30 yrs	15~20 yrs

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