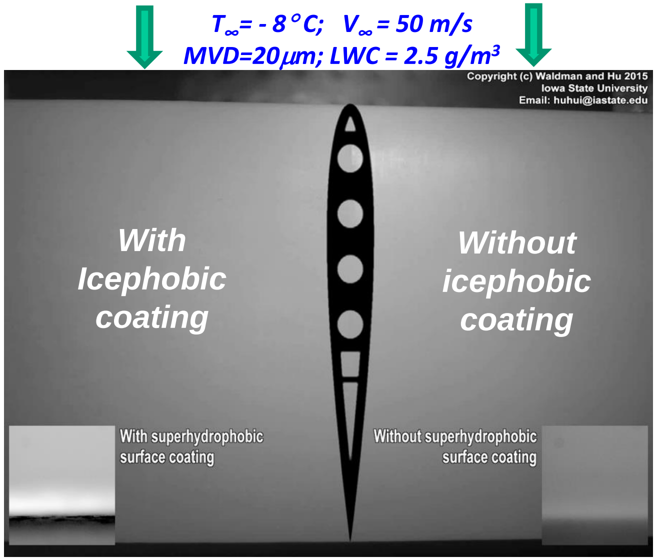
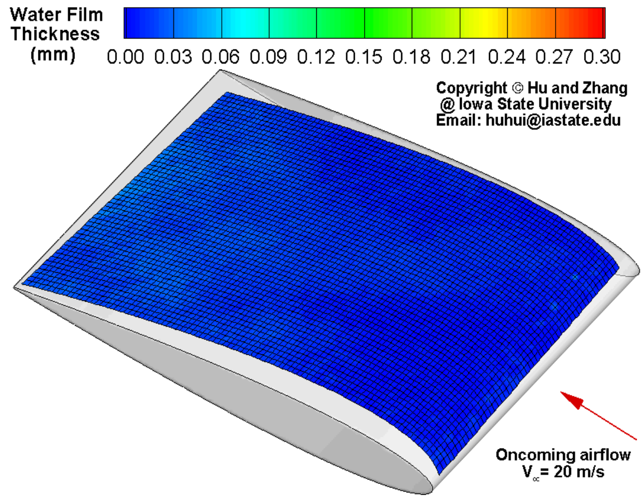
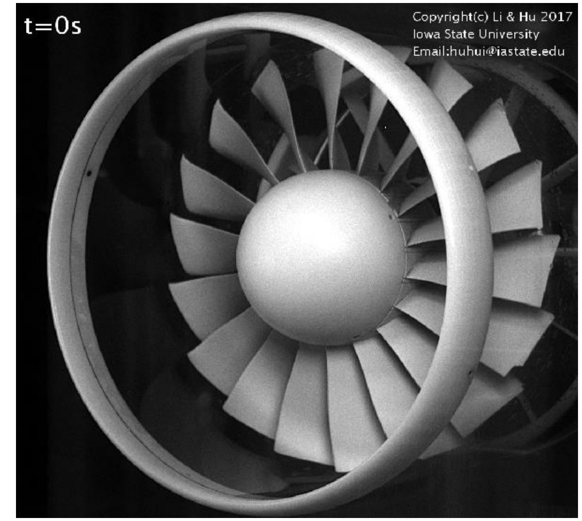


Dynamic water runback on an airfoil surface





Overview of Research Activities on Aircraft Icing Physics & Anti-/De-Icing @ Iowa State University

Dr. Hui HU

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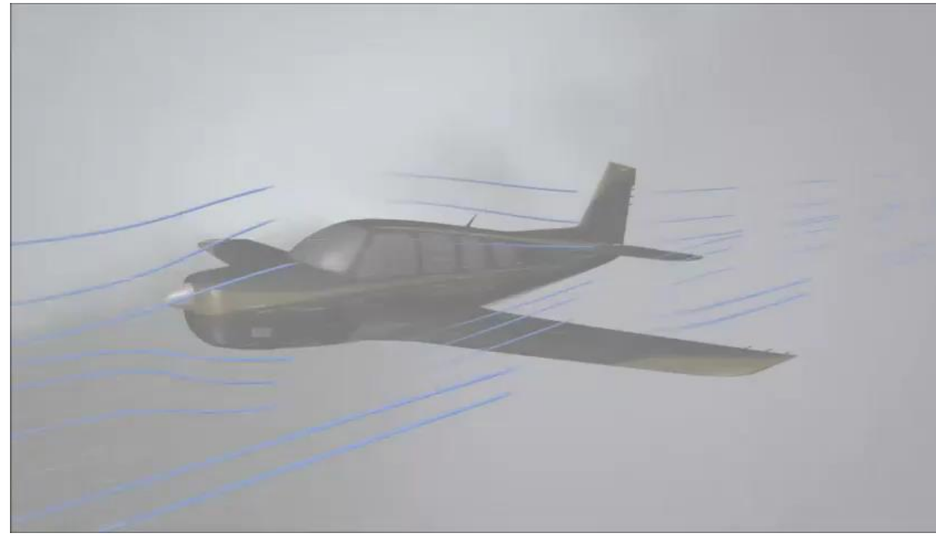
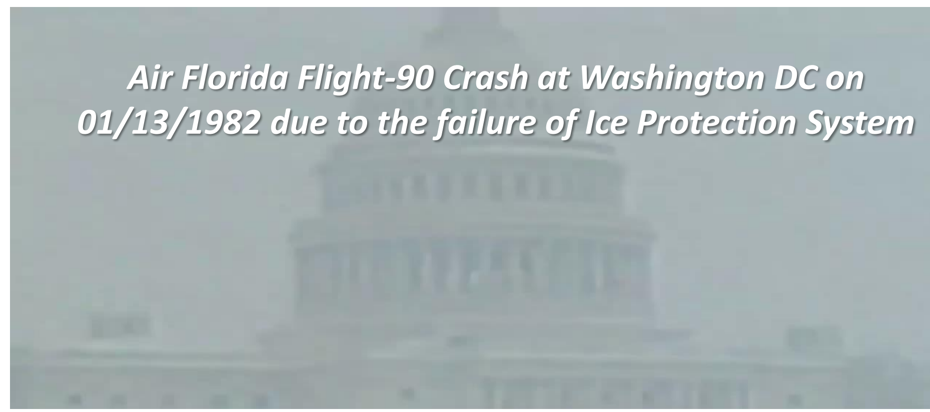
Aircraft Icing and Aero-Engine Icing Phenomena

- ***Aircraft icing, including aero-engine icing,*** ***is widely recognized as a significant hazard to aircraft operations in cold weather.***

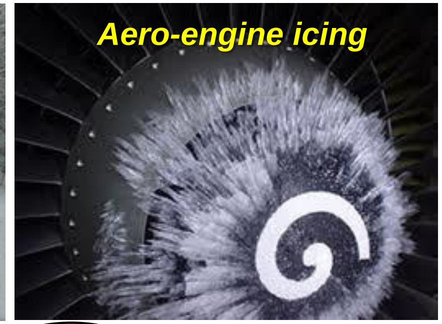
- ***While research progress has been made in recent years, aircraft icing remains as an important unsolved problem at the top of the National Transportation Safety Board's most wanted list of aviation safety improvements.***





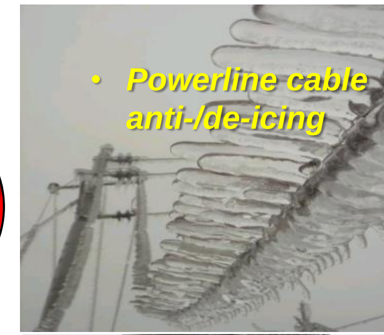
Air Florida Flight-90 Crash at Washington DC on 01/13/1982 due to the failure of Ice Protection System

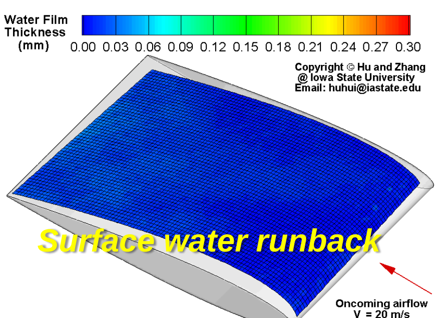
❑ ISU Icing Physics and Anti-/De-icing (IPAD) Center

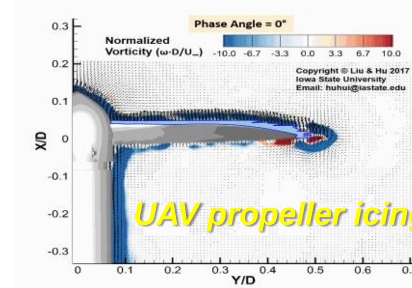


ISU Icing Physics & Anti-/De-icing Research Center

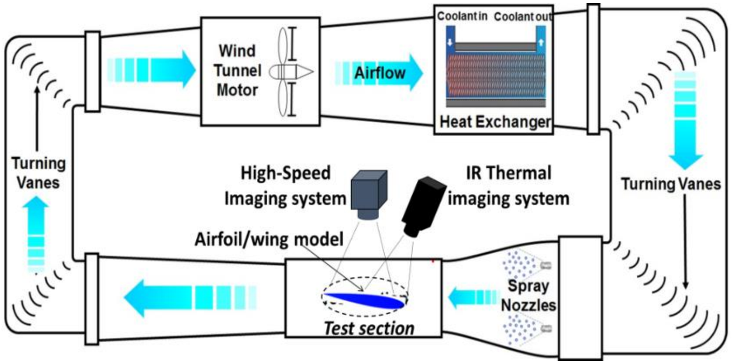
- NDE, MEMS sensors for in-flying icing detection
- Experimental aerodynamics & icing tunnel testing
- CFD &multiphase modeling
- UAS/MAV, Rotorcraft, wind turbine, power lines
- Syetem design and MDO for anti-/de-icing strategy
- Aero-structure designs for icing mitigation & protection.
- Smart materials, Micro & Nano Mechanics
- Super-hydrophobic coatings and surface engineering



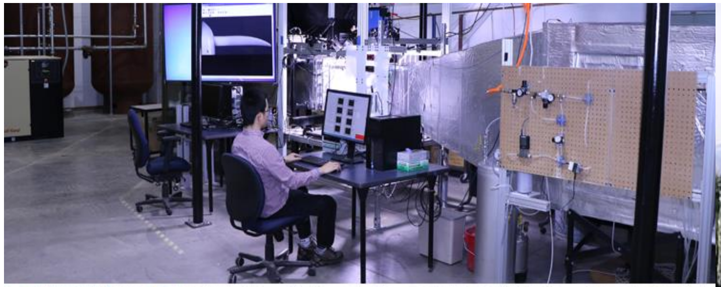


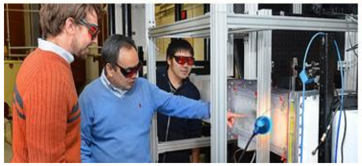


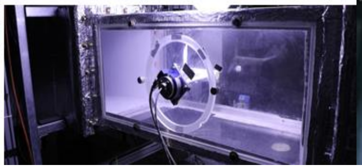
❑ ICING RESEARCH TUNNEL @ IOWA STATE UNIVERSITY (ISU-IRT)



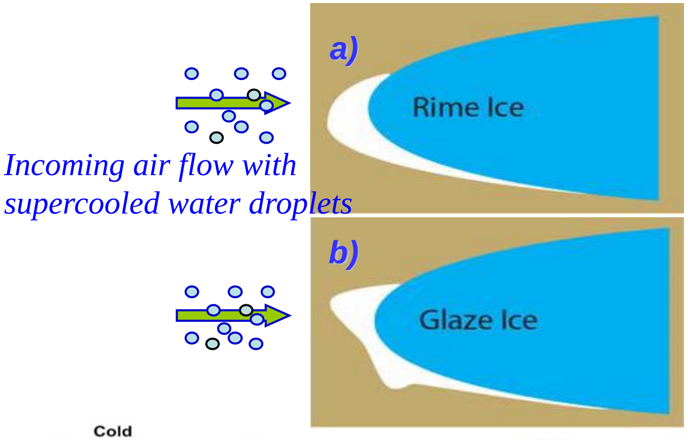
- *ISU Icing Research Tunnel (ISU-IRT), donated by Collins Aerospace System, is a new refurbished, research-grade multi-functional icing research tunnel.*
- ***The working parameters of the ISU-IRT include:***
  - ***Test section:*** ***0.4m × 0.4m×2.0m***
  - ***Airflow velocity:*** ***V_{∞} = 5 ~ 100 m/s;***
  - ***Temperature:*** ***T_{∞} = - 25 °C ~ 20 °C;***
  - ***Droplet size:*** ***$D_{droplet}$ = 10 ~ 100 μm;***
  - ***Liquid Water Content:*** ***LWC = 0.1 ~ 10 g/m³***
- ***The large LWC range allows ISU-IRT to be run over a wide range of conditions (i.e., from dry rime to wet glaze icing).***
- ***We received ~$4.0 M in funded research in the past 5 years from NASA, NSF, FAA, NAVY, GE, P&W, UTAS, DuPont…***

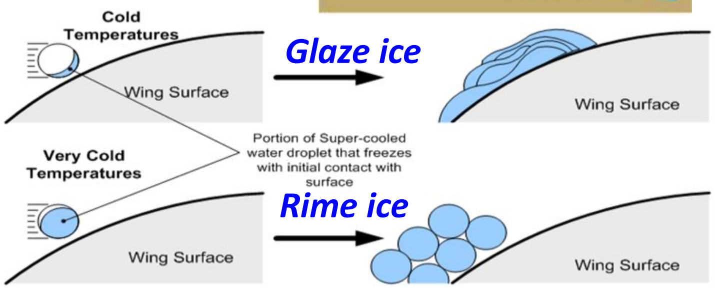


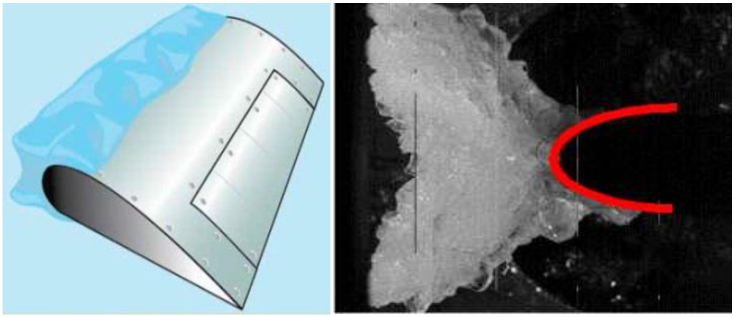


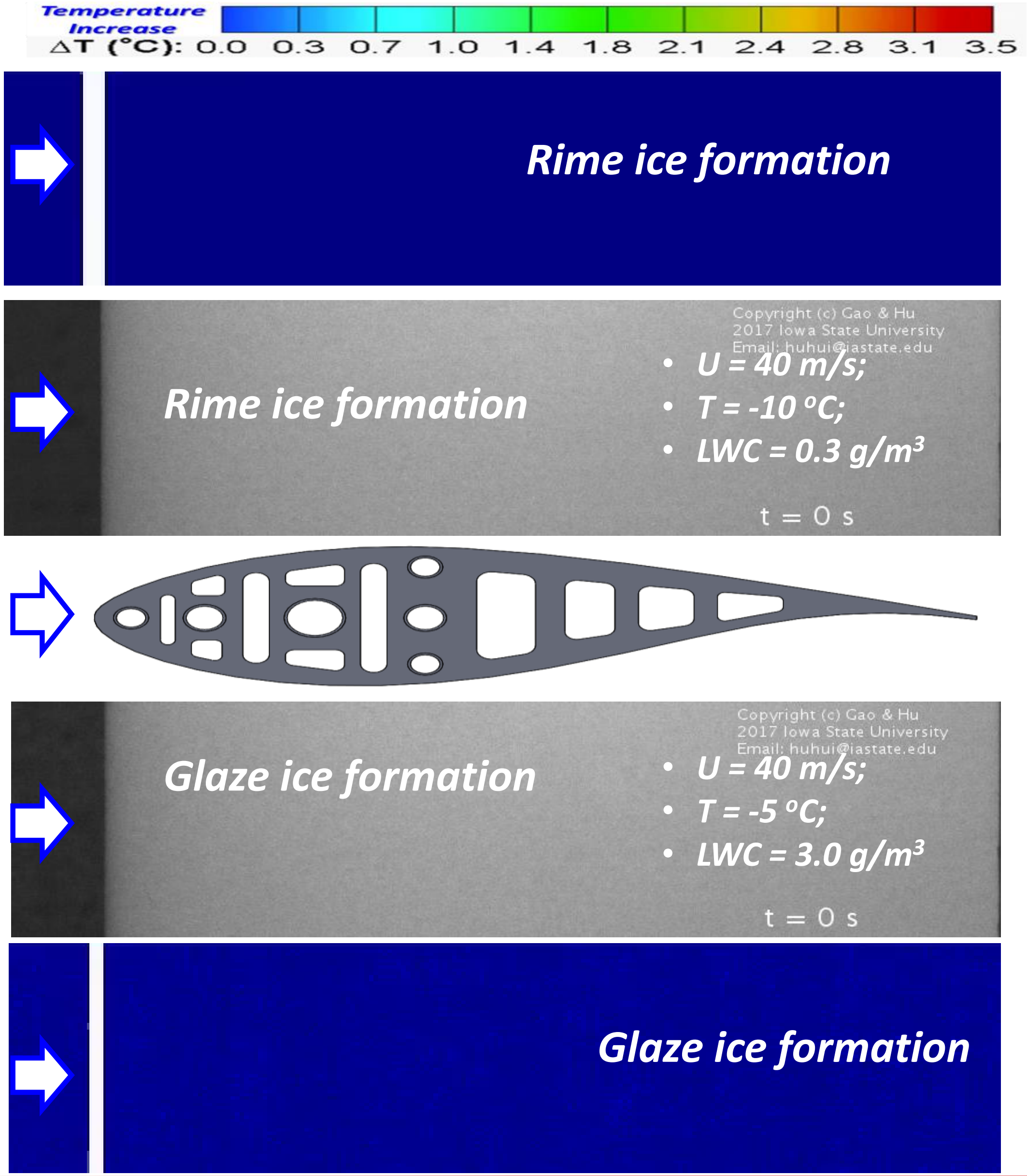


❑ Impact Icing Physics: Rime Icing and Glaze Icing



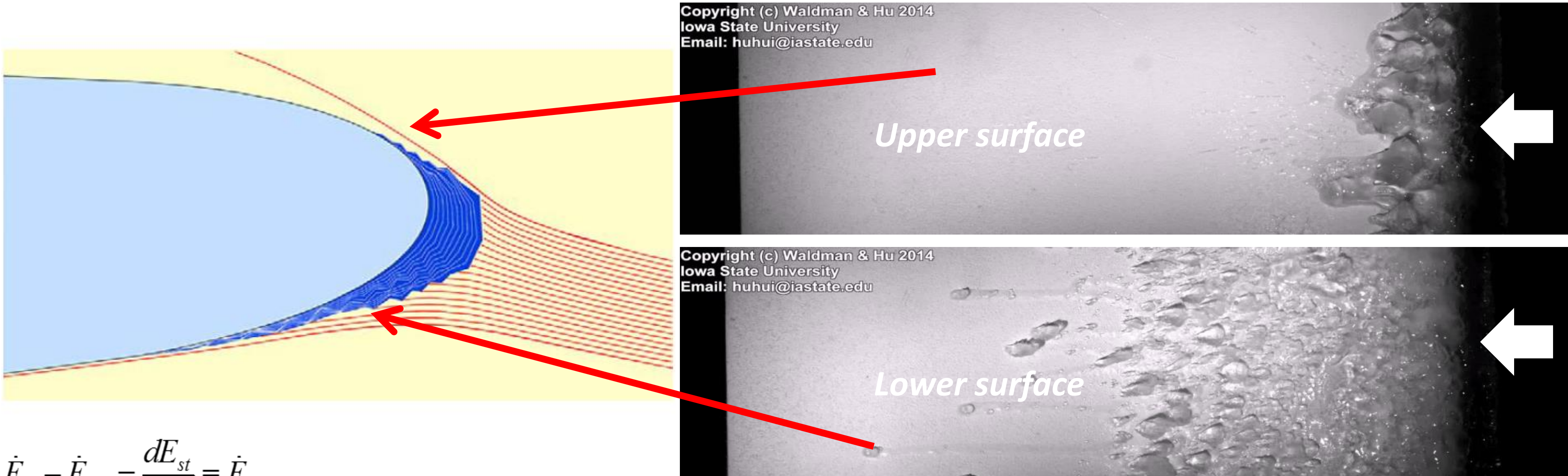






- *Glaze ice is the most dangerous type of ice.*
- *It can form much more complicated ice shapes, and will be much more difficult to remove once built up.*

❑ Unsteady Heat Transfer during Ice Accretion Over an Airfoil Surface



$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{st}}{dt} \equiv \dot{E}_{st}$$

$$\dot{E}_{in} = \dot{Q}_{adh} + \dot{Q}_{kin} \qquad \dot{E}_{st} = \left(\dot{Q}_{latent} + \dot{Q}_{ss}\right)$$

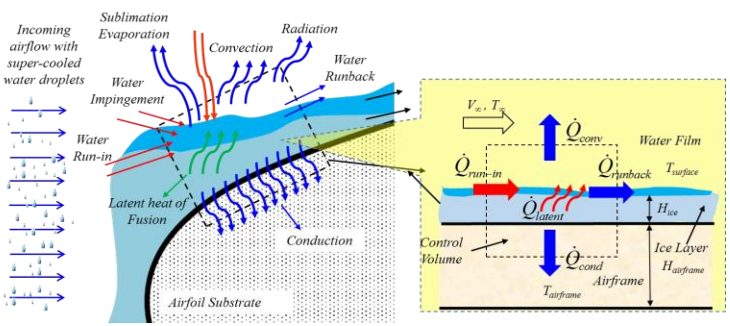
$$\dot{E}_{out} = \dot{Q}_{conv} + \dot{Q}_{sub/evp} + \dot{Q}_{cond}$$

$$\left[\dot{Q}_{adh} + \dot{Q}_{kin}\right] - \left[\dot{Q}_{conv} + \dot{Q}_{sub/evp} + \dot{Q}_{cond}\right] = \left(\dot{Q}_{latent} + \dot{Q}_{ss}\right)$$

- ***Adiabatic heating:*** ***The heat introduced by air friction on the object is from a viscous adiabatic heat which occurs inside the boundary layer.***
  (Fortin et al., 2006) $\dot{Q}_{adh} = h_{cv} \cdot (T_{rec} - T_{\infty}) \cdot A$ $\quad T_{rec} = T_{\infty} + r \cdot \frac{T_{\infty}}{T_e} \cdot \frac{U_e^2}{2 \cdot Cp_{air}}$ $\quad r = \sqrt{Pr}$ $\quad Pr = \frac{Cp_{air} \cdot \mu_{air}}{k_{air}}$
- ***Kinetic energy:*** ***associated with the droplets impacting onto the airfoil surface.***
  (Myers, 2001) $\dot{Q}_{kin} = \frac{1}{2} \cdot \dot{m}_{imp} \cdot V_{imp}^2$ $\quad \dot{m}_{imp} = LWC \cdot V_{imp} \cdot A$
- ***Evaporation and Sublimation***
  (Dong et al., 2015) $\dot{Q}_{sub/evp} = \dot{m}_{es} \cdot \left[\eta \cdot L_i + (1-\eta) \cdot L_w\right]$,
  - *to be estimated directly. Being negligible terms with small quantities.*

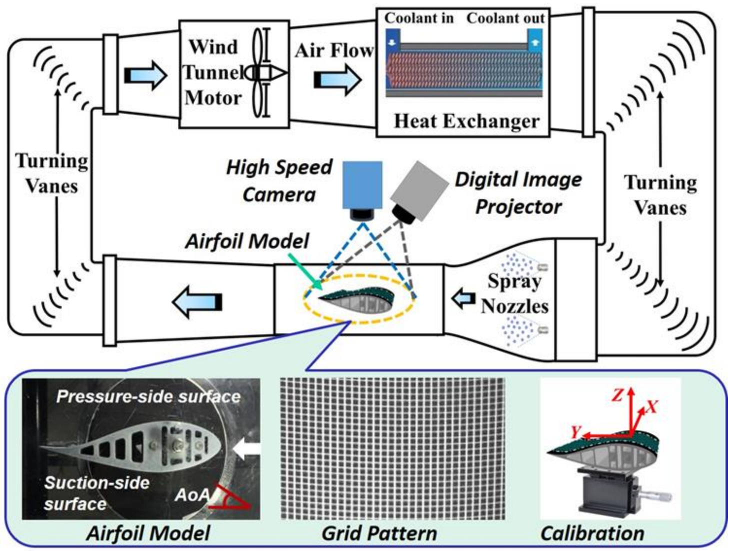
- ***Convective heat transfer*** $\quad \dot{Q}_{conv} = h_{cv} \cdot (T_s - T_{\infty}) \cdot A$
- ***Conductive heat transfer*** $\quad \dot{Q}_{cond} = \frac{A \cdot (T_s - T_{airfoil})}{R_{tot,cond}}$
  - *to be evaluated based on the measurements of heat flux sensors and thermocouples*

- ***Latent heat of fusion*** $\quad \dot{Q}_{latent} = \dot{m}_{freeze} \cdot L_s$
- ***Sensible heat*** $\quad \dot{Q}_{ss} = \dot{m}_{freeze} \cdot Cp_i \cdot (T_f - T_s) + (\dot{m}_w - \dot{m}_{freeze}) \cdot Cp_w \cdot (T_f - T_s)$
  (Henry et al., 2000)
  - *To be estimated based on the DIP measurements of accreted ice mass and characteristics of runback surface water flow.*

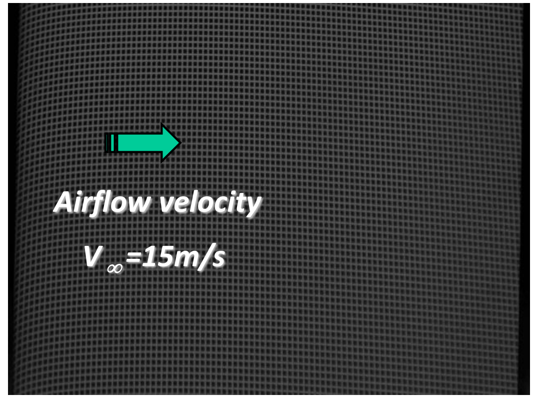


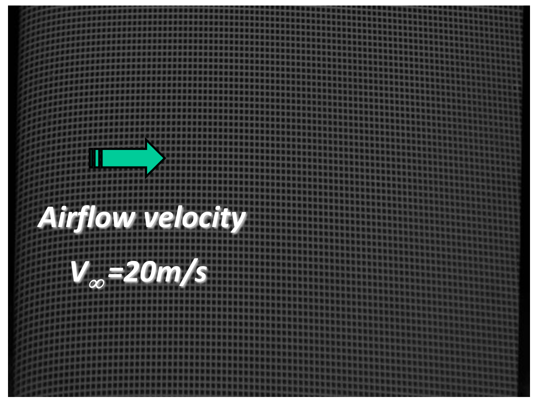
- *Liu & Hu (2018) "An Experimental Investigation on the Unsteady Heat Transfer Process over an Ice Accreting Airfoil Surface", Intel. J. Heat&Mass Transfer, 122, pp707-718.*
- *Li & Hu (2019) "Effects of Thermal Conductivity of Airframe Substrate on the Dynamic Ice Accretion Process", Intl. J. of Heat & Mass Transfer, 131, pp1184-1195.*

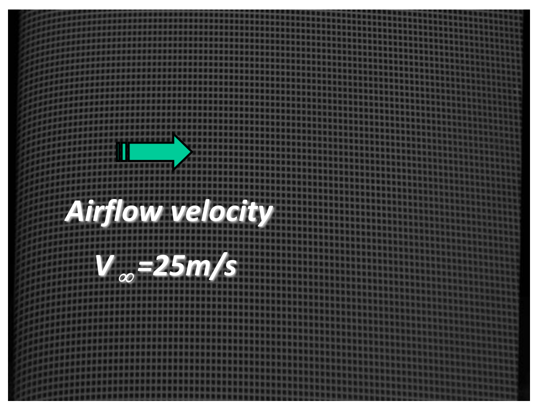
❑ Icing Physics: Transient Behavior of Wind–Driven Water Runback

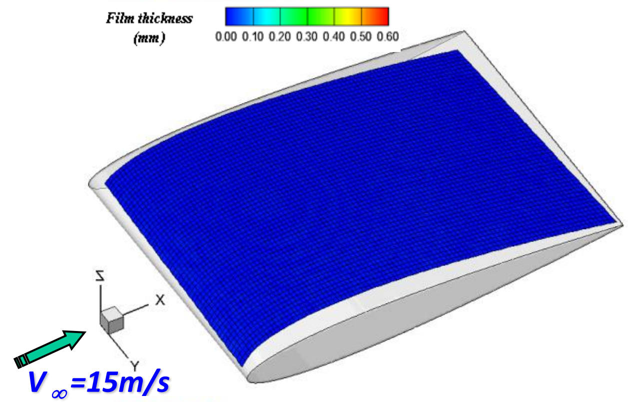


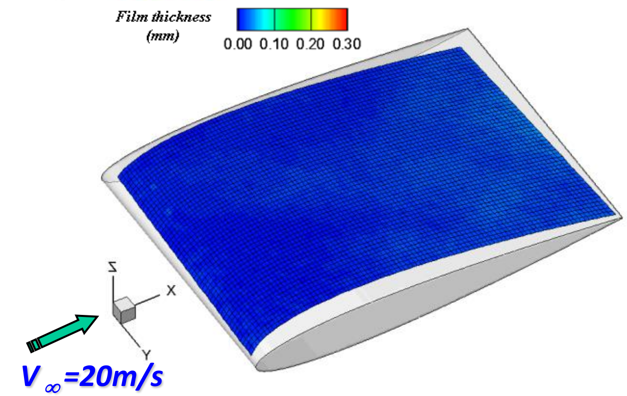
- *Setup for DIP Measurements*

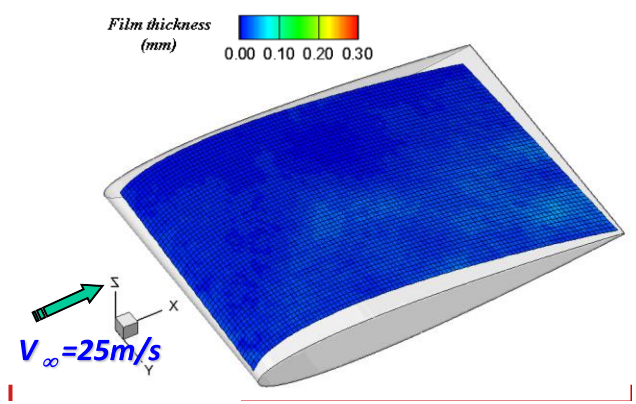










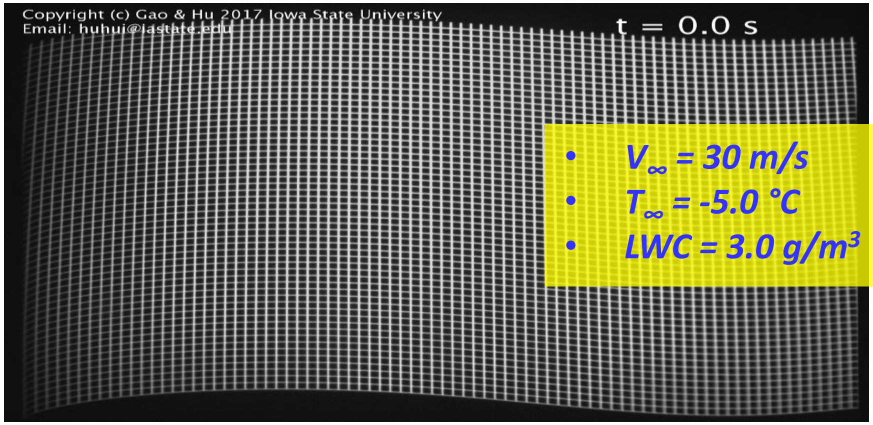


Test Conditions:

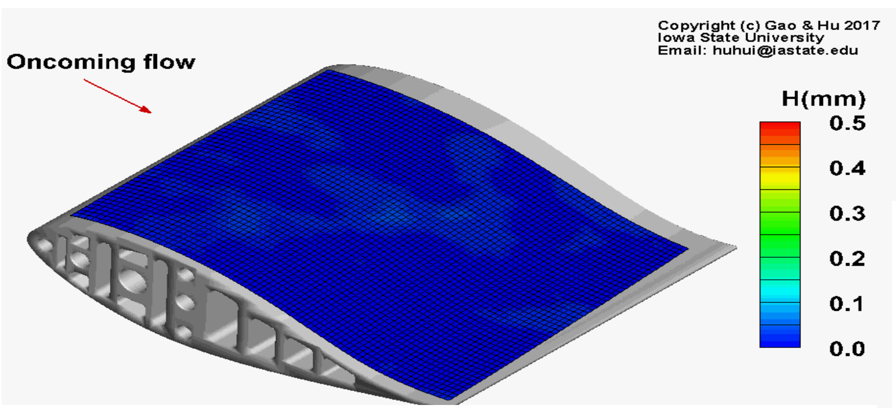
- *Angle of attack:* $\alpha \approx 0.0$ *deg.*
- *Temperature:* $T \approx 20$ *°C.*
- *LWC Level : LWC = 3.0 g/m³*
- *Frame rate :* $f = 30$ *Hz*

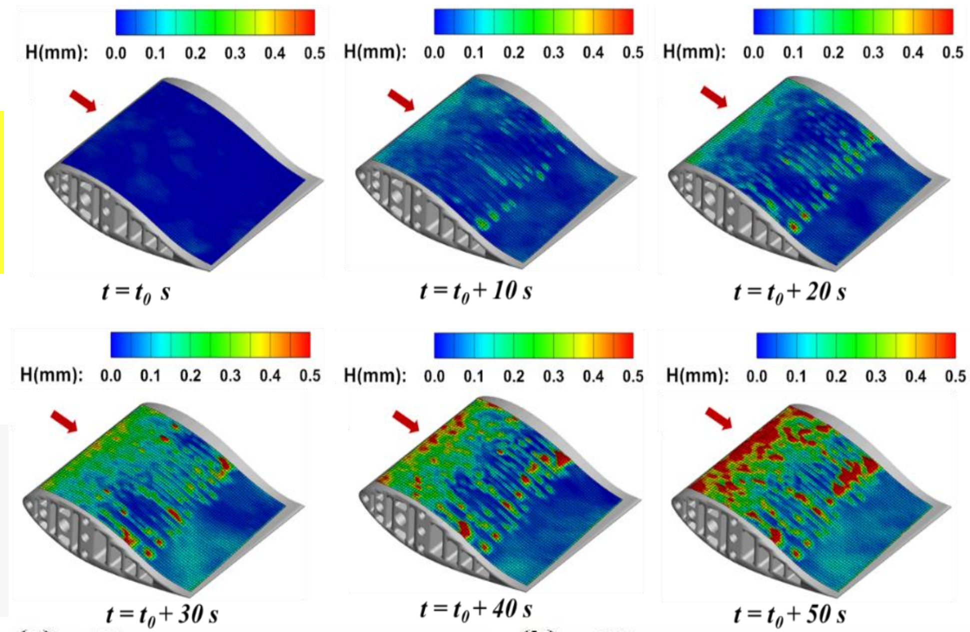
- *K. Zhang, W. Tian and H. Hu, , Experiments in Fluids, 56:173 (16 pages), 2015*

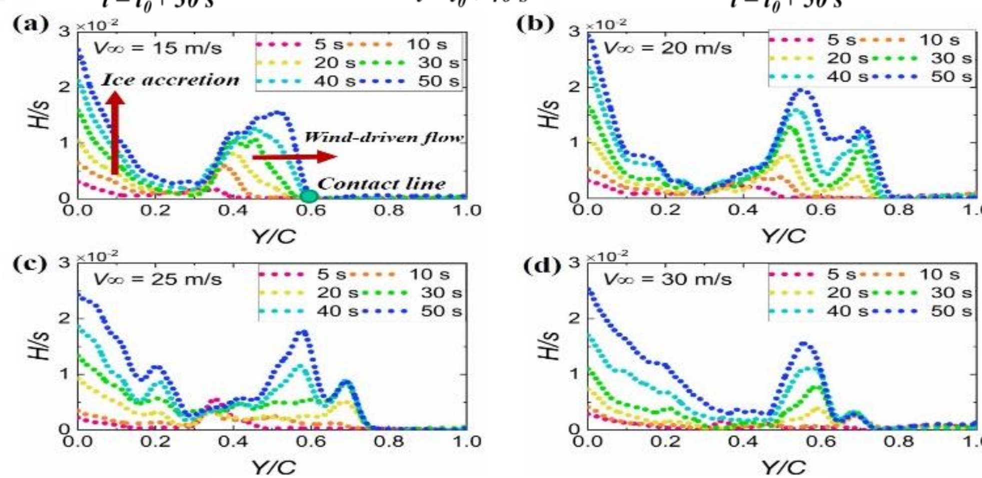
❑ Dynamic Surface Water Runback and Glaze Ice Accretion Process

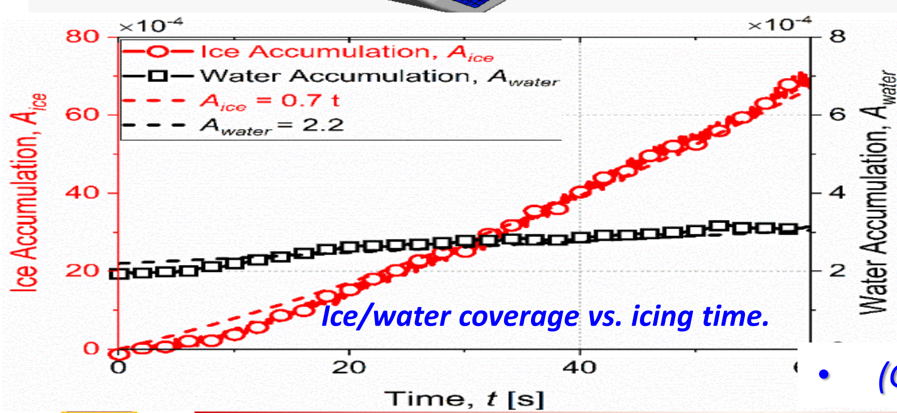


- V_∞ = 30 m/s
- T_∞ = -5.0 °C
- LWC = 3.0 g/m³







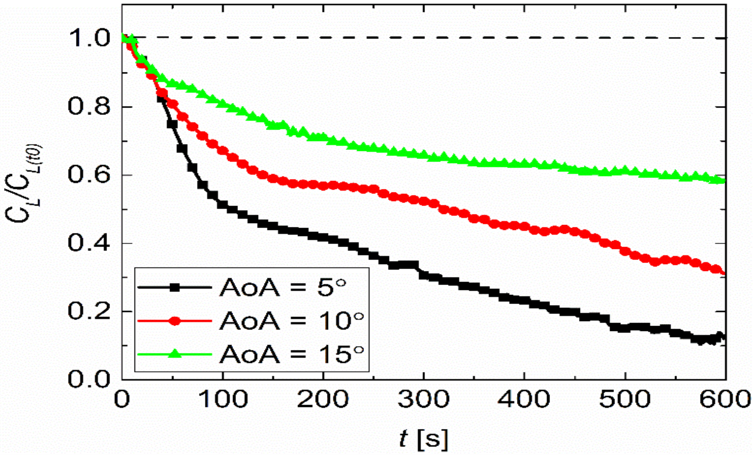


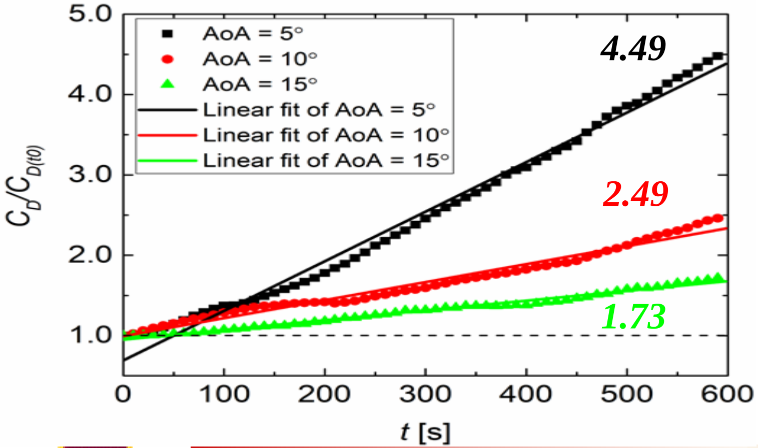
Ice/water coverage vs. icing time.

- *water/ice thickness vs. airflow velocity*

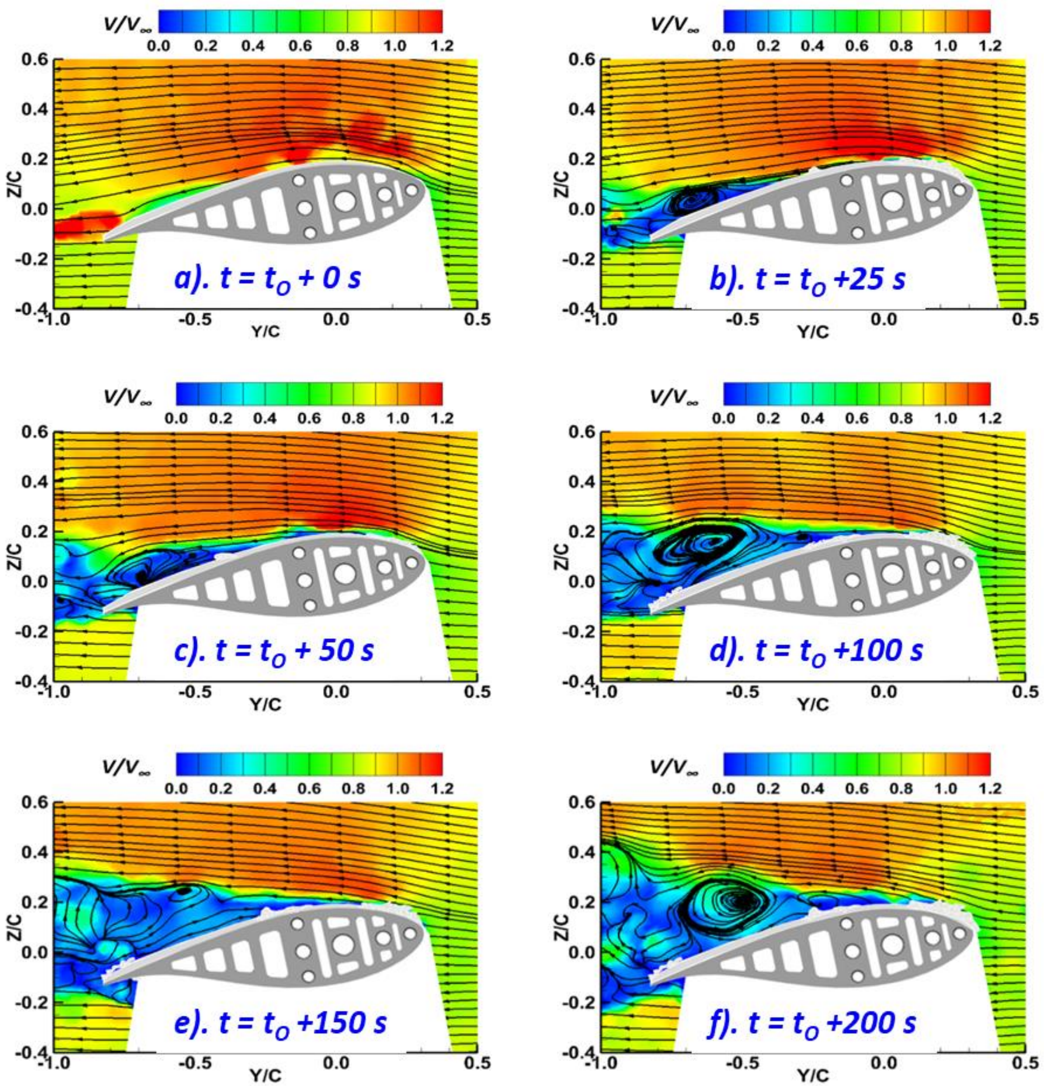
- *(Gao et al., International Journal of Heat and Mass Transfer, 2020)*

❑ Aerodynamic Performance Degradation due to Ice Accretion



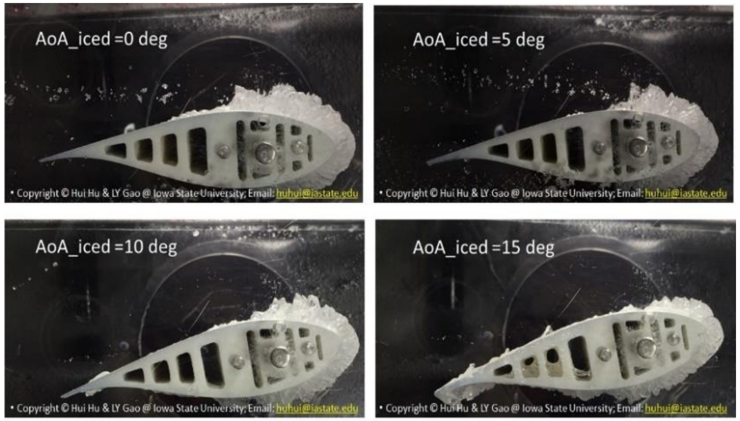


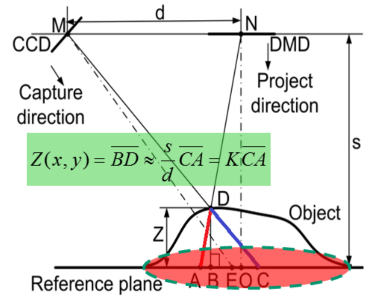
- $T_\infty = -5.0\ ^oC$; $V_\infty = 40.0$ m/s; LWC = 1.1 g/m^3, AOA=10^0

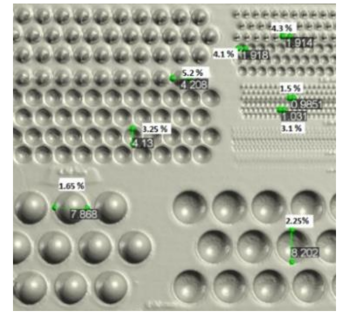


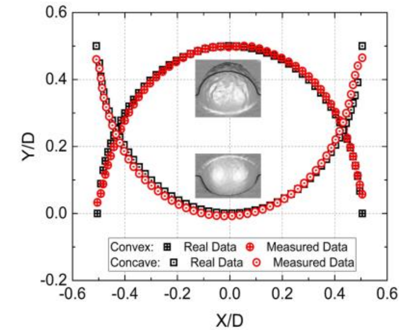
- *Gao et al., Renewable Energy, 133(4), 663-675, 2019.*

❑ Qualification of Complex 3D Ice Shapes Accreted on Airfoil Surface



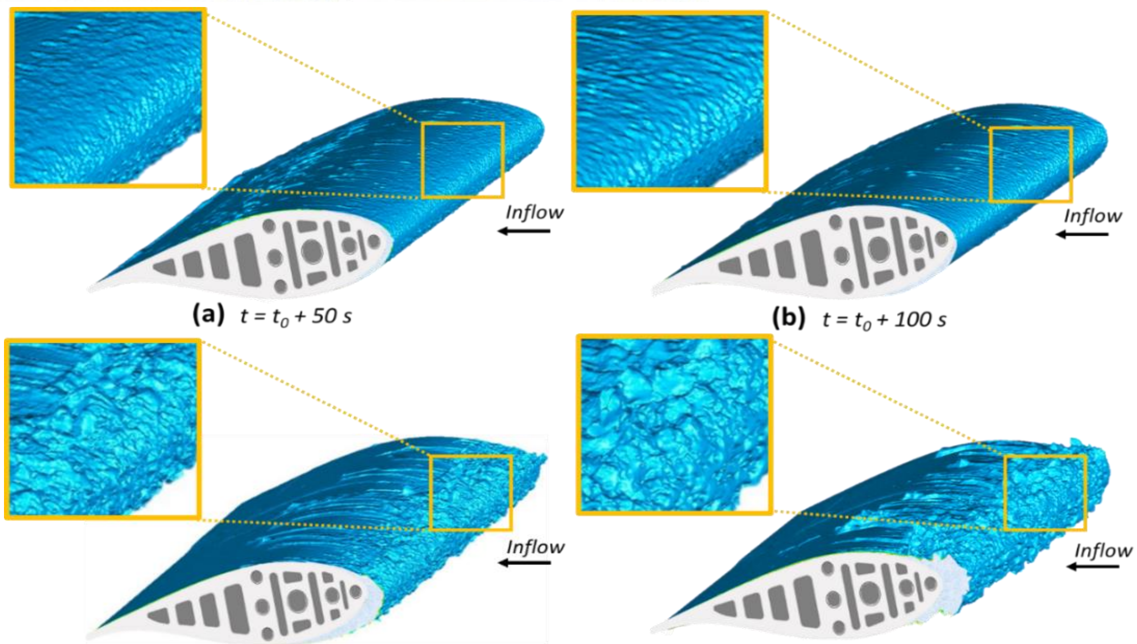






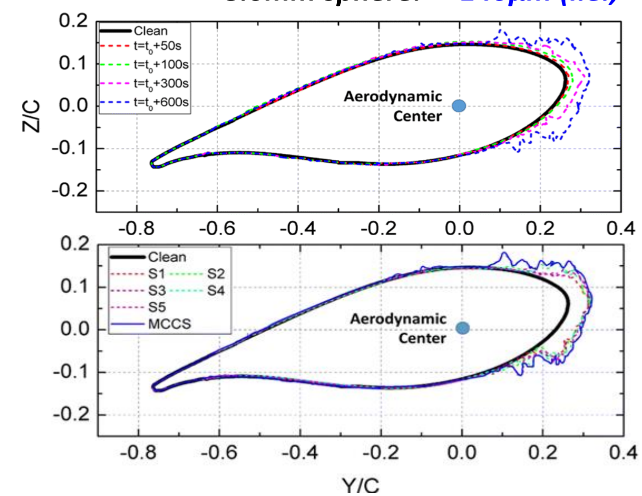
Digital Image projection (DIP) technique

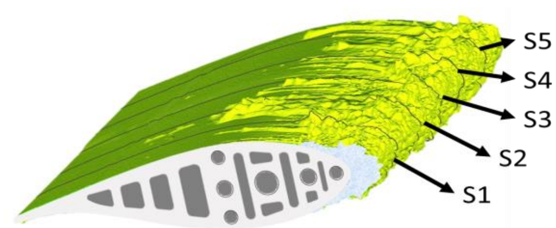
Measurement uncertainty:
8.0mm sphere: ~ 140µm (i.e., < 2.0%)



(a) $t = t_0 + 50$ s
(b) $t = t_0 + 100$ s
(c) $t = t_0 + 300$ s
(d) $t = t_0 + 600$ s

DIP canning technique for 3D ice shape measurements

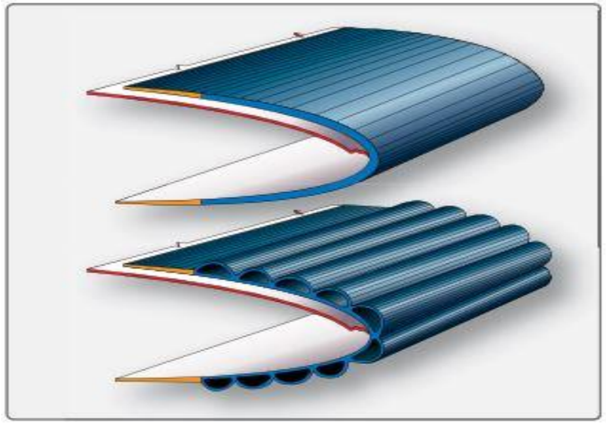


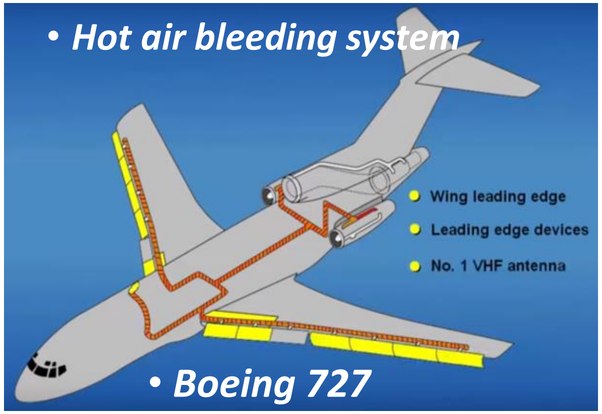


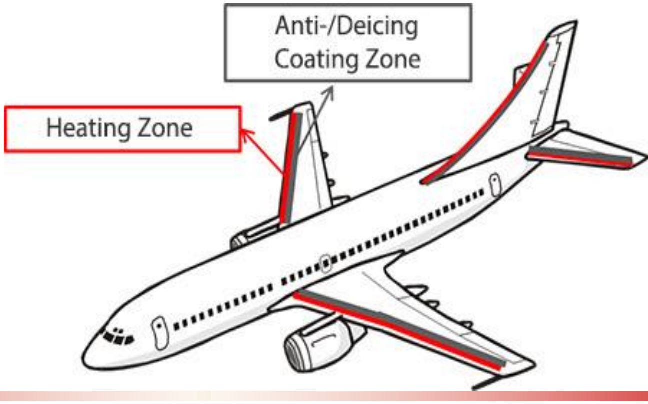
• LY Gao, R. Veerakumar, Y. Liu, and H. Hu. "Quantification of the 3D Shapes of the Ice Structures Accreted on a Wind Turbine Airfoil Model", Journal of Visualization, Vol.22, No. 4, pp 661–667, 2019.

❑ Various Active and Passive Anti-/De-Icing Strategies

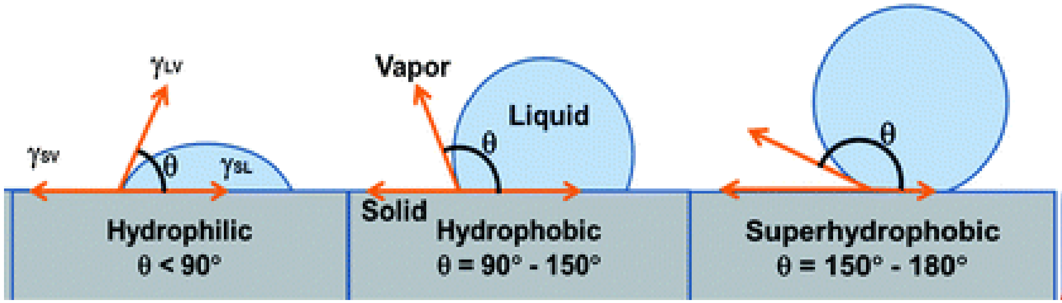
- ❖ *Active Methods:* ***rely on external energy input for anti-/de-icing operation:***
  - ➢ ***Pneumatic inflating systems:*** *Deform to cause ice crack-off.*
  - ➢ ***Hot air bleeding systems:*** *Provide heat air to melt out ice.*
  - ➢ ***Electro-thermal systems:*** *Provide heat flux by using electrical heater*
  - ➢ ***DBD Plasma Based Anti-/De-icing Systems.***
- ❖ ***Passive methods:*** ***take advantage of the physical properties of airframe surface to prevent ice formation.***
  - ➢ ***Hydro- and Ice-phobic materials:*** *Water repellent; Smaller ice adhesion forces.*

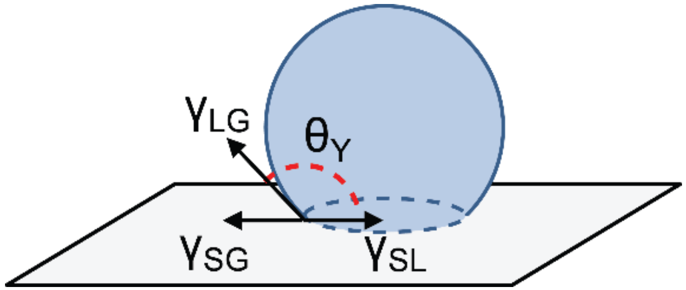






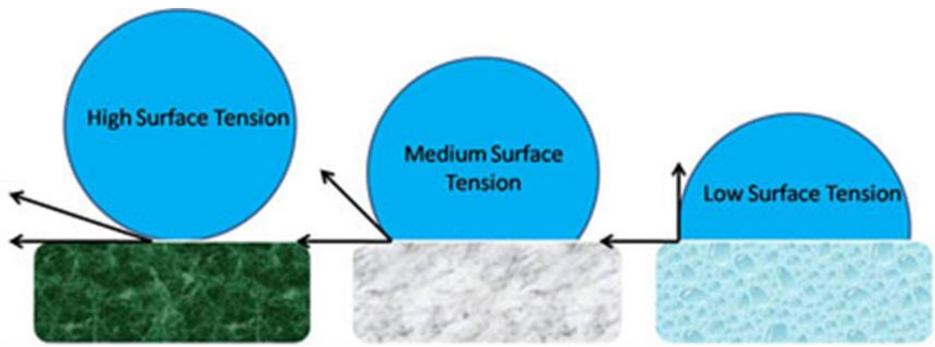
❑ Surface Wettability: Hydrophilic, Hydrophobic, & Superhydrophobic



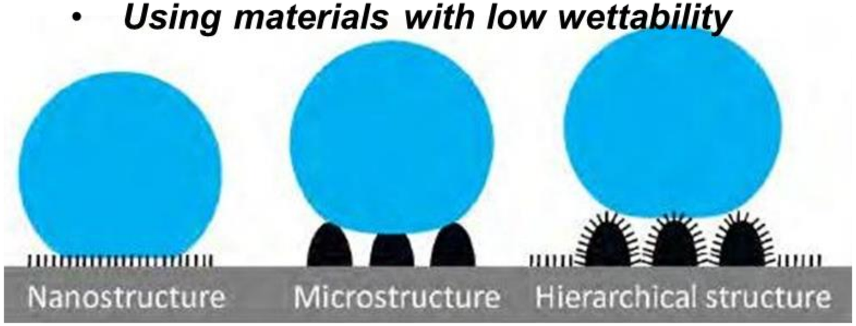


$$\gamma_{LG}\cos\theta_Y = \gamma_{SG} - \gamma_{LS}.$$

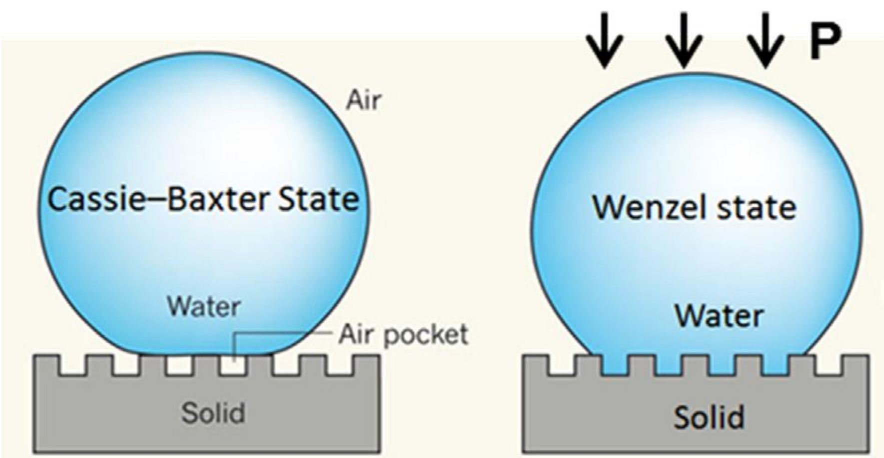
- ***A water droplet over a smooth surface***



- ***Using materials with low wettability***



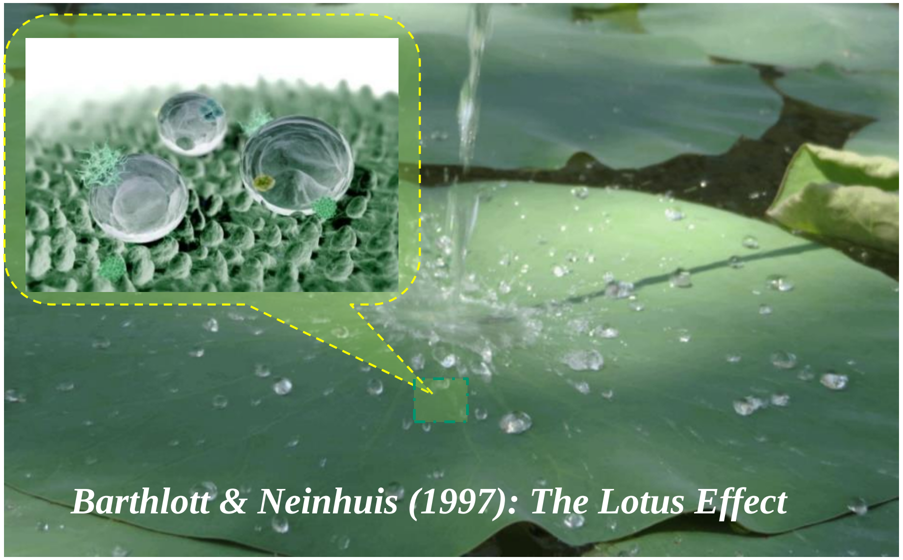
- ***Making structured surface (creating micro-/nano- structures over the surface)***



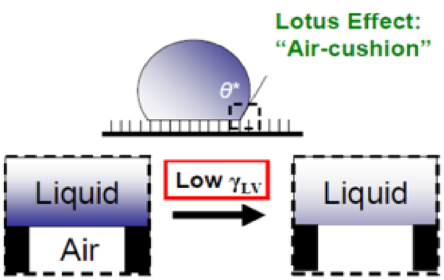
$$\cos\theta_{CB} = \varphi\cos\theta_Y + \varphi - 1 \qquad \cos\theta_W = n\cos\theta_Y$$

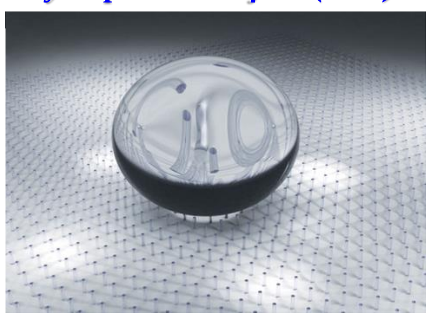
- ***A water droplet over a rough surface***

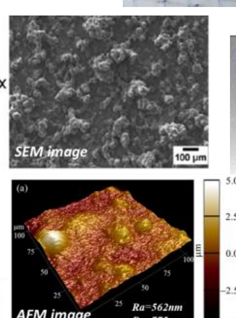
❑ Bio-Inspired Ice Phobic Coatings for Aircraft Icing Mitigation

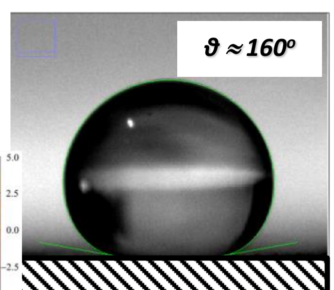


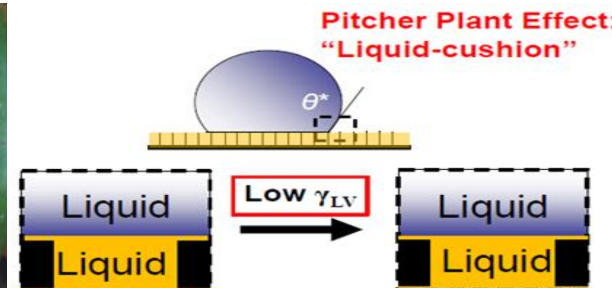
- *Lotus-leaf-inspired Super-Hydrophobic Surface (SHS)*





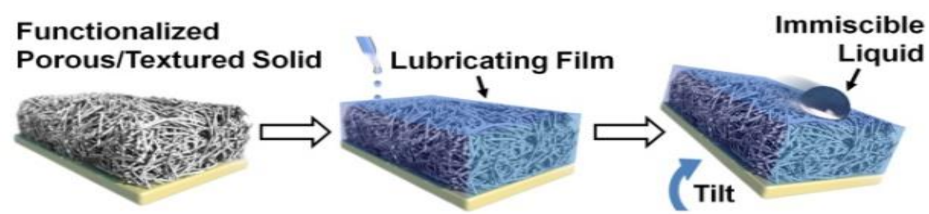


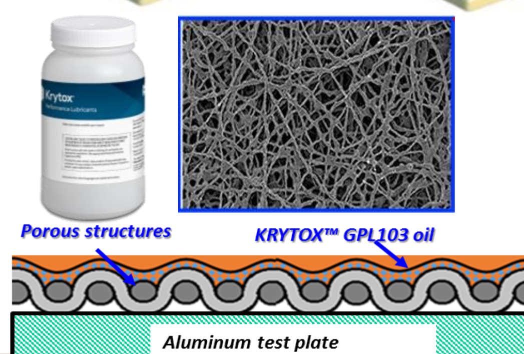


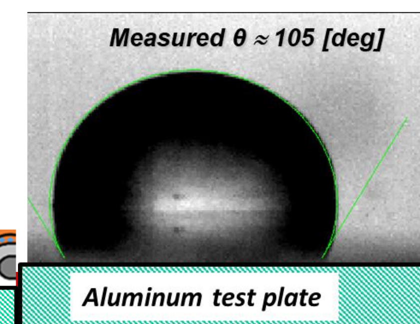


u et

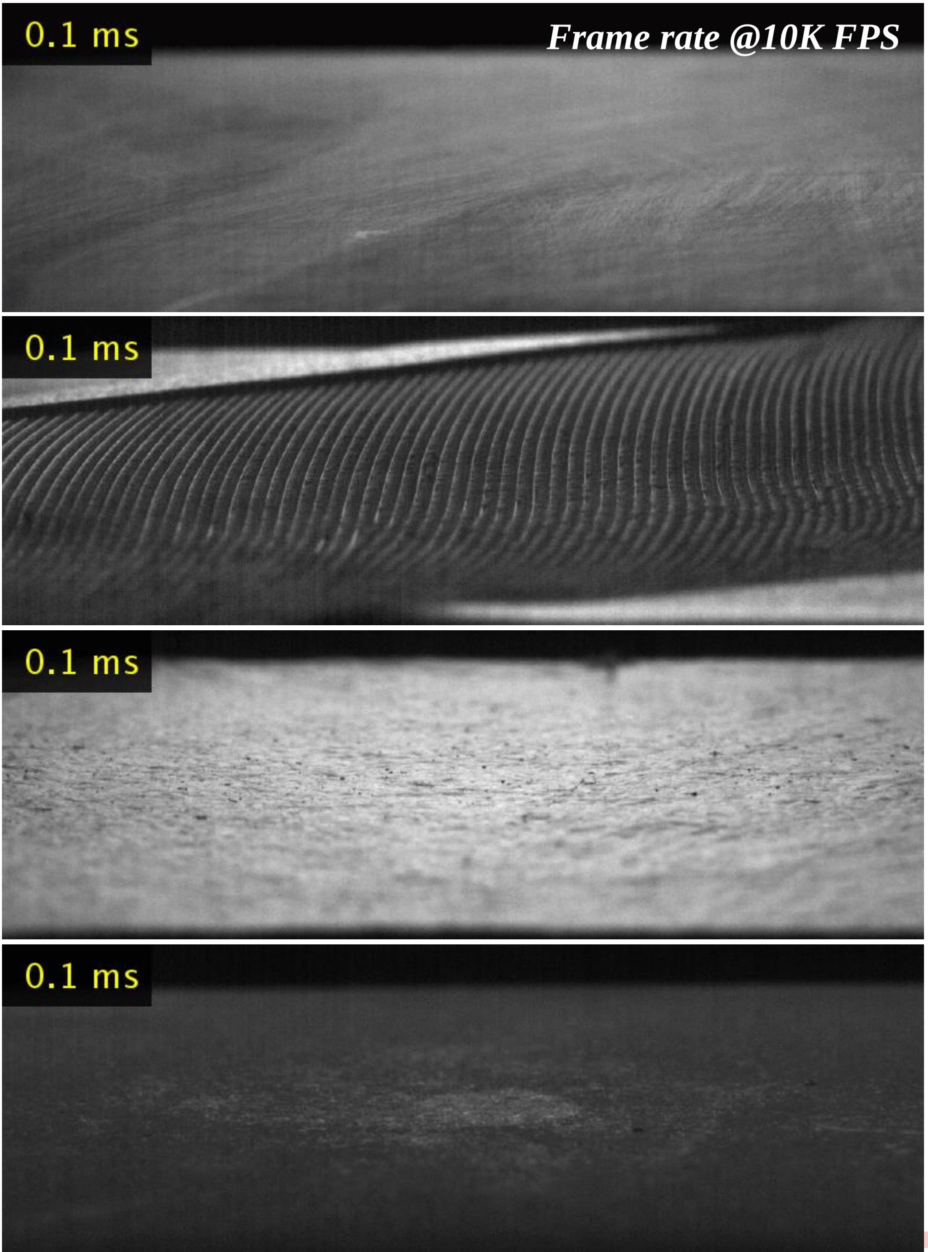
- *Slippery Liquid-Infused Porous Surfaces (SLIPS)*



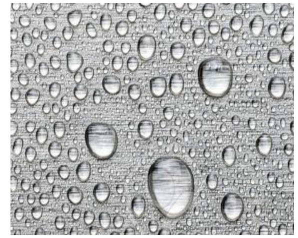




❑ Dynamic Droplet Impingement onto Different Surfaces

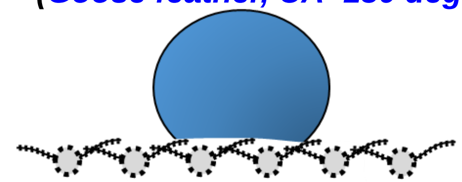


We ≈ 2, 000

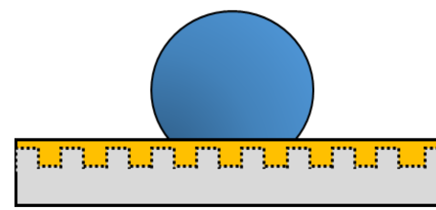


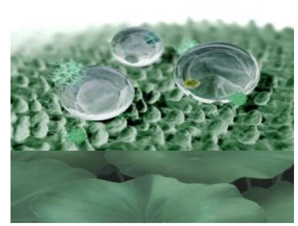
Hydrophilic
(Comparison baseline, CA=65 deg..)

Feather
(Goose feather, CA=130 deg.)

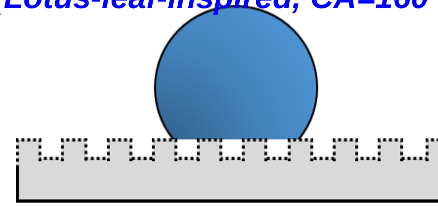


SLIPS
(Pitcher-plant-inspired. CA=105 deg.)



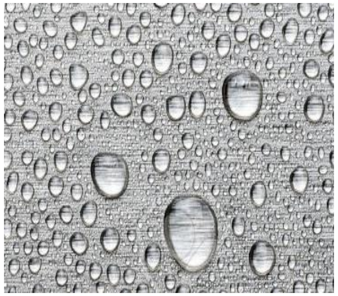


Super-hydrophobic
(Lotus-leaf-inspired, CA=160 deg.)

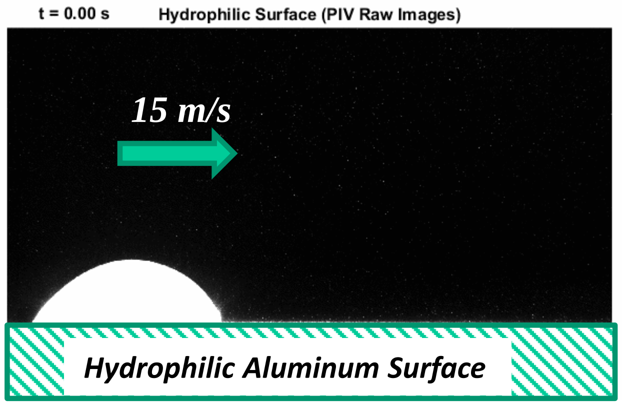


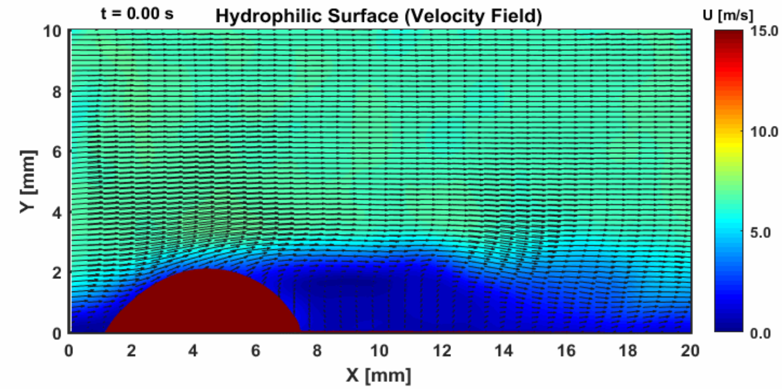
- ***LQ Ma, HX Li, and H. Hu.*** *An Experimental Study on the Dynamics of Water Droplet Impingement onto Bio-inspired Surfaces with Different Wettability.* ***AIAA-2017-0442***, *SciTech2017.*

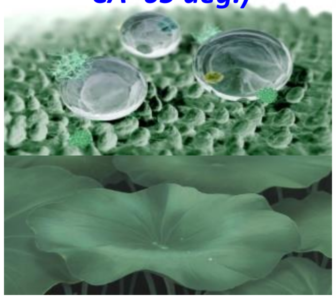
❑ Transient Behavior of Wind–Driven Film/Rivulet Flows



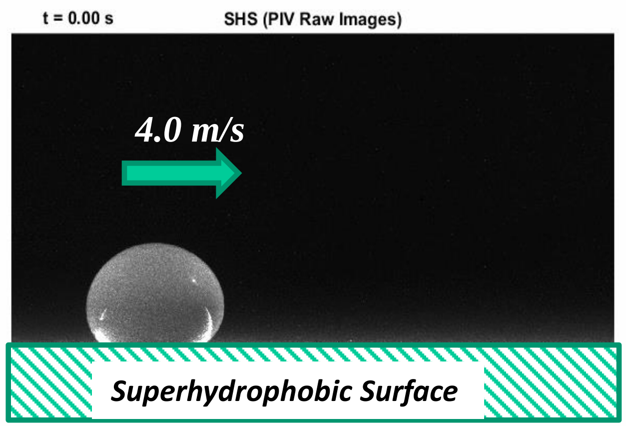
Hydrophilic
(Comparison baseline, CA=65 deg.)

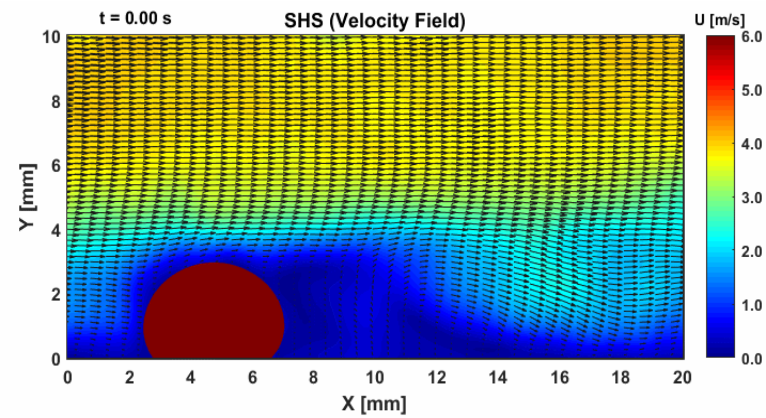




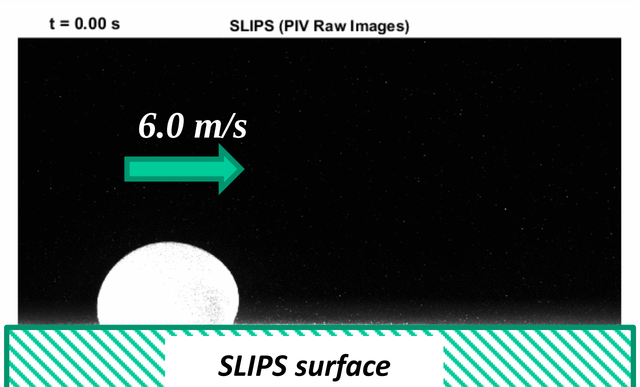


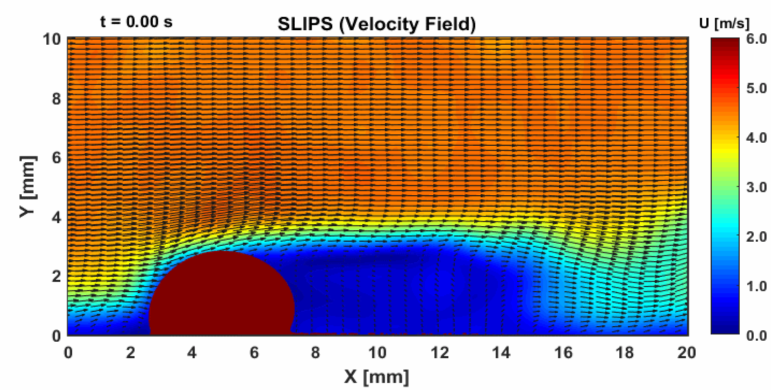
Super-hydrophobic surface
(Lotus-leaf-inspired, CA=160 deg.)



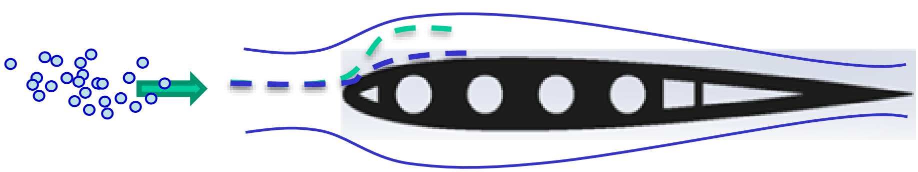


SLIPS
(Pitcher-plant-inspired, CA=110 deg.)

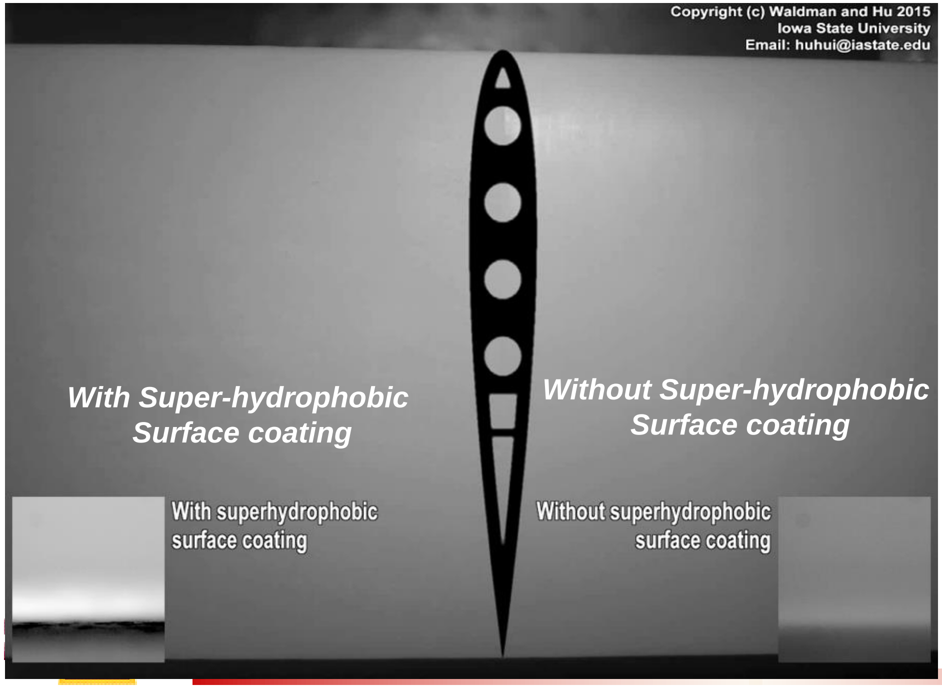




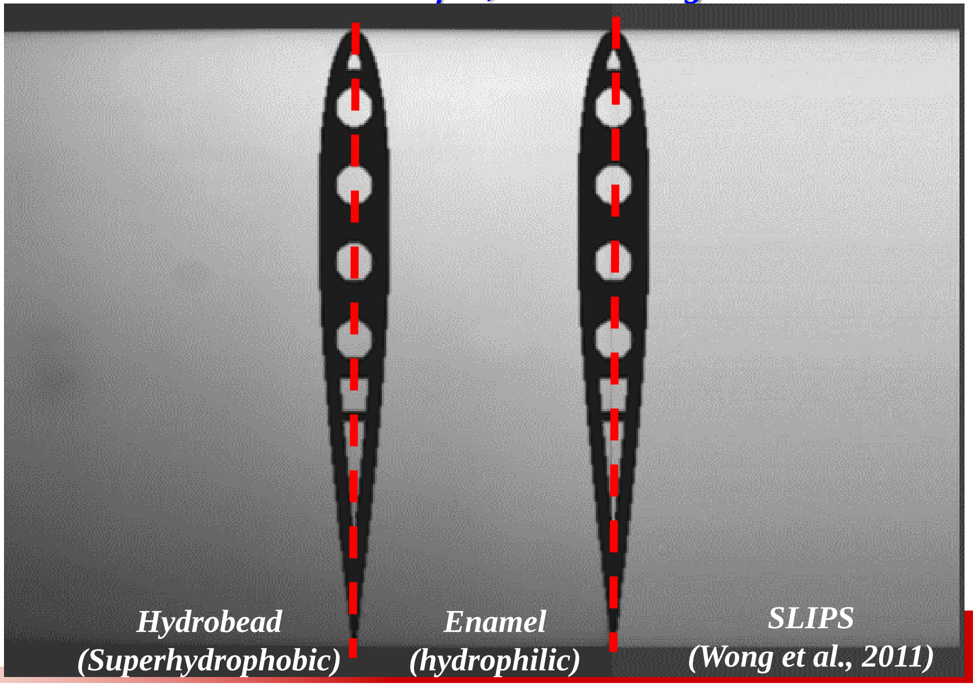
Effects of Bio-Inspired Coatings on Impact Ice Accretion



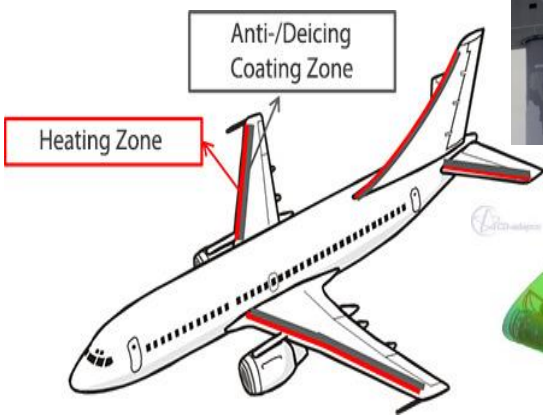
$T_\infty = -8\,^\circ C$; $V_\infty = 50\ m/s$
$MVD = 20\,\mu m$; $LWC = 2.5\ g/m^3$



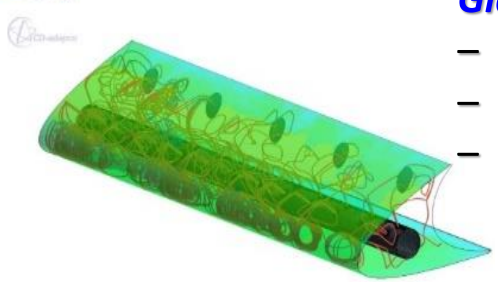
$T_\infty = -4\,^\circ C$; $V_\infty = 40\ m/s$
$MVD = 40\,\mu m$; $LWC = 2.5\ g/m^3$



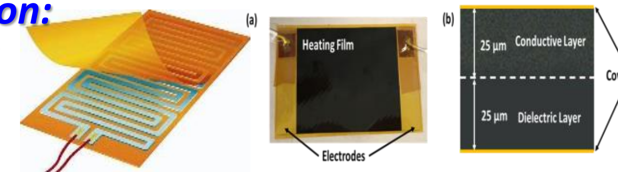
❑ Hybrid Ant-/De-Icing Strategy with Heating + Icephobic Coatings



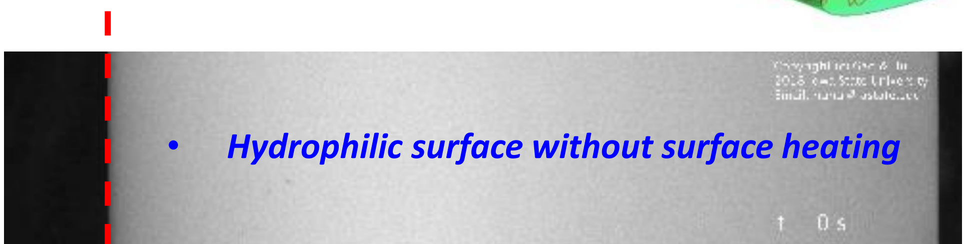
- Wind turbine icing and anti-/de-icing



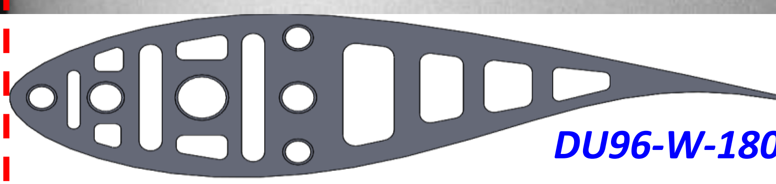
Glaze Icing Condition:
- $LWC = 2.0\ g/m^3$
- $T_\infty = -5\ ℃$
- $V_\infty = 40\ m/s$

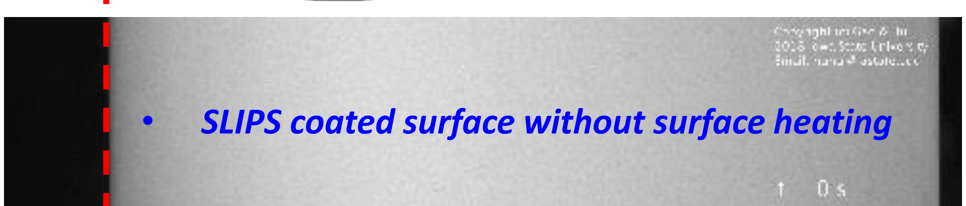


- Photo of the DuPont™ Kapton® RS
- Cross section view

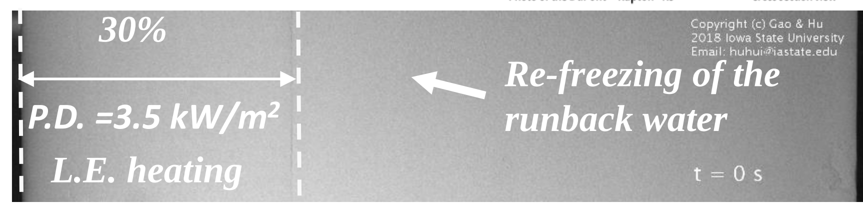


- Hydrophilic surface without surface heating

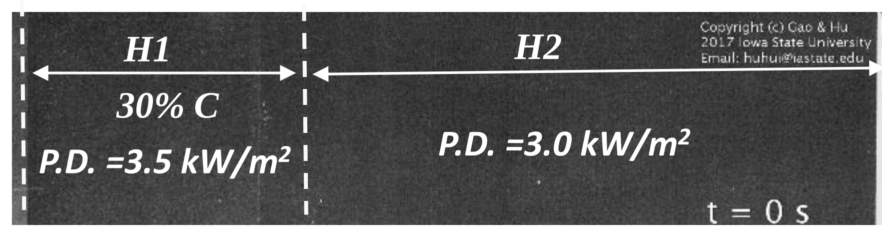




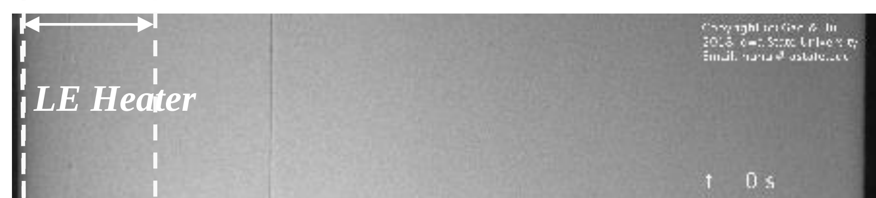
- SLIPS coated surface without surface heating



- With leading edge heating + hydrophiid surface



With "2RH" surface heating (Successful anti-/de-icing)



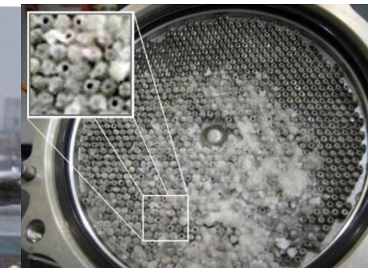
- Leading edge heating + SHS (~ 90% energy saving)

- Gao et al., Renewable Energy, 133(4), 663-675, 2019.

❑ Aero-Engine Icing Physics and Anti-/De-Icing

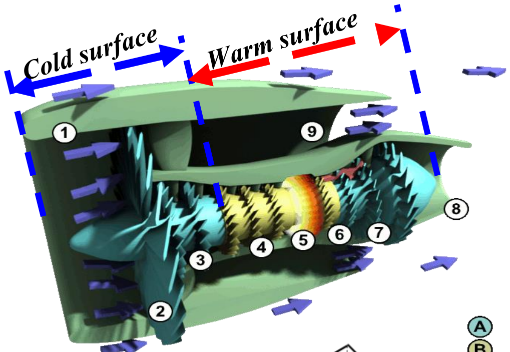
- Aero-engine icing problem has been known since 1950s.
- More than 100 jet engines experience icing-related "power-loss" events since 1990.
- "Power loss" of the aero-engine, including surge, stall, flameout, or roll back, can result in a sub-idle operating condition.

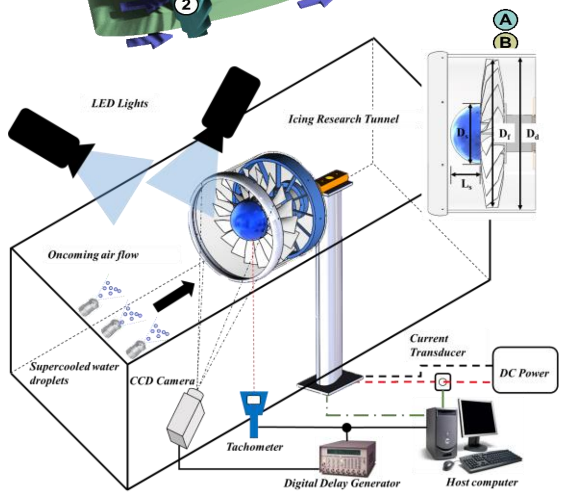
British Airways B777 crash , 01/17/2008.

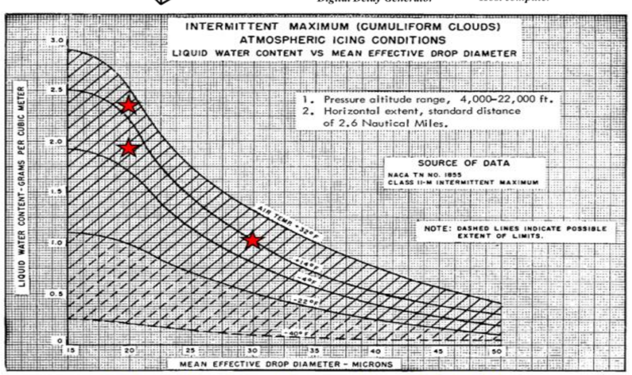


- Ice crystals in the jet fuel were blamed as the cause of the accident, clogging the fuel-oil heat exchanger of engine.

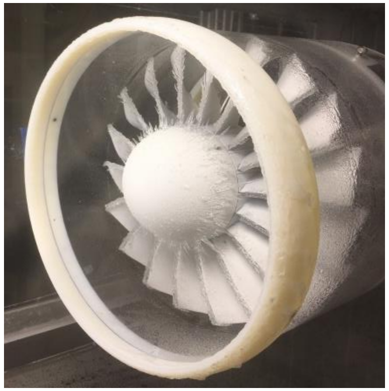
❑ Experimental Setup for Aero-Engine Icing Study

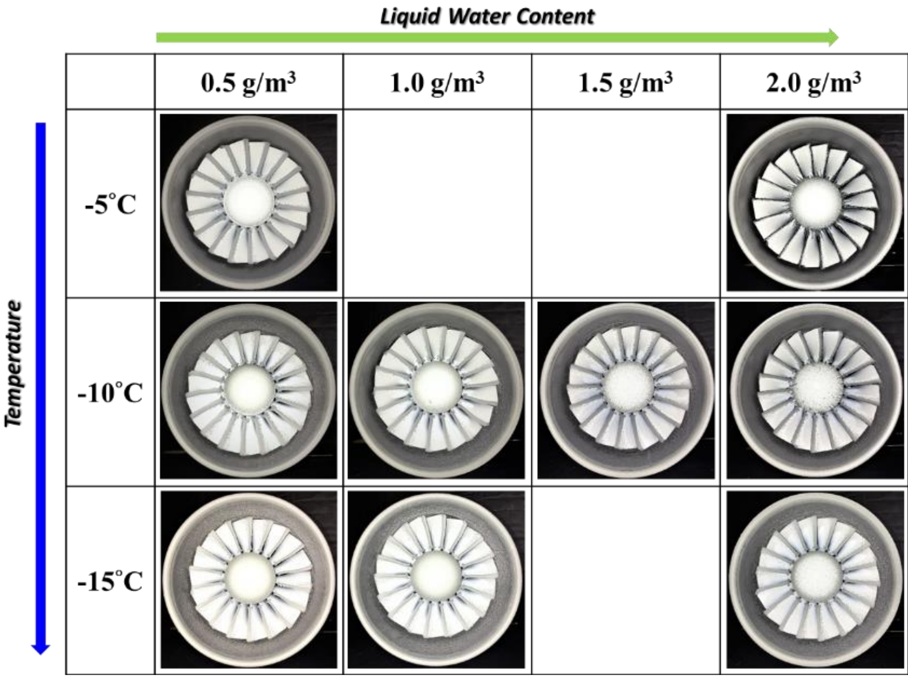






Intermittent maximum atmospheric icing conditions from 14 CFR Part 25 Appendix C[1]





Parameters	CFM 56-2/3 Turbofan	Aero-engine Model
Diameter of (m)	1.52	0.2
Max Rotation Speed (rpm)	5175	4000
Cruising Speed (m/s)	222 (0.74 Ma)	15
Cruising Rotation Speed (rpm)	4900	2500
Temperature Range (°C)	-40 ~ 20	-15 ~ -5
Liquid Water Content (g/m³)	0.1 ~ 2.0	0.6 ~ 2.4
Advanced Ratio, J	1.80	1.80

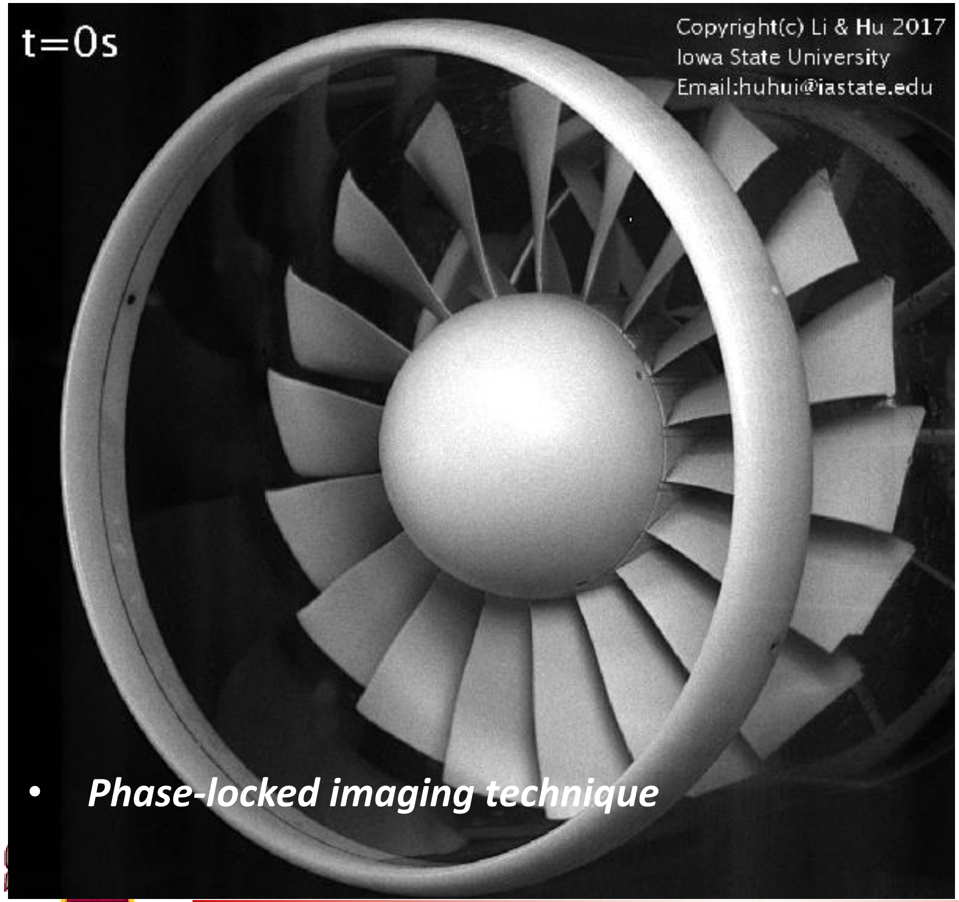
Dynamic Ice Accreting Process over Rotating Fan Blades

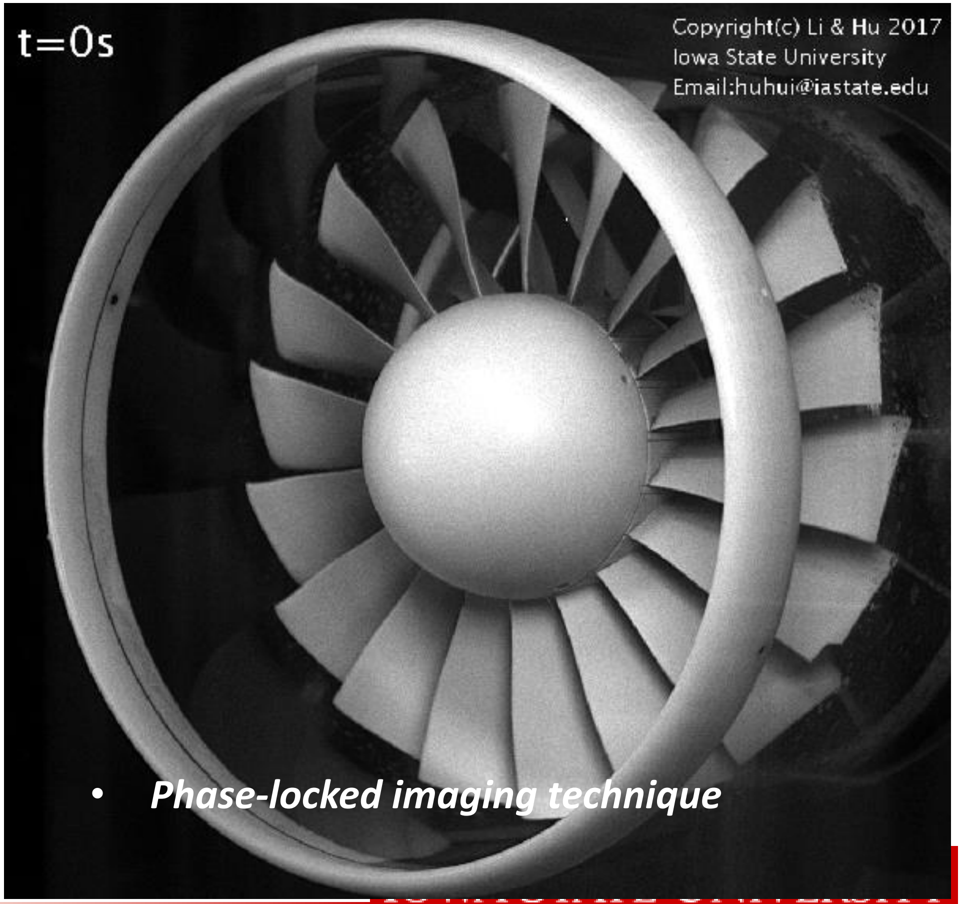
Glaze icing condition:

- V_∞ = 15 m/s;
- T_∞ = -5 ℃,
- LWC = 2.0 g/m^3
- Rotation = 2,500 rpm

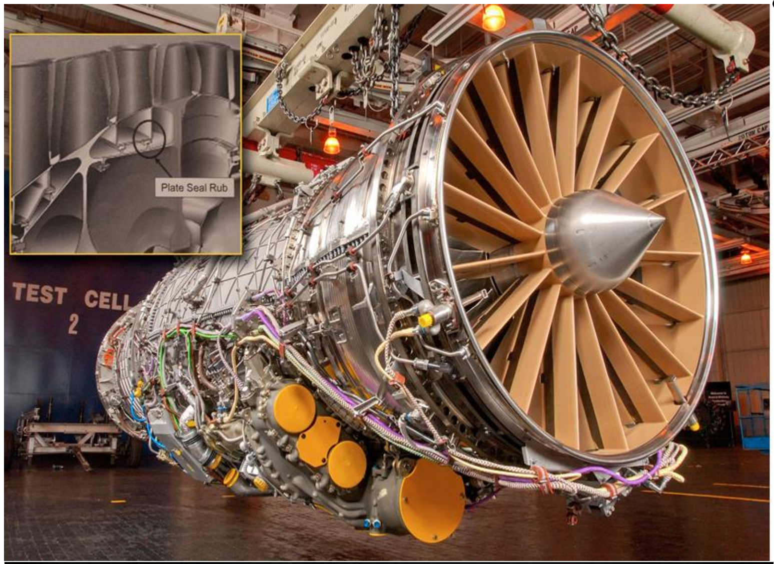
Rime icing condition:

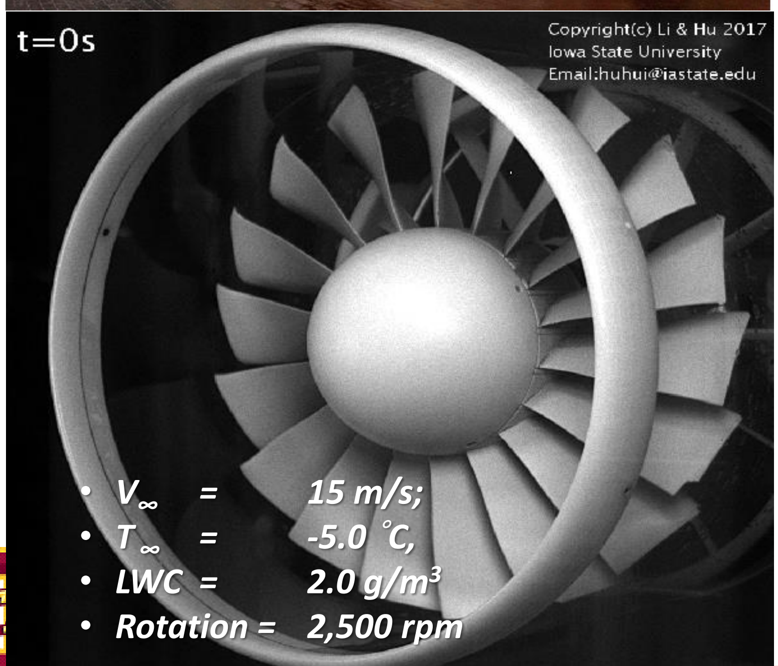
- V_∞ = 15 m/s;
- T_∞ = -15 ℃,
- LWC = 0.5 g/m^3
- Rotation = 2,500 rpm



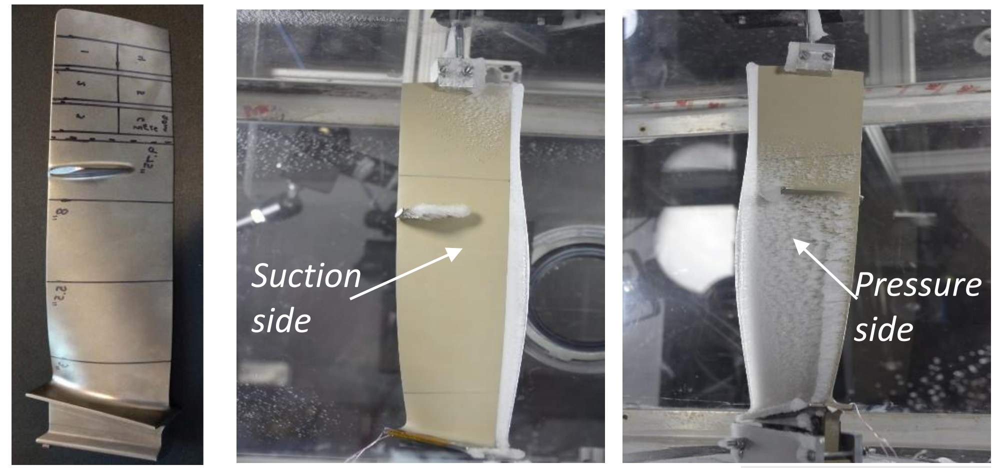


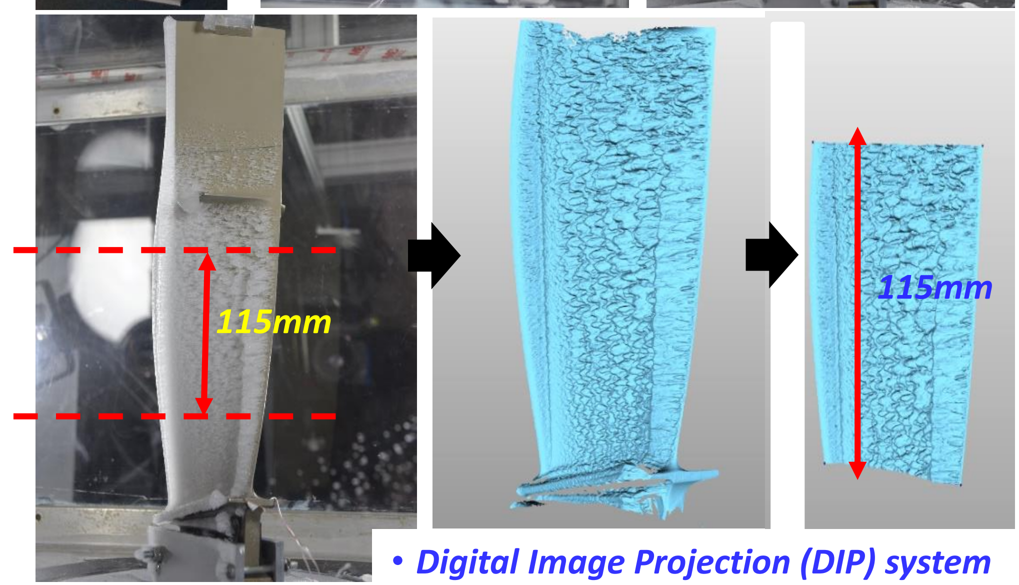
❑ Durable Metal-based Icephobic Coating for Aero-Engine Icing Protection





- *The Durable Metal-based Icephobic Coating is developed by Dr. Tuteja group @ Univ. of Michigan (Golovin et al., Science 364, 371–375 (2019).*

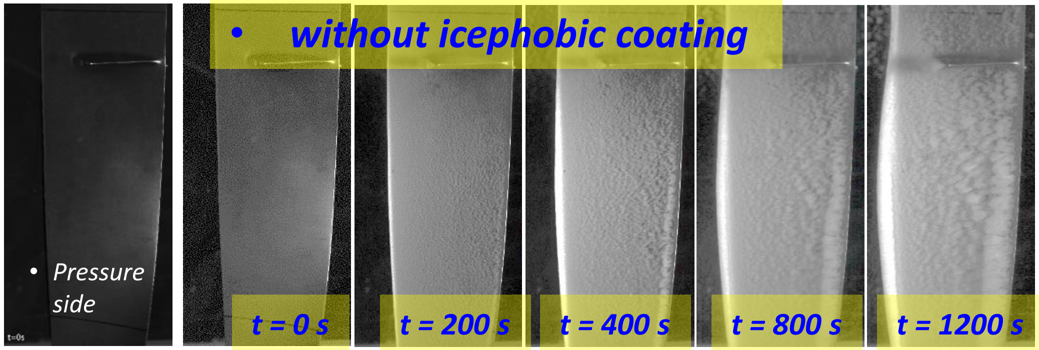


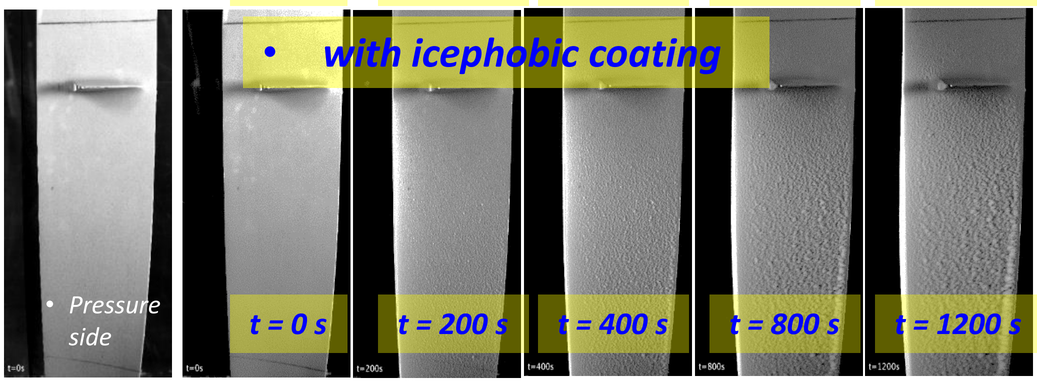


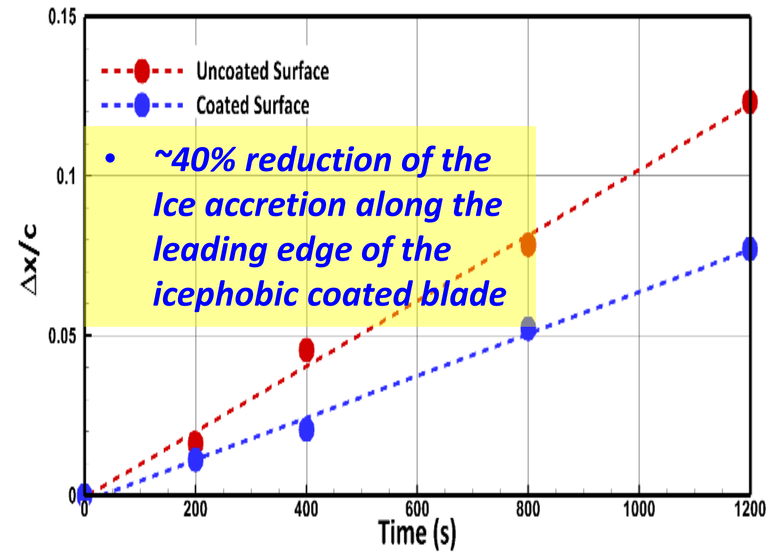
- *Digital Image Projection (DIP) system for 3D ice shape measurements*

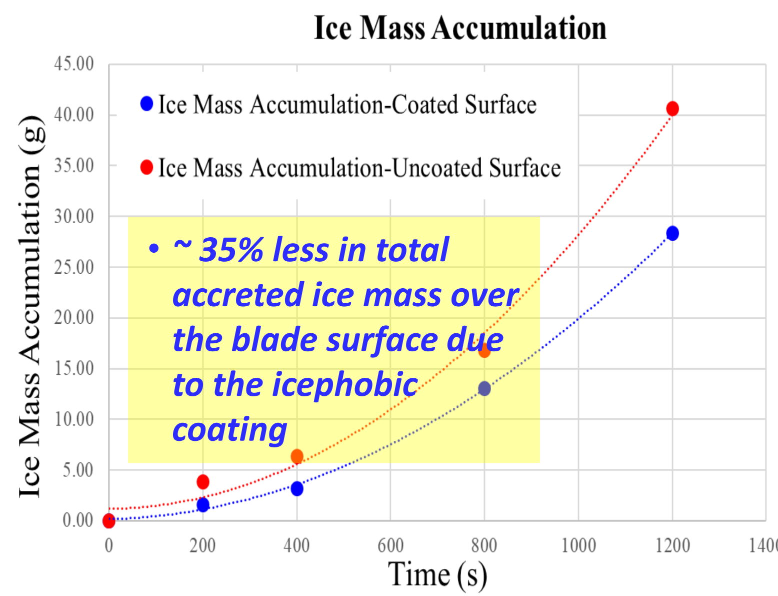
Icing mitigation over Aero-engine Fan Blades due to Icephobic Coating

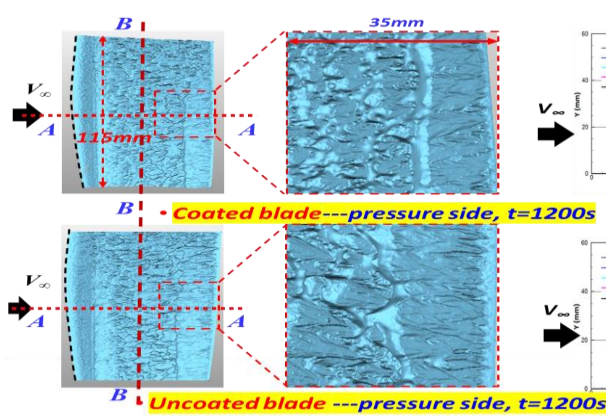
- *Test conditions: V_∞=50m/s; T_∞ = -18°C; LWC=0.3 g/m^3*

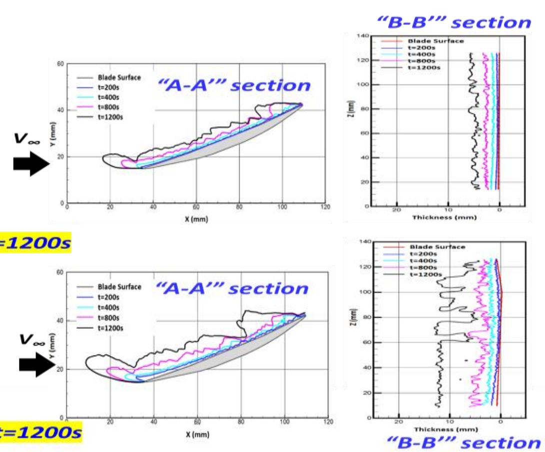




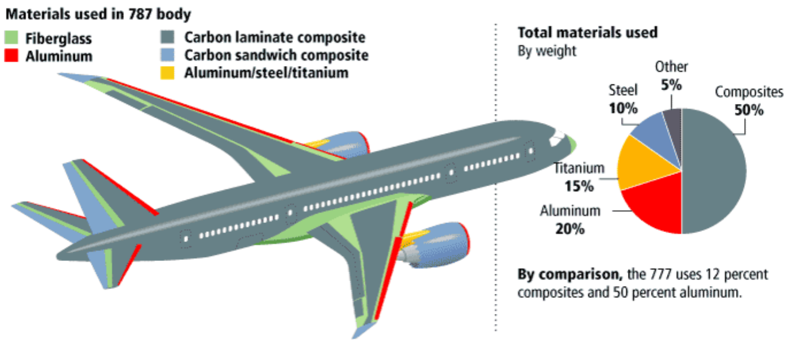








❑ Effects of Aero-Engine Blade Materials on Ice Accretion Process

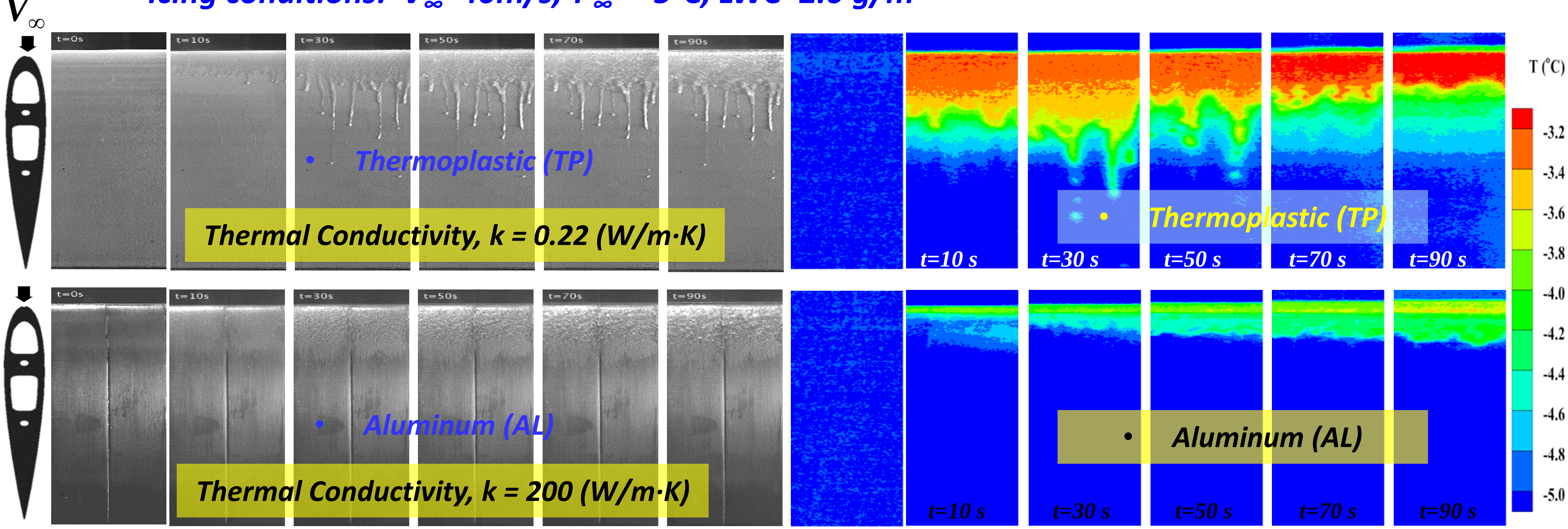


- CFM 56 titanium fan blade

- GE90 composites fan blade

Thermal Conductivity	Thermoplastic ULTEM®1010	Titanium	Stainless steel	6061 Aluminum
K, (W/m·K)	0.22	~60	15~50	200

- Icing conditions: V_∞=40m/s, T_∞ = -5°C, LWC=2.0 g/m³



- LK Li, Y. Liu, ZC Zhang and H. Hu, International Journal of Heat and Mass Transfer, Vol. 131, pp1184-1195, 2019

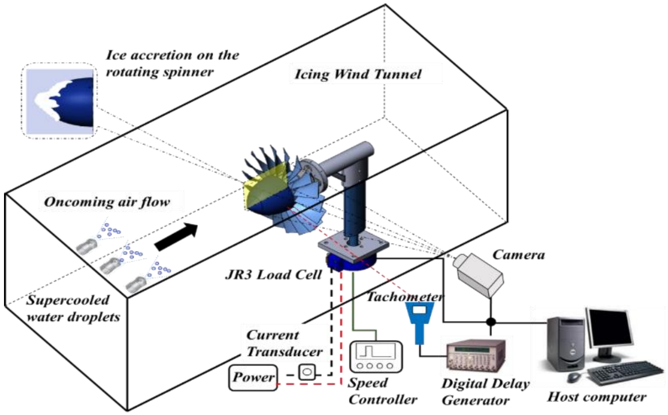
❑ How to Distinguish RR, PW, GE Engines – Shape of Engine Spinner

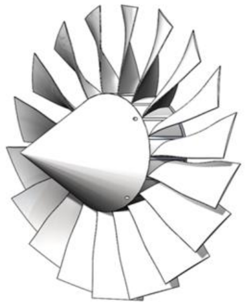
Rolls-Royce | Pratt & Whitney (A United Technologies Company) | GE Aviation

- *RR Trent-XWB*

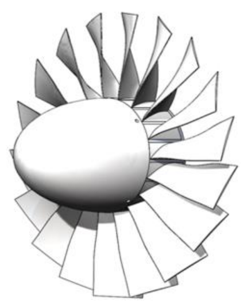
- *PW 1000G*

- *GE 90*

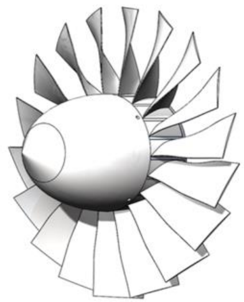




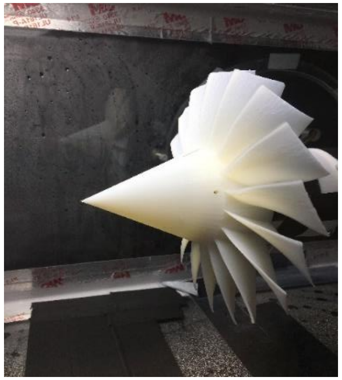
- *Conical spinner*

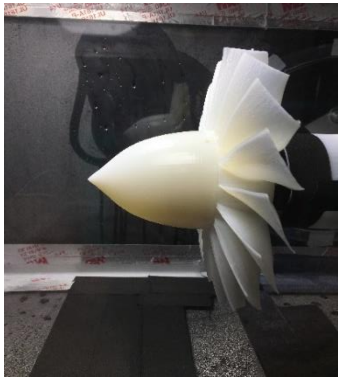


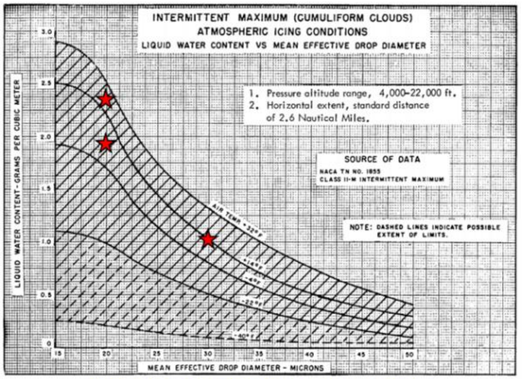
- *Elliptical spinner*



- *Coniptical spinner*





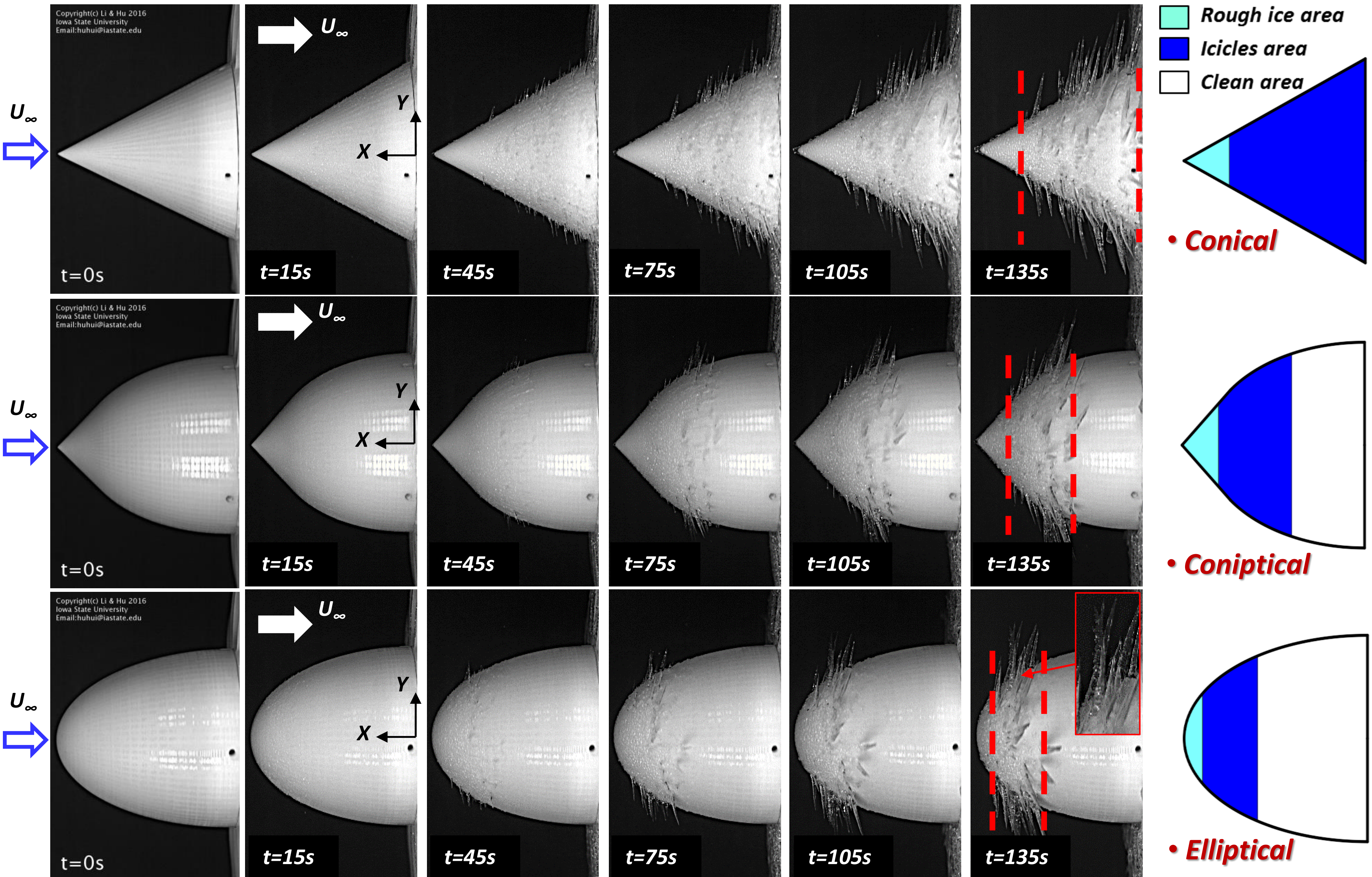


Intermittent maximum atmospheric icing conditions from 14 CFR Part 25 Appendix C[1]

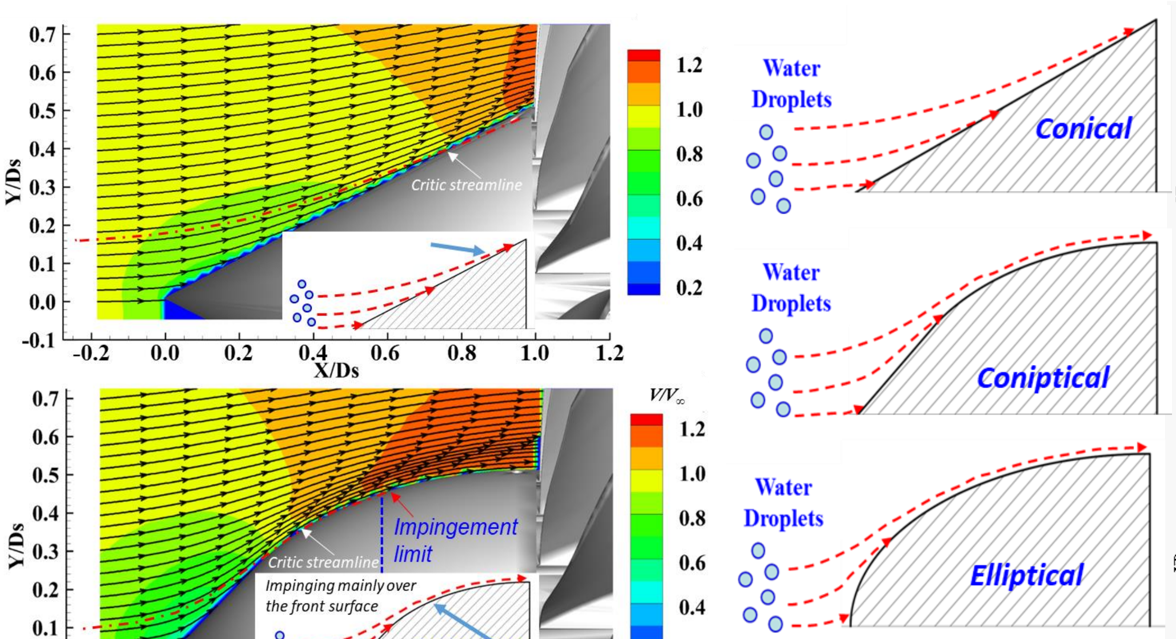
Parameters	CFM 56-2/3 Turbofan	Aero-engine Model
Diameter of (m)	1.52	0.2
Max Rotation Speed (rpm)	5175	4000
Cruising Speed (m/s)	222 (0.74 Ma)	15
Cruising Rotation Speed (rpm)	4900	2500
Temperature Range (°C)	-40 ~ 20	-15 ~ -5
Liquid Water Content (g/m^3)	0.1 ~ 2.0	0.6 ~ 2.4
Advanced Ratio, J	1.80	1.80

❑ Dynamic Ice Accretion over the Surfaces of Rotating Spinners

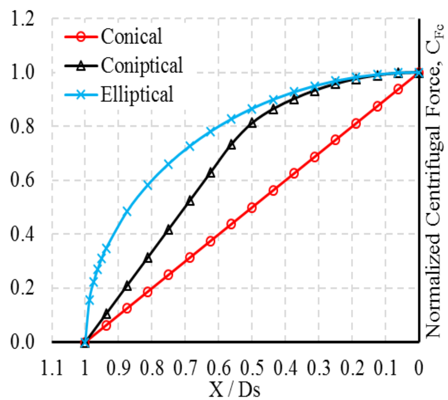
Glaze icing: U_∞ =15 m/s, T_∞ = -5ºC , LWC=2.4 g/m^3, J=1.8

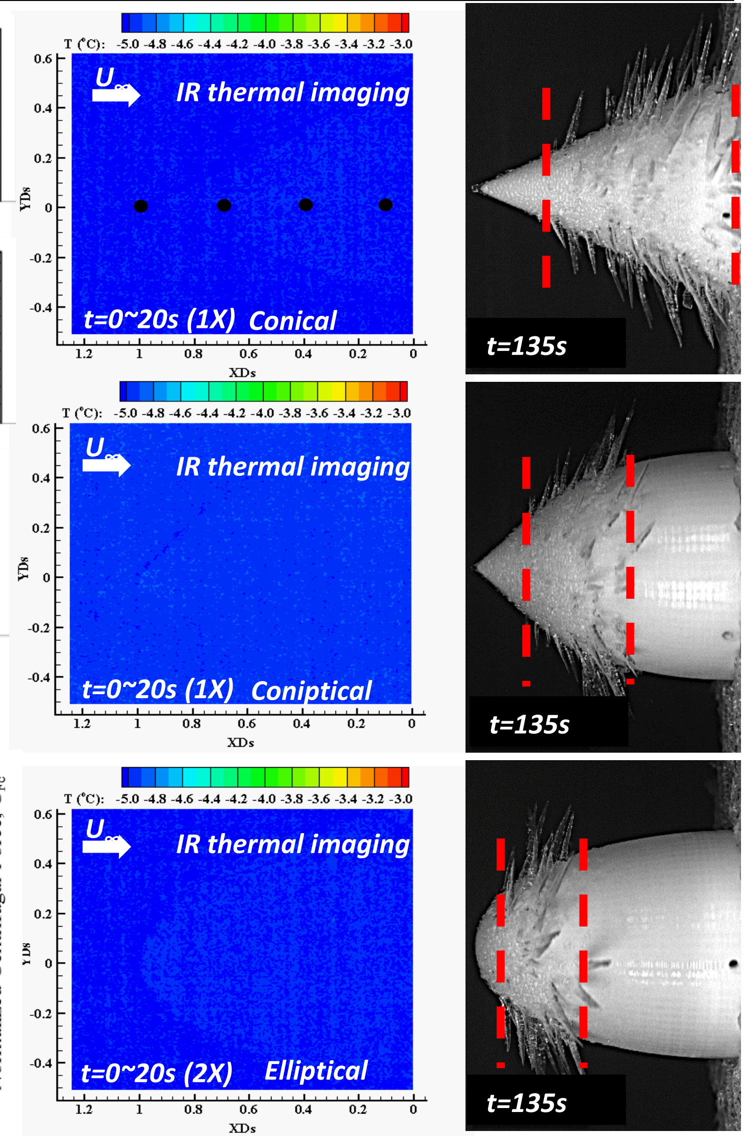


Dynamic Ice Accretion over the Surfaces of Rotating Spinners



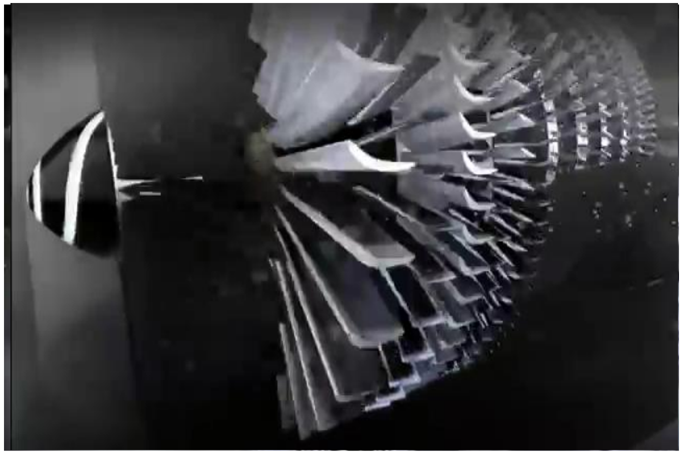
$$C_{Fc} = \frac{F_{c,r}}{F_{c,r=\max}} = \frac{m\omega^2 r}{m\omega^2 r_{\max}} = \frac{r}{r_{\max}}$$



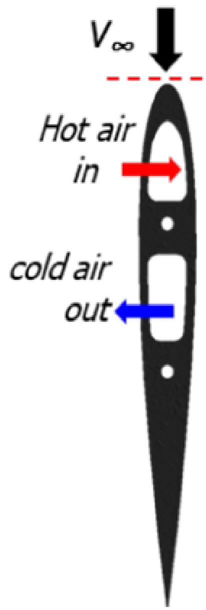


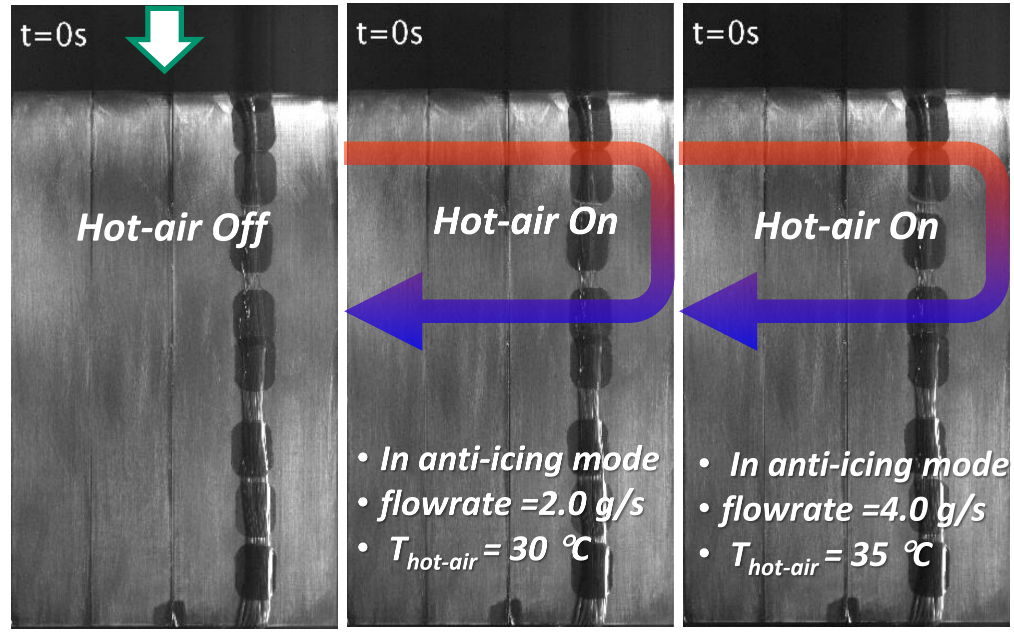
- ***LK Li, Y. Liu, H. Hu.*** *"An Experimental Study on Dynamic Ice Accretion Process over the Surfaces of Rotating Aero-Engine spinners". Experimental Thermal and Fluid Science, Vol.109, 109879 (13 pages), 2019.*

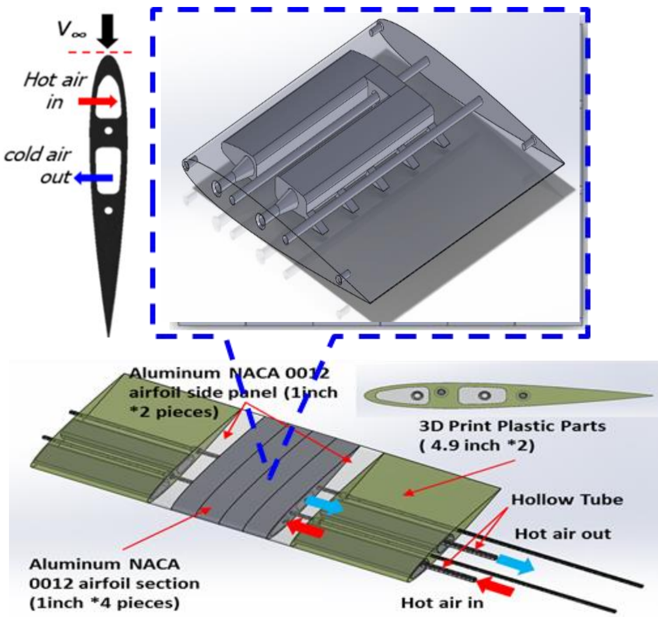
❑ Hot-Air-Based Icing Protecting System for Engine Inlet-Guild-Vanes



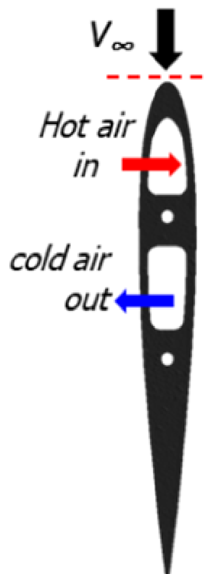
- *Ice accretion on Inlet-Guild-Vanes (IGV)*

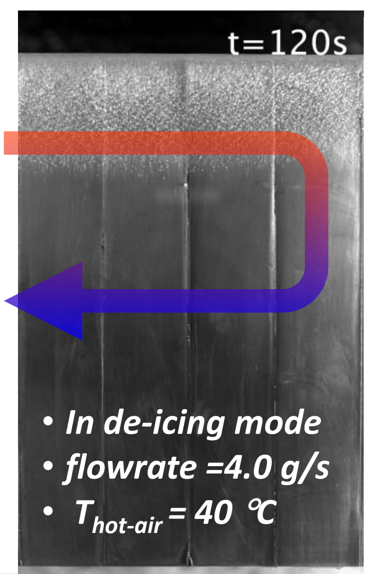


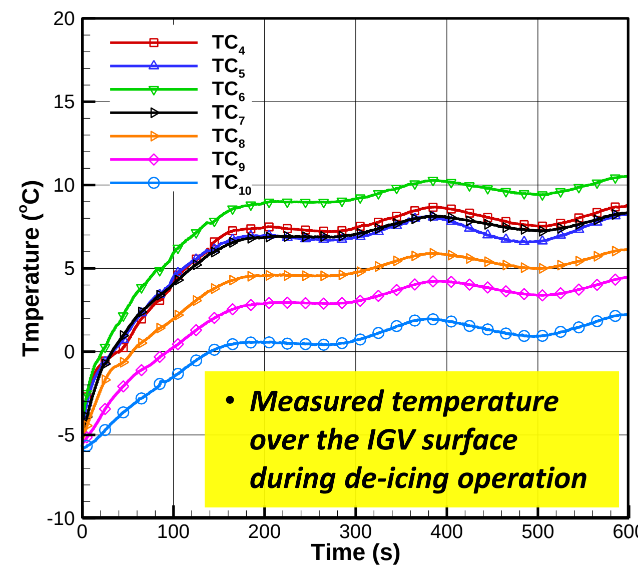




Hot-air-based IGV anti-/de-icing system







❑ Aero-Engine Icing Physics and Anti-/De-Icing

Aero-engine Icing Phenomena

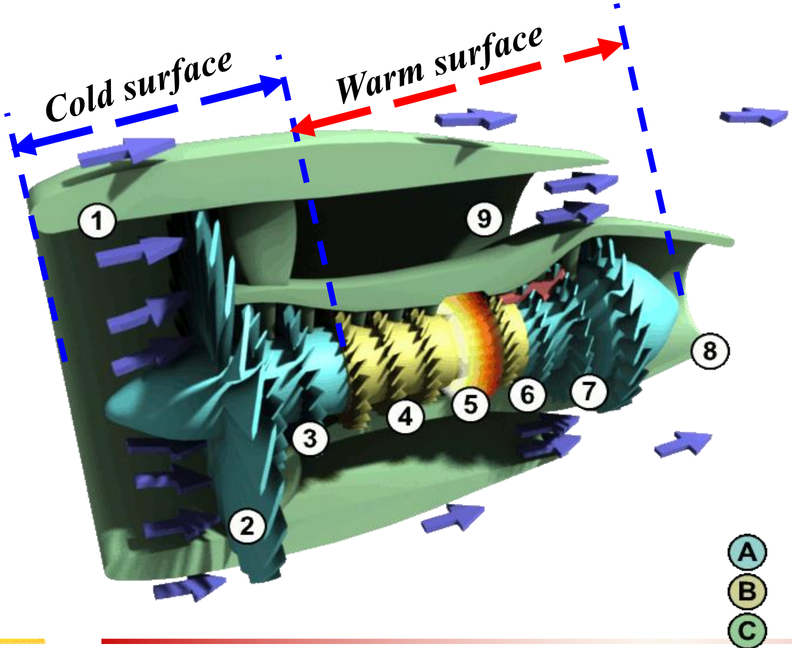
Supercooled water droplet icing

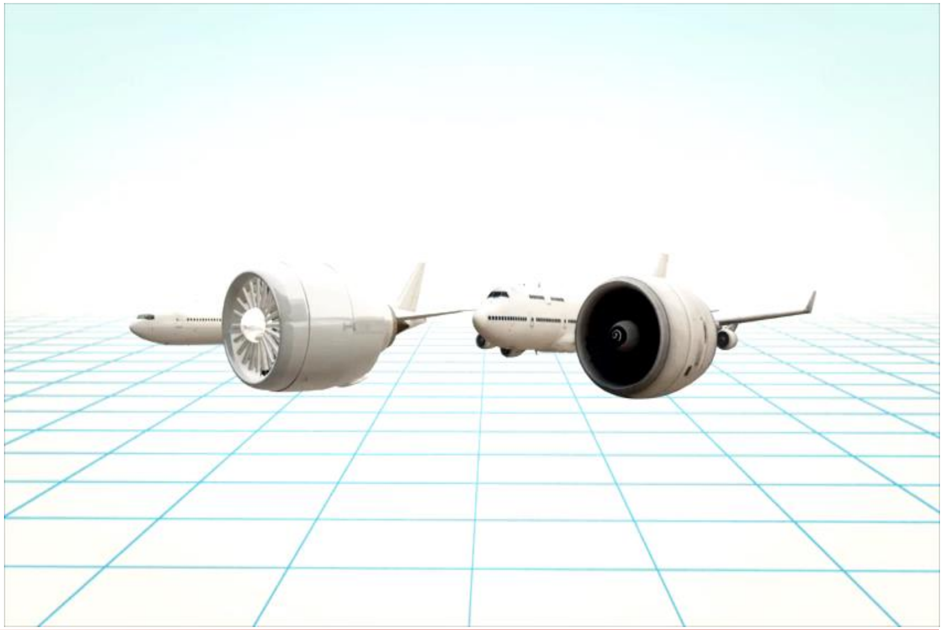
- *Similar to the airframe icing.*
- *Cold airflow with supercooled water droplets, freezing drizzle and freezing rain.*
- *Mostly happen at inlet, spinner and fan blades.*
- *Additional effects of rotation motion.*

Ice crystals icing

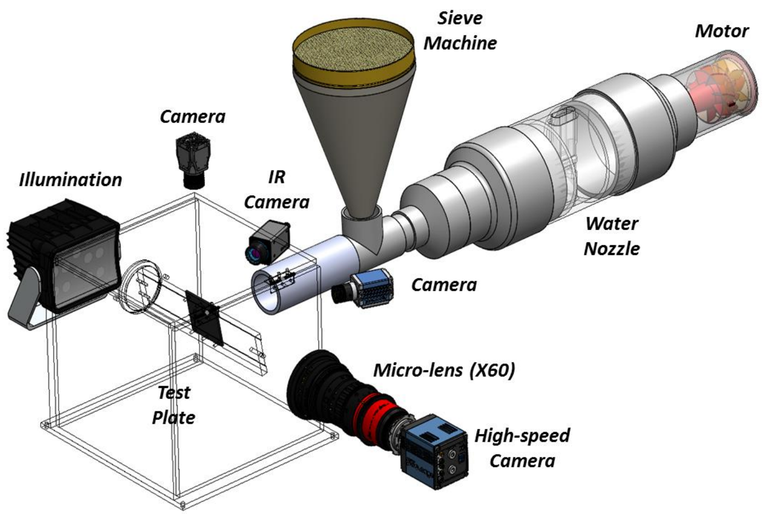
- *Cold airflow with ice crystals*
- *Ice crystals melt to form mixed phase icing.*
- *Mostly happen over the surfaces of heated IGV & sensors, low-pressure compressor blades.*

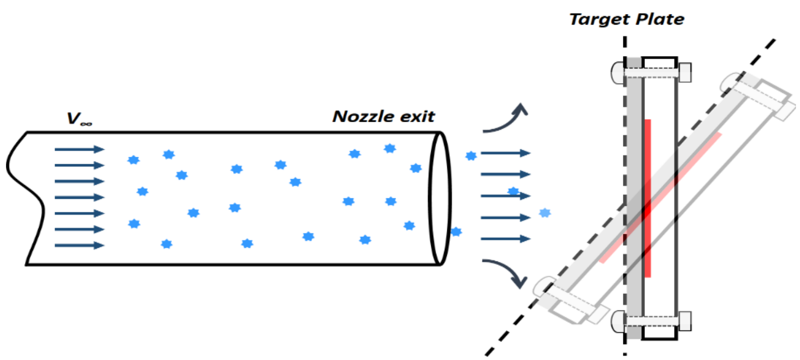
(Ice crystal icing test rig is ready in 2019 fall)

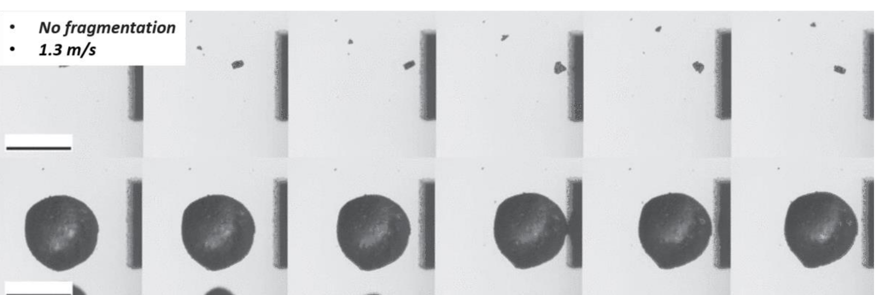




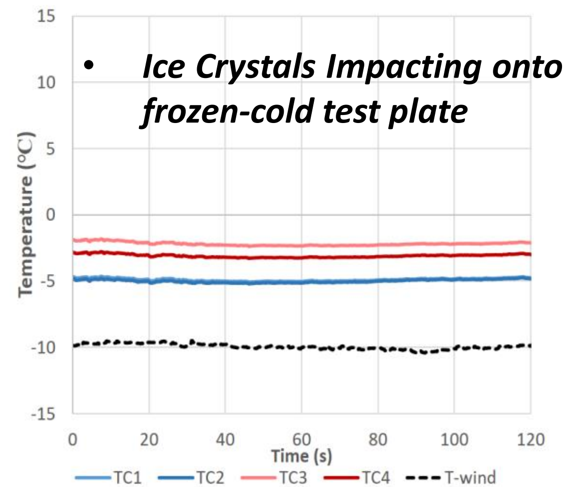
❑ Experimental Characterization of Ice Cristal Icing over Heated Surfaces

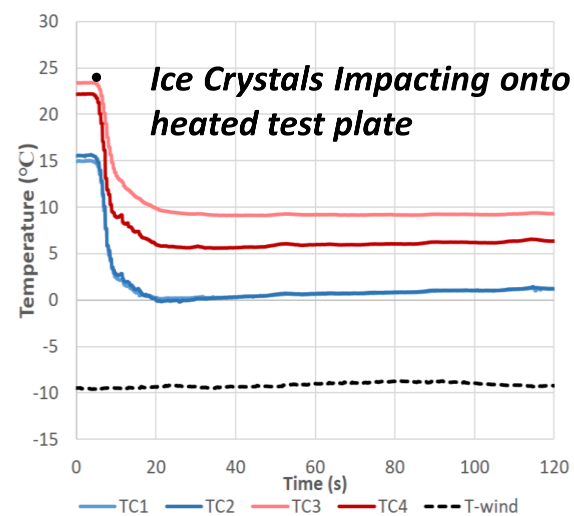






- V_∞ = 20 m/s, IWC = 2.5g/m^3, T_∞ = -10 ℃, T_{plate} = -5 ℃,

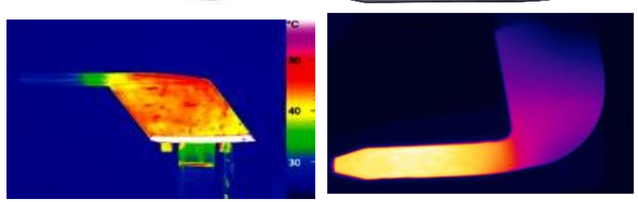


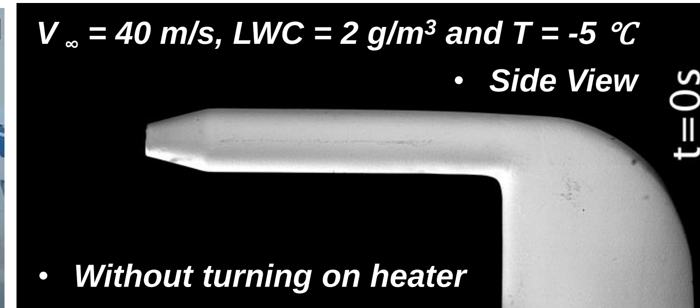


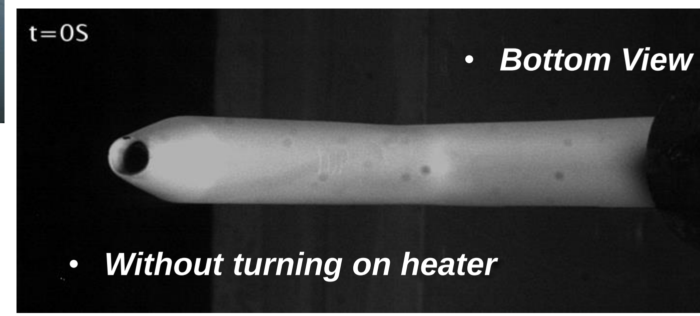
- V_∞ = 20 m/s, IWC = 2.5g/m^3, T_∞ = -10 ℃, T_{plate} = 15 ℃,

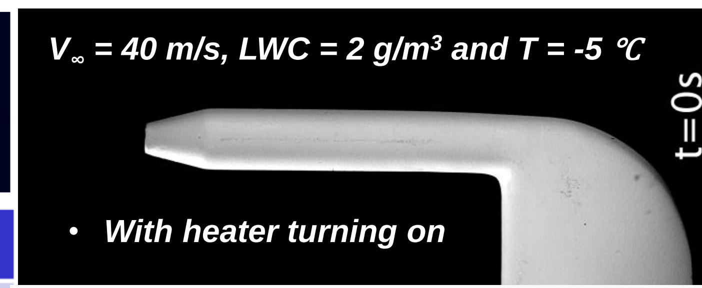
❑ Pitot Probe Icing Mitigation with Icephobic Coatings

- *Ice accretion in or around the pitot probes can led to a false readings to cause wrong reactions of the flight control system, which may result in deadly aircraft crashes.*
- *In June 1, 2009, Air France Flight 447 from crashed into the Atlantic Ocean and killed all 228 people on board.*
- *On February 11, 2018, Saratov Airlines Flight 703, from Moscow to Orsk in Russia, crashed shortly after take-off, killing all 71 people on board.*

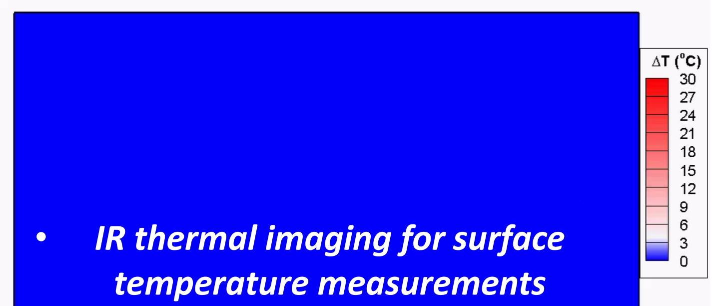




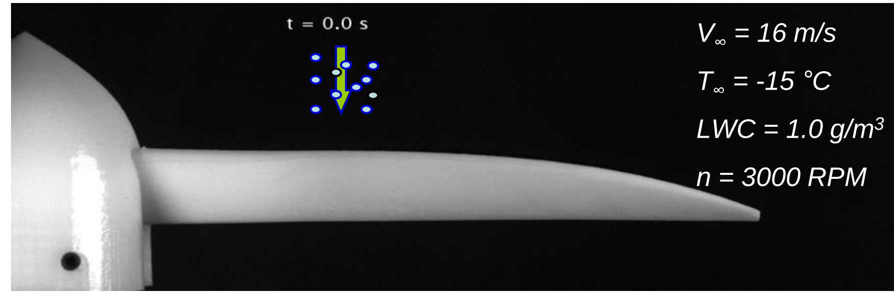


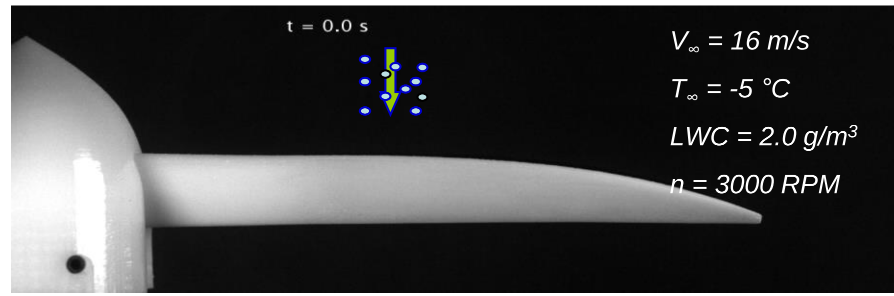


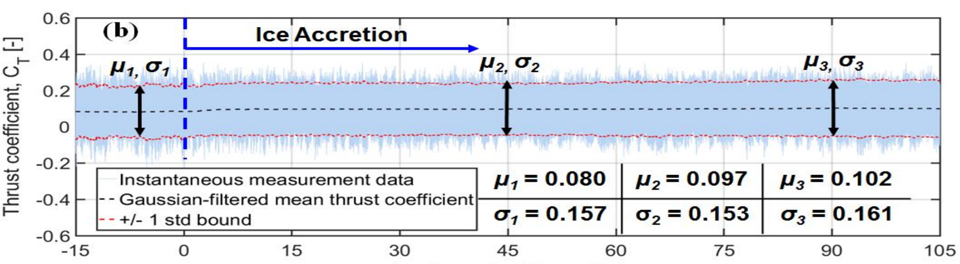
Power (W)	Leading edge ice removal (within 200 s)		Holder ice removal (within 200 s)	
	Heating	Hybrid	Heating	Hybrid
6.4	×	×	×	×
9.5	√	√	×	×
13.8	√	√	×	×
24	√	√	×	√
35	√	√	×	√
40	√	√	×	√
48	√	√	√	√

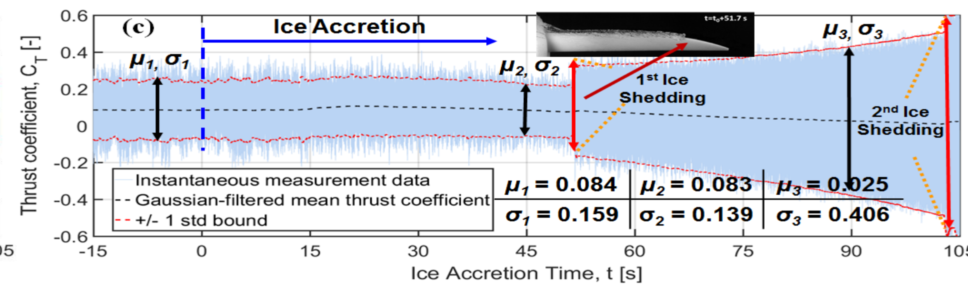


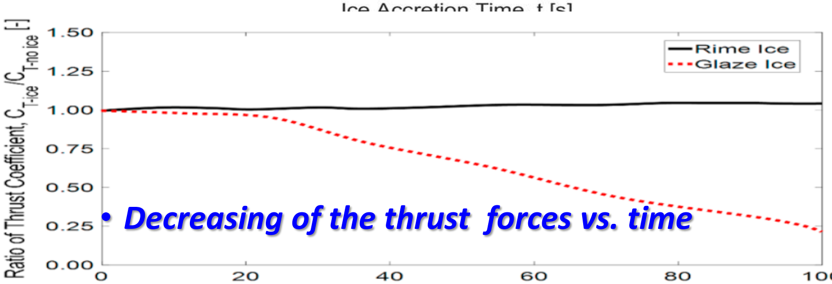
❑ UAS Propeller Performance Degradation Due to Ice Accretion

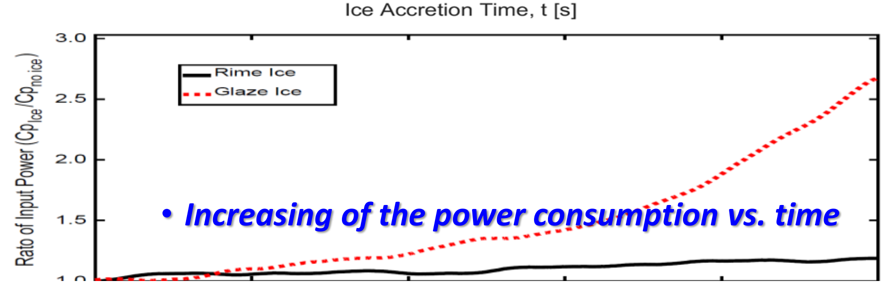






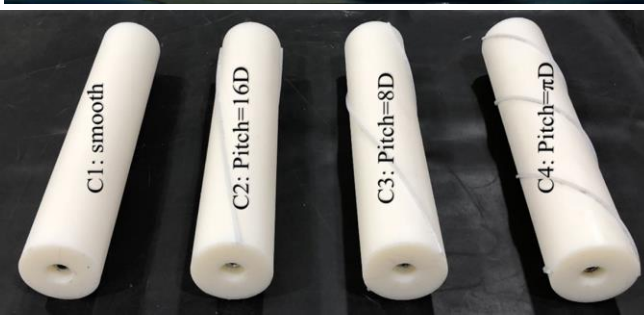


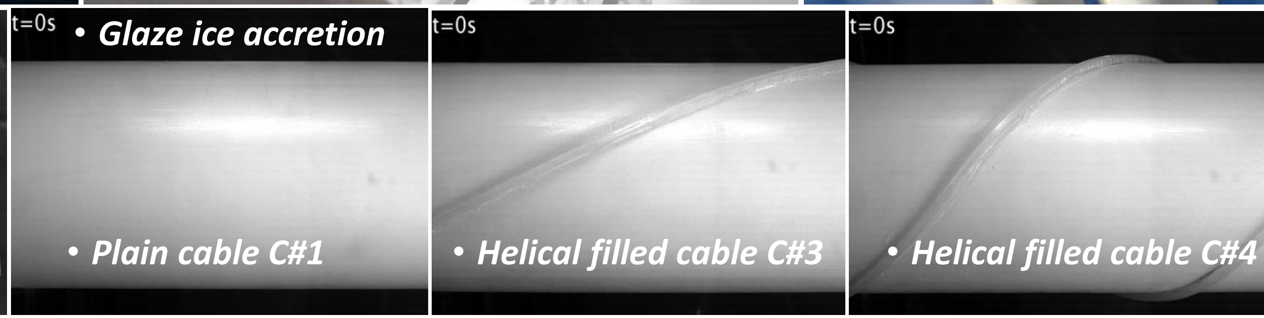


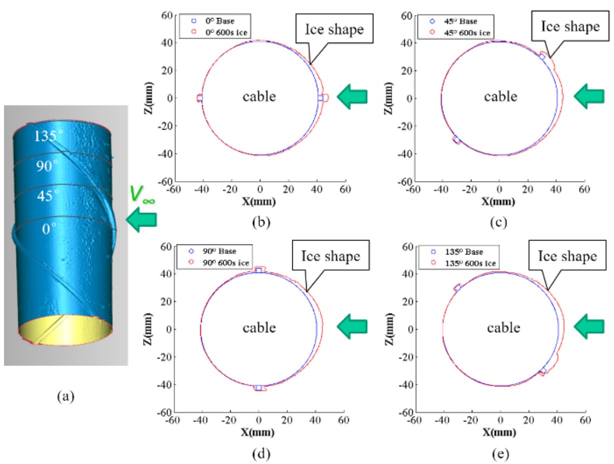


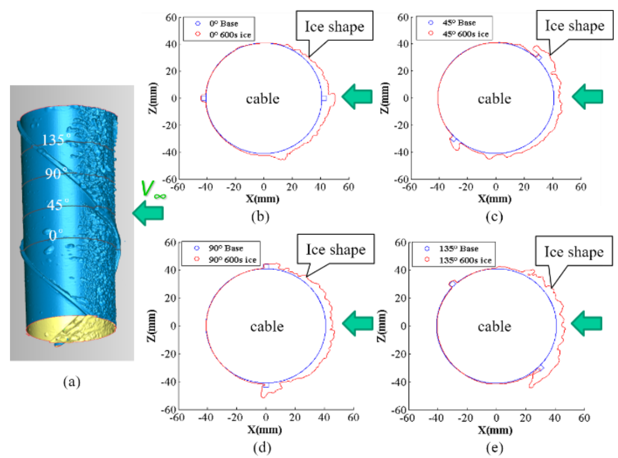
- ***Y. Liu, LK. Li, WL Chen, W. Tian and H. Hu,** "An Experimental Study on the Aerodynamic Performance Degradation of a UAS Propeller Model Induced by Ice Accretion", Experimental Thermal and Fluid Science, Vol.102, pp101-112, 2019*

❑ Icing Physics & Anti-/De-Icing of Bridge Stay Cables

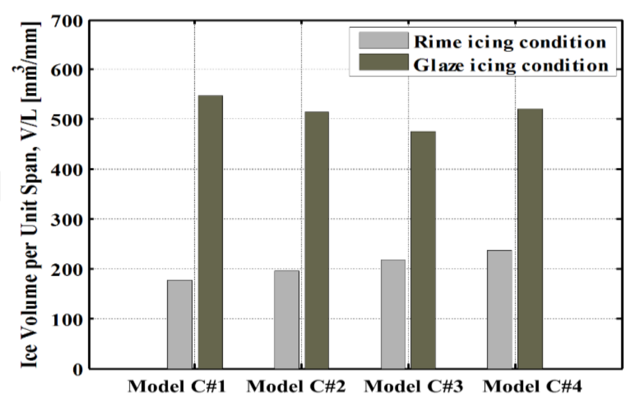






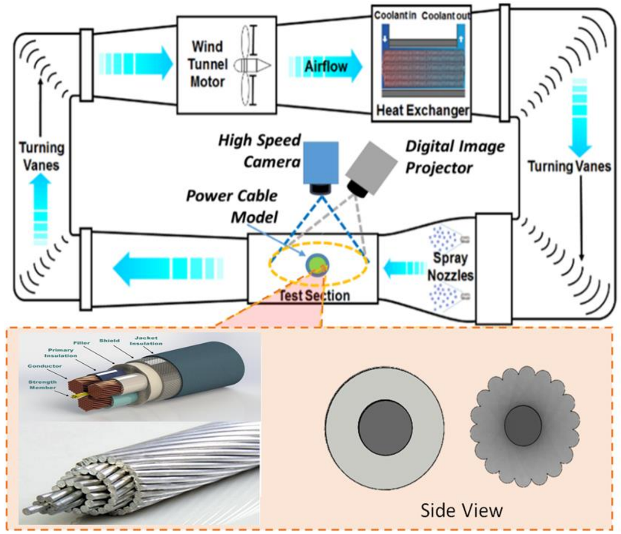


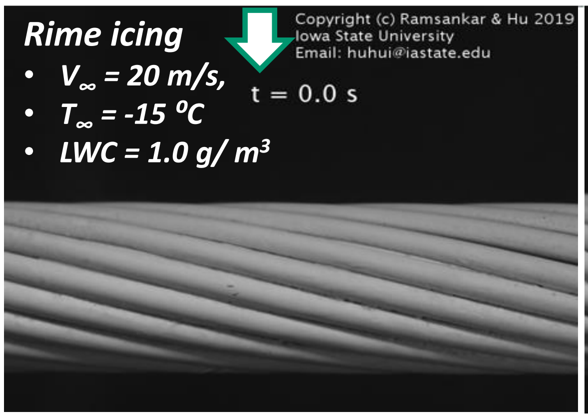
• *Comparison of accreted ice on the cable*

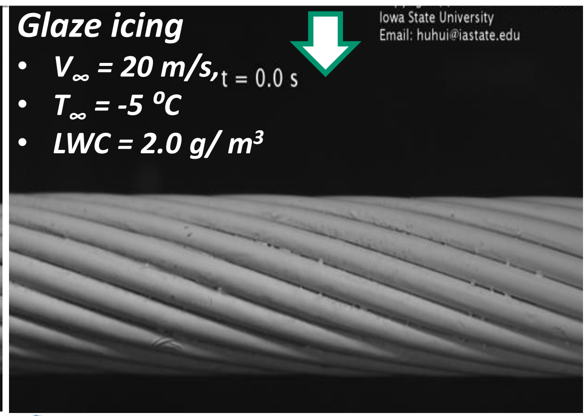


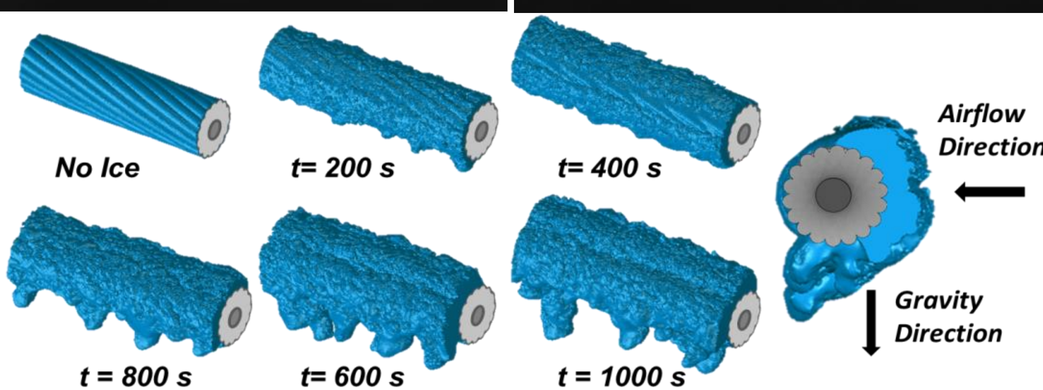
- *Rime icing: $V_\infty = 20$ m/s; $T_\infty = -15$ ℃, LWC = 1.0 g/m³*
- *Glaze icing: $V_\infty = 20$ m/s; $T_\infty = -5$ ℃, LWC = 2.0 g/m³*

❑ Icing Physics & Anti-/De-Icing of Power Transmission Cables

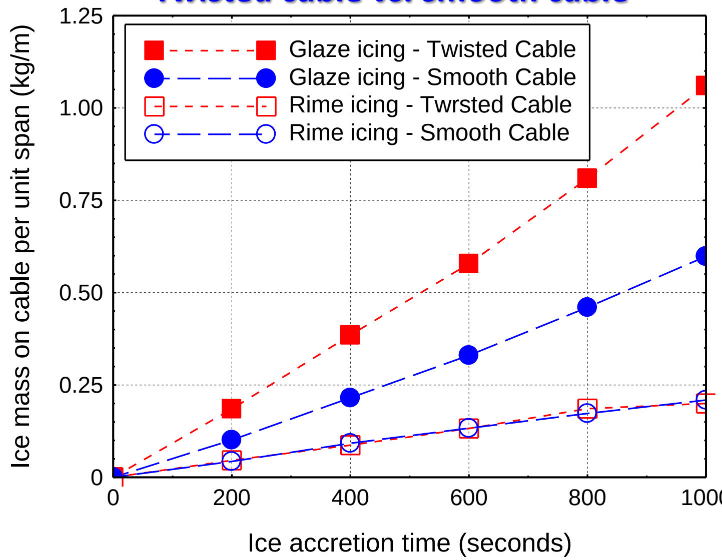








Twisted cable vs. smooth cable



- *R. Veerkumar, LY Gao, Y. Liu and H. Hu. Dynamic Ice Accretion Process and Its Effects on the Aerodynamic Drag Characteristics of a Power Transmission Cable Model. Cold Regions Science and Technology, Vol. 169, 102908 (11 pages), 2020*

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  - *Current postdocs & scholars:* *Y. Liu, WW Zhou*
  - *Current Graduate Students:* *ZC Zhang; R. Veerakumar; HY Hu; NH Han; LQ Tian; M. Siddique; F. Al-Masri (MS)*
  - *Former Postdocs & Scholars:* *Y Liu; Z. Jin; B. Johnson, W. Chen, Z. Yang; W. Tian; WH Ma; W. Yuan; F. Chen*
  - *Former PhD Students:* *Y. Zhang; M. Yu; Z. Yang; Z. Jin; N. Cooper; A. Ozbay; K. Zhang; J. Ryon; Z. Wang; Y. Liu WW Zhou; K. Morteza; P. Premaratne; LX Li; Z. Ning; LQ Ma; LK Li; LY Gao*
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Thank You Very Much For Your Time!
Questions?

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