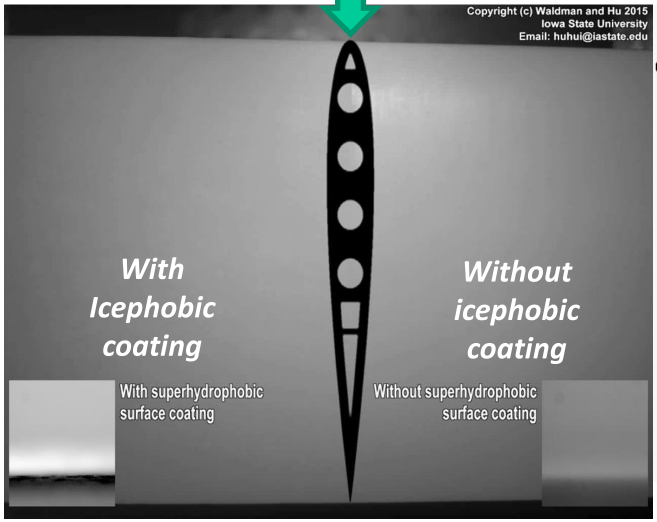
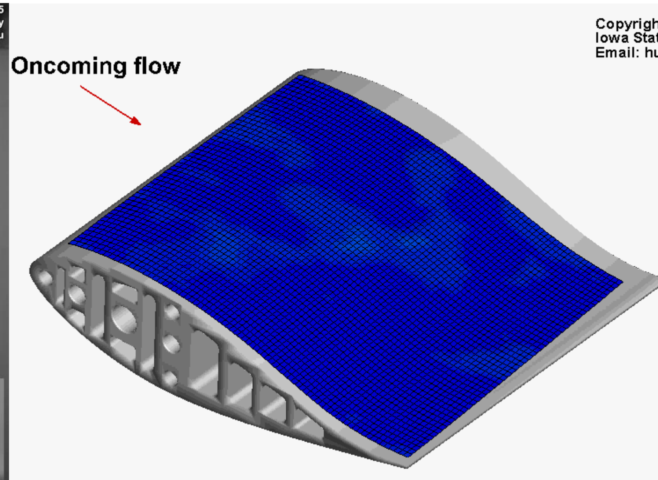
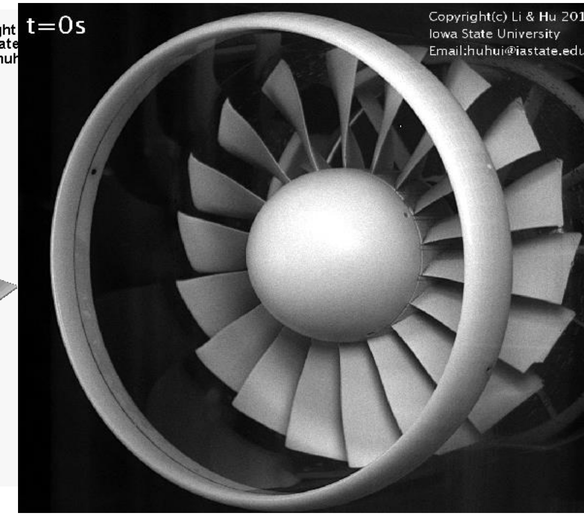




• *Glaze icing over an airfoil surface*



AIRCRAFT ICING PHYSICS & INNOVATIVE ANTI-/DE-ICING STRATEGIES FOR AIRCRAFT ICING MITIGATION

Dr. Hui HU

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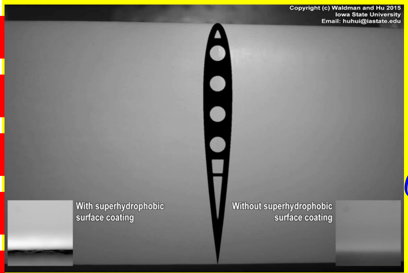
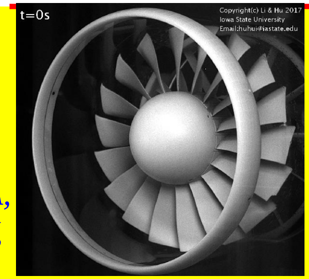
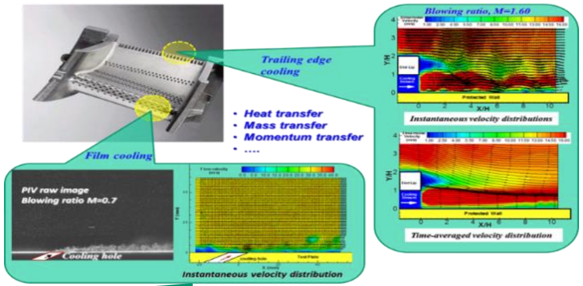
IOWA STATE UNIVERSITY
Aircraft Icing Physics & Anti-/De-icing Technology Laboratory

❑ My Research Portfolio



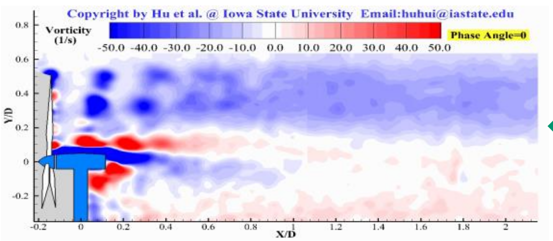
Aircraft/Aero-engine icing physics and de-/anti-icing (Sponsors: NASA, FAA, NSF., P&W, DuPont...)



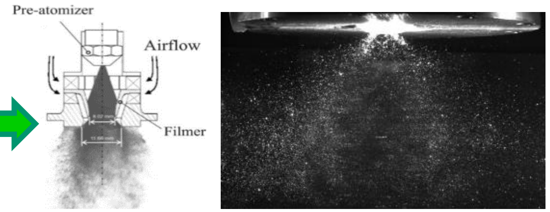


Film Cooling & Heat Transfer of Gas Turbines (Sponsors: AFOSR, DoE, GE)

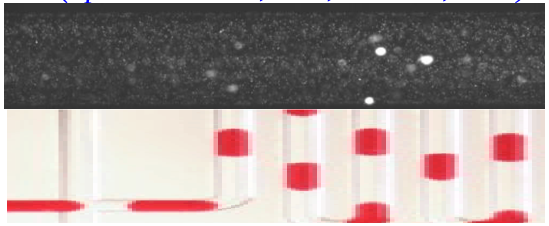
Advanced Flow Diagnostics & Instrumentation (PIV, PLIF, MTV, MTT, DIP ...)



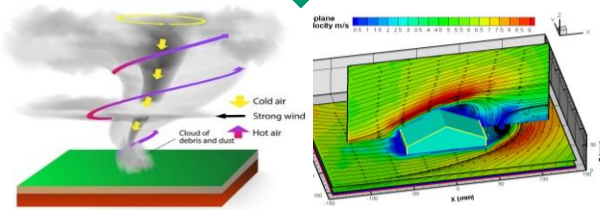
Wind Turbine Aeromechanics (Sponsors: NSF, IEC, DuPont, DoE)



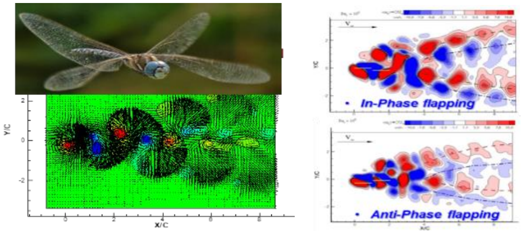
Fuel spray characterization & atomization (Sponsors: NSF, DoE, UTAS, Honeywell)



Microfluidcs & Nanofluidics, Micro-scale heat transfer (Sponsors: NSF, AFOSR)



Flow –Structure-Interaction (FSI) in Tornado, Microburst and Snow/Storms(Sponsors: NSF, NOAA)



Bio-inspired aerodynamics and UAS designs (Sponsors: AFOSR, NSF)

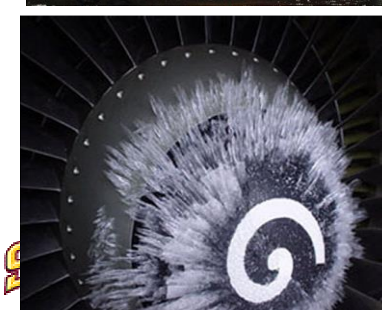
❑ Thanks to Research Sponsors:

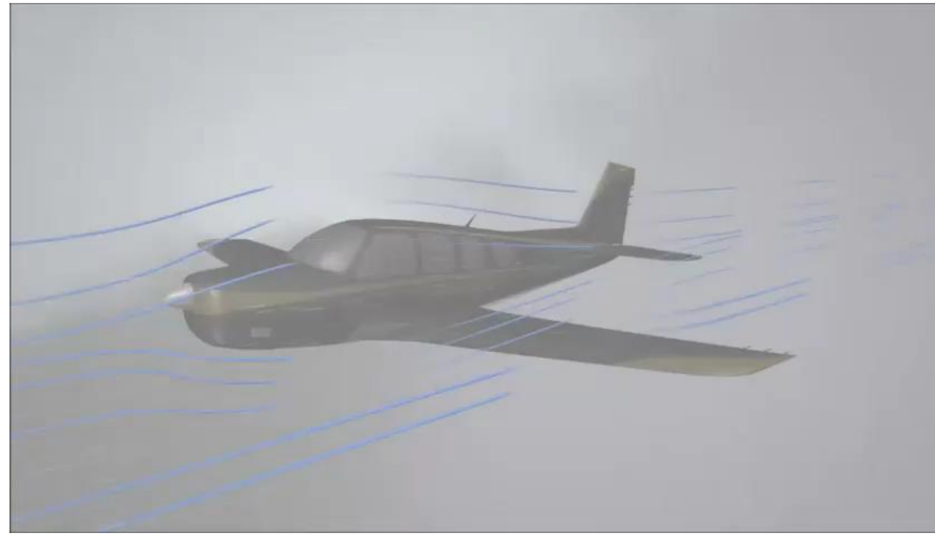
NSF · Department of Energy · NASA · NOAA · GE · IAWind.org · General Atomics · DuPont · Air Force Office of Scientific Research · Air Force Research Laboratory · United States Navy · The Great Seal of the State of Iowa · Pratt & Whitney (A United Technologies Company) · The Ames Laboratory (Creating Materials & Energy Solutions, U.S. Department of Energy) · Avangrid Renewables · Collins Aerospace · Goodrich · Physical Sciences Inc.

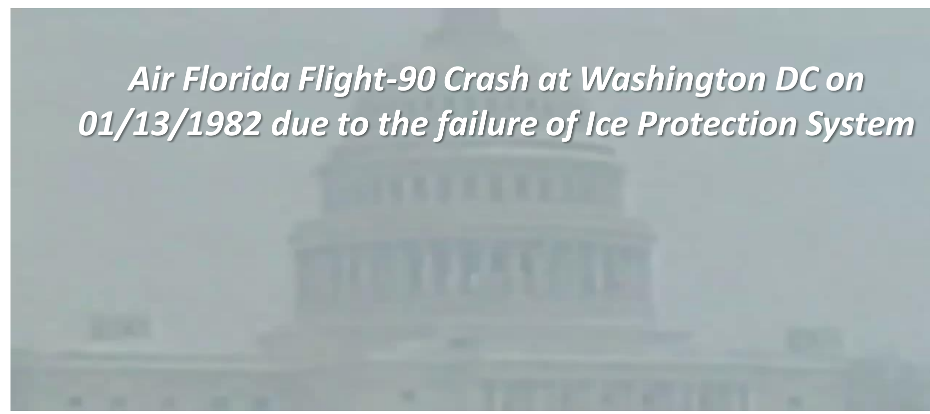
❑ Introduction: Aircraft Icing and Anti-/De-Icing

- *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.***

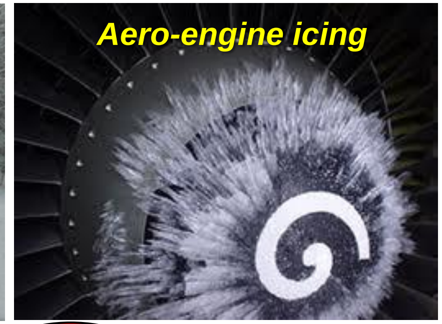






Air Florida Flight-90 Crash at Washington DC on 01/13/1982 due to the failure of Ice Protection System

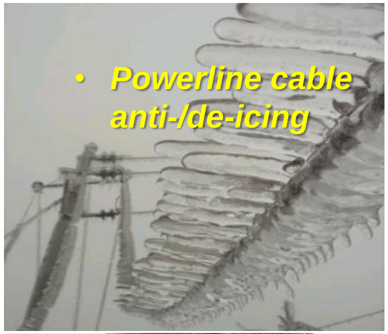
❑ ISU Icing Physics and Anti-/De-icing (IPAD) Center

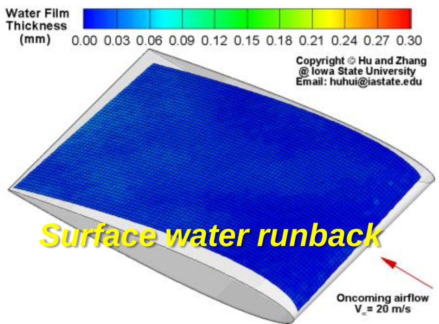


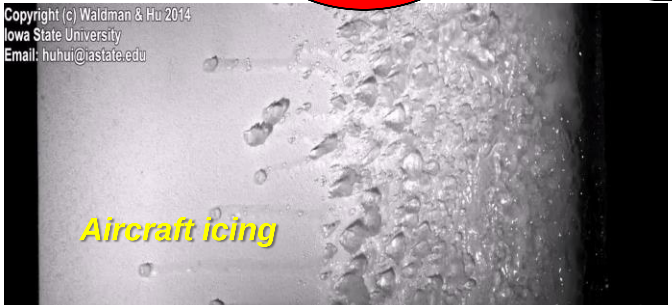
- NDE, MEMS sensors for in-flying icing detection
- Experimental aerodynamics & icing tunnel testing
- CFD &multiphase modeling
- UAS/MAV, Rotorcraft, wind turbine, power lines

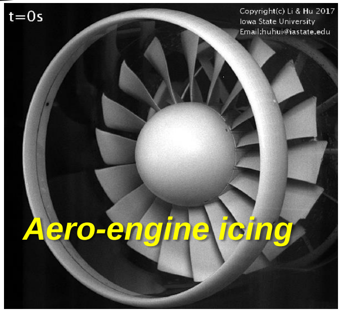
ISU Icing Physics & Anti-/De-icing Research Center

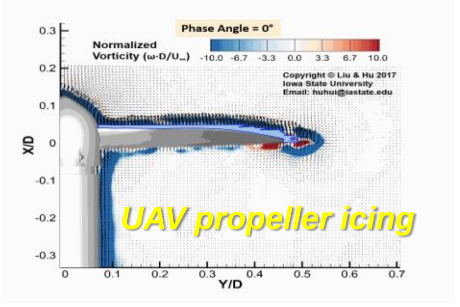
- Syetem design and MDO for anti-/de-icing strategy
- Aero-structure designs for icing mitigation & protection.
- Smart materials, Micro & Nano Mechanics
- Super-hydrophobic coatings and surface engineering



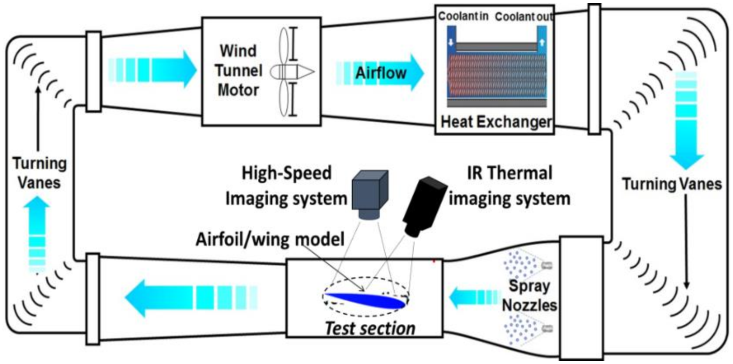




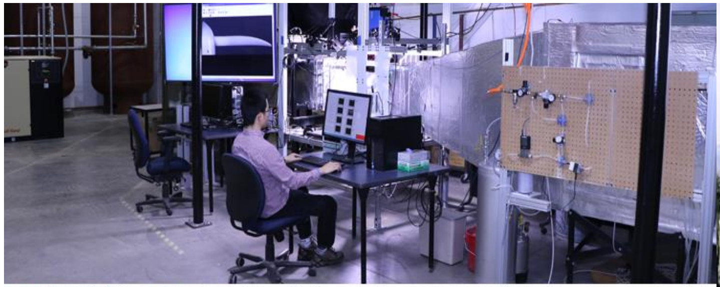


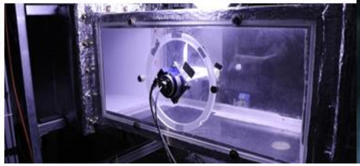


❑ Icing Research Tunnel @ Iowa State University (ISU-IRT)



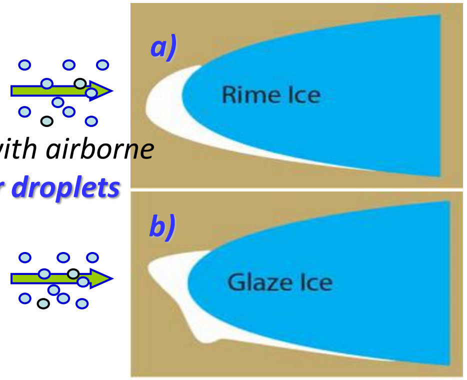
- *ISU Icing Research Tunnel (ISU-IRT), donated by Collins Aerospace System, is a new refurbished, research-grade multi-functional icing research tunnel.*
- *The working parameters of the ISU-IRT include:*
  - *Test section:* $0.4m \times 0.4m \times 2.0m$
  - *Airflow velocity:* $V_{\infty} = 5 \sim 100\ m/s$;
  - *Temperature:* $T_{\infty} = -25\ ^{\circ}C \sim 20\ ^{\circ}C$;
  - *Droplet size:* $D_{droplet} = 10 \sim 100\ \mu m$;
  - *Liquid Water Content:* $LWC = 0.1 \sim 10\ g/m^3$
- *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…*



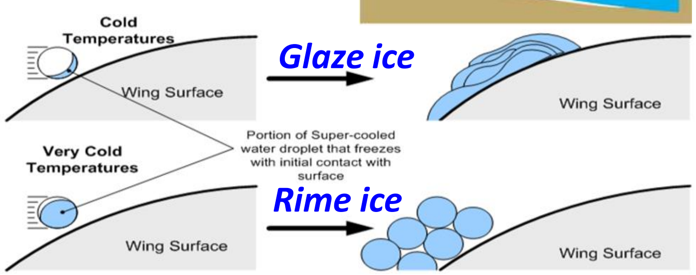


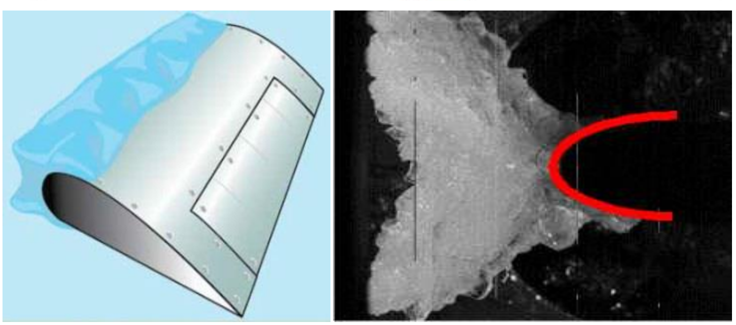
❑ Impact Icing Phenomena: Rime Icing and Glaze Icing

• *Aircraft icing is a complex, multiphase flow problem coupled with heat transfer & phase changing.*

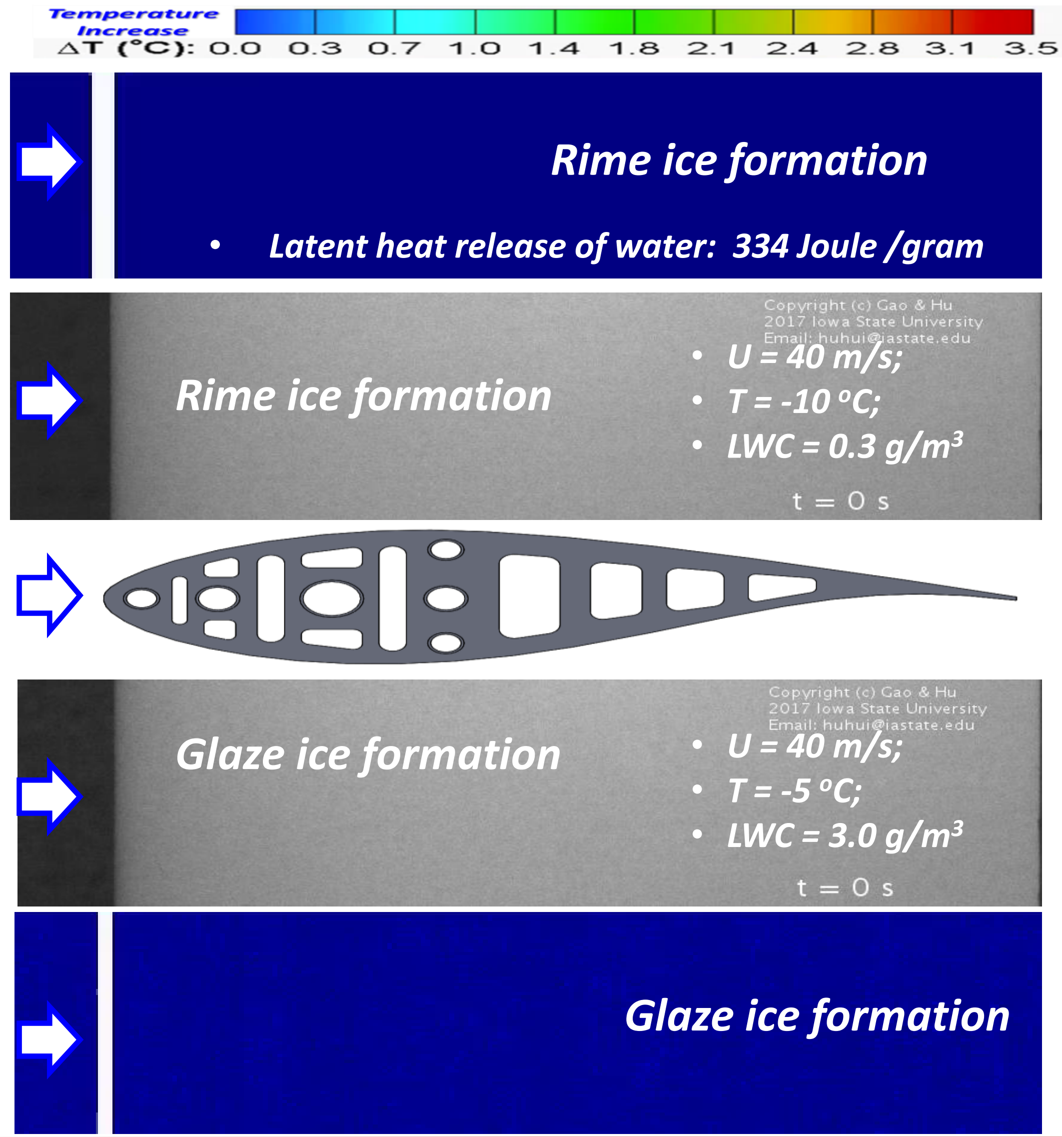


Incoming airflow with airborne ***supercooled water droplets***



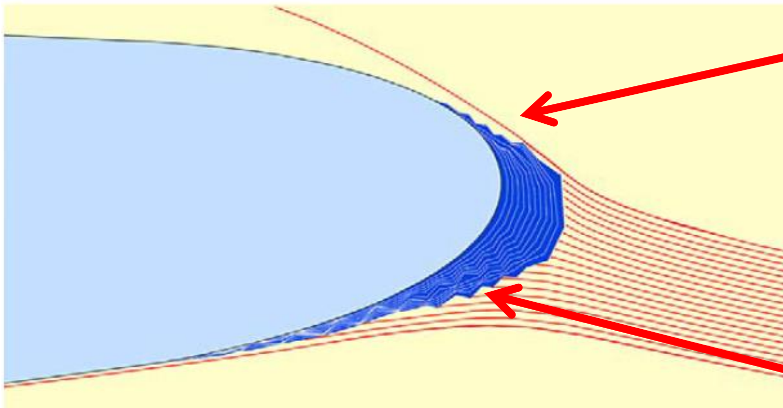


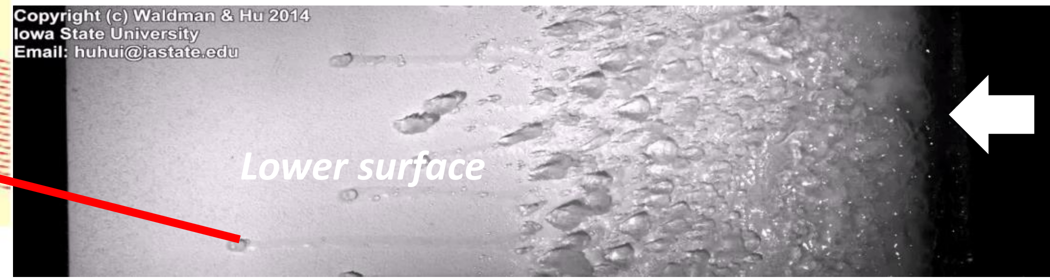
- ***Glaze ice is the most dangerous type of ice.***
- ***It can form much more complicated ice shapes, and will be much more difficult to remove once built up.***



❑ Icing Physics: Unsteady Heat & Mass Transfer during Icing Process

- *Icing is a very complex, multiphase flow problem coupled with heat transfer & phase changing.*



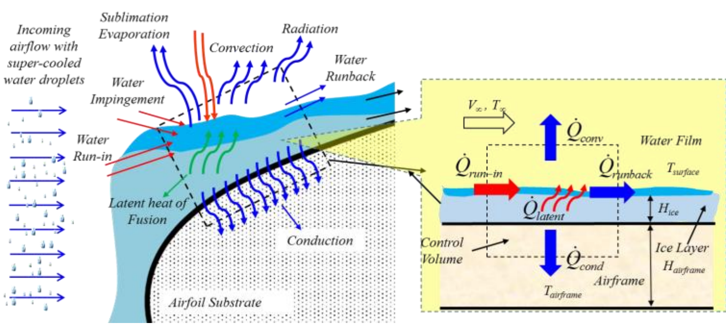


$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{st}}{dt} \equiv \dot{E}_{st}$$

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

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

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



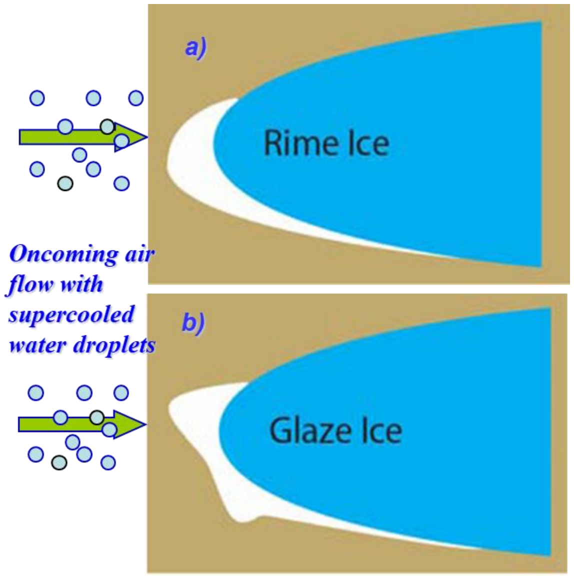
- **Adiabatic heating:** **The heat introduced by air friction on the object is from a viscous adiabatic heat which occurs inside the boundary layer.**
  (Fortin et al., 2006) $\dot{Q}_{adh} = h_{cv} \cdot (T_{rec} - T_\infty) \cdot A$ $\quad T_{rec} = T_\infty + r \cdot \frac{T_\infty}{T_e} \cdot \frac{U_e^2}{2 \cdot Cp_{air}}$ $\quad r = \sqrt{Pr}$ $\quad Pr = \frac{Cp_{air} \cdot \mu_{air}}{k_{air}}$
- **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.*

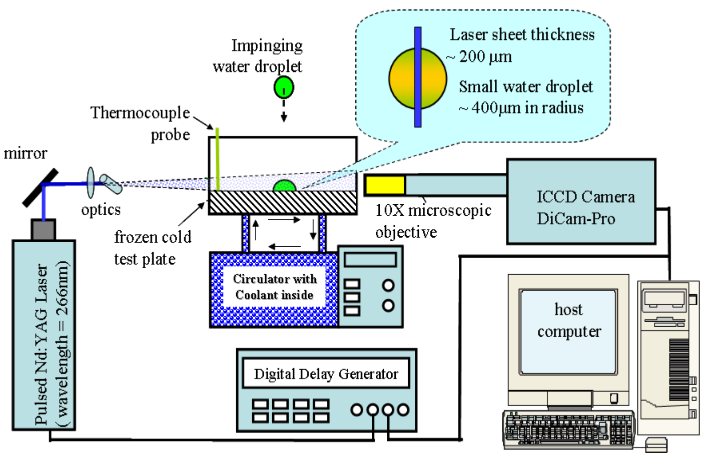
- **Convective heat transfer** $\dot{Q}_{conv} = h_{cv} \cdot (T_s - T_\infty) \cdot A$
- **Conductive heat transfer** $\dot{Q}_{cond} = \frac{A \cdot (T_s - T_{airfoil})}{R_{tot,cond}}$
  - *to be evaluated based on the measurements of heat flux sensors and thermocouples*

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

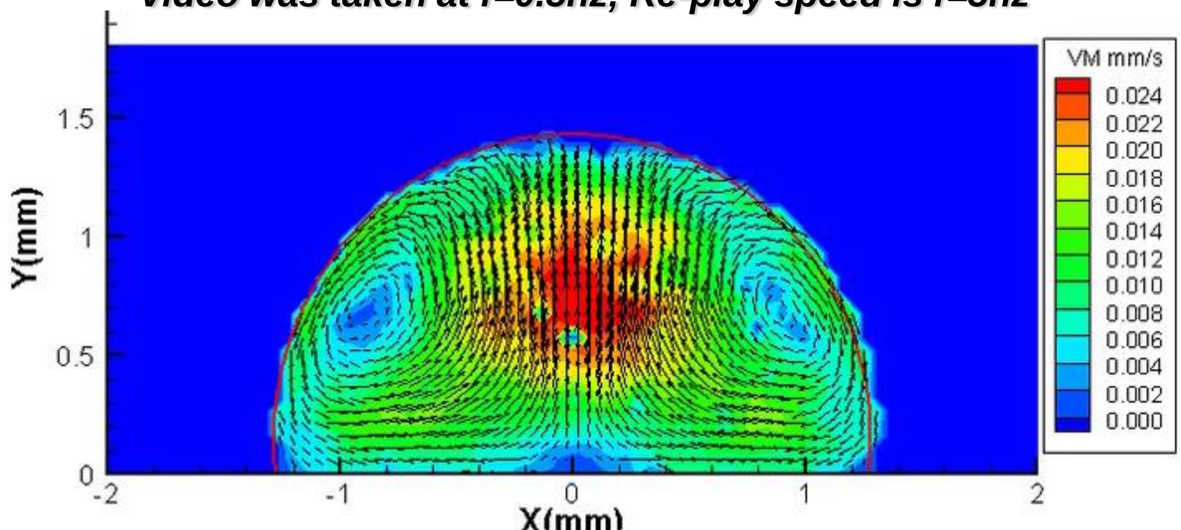
- *Liu & Hu (2018) "An Experimental Investigation on the Unsteady Heat Transfer Process over an Ice Accreting Airfoil Surface", Intel. J. Heat&Mass Transfer, 122, pp707-718.*
- *Li & Hu (2019) "Effects of Thermal Conductivity of Airframe Substrate on the Dynamic Ice Accretion Process", Intl. J. of Heat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

❑ Icing Physics: Surface-Tension Induced Marangoni Flow inside Droplets





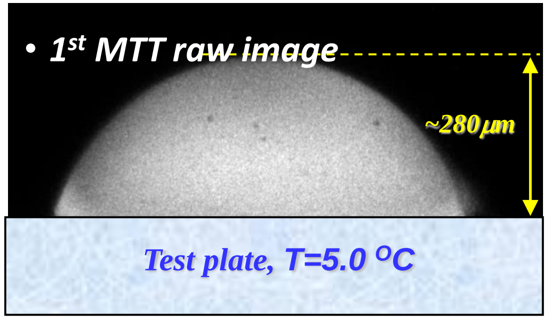
Temperature of Plate, T_{Wall}=21.9 ^{O}C
Video was taken at f=0.5hz; Re-play speed is f=5hz



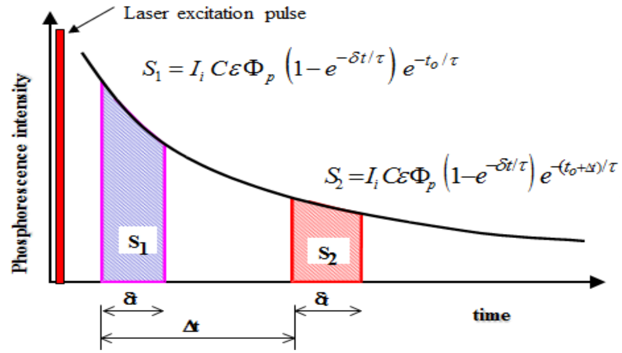
- *(Hu and Jin, Int. J. of Multiphase Flow, Vol. 36, No.8, pp672–681, 2010)*

❑ Unsteady Heat Transfer & Mass Transfer Inside Impinged Droplets

- *Measurements by using a novel Molecular Tagging Thermometry (MTT) Technique (USA Patent No: 2006/0146910)*



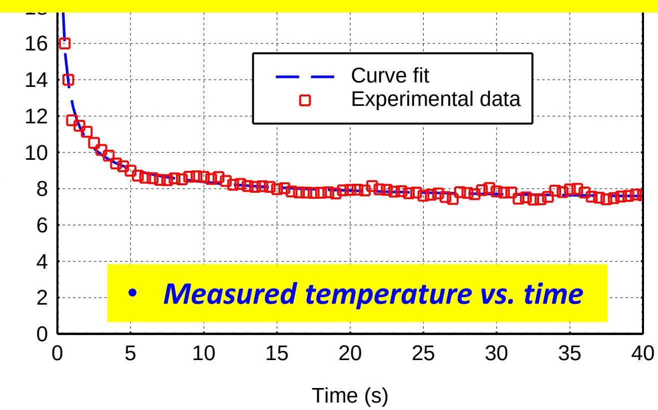
a). The 1st phosphorescence image acquired at 0.5ms after excitation laser pulse



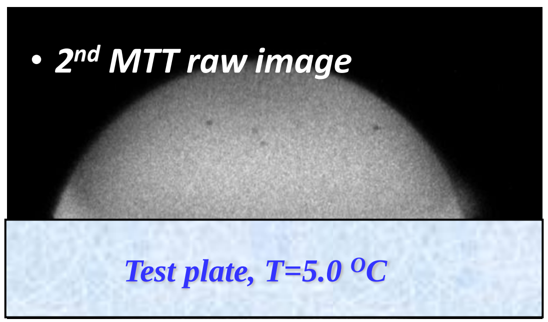
$$S_1 = I_i C\varepsilon\Phi_p \left(1 - e^{-\delta t/\tau}\right) e^{-t_o/\tau}$$

$$S_2 = I_i C\varepsilon\Phi_p \left(1 - e^{-\delta t/\tau}\right) e^{-(t_o+\Delta t)/\tau}$$

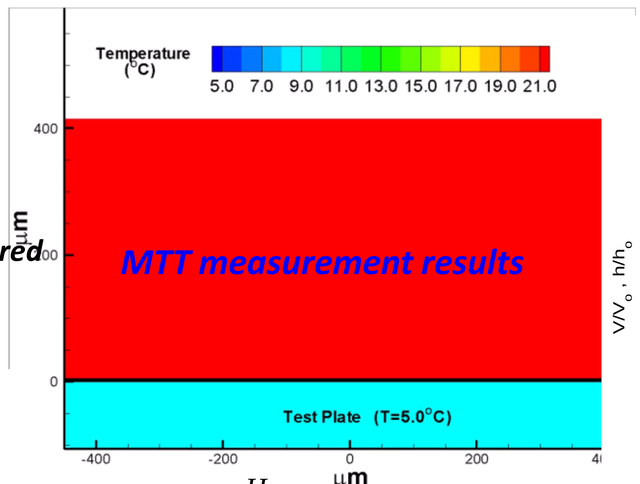
- *Time chart for MTT measurements*



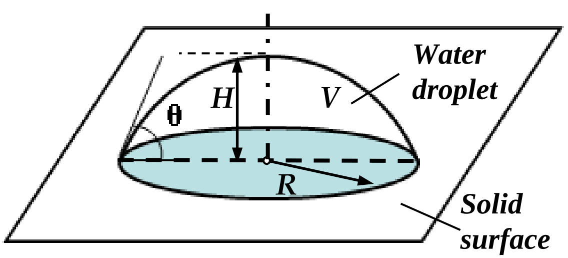
- *Measured temperature vs. time*



b). The 2nd phosphorescence image acquired at 3.5ms after the same laser pulse

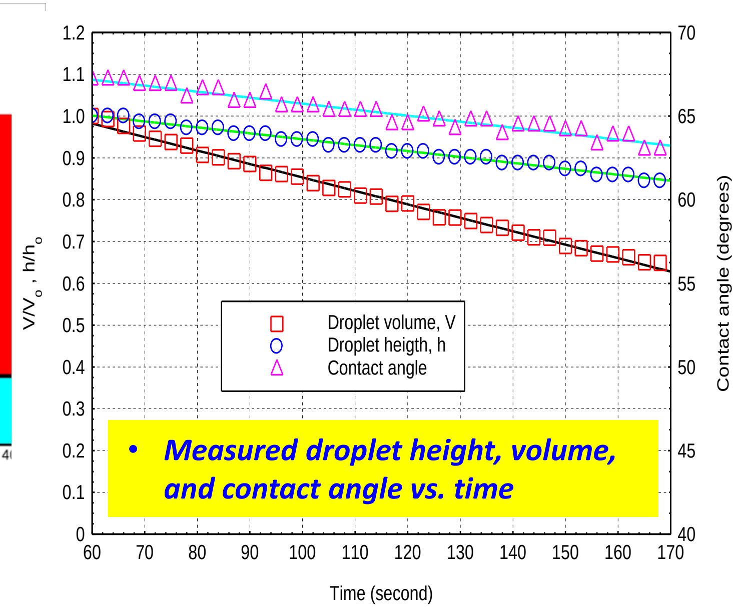


MTT measurement results



$$\theta = 2\tan^{-1}\left(\frac{H}{R}\right)$$

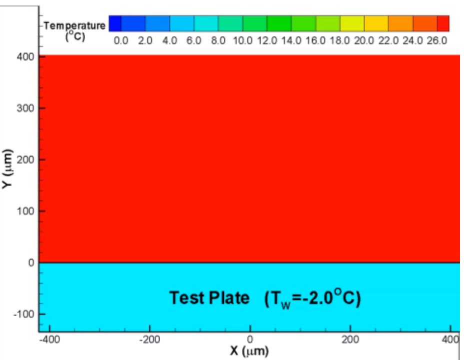
$$V = \frac{\pi R^3 (1-\cos\theta)^2 (2+\cos\theta)}{3\sin^3\theta}$$



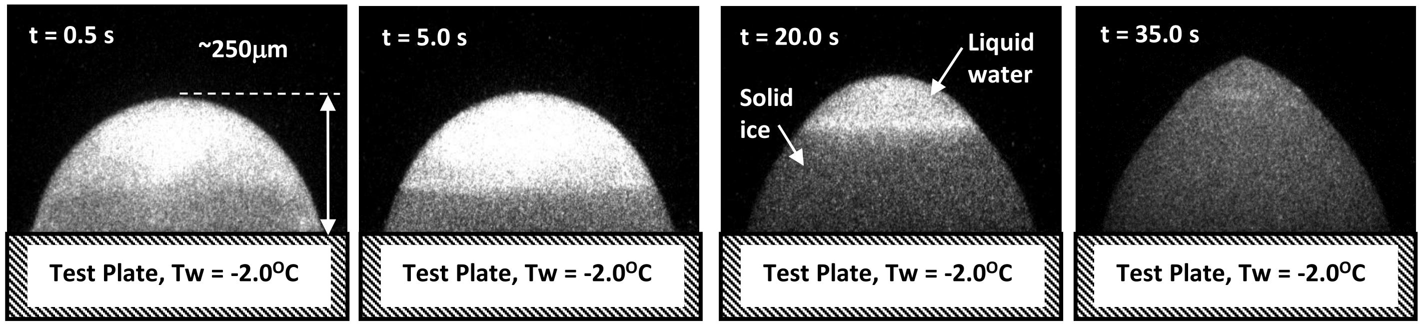
- *Measured droplet height, volume, and contact angle vs. time*

- ***Hu H & Huang D,** "Simultaneous Measurements of Droplet Size and Transient Temperature within Surface Water Droplets", AIAA Journal, Vol.47, No.4, pp813-820, 2009*

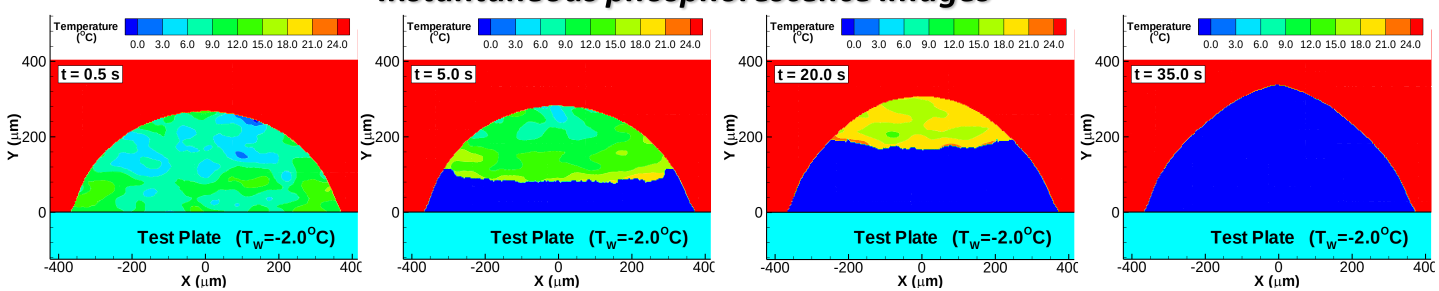
❑ Icing Physics: Dynamic Phase Changing Process of Icing Droplets



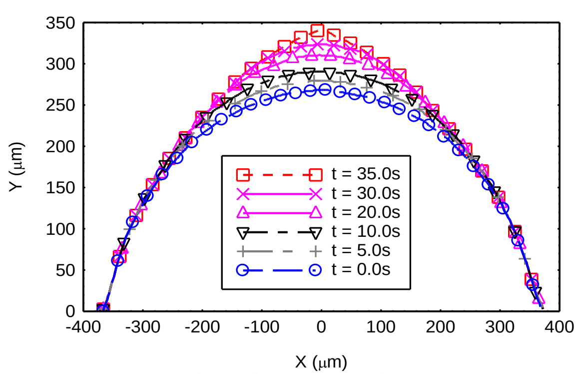
MTT measurement results



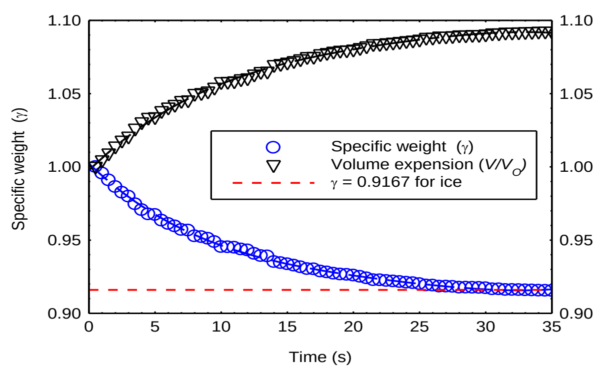
Instantaneous phosphorescence images



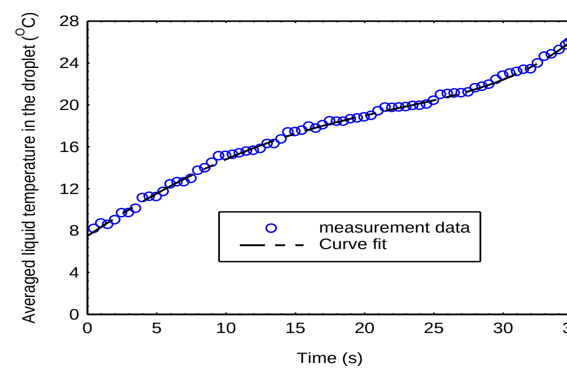
Dynamic phase changing process inside an icing droplets



Droplet shape vs. time



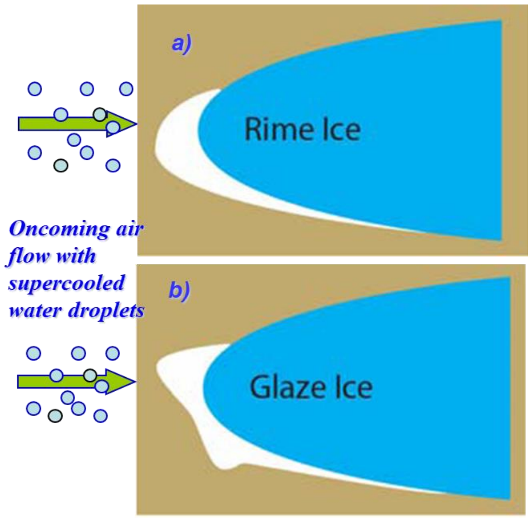
Droplet volume and density changes vs. time

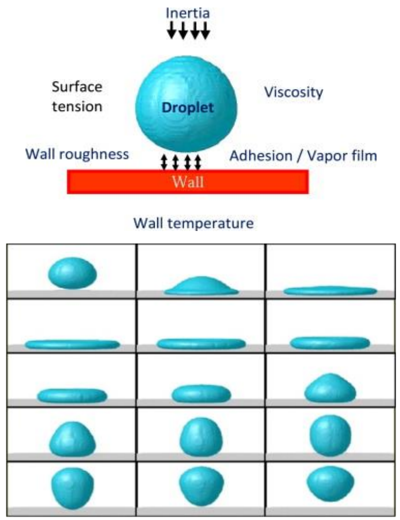


Temperature of the remaining water vs. time

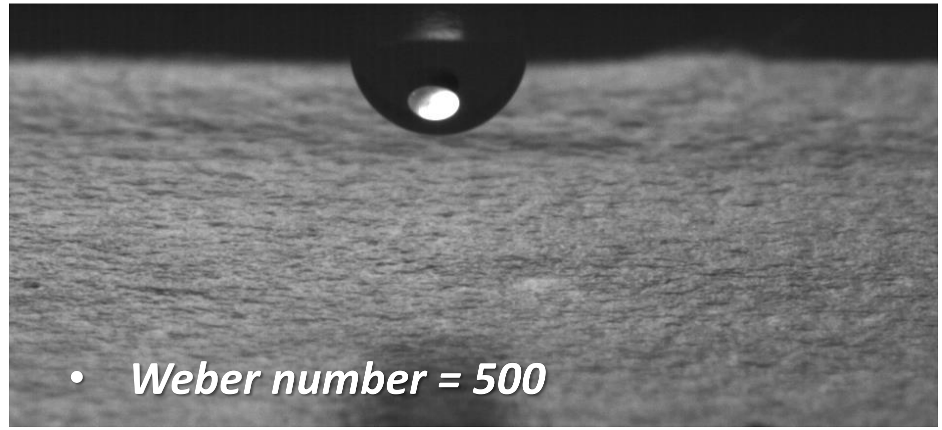
- ***Hu H, Jin Z, Koochesfahani MM, Lum C, Nocera D**, "Experimental Investigations of Micro-Scale Flow and Heat Transfer Phenomena by using Molecular Tagging Techniques", Measurement Science and Technology, Vol.21, No.8. 085401, 2010.*

❑ Icing Physics: Impinging Dynamics of Droplets onto Airfoil Surface

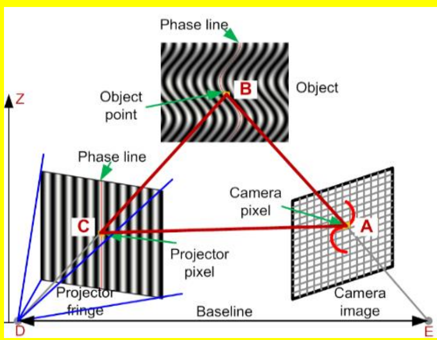


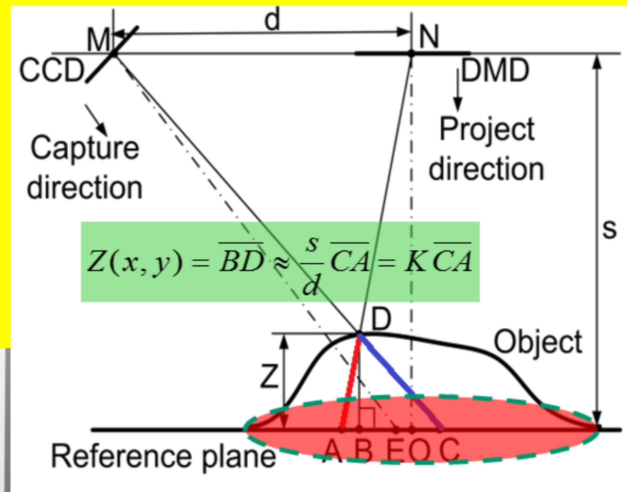


- *High-speed imaging of droplet impacting process*

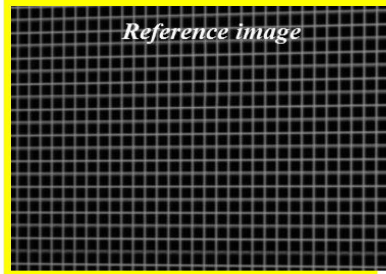


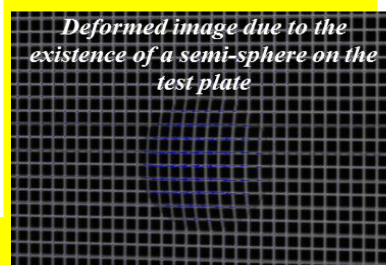
- *A novel Digital Image Projection (DIP) Technique for surface topology measurements (USA Patent Pending)*

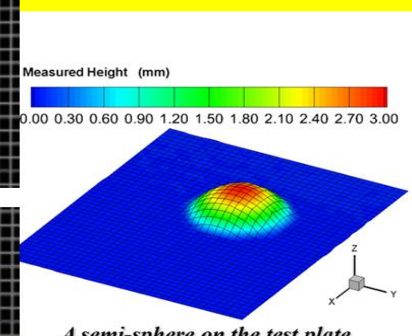




Digital Image Projection (DIP) Technique



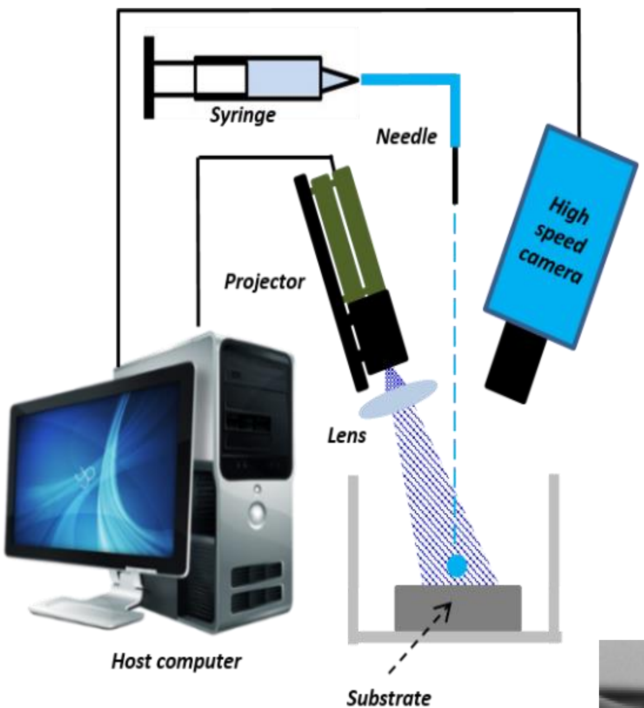




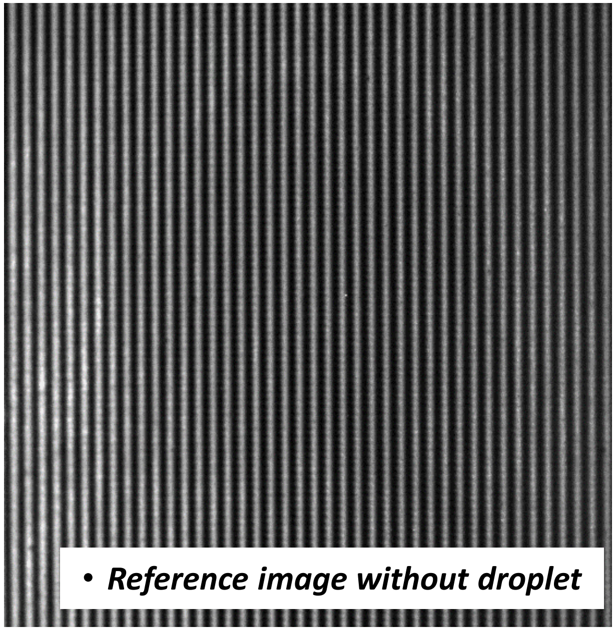
DIP measurement results

- *(Zhang, Tian & Hu, Exp. In Fluids, 56:173, 2015.)*

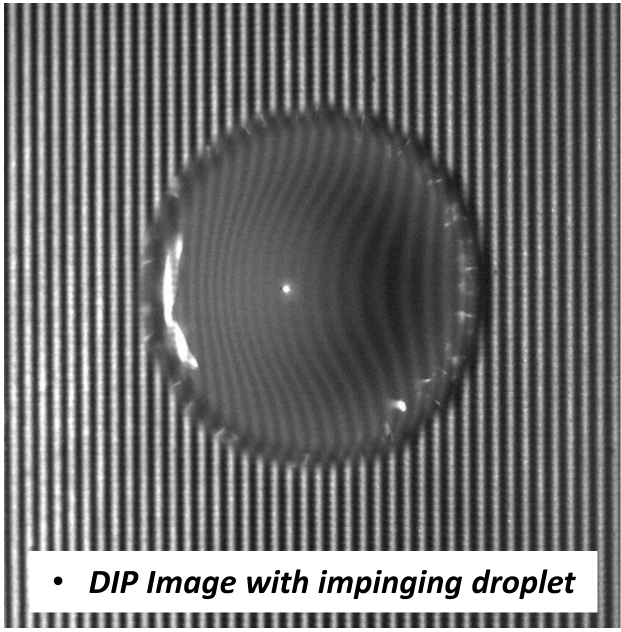
❑ Icing Physics: Impinging Dynamics of Droplets onto Airfoil Surface



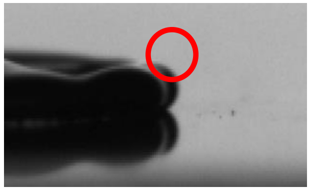
- *Setup for DIP Measurements*

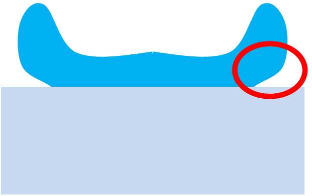


- *Reference image without droplet*

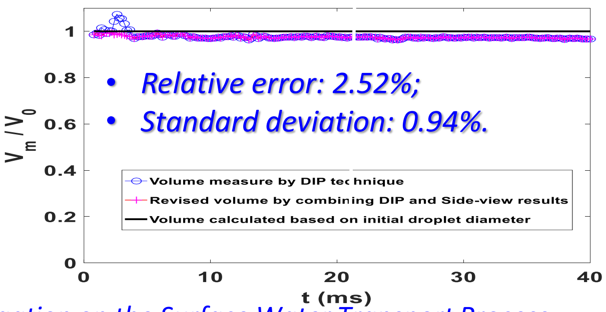


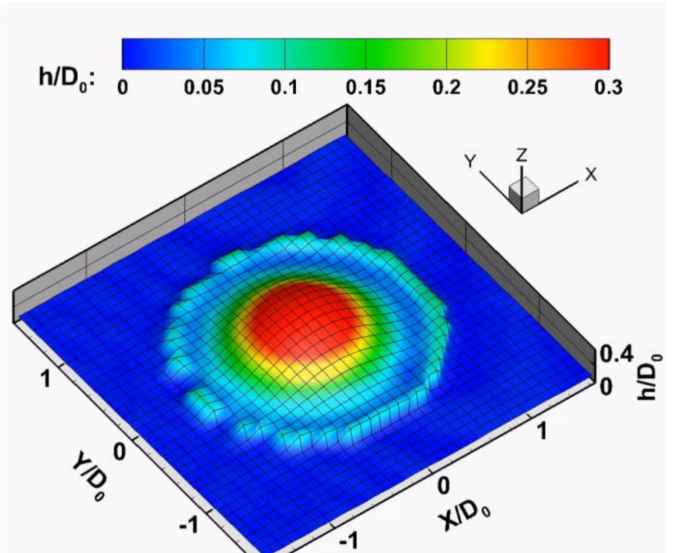
- *DIP Image with impinging droplet*





• ***Diameter:***	***D = 2.4mm***
• ***Impact velocity:***	***V=1.60m/s***
• ***Reynolds number:***	***Re = 4000***
• ***Weber number:***	***We = 90***

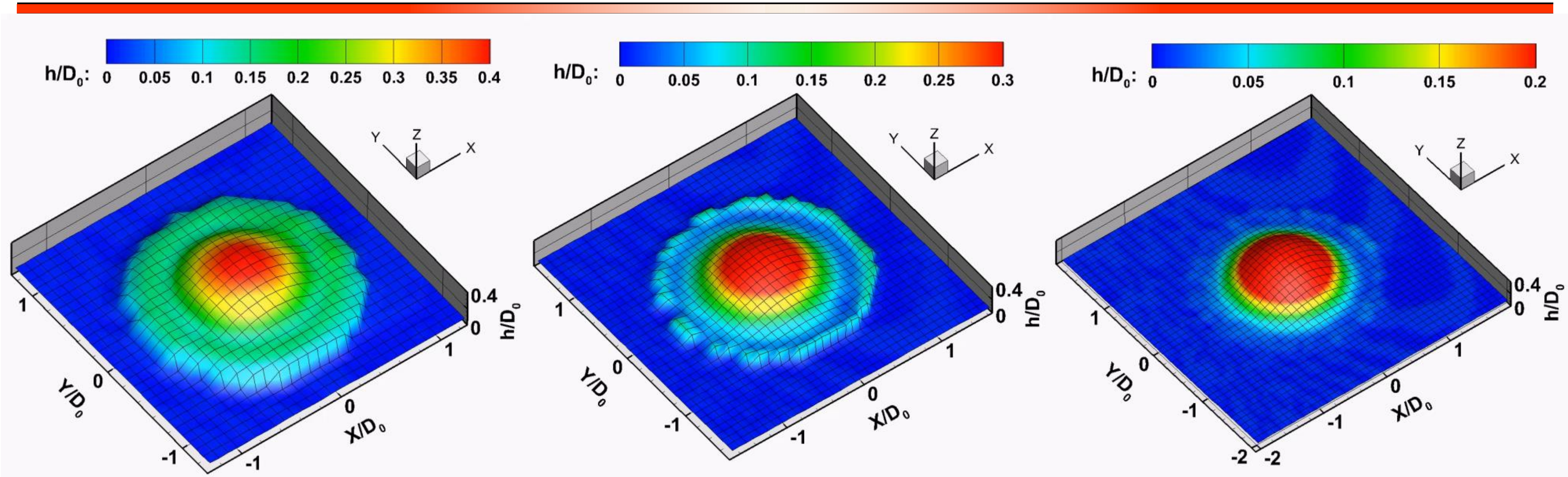




- ***DIP Measurement result***

- ***Zhang, Tian & Hu, 2015.*** *An Experimental Investigation on the Surface Water Transport Process over an Airfoil by using a Digital Image Projection Technique. Exp. Fluids, 56:173.*

❑ DIP Measurements of Dynamic Droplet Impinging Process

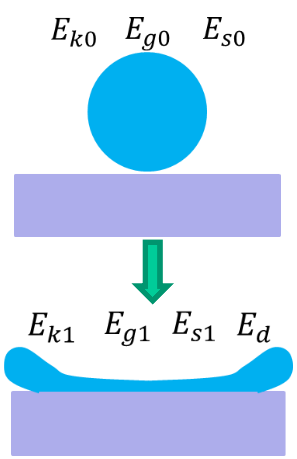


- *Diameter: 2.4mm,*
- *Impact velocity: 0.77m/s;*
- *Re: =1900; We: = 25;*

- *Diameter: 2.4mm,*
- *Impact velocity: 1.60m/s;*
- *Re = 4000; We = 110;*

- *Diameter: 2.4mm,*
- *Impact velocity: 2.12m/s;*
- *Re = 5300; We = 195;*

- ***Energy budget during droplet impact process:***



$$\underbrace{E_{k0} + E_{p0} + E_{s0}}_{\text{Before impact}} = \underbrace{E_k + E_p + E_s + W}_{\text{During impact}}$$

$$E_{k0} = \frac{1}{2} m v^2 = \frac{\pi}{12}\rho v^2 d_0^3$$

$$E_{g0} = mgh = \frac{\pi}{12}\rho g d_0^4$$

$$E_{s0} = \gamma S = \pi d_0^2 \gamma$$

$$E_k = \frac{1}{2} m v^2 \quad E_g = mgh$$

$$W = f(v, \mu)$$

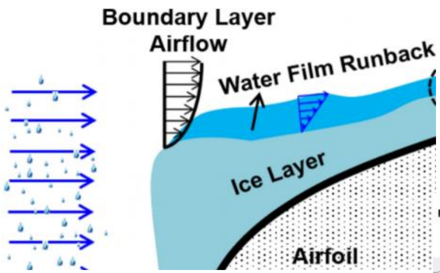
$$E_s = \gamma\left[A - \frac{\pi d^2}{4}\cos\theta\right]$$

We	E_0 ($10^{-6}J$)	E_{df} ($10^{-6}J$)	E_{d1} ($10^{-6}J$)	E_{d1}/E_{df}
25	3.16	2.69	2.30	85.2%
110	10.11	9.06	8.67	95.6%
195	16.71	14.67	14.22	96.9%

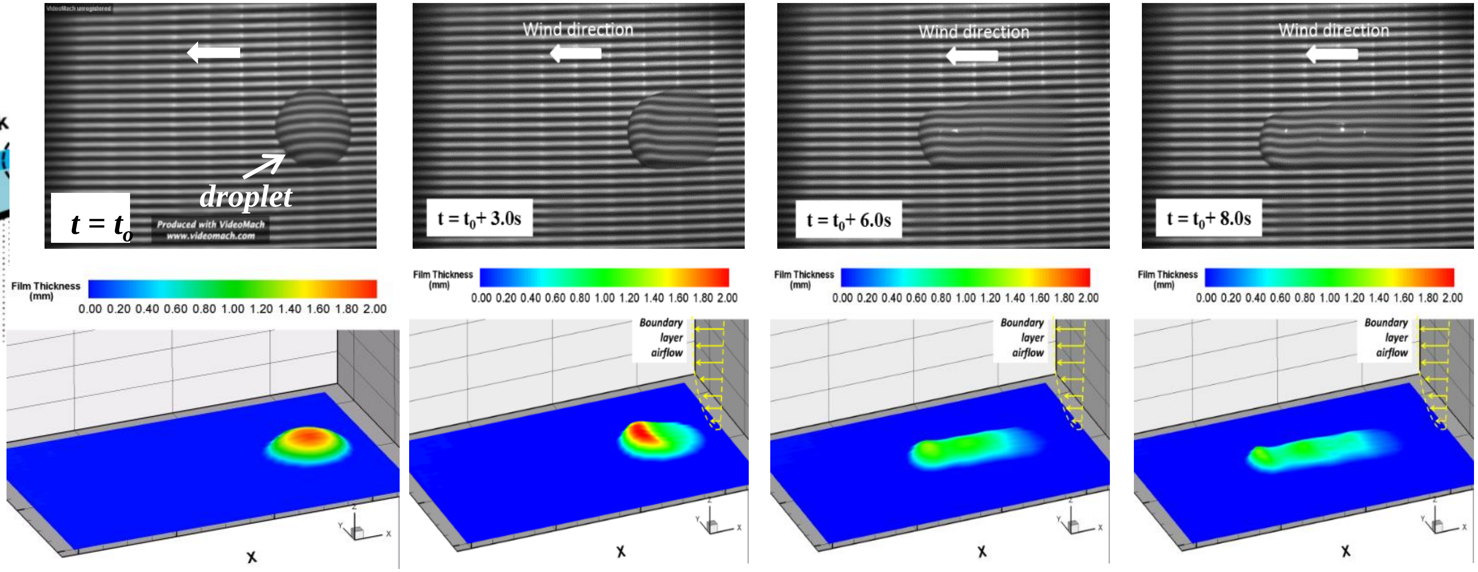
Viscous dissipation function: $\phi \propto \mu U_0^{\ 2}$

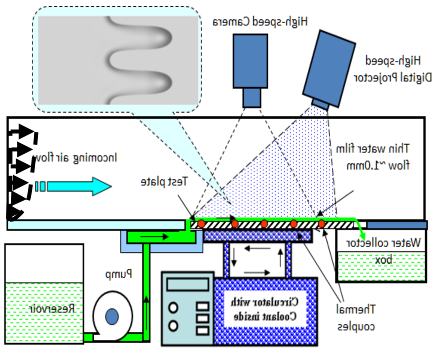
- ***The energy dissipated during the spreading stage would increase as the increase of the Weber number;***
  - ***(S. Chandra & C. T. Avedisian, Proc. R. Soc., 1991)***

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

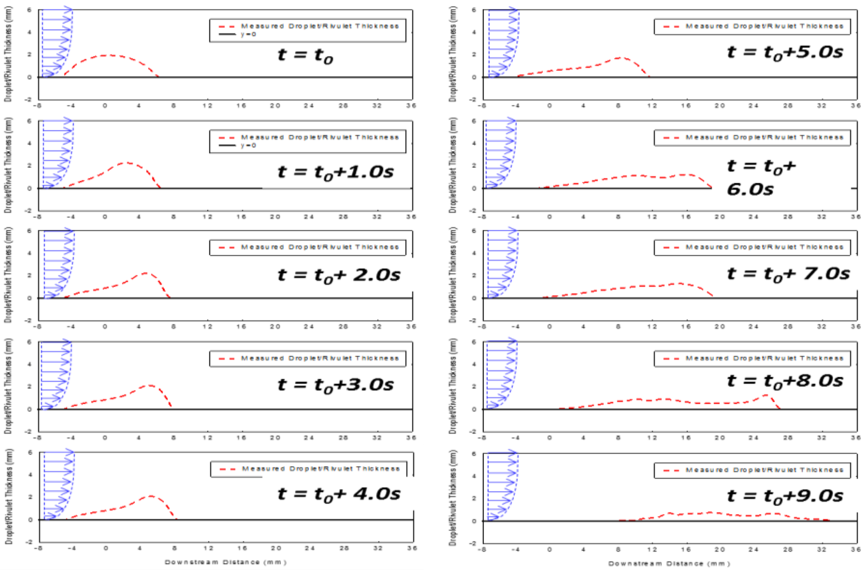


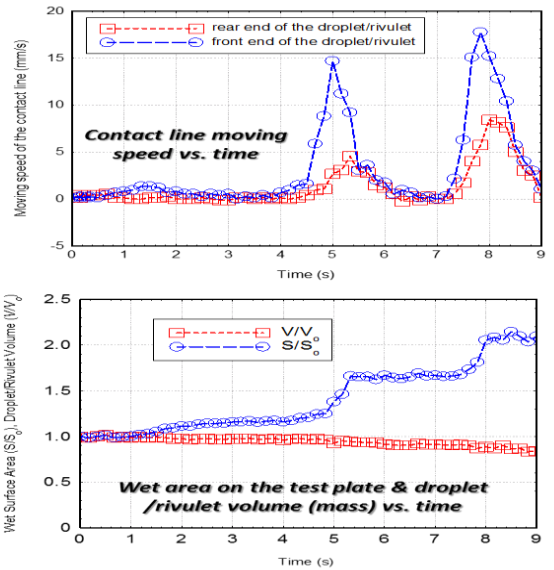
- *Glaze icing process*





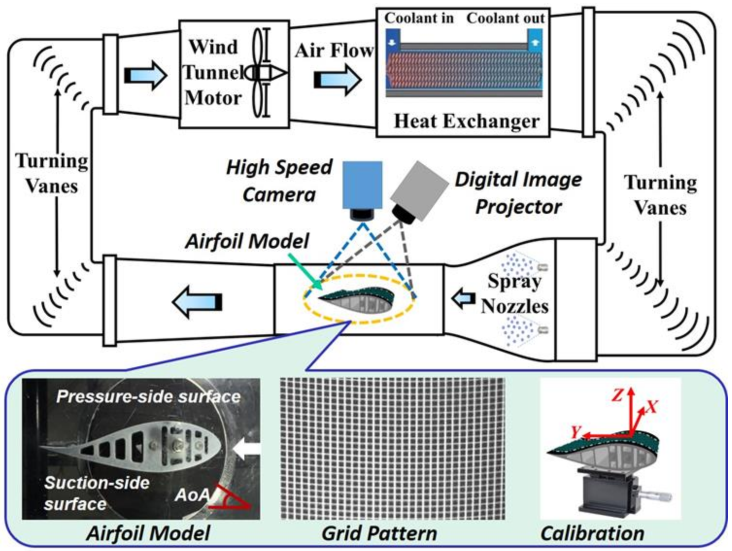
- *Setup for DIP Measurements*



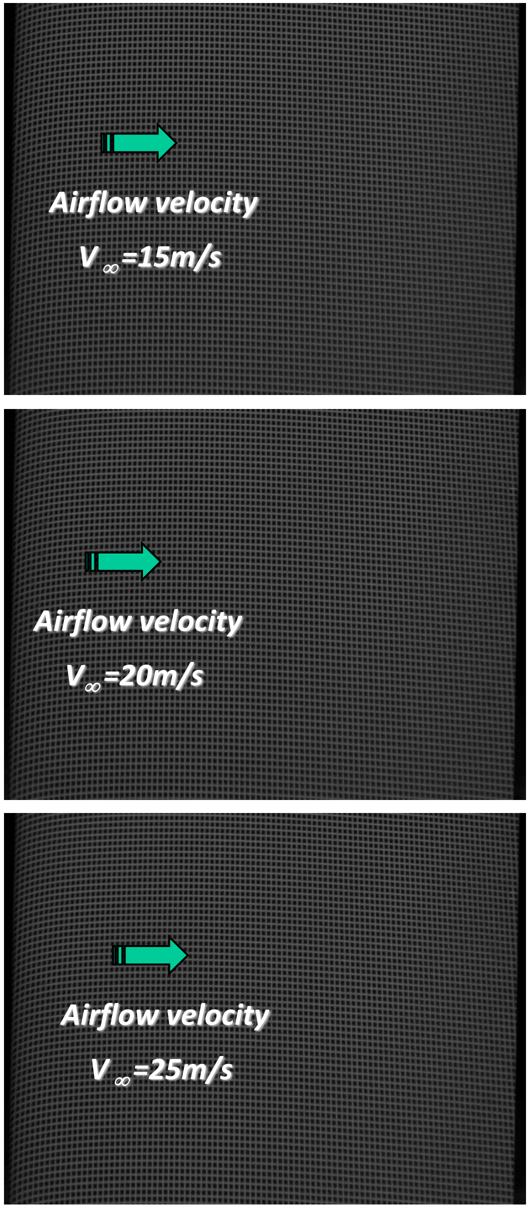


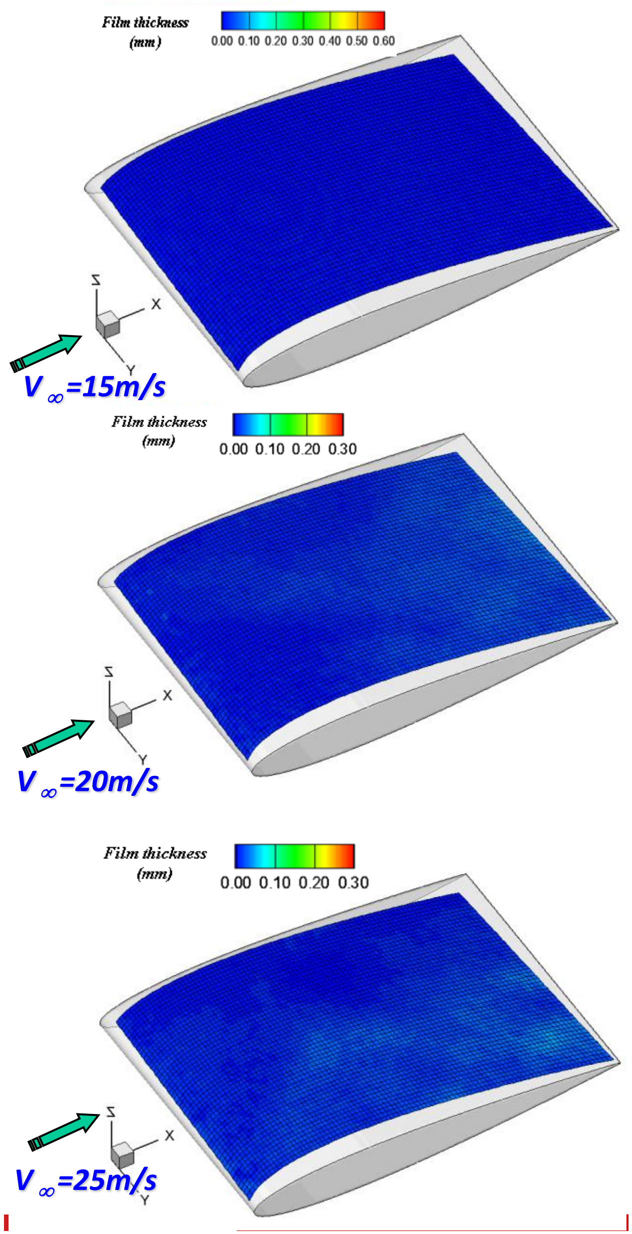
- **H. Hu, B. Wang, K. Zhang, W. Lohry and S. Zhang,** *"Quantification of Transient Behavior of Wind-Driven Surface Droplet/Rivulet Flows by using a Digital Fringe Projection Technique", Journal of Visualization, Vol. 18, No.4, pp705-718, 2015.*

❑ 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/m^3
- Frame rate : f = 30 Hz

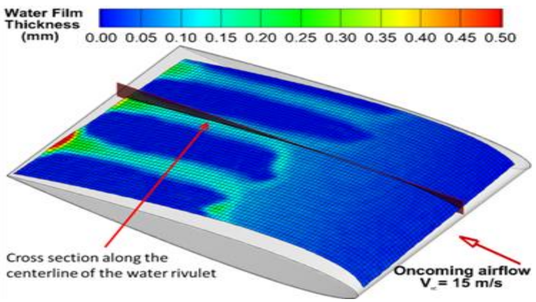
- *K. Zhang, W. Tian and H. Hu, , Experiments in Fluids, 56:173 (16 pages), 2015*

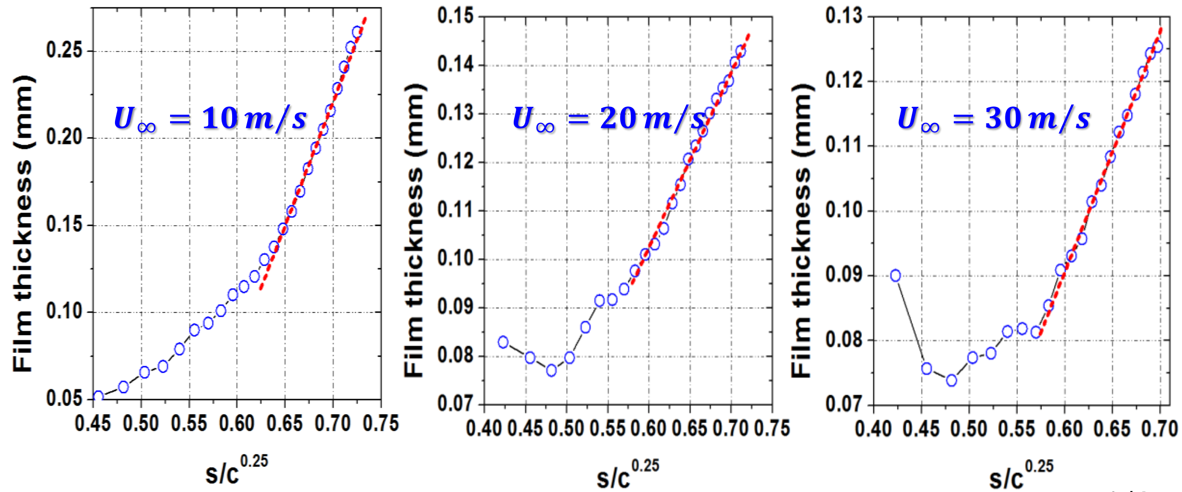
❑ Icing Physics: Transient Behavior of Wind–Driven Water Runback

- **Water Runback Scaling Law #1:**

- *Feo (2001) & Rothmayer (2003) predicted theoretically that wind- driven water film thickness would follow a $x^{1/4}$ law :*

$$h \sim x^{1/4}$$



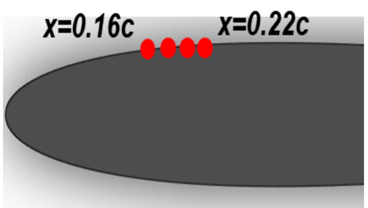


- *Measured water film thickness was found to be proportional to $x^{1/4}$ only when the distance $S^{1/4}$>1.9 (i.e., > 13%c).*

- **Water runback scaling law #2:**

- *Based on the assumption of airflow being laminar, Feo (2001) & Rothmayer (2003) also suggested that:*

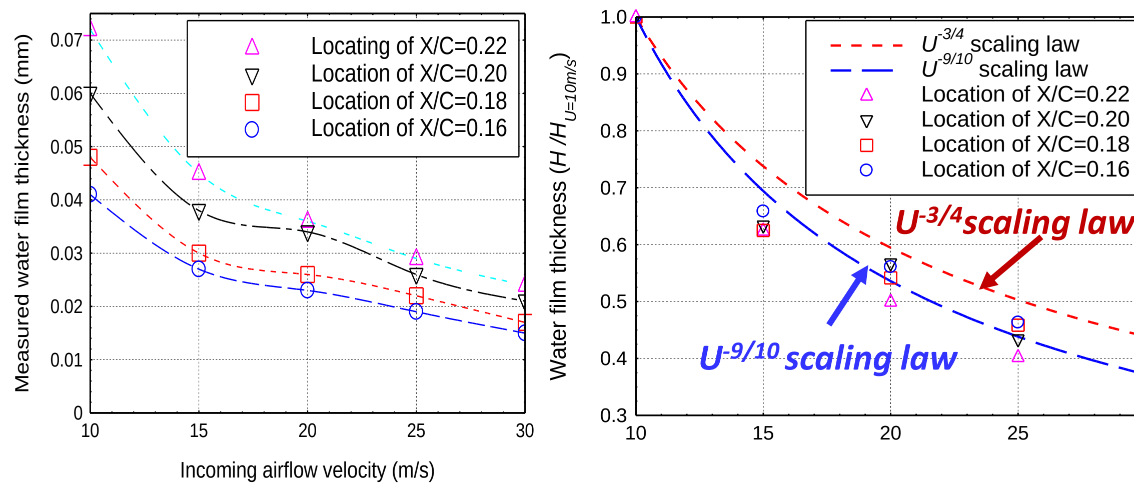
$$h \sim U_{\infty}^{-3/4}$$



- *With airflow being turbulent:*

$$C_f = \frac{0.074}{Re_x^{1/5}} \quad \tau \sim U_{\infty}^{9/5}$$

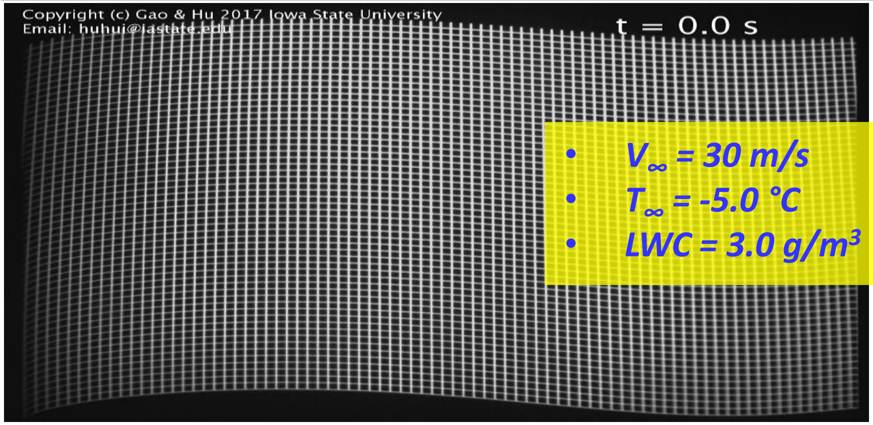
$$h \sim U_{\infty}^{-9/10}$$



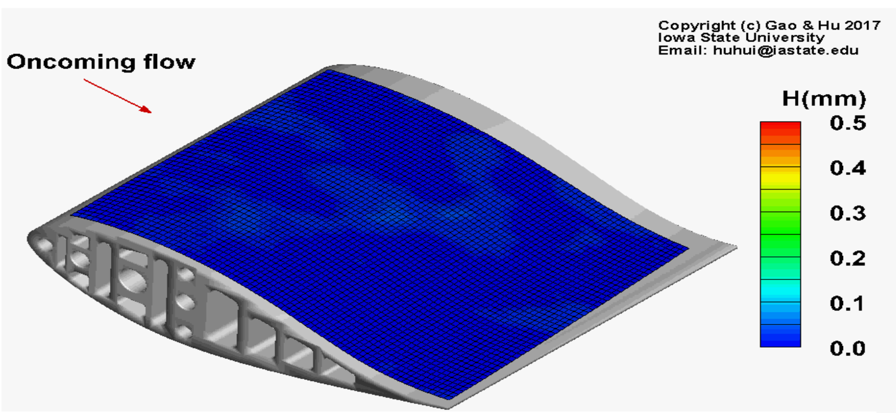
- *Measured water film thickness vs. incoming airflow velocity*

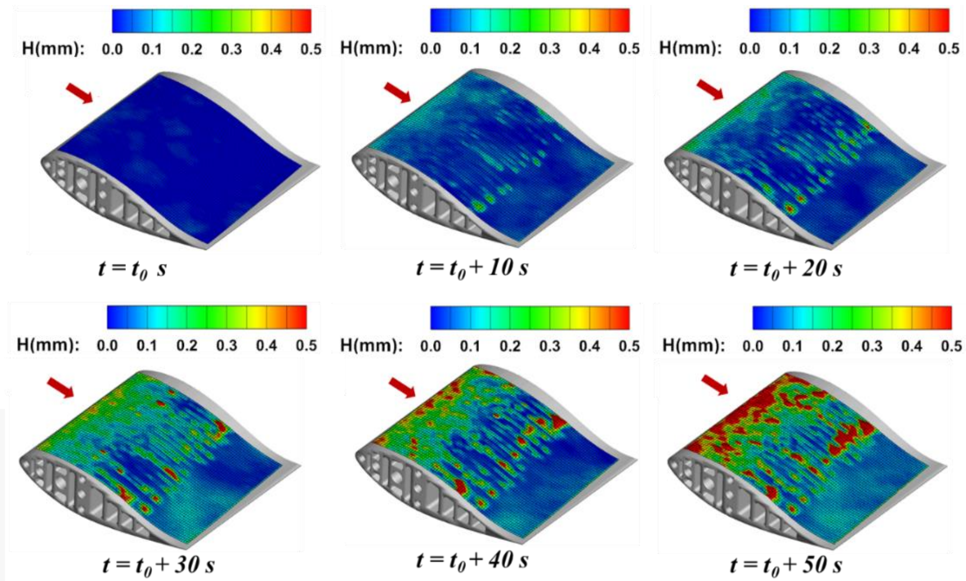
- *K. Zhang, W. Tian and H. Hu, "An Experimental Investigation on the Surface Water Transport Process over an Airfoil by using a Digital Image Projection Technique", Experiments in Fluids, 56:173 (16 pages), 2015*

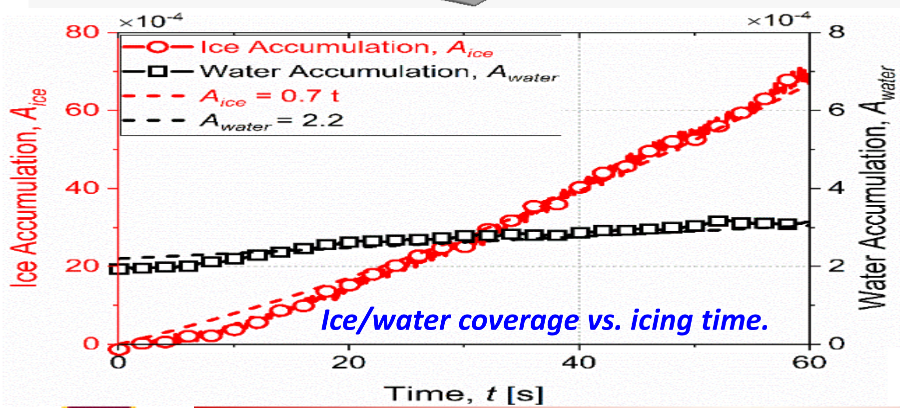
❑ Icing Physics: Dynamic Water Runback & Glaze Ice Accretion Process



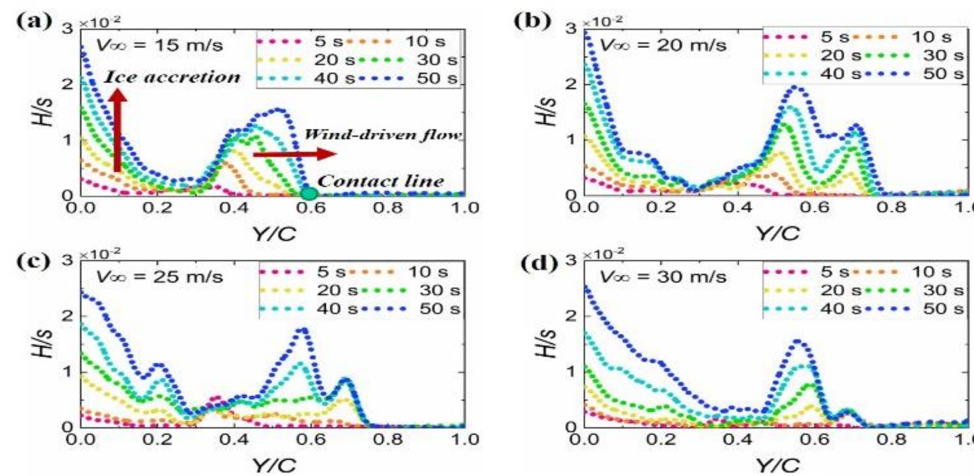
- V_∞ = 30 m/s
- T_∞ = -5.0 °C
- LWC = 3.0 g/m³







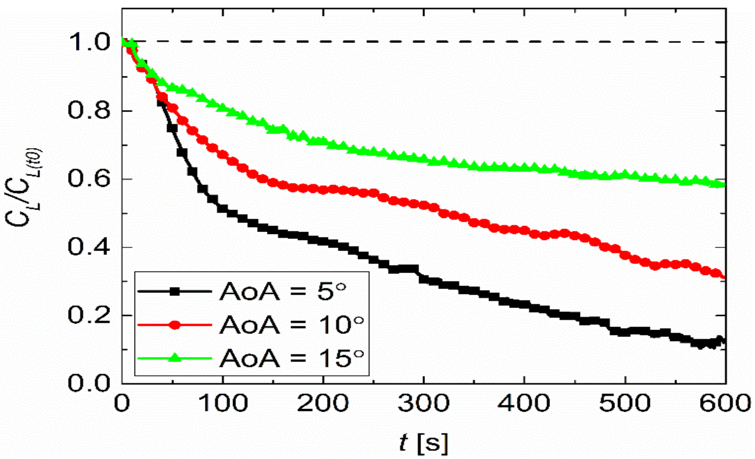
Ice/water coverage vs. icing time.

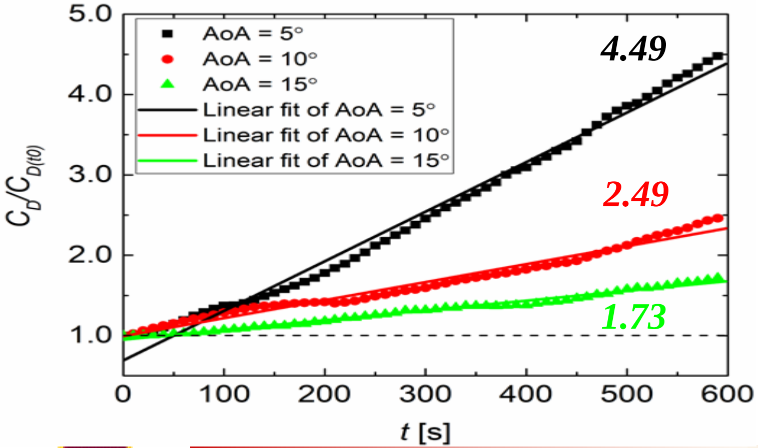


- water/ice thickness vs. airflow velocity

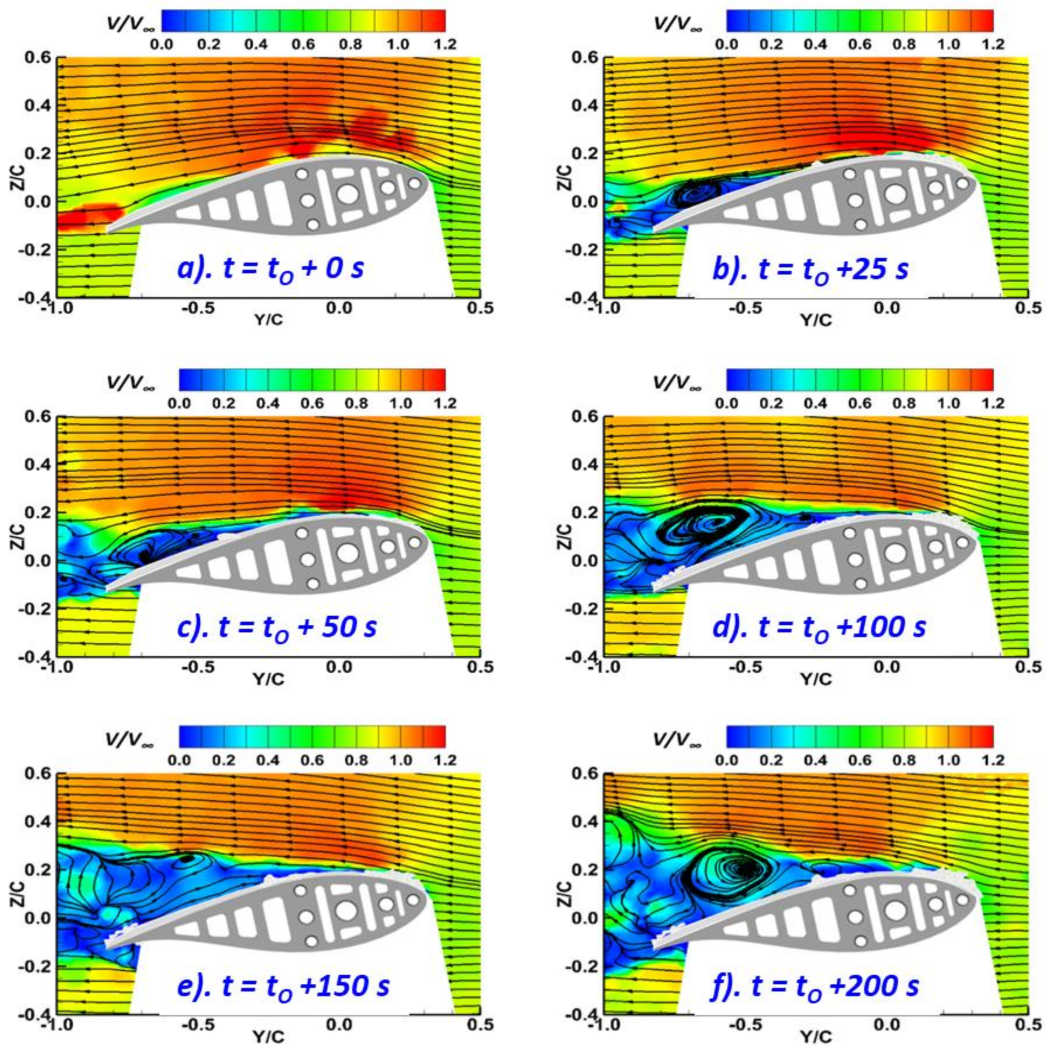
- (Gao et al., International Journal of Heat and Mass Transfer, 2020)

❑ Airfoil Aerodynamic Performance Degradation due to Ice Accretion





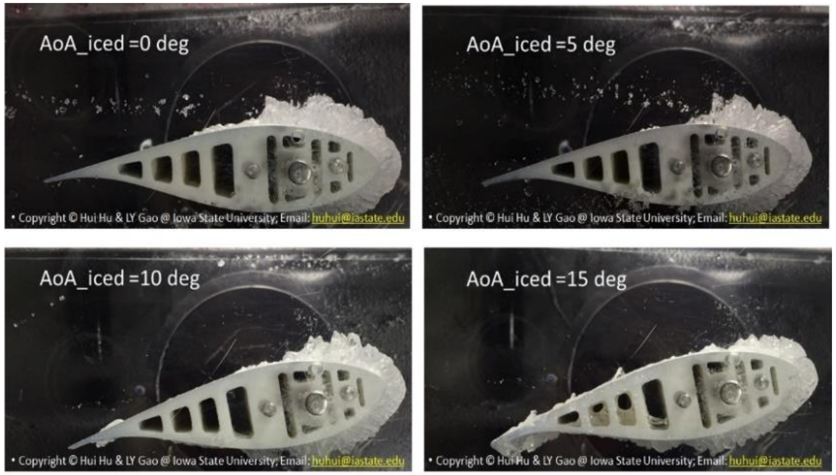
- $T_\infty = -5.0\ ^oc$; $V_\infty = 40.0$ m/s; LWC = 1.1 g/m^3, AOA=10^0

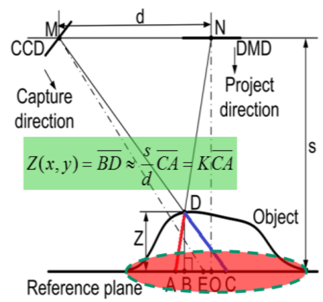


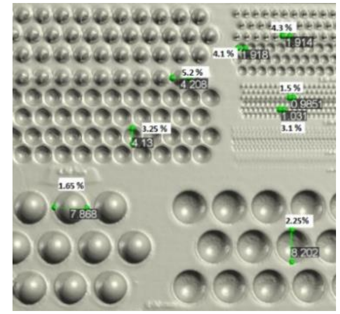
PIV measurements of the airflow over an ice accreting airfoil surface

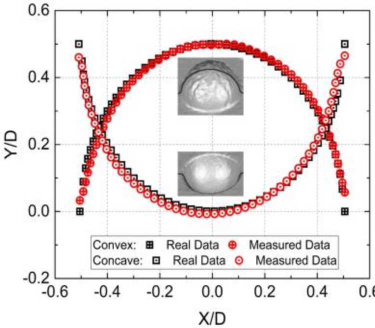
- *Gao et al., Renewable Energy, 133(4), 663-675, 2019.*

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



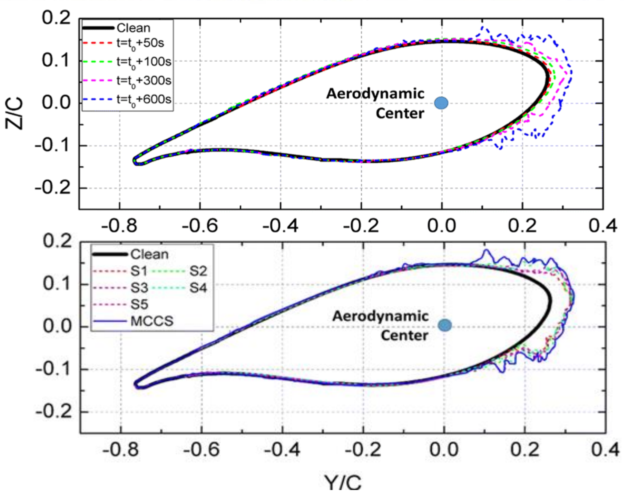


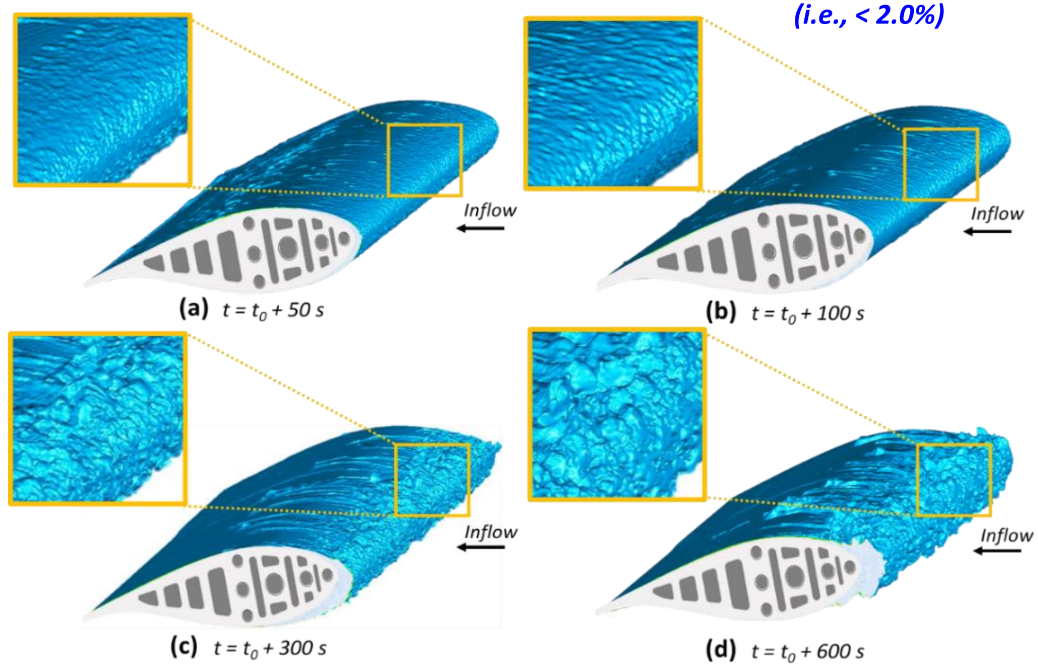


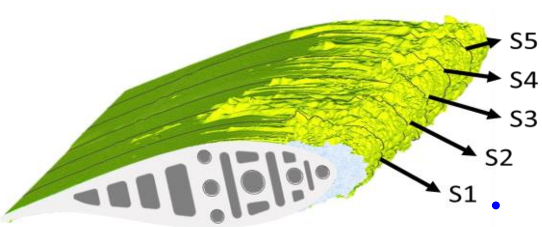


• ***DIP-based 3D shape scanning technique***

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





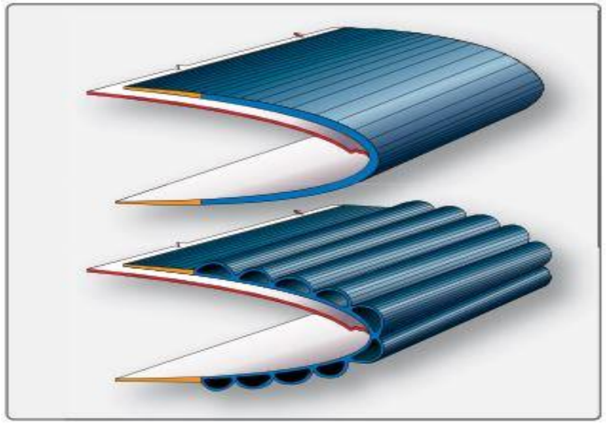


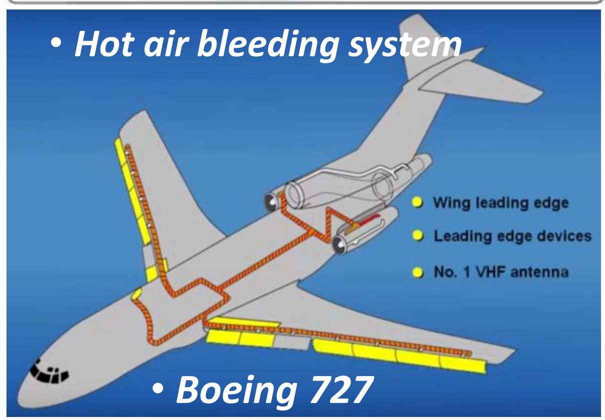
DIP canning technique for 3D ice shape measurements

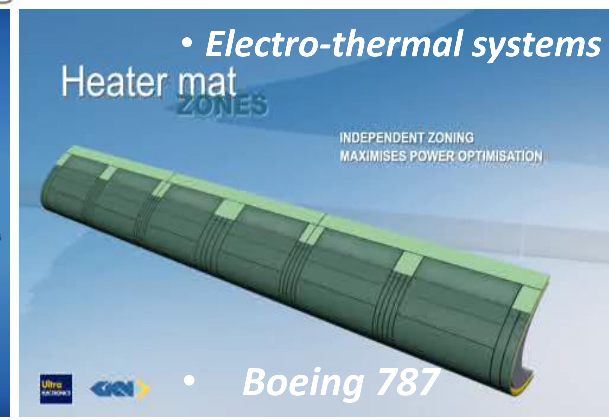
• ***Gao, Veerakumar, Liu, Hu.*** *"Quantification of the 3D Shapes of the Ice Structures Accreted on a Wind Turbine Airfoil Model", Journal of Visualization, Vol.22, No. 4, pp 661–667, 2019.*

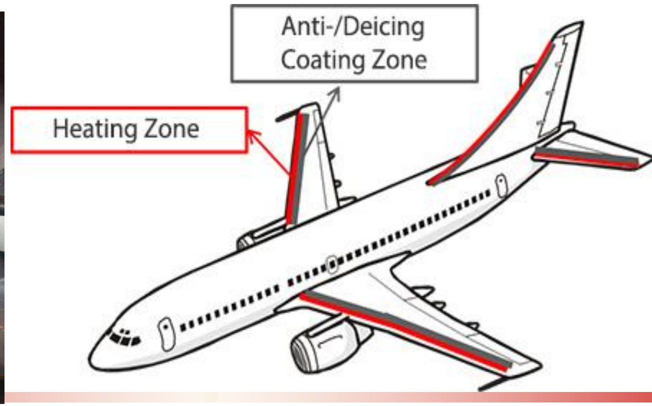
❑ Anti-/De-Icing Strategies: Active Methods & Passive Methods

- ❖ ***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*

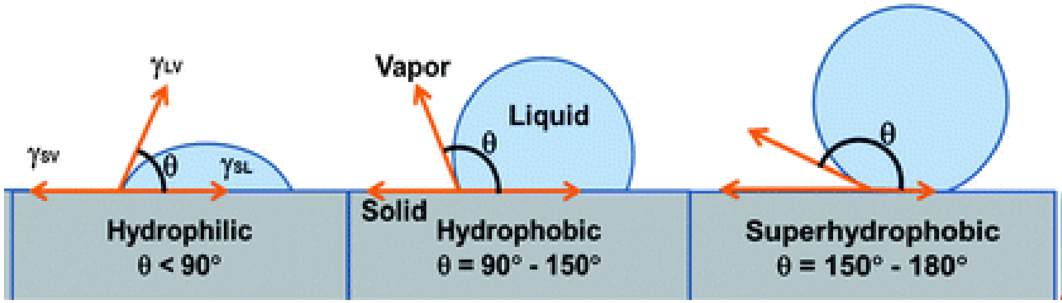


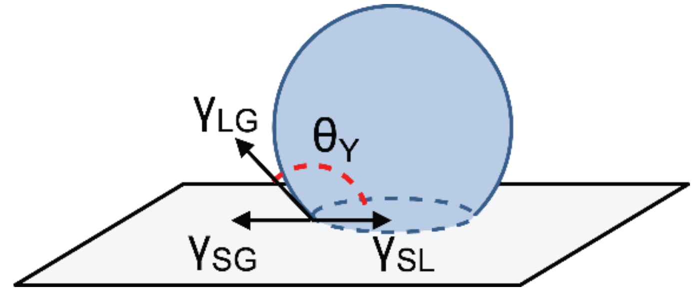






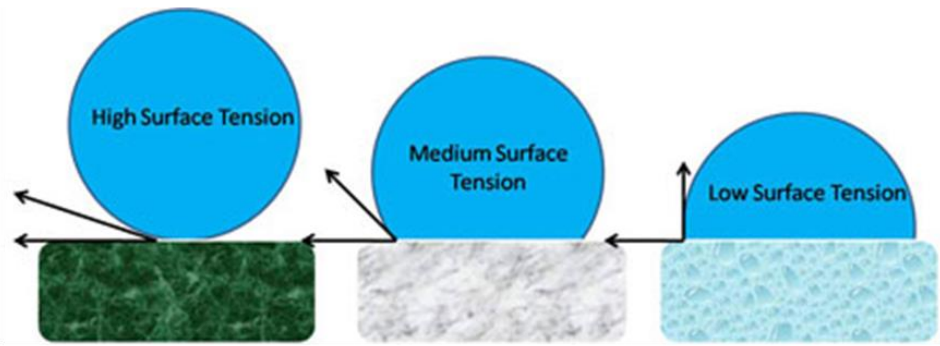
❑ Surface Wettability: Hydrophilic, Hydrophobic, & Superhydrophobic



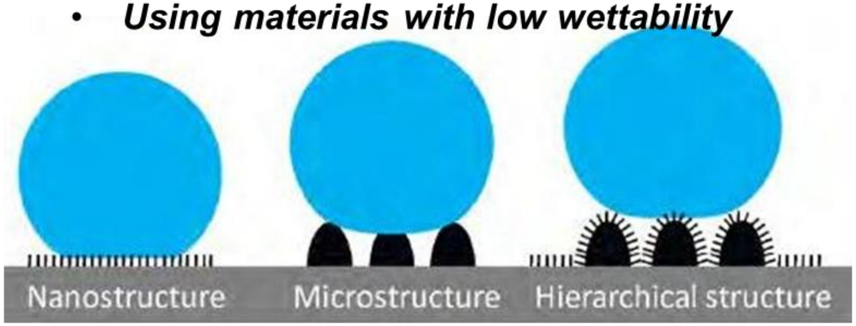


$$\gamma_{LG} \cos\theta_Y = \gamma_{SG} - \gamma_{LS}.$$

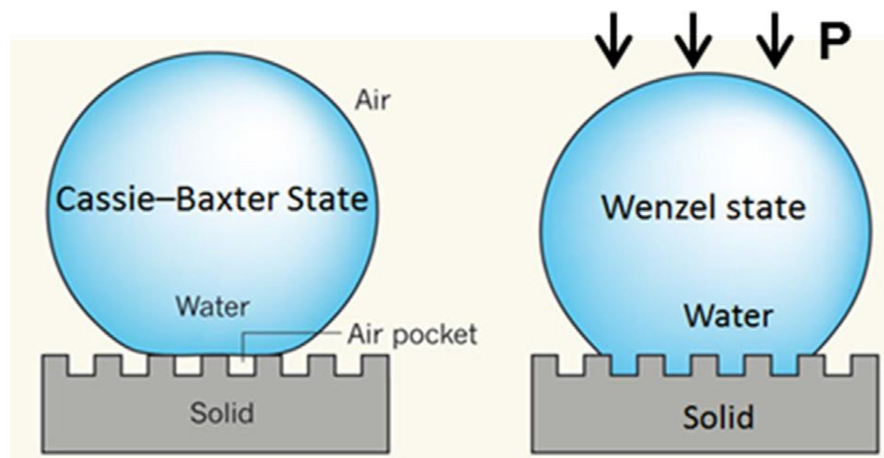
- ***A water droplet over a smooth surface***



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



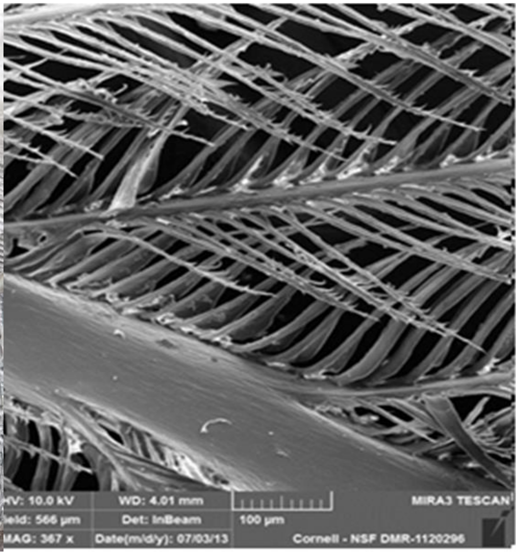
- ***Making structured surface***
(creating micro-/nano- structures over the surface)



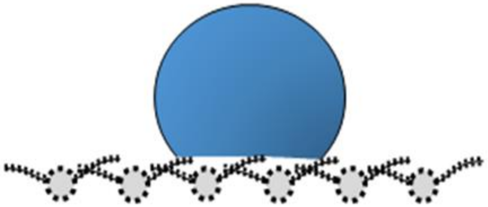
$$\cos\theta_{CB} = \varphi\cos\theta_Y + \varphi - 1 \qquad \cos\theta_W = n\cos\theta_Y$$

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

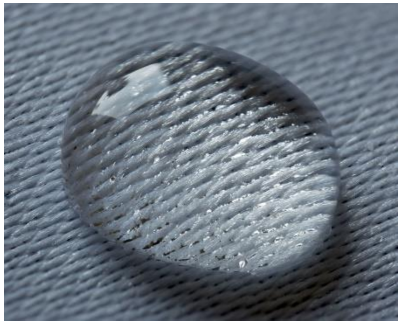
❑ Bird-Feather-Inspired Technology



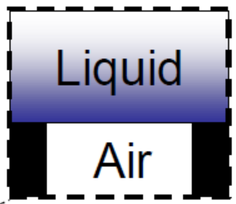
$\theta \approx 120^O \pm 20^O$

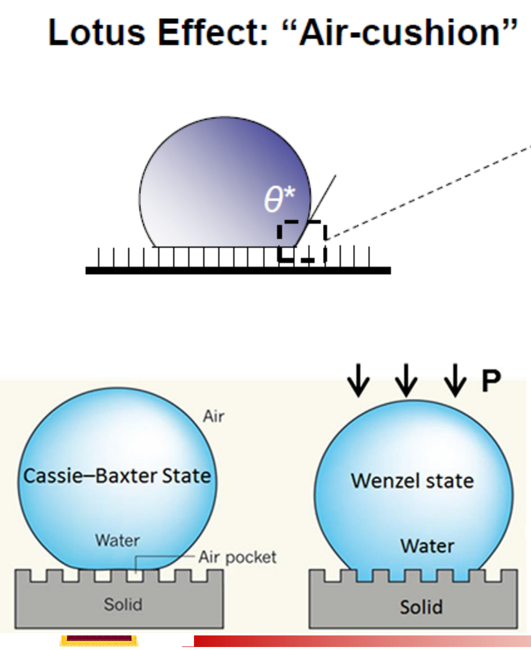


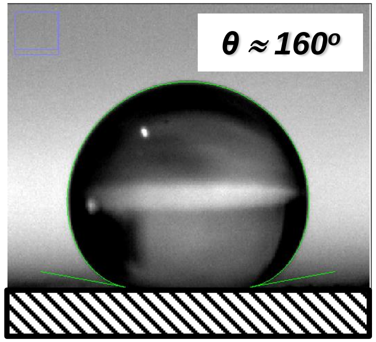
- *Air permeable multi-scale interlaced micro-/nano structures*

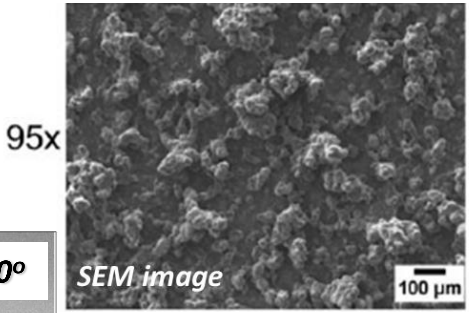


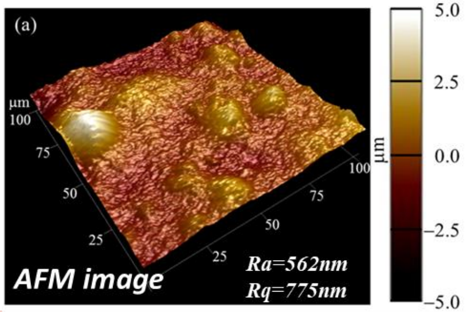
❑ Lotus-Leaf-Inspired Technology









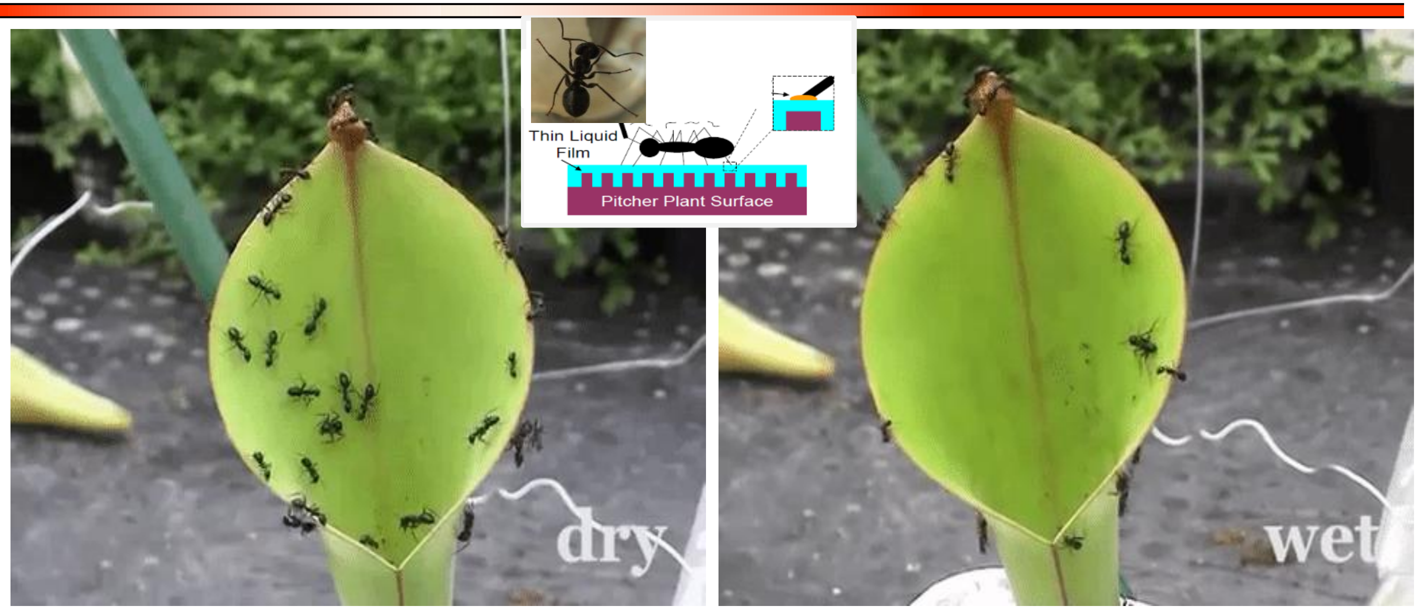


- ***Hydrobead® coating.***
  - ***Spray onto aluminum test plates.***
  - ***Both Hydrobead® standard & enhancer were applied.***

http://www.hydrobead.com

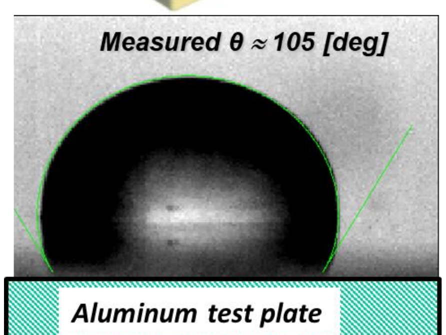
❑ Pitcher-Plant-Inspired Technology

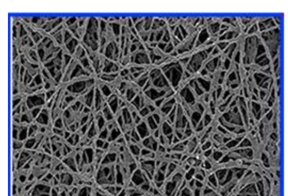

Bohn & Federle, PNAS (2004)



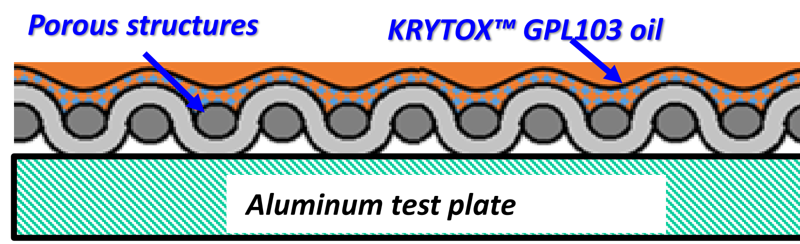
SLIPS: Slippery Liquid-Infused Porous Surfaces

Wong, Aizenberg et al., ***Nature***, 477: 443 – 447 (2011)





STERLITECH Corporation



- ***Teflon nanofibrous membranes:***
  - *Having an average pore size of ≥ 200 nm*
  - *Its polypropylene film was sticked to an aluminum substrate.*
- ***KRYTOX™ GPL103 oil:***
  - *Clear, colorless, fluorinated synthetic oils that are nonreactive, nonflammable,*
  - *Safe in chemical and oxygen service, and are long-lasting.*

❑ Anti-Frosting vs. Impact Icing Mitigation

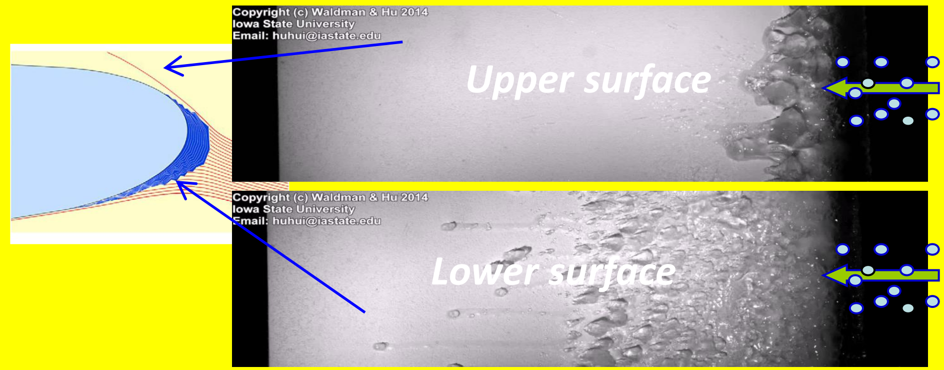
- *Most previous studies were performed based on static tests for anti-frosting applications.*
- *Very little can be found in literature to evaluate the ice-phobic coatings for "impact icing" mitigation pertinent to aircraft icing phenomena, in either dry rime or/and wet glaze icing conditions.*

Anti-Frosting:

- *Icing process is almost static, and ice accretion rate is very slow.*

Impact Icing:

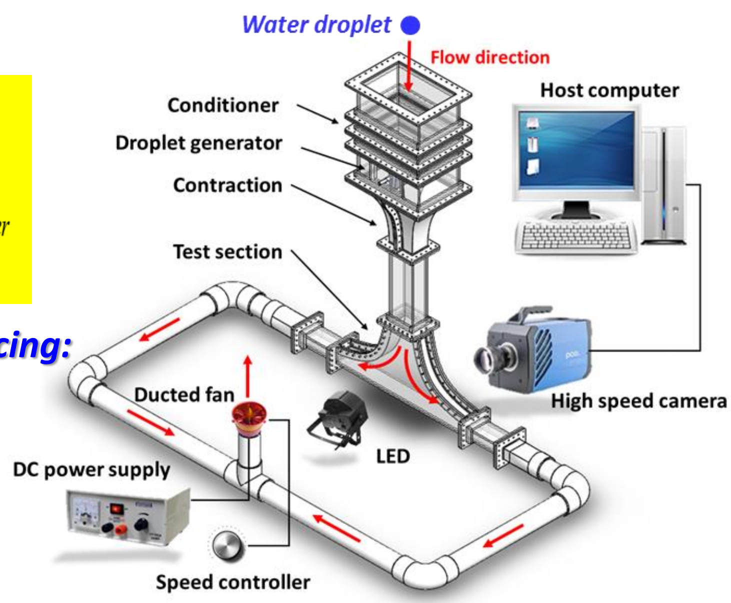
- *Duration of icing is vey short; high-speed droplet impacting (>100 m/s).*

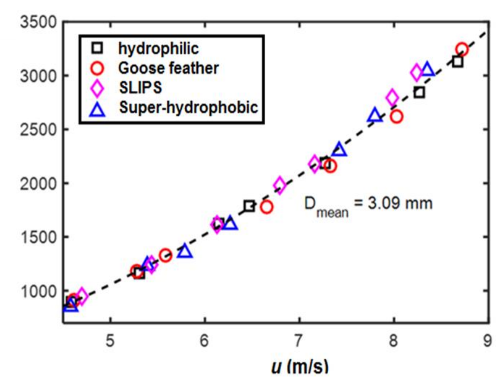


- ***Parameters to characterize impact icing:***

- Weber number $We = \rho D V_{impact}^2 / \sigma$
- Reynolds number $Re = \rho D V_{impact} / \mu$
- Ohnesorge number $Oh = \mu / \sqrt{\rho \sigma D} = \sqrt{We} / Re$

ρ: Water density
μ: Water viscosity
σ: Surface tension
D: Droplet diameter
U: Impact velocity



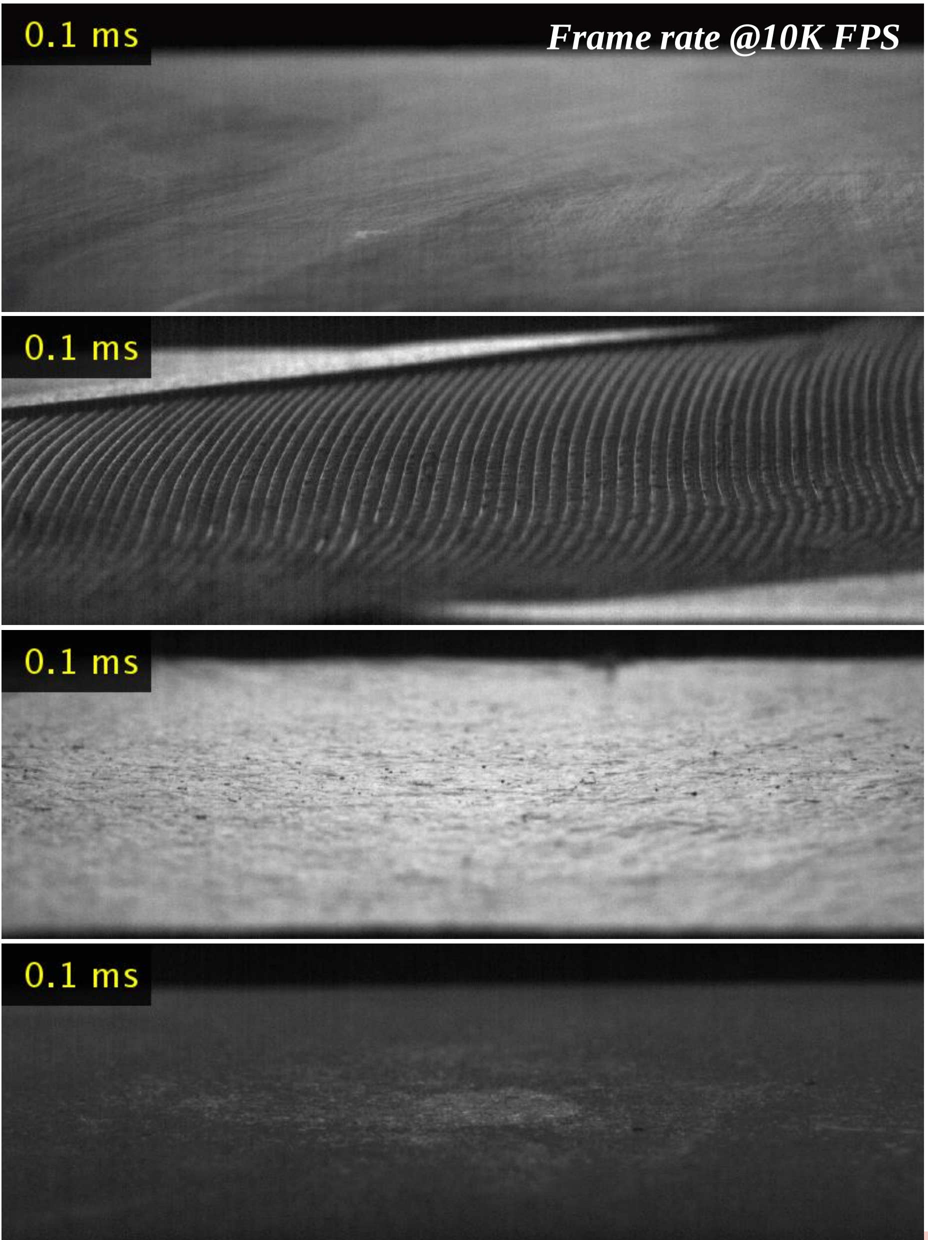


Typical parameters pertinent to aircraft icing:

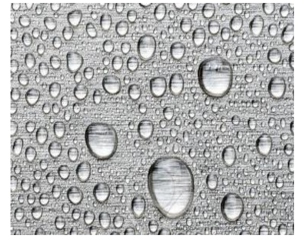
- $D_{droplet}$ = 20 μm
- $V_{impacting}$ = 100 m/s
- We ≈ 2,250
- Re ≈ 500
- Oh ≈ 0.071

- $D_{droplet}$ = 3.0 mm
- $V_{impating}$ = 10 m/s
- Re = 1,500
- We = 4,000

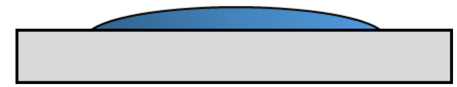
❑ Dynamic Droplet Impingement onto Different Surfaces



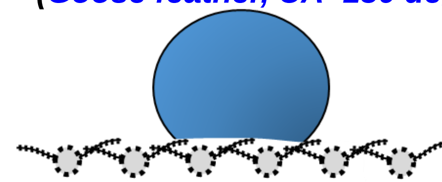
We ≈ 2, 000



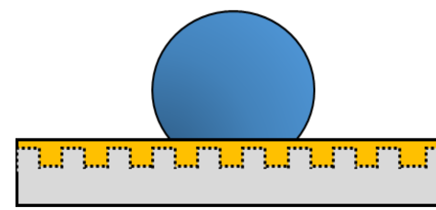
Hydrophilic
(Comparison baseline, CA=65 deg..)

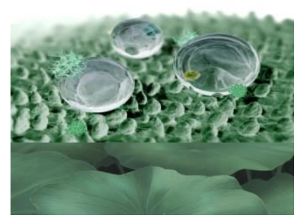


Feather
(Goose feather, CA=130 deg.)

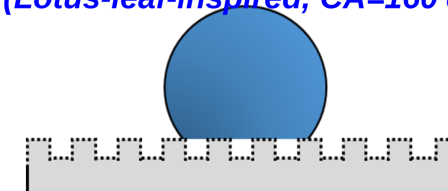


SLIPS
(Pitcher-plant-inspired. CA=105 deg.)



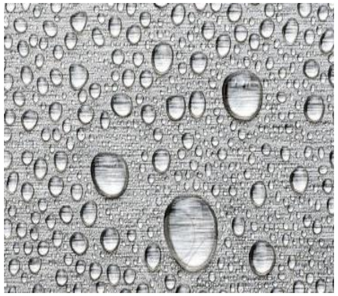


Super-hydrophobic
(Lotus-leaf-inspired, CA=160 deg.)



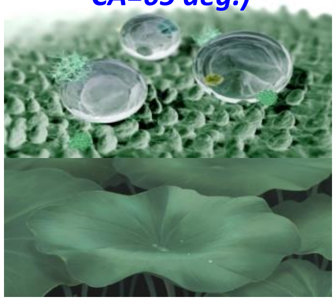
- ***LQ Ma, HX Li, and H. Hu.*** *An Experimental Study on the Dynamics of Water Droplet Impingement onto Bio-inspired Surfaces with Different Wettability.* ***AIAA-2017-0442****, SciTech2017.*

❑ Transient Behavior of Wind–Driven Film/Rivulet Flows



Hydrophilic

(Comparison baseline, CA=65 deg.)

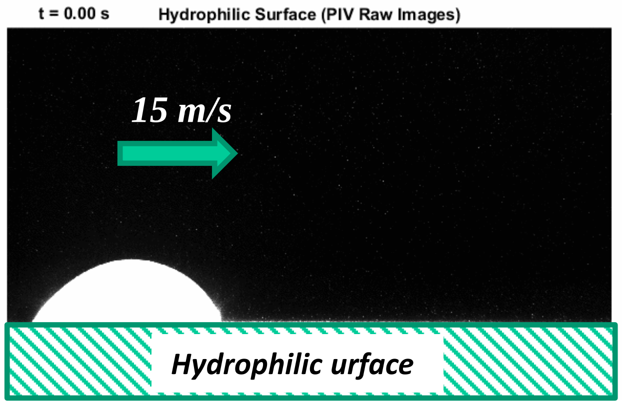


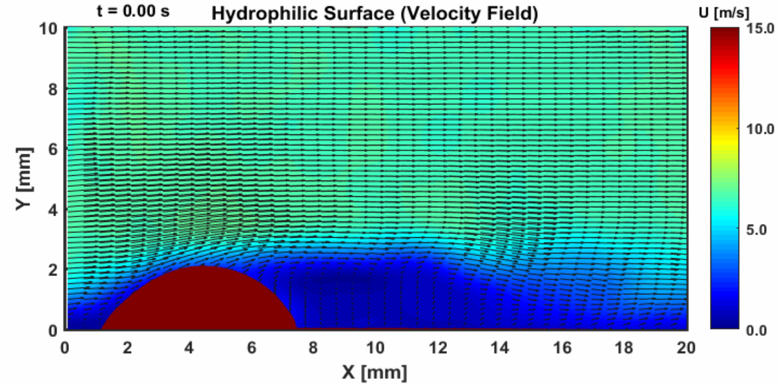
Super-hydrophobic surface

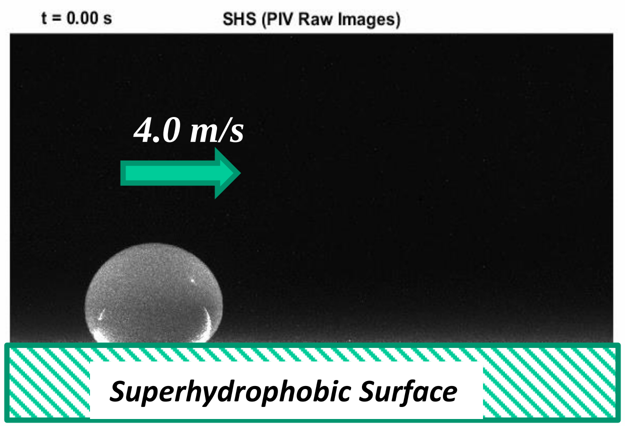
(Lotus-leaf-inspired, CA=160 deg.)

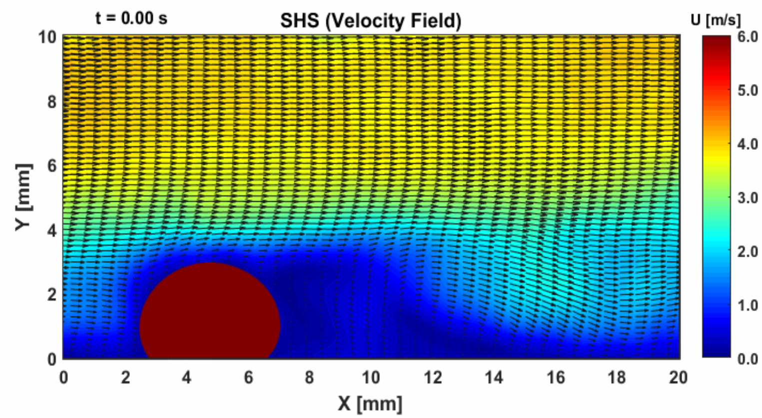
SLIPS

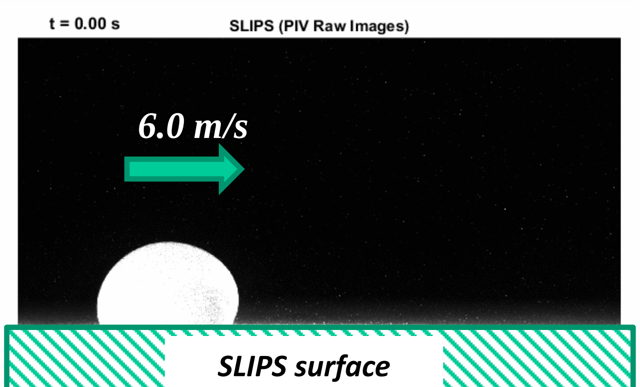
(Pitcher-plant-inspired, CA=110 deg.)

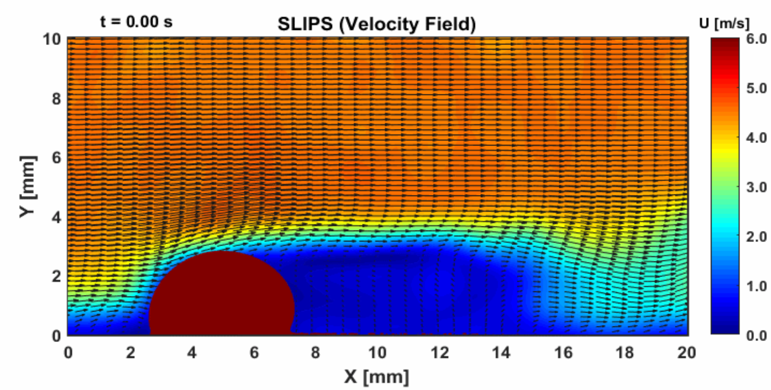




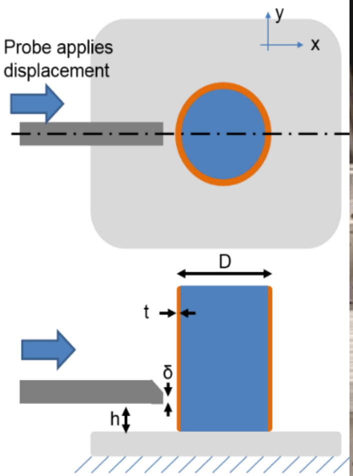


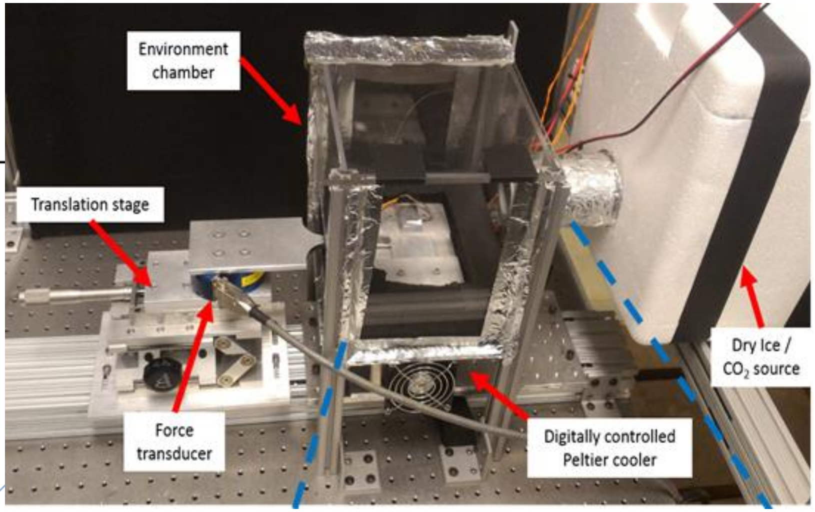


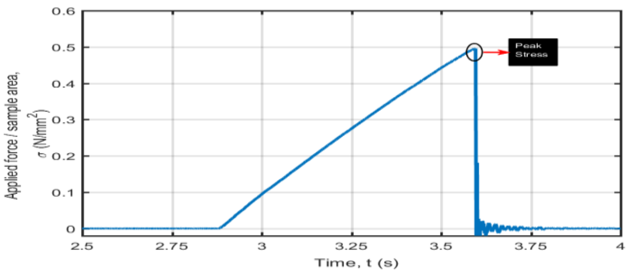




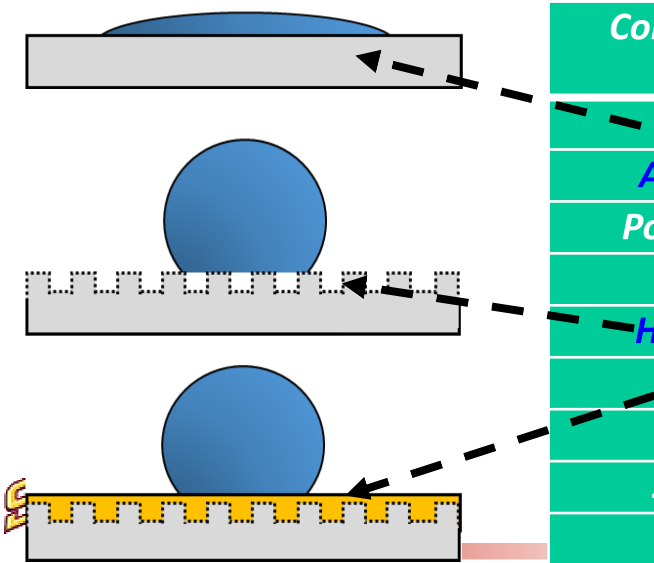
❑ Measurements of Ice Adhesion Strength over Different Surfaces





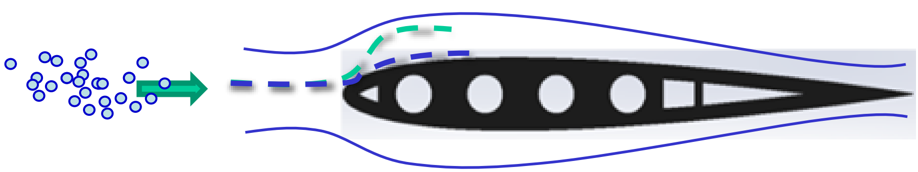


- ***Ice adhesion strength over different surfaces:***



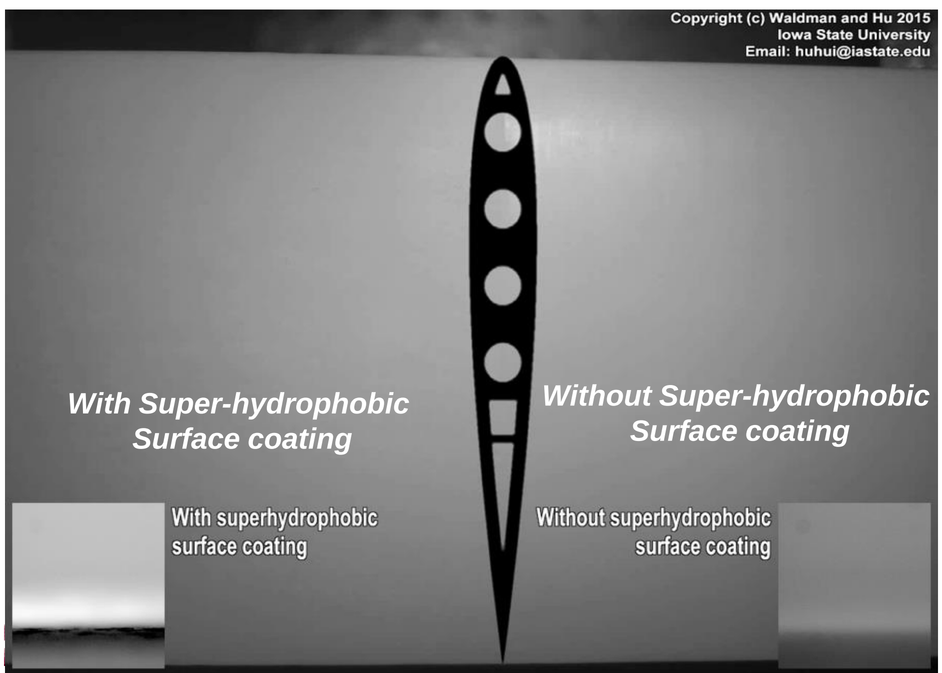
Compared Surfaces	Ice adhesion strength at T_{wall} = -10 °C [KPa]	Std. deviation @ T_{wall} = -10 °C [KPa]
Al, 220 Grit	450	70
Al, mirror finish	130	60
Polymer (Enamel)	1400	130
Teflon	420	60
Hydro-bead SHS	120	30
SLIPS	60	10
PFA plastic	570	60
Stainless steel	550	130
NeverWet	420	40

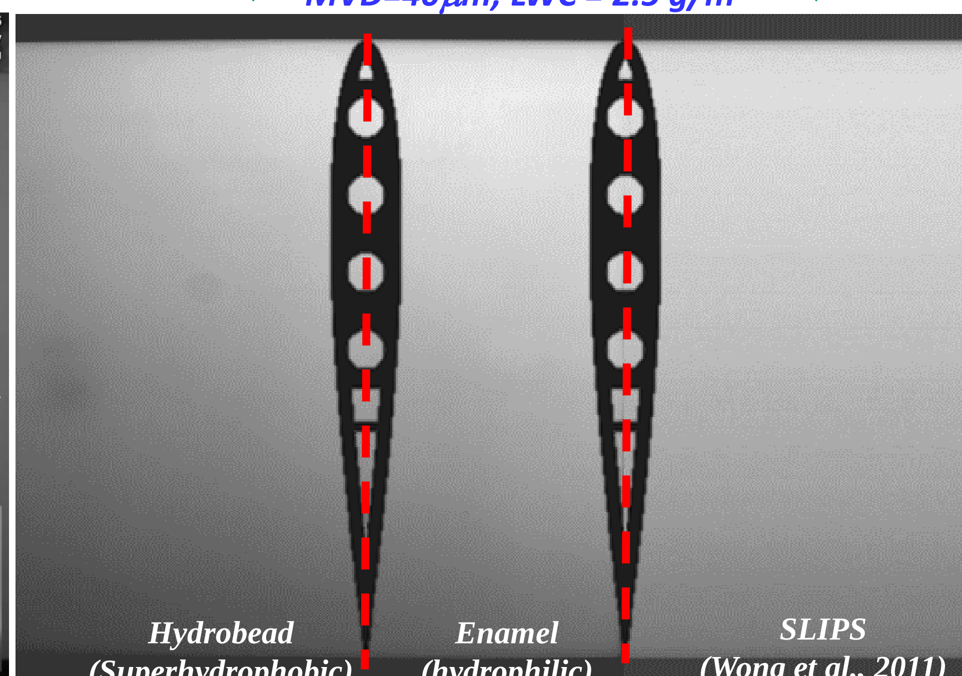
❑ Effects of Bio-Inspired Coatings on Impact Ice Accretion



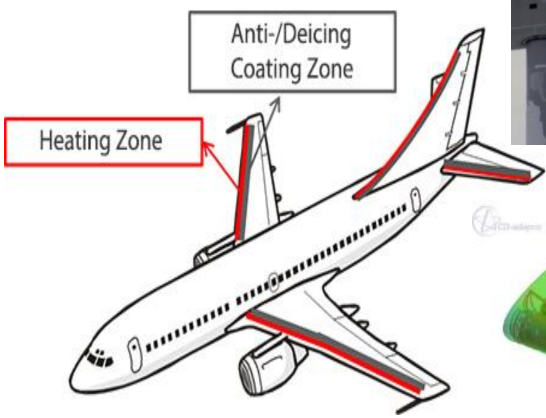
T_{∞}= - 8 °C; V_{∞} = 50 m/s
MVD=20 μm; LWC = 2.5 g/m^3

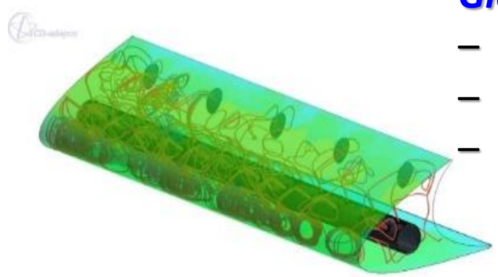
T_{∞}= - 4 °C; V_{∞} = 40 m/s
MVD=40 μm; LWC = 2.5 g/m^3





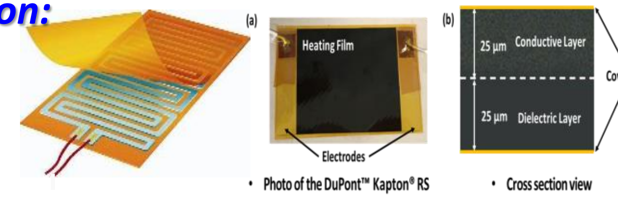
❑ Hybrid Anti-/De-Icing Strategy: Minimized Heating + Icephobic Coatings



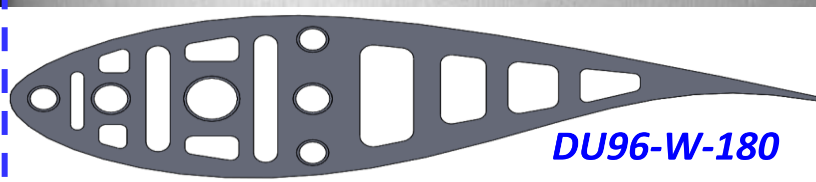


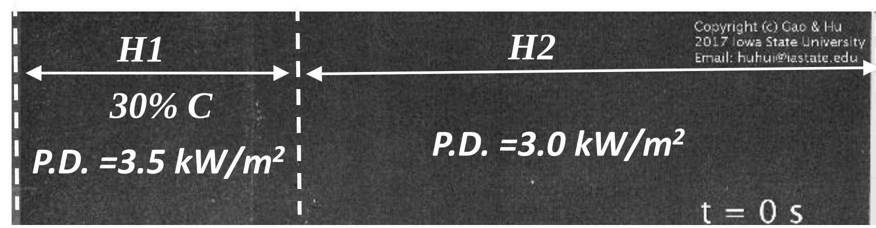
Glaze Icing Condition:

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



- **With leading edge heating only**



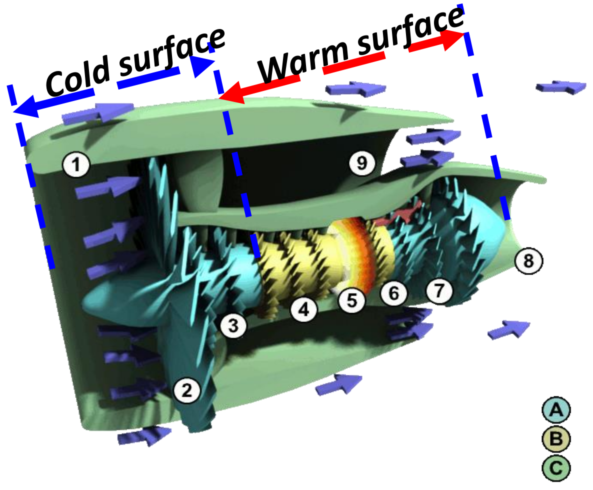


- **With massive surface heating (Successful anti-/de-icing)**

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

- **Leading edge heating + SHS (~ 95% energy saving)**

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



Aero-engine Icing Phenomena

Supercooled water droplet icing

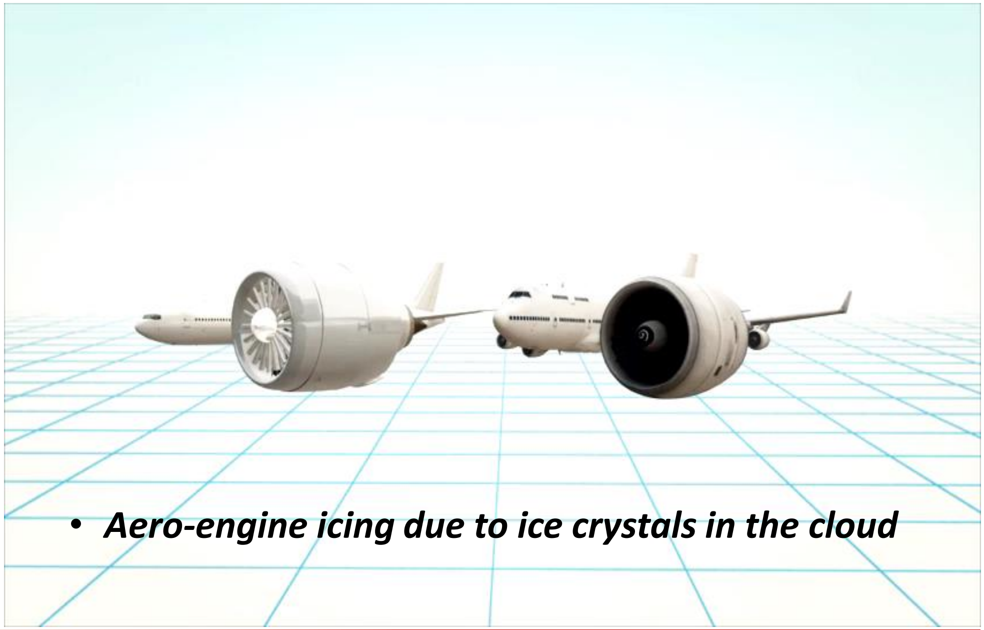
- Similar to the airframe icing.
- Cold airflow with supercooled water droplets, freezing drizzle and freezing rain.
- Mostly happen at inlet, spinner and fan blades.
- Additional effects of rotation motion.

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.

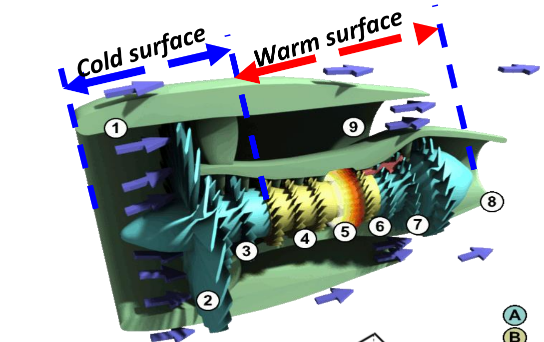
(Ice crystal icing test rig is ready in 2019 fall)

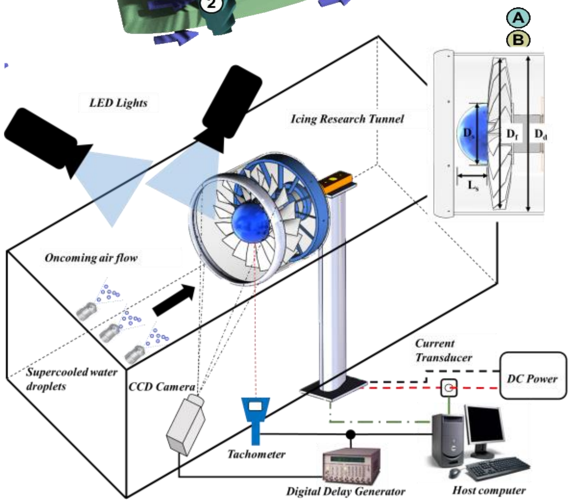
- *Aero-engine icing due to supercooled water droplets*

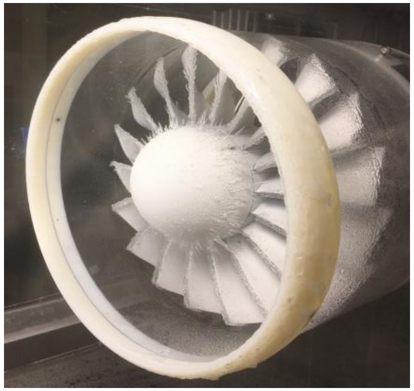


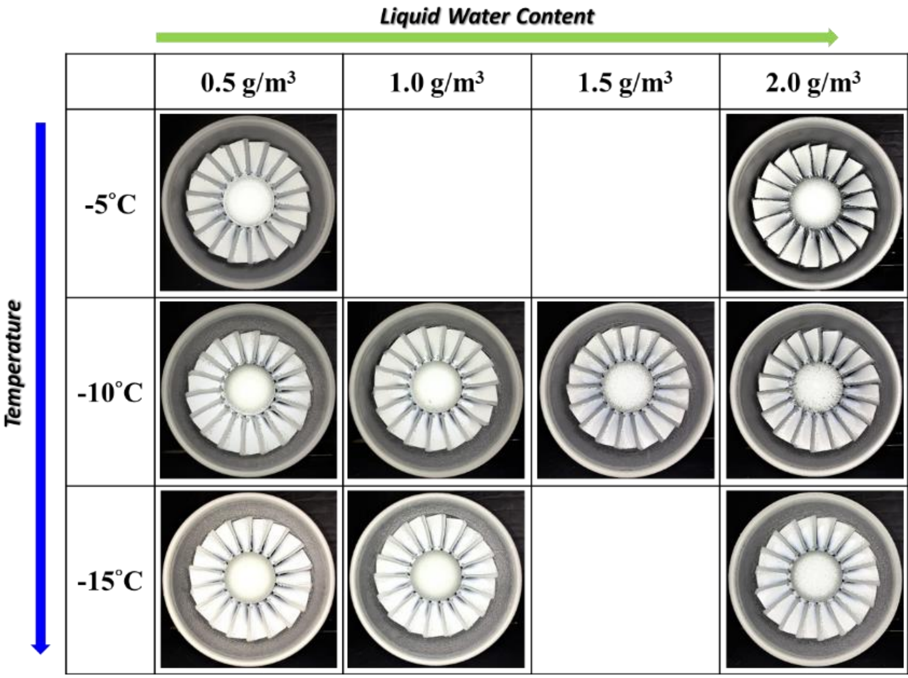
- *Aero-engine icing due to ice crystals in the cloud*

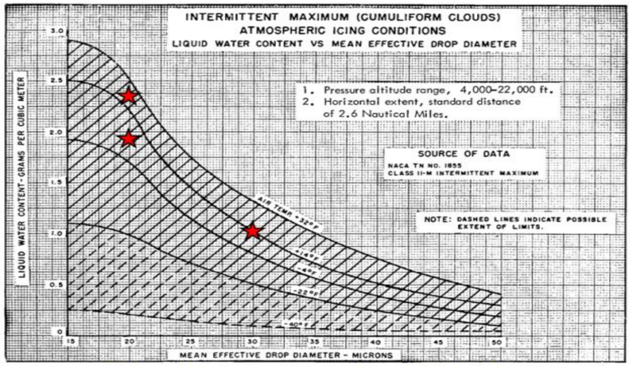
Experimental Setup for Aero-Engine Fan Blade Icing Study











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

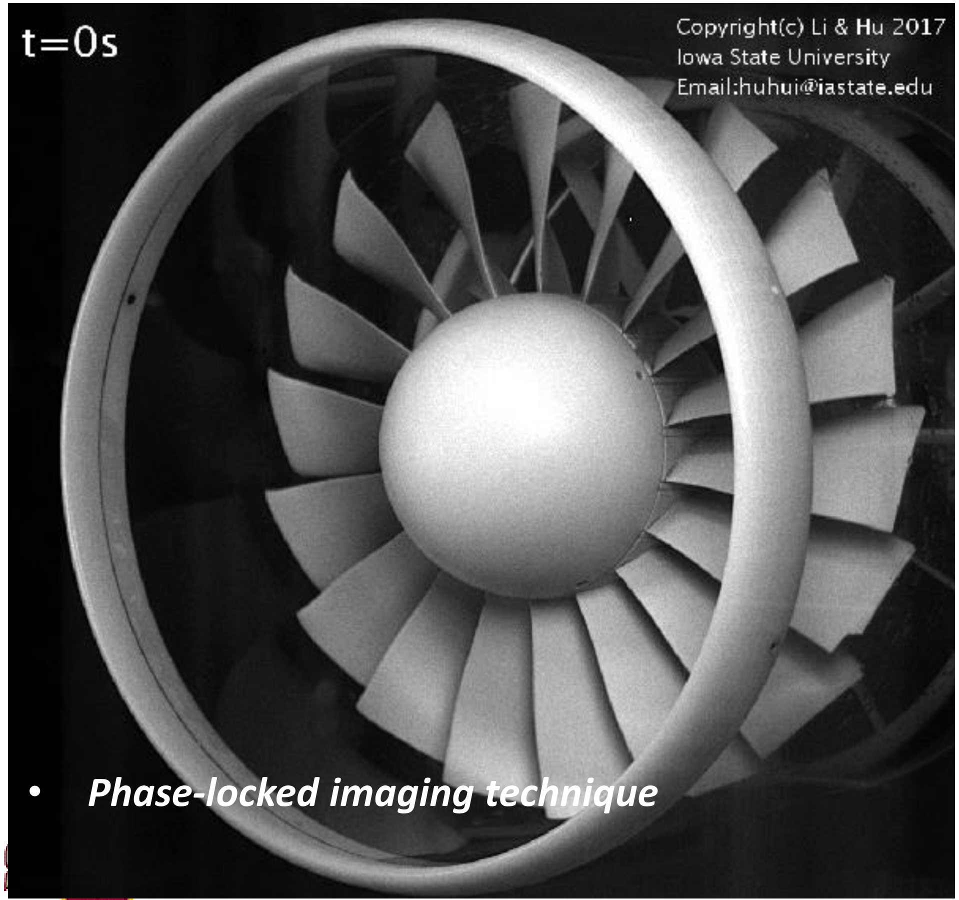
Dynamic Ice Accreting Process over Rotating Fan Blades

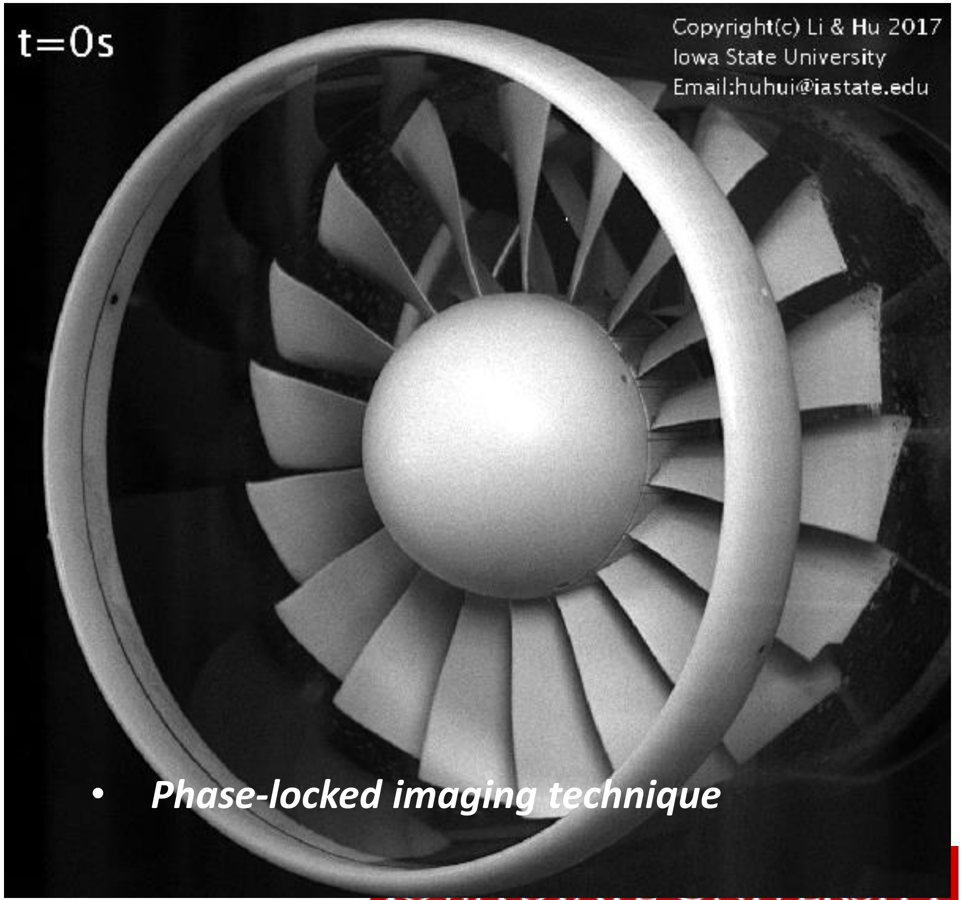
Glaze icing condition:

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

Rime icing condition:

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



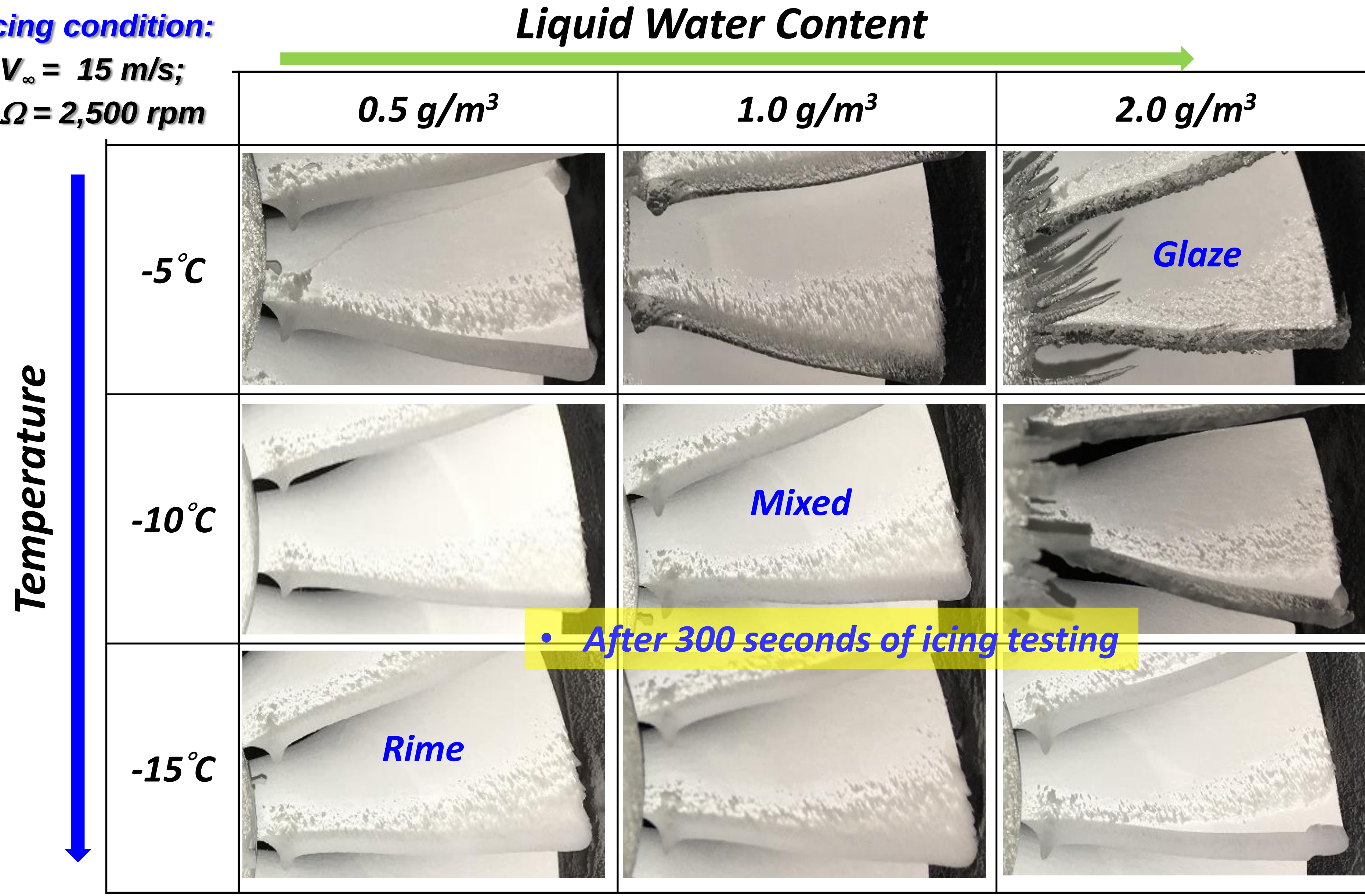


- *Phase-locked imaging technique*
- *Phase-locked imaging technique*

❑ Dynamic Ice Accreting Process over Rotating Fan Blades

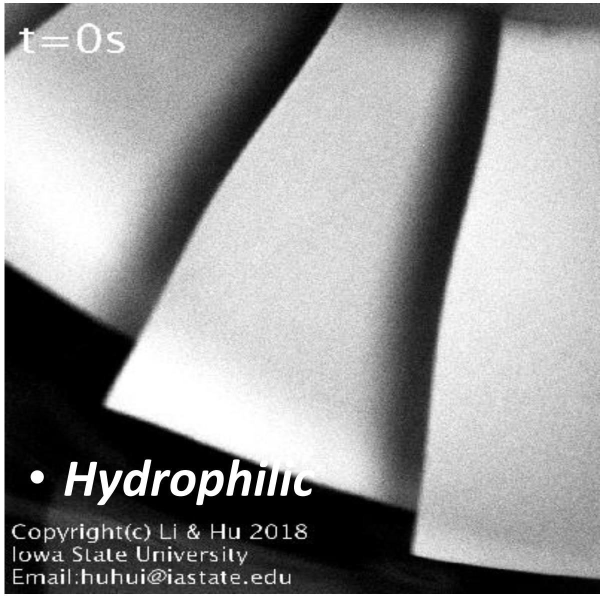
Icing condition:

- V_{∞} = 15 m/s;
- Ω = 2,500 rpm



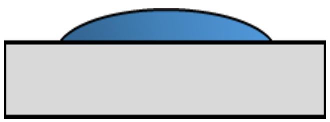
Hydro-/Ice-Phobic Coatings for Aero-Engine Icing Mitigation

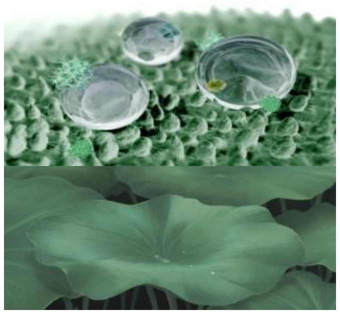
- $V_\infty = 20$ m/s;
- $T_\infty = -10$ ℃;
- LWC = 2.0 g/m^3;
- n = 2,500rpm



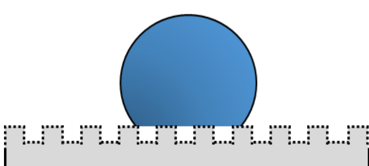
- After 300 seconds of icing testing

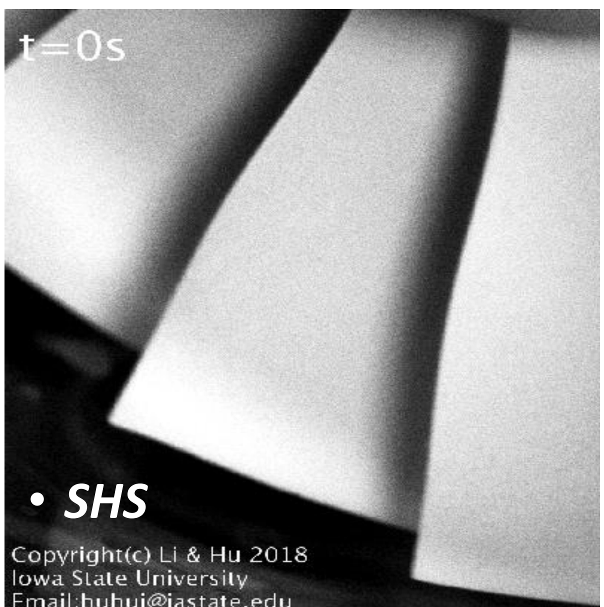
Hydrophilic
(Baseline, CA=65 deg.)

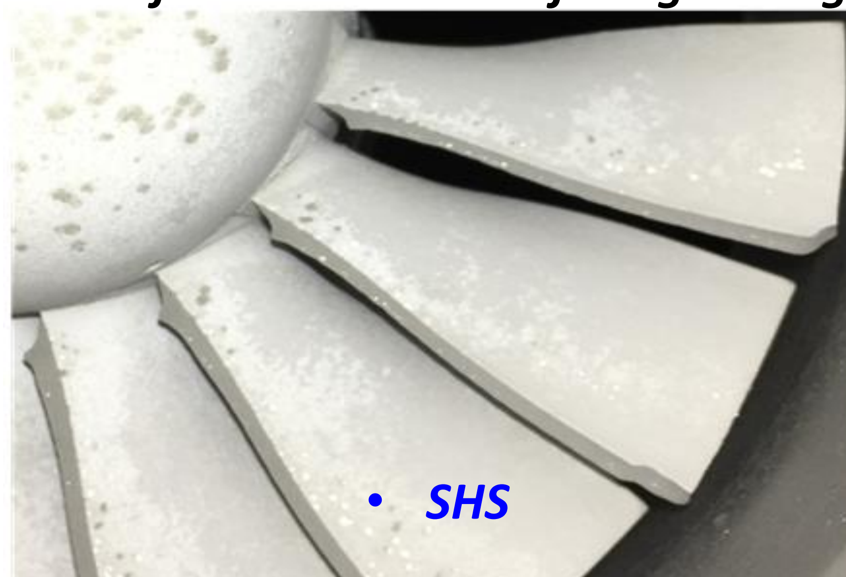




Super-hydrophobic
(CA=160 deg.)

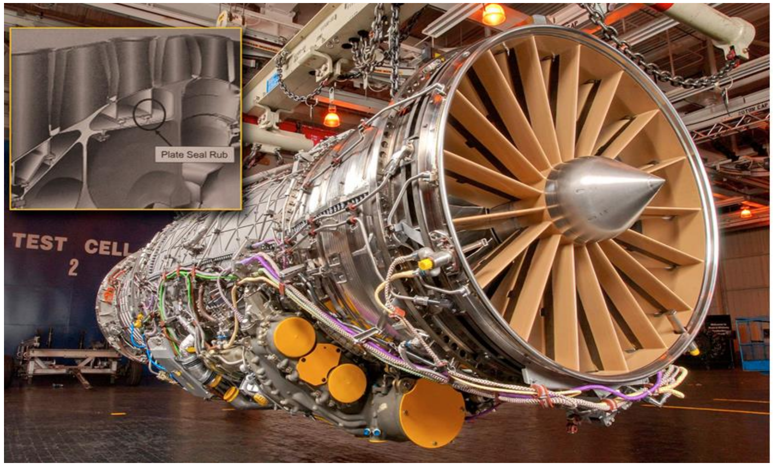


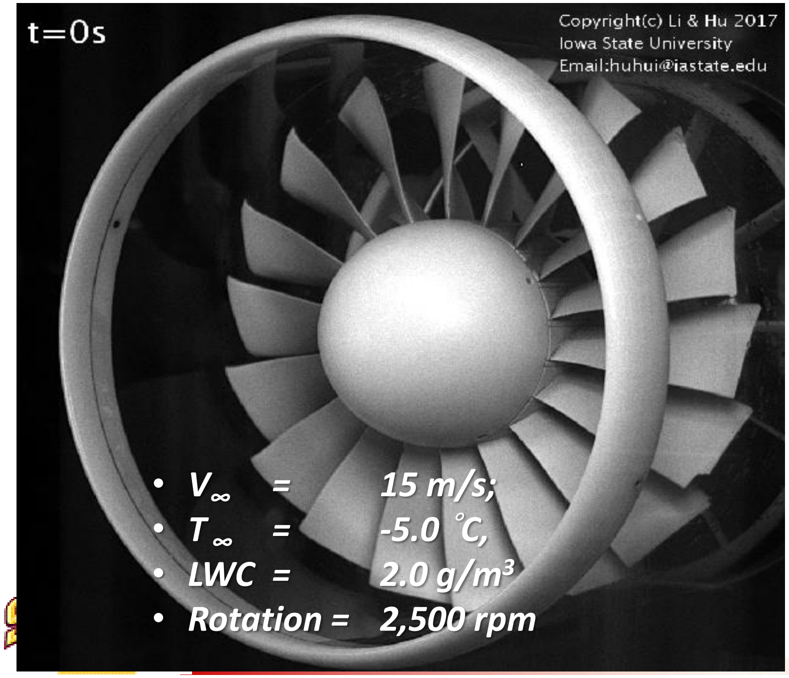




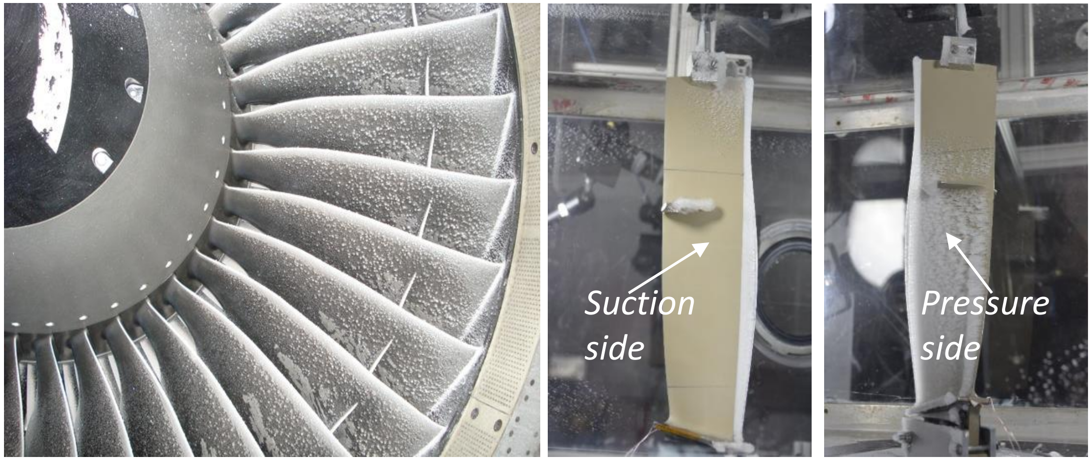
❑ Durable Metal-based Icephobic Coating for Aero-Engine Icing Protection

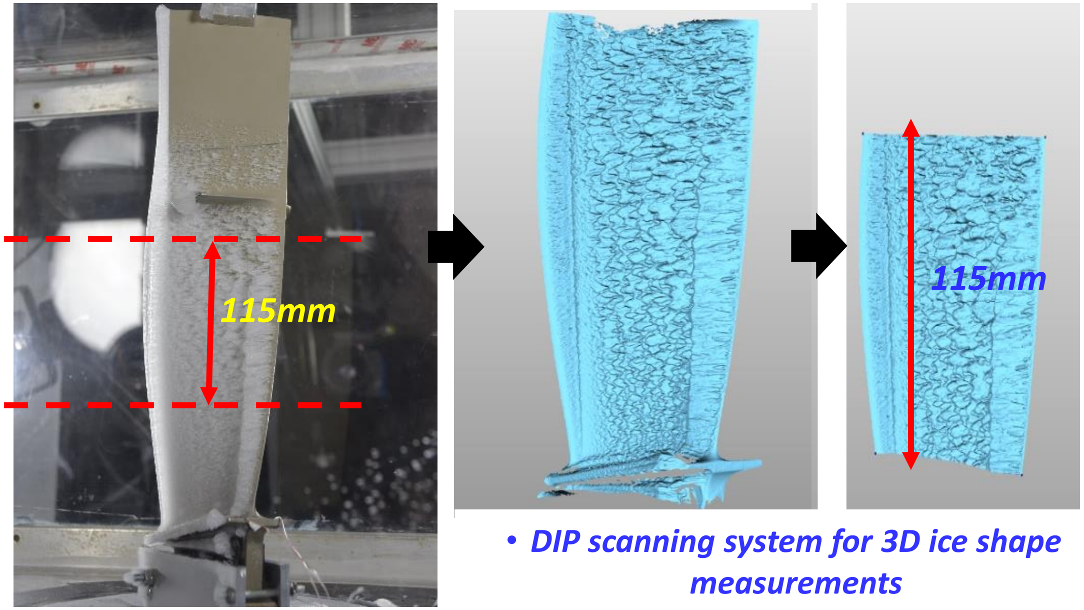
- *Project currently funded by NAVY STTR 1&2*





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





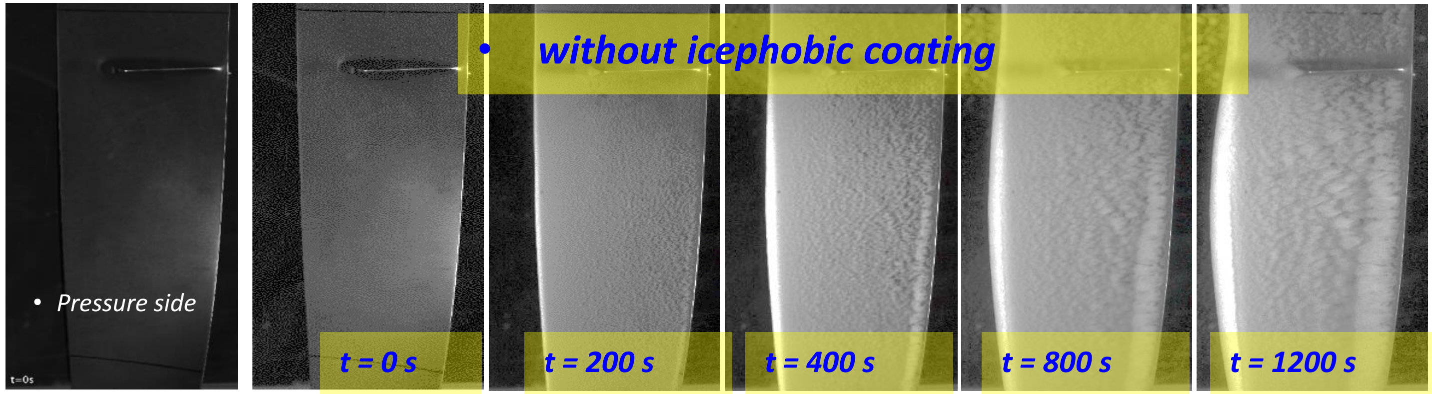
- *DIP scanning system for 3D ice shape measurements*

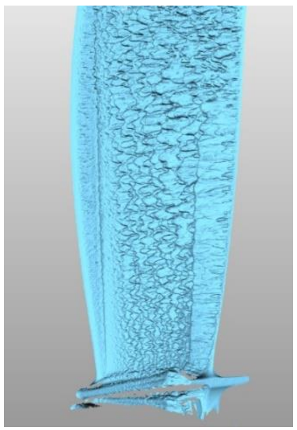
❑ Icing mitigation over Fan Blades with Durable Icephobic Coatings

Test conditions:

- V_∞=50m/s;
- T_∞ = -18°C;
- LWC=0.3 g/m³

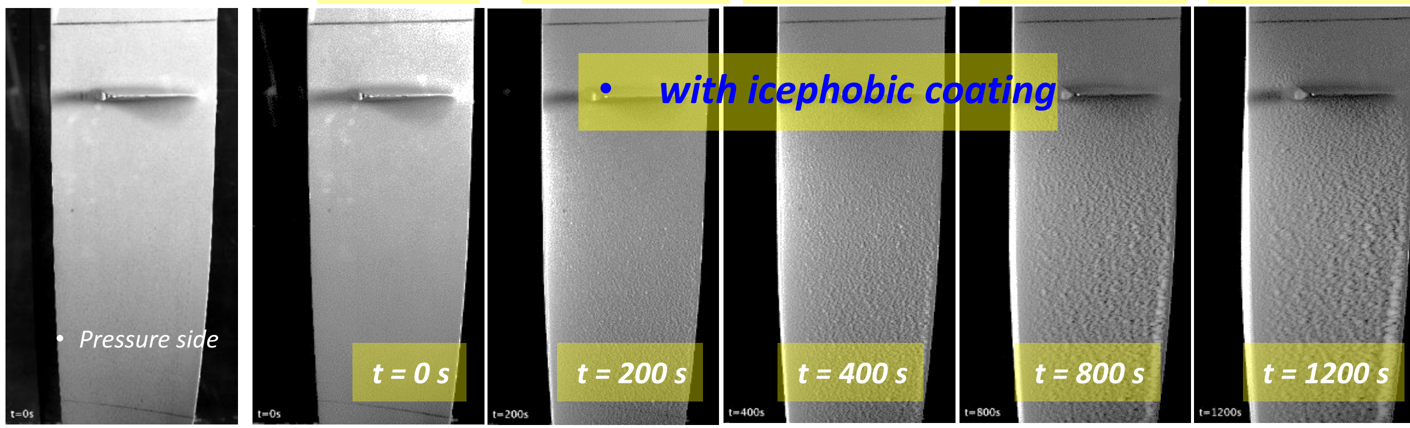
V_∞

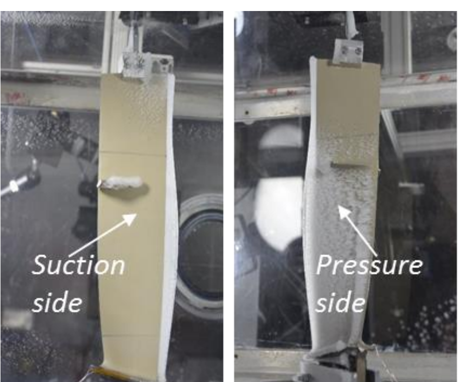


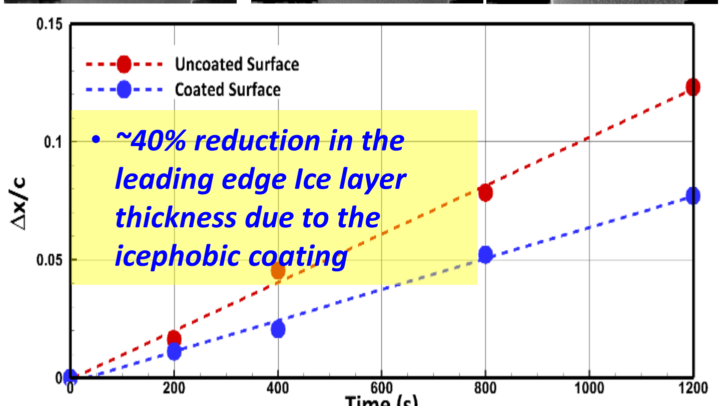


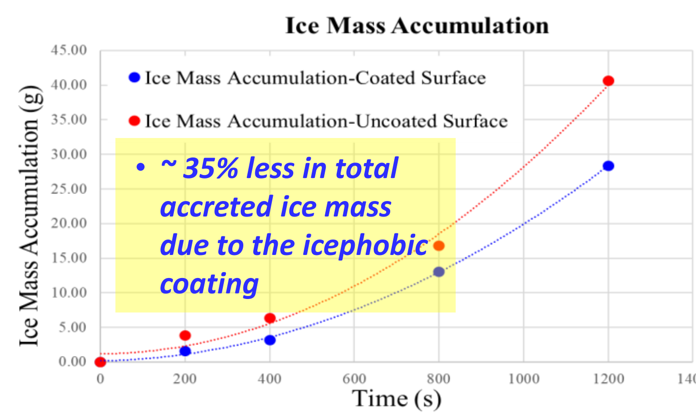
- DIP based 3D scanning results

V_∞



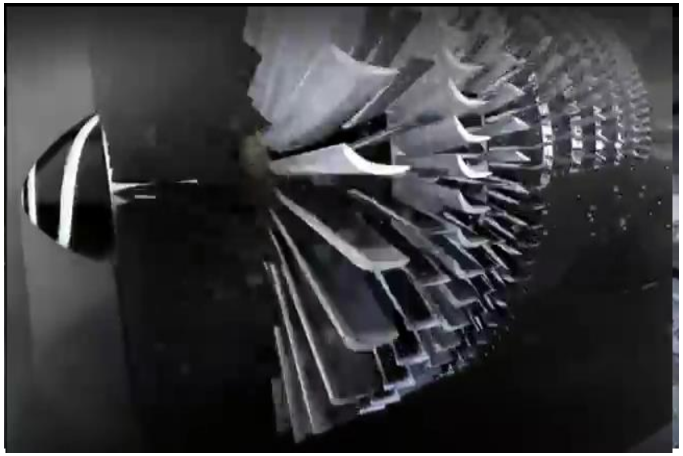




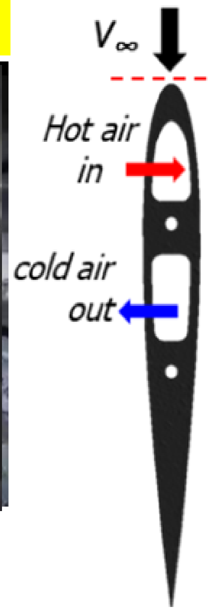


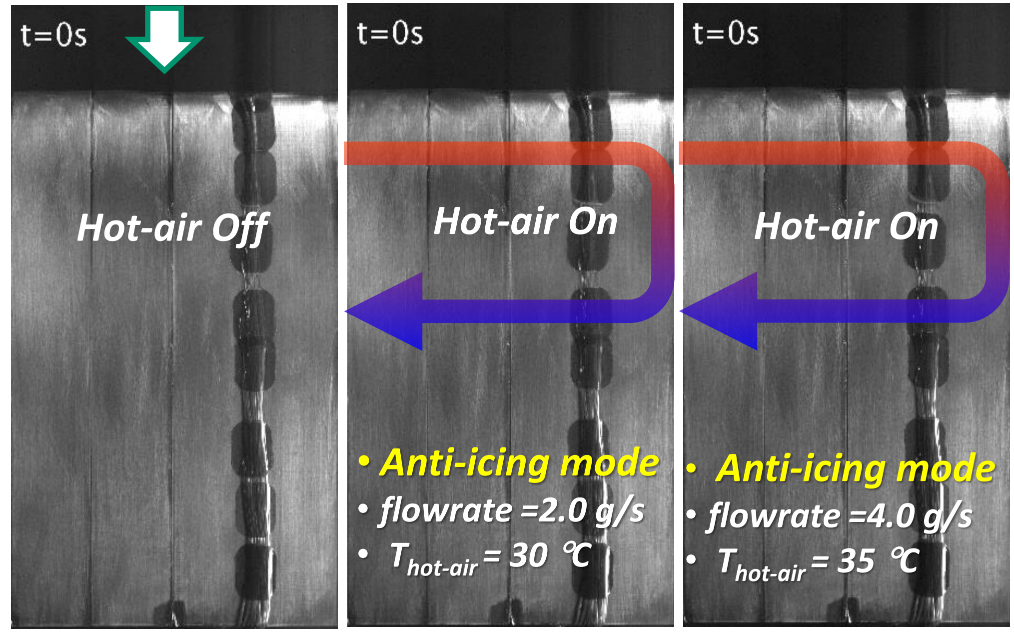
❑ Hot-Air-Based Anti-/De-Icing System for Engine Inlet-Guild-Vanes

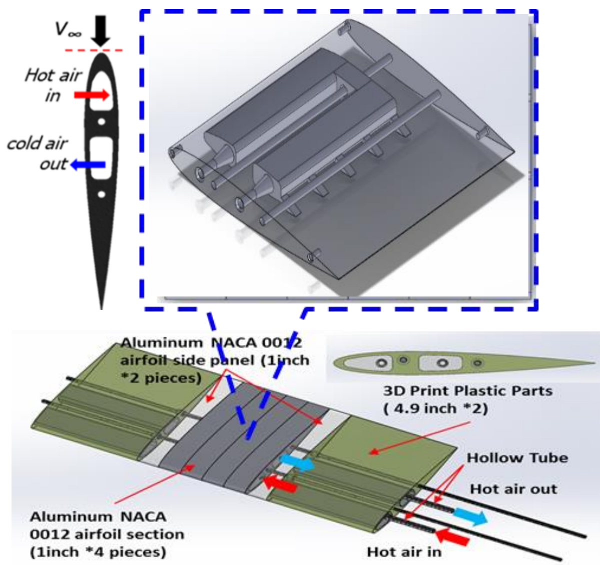
- *Project currently funded by P&W*



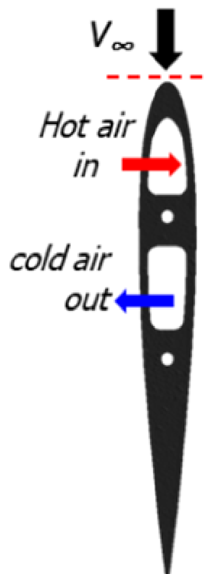
- *Ice accretion on Inlet-Guild-Vanes (IGV)*

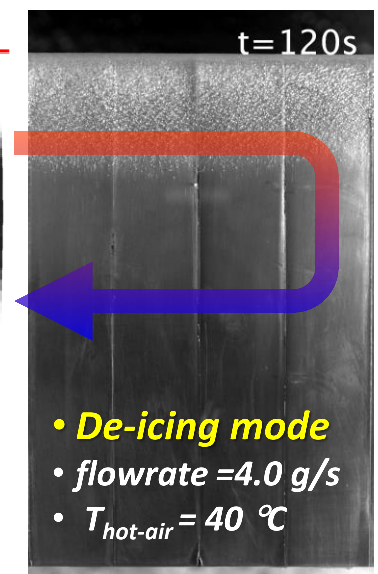


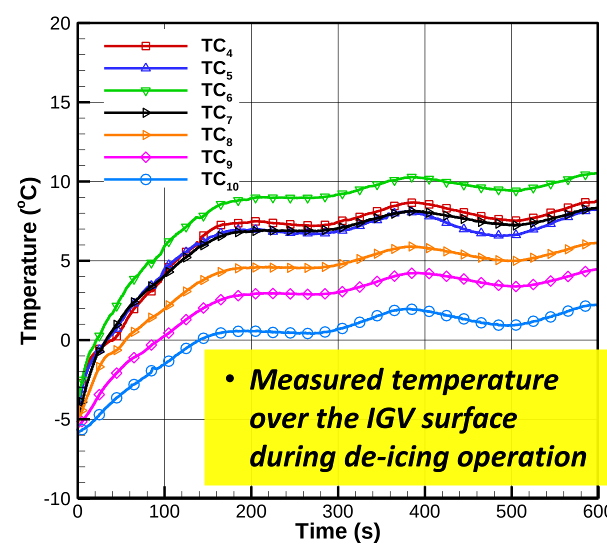




Hot-air-based IGV anti-/de-icing system







- *Measured temperature over the IGV surface during de-icing operation*

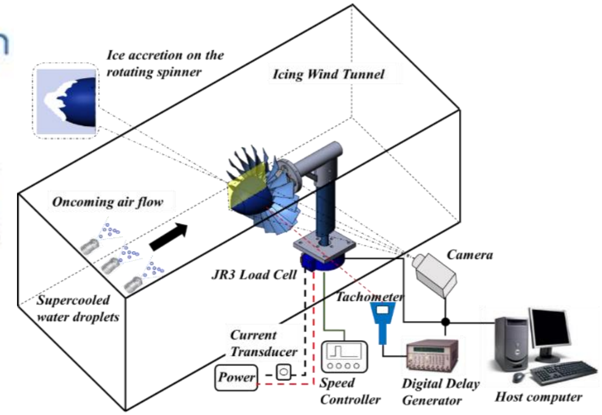
❑ RR, PW, GE Engines – Different Shapes of Engine Spinners

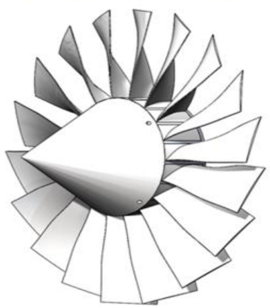
Rolls-Royce | Pratt & Whitney, A United Technologies Company | GE Aviation

- *RR Trent-XWB*

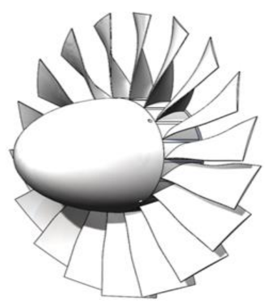
- *PW 1000G*

- *GE 90*

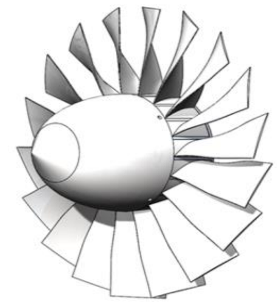




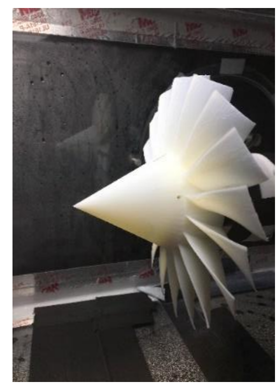
- *Conical spinner*

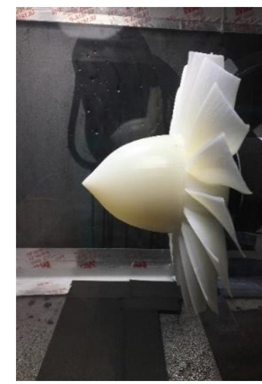


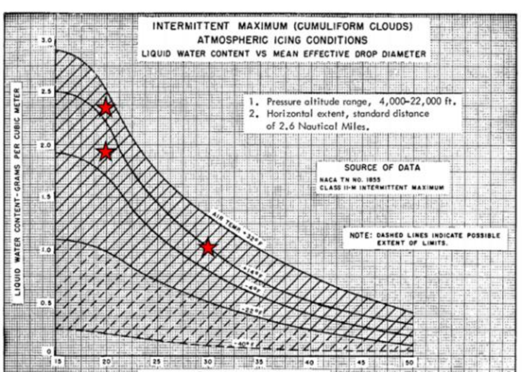
- *Elliptical spinner*



- *Coniptical spinner*



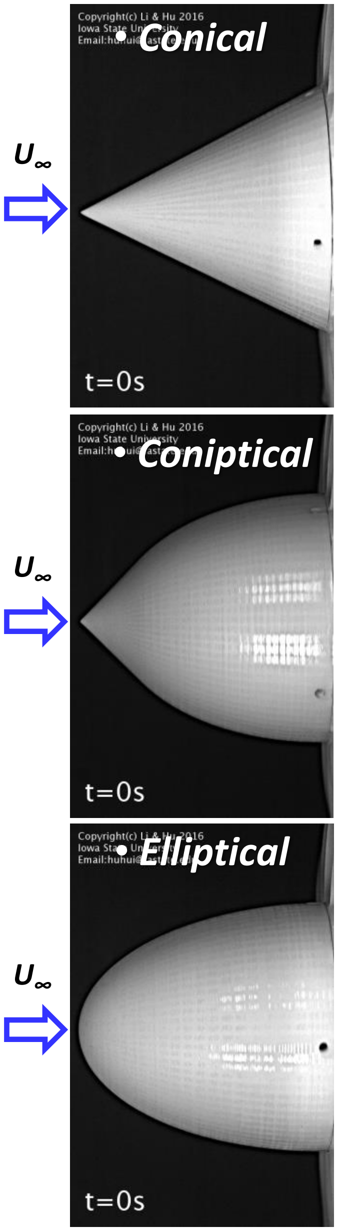


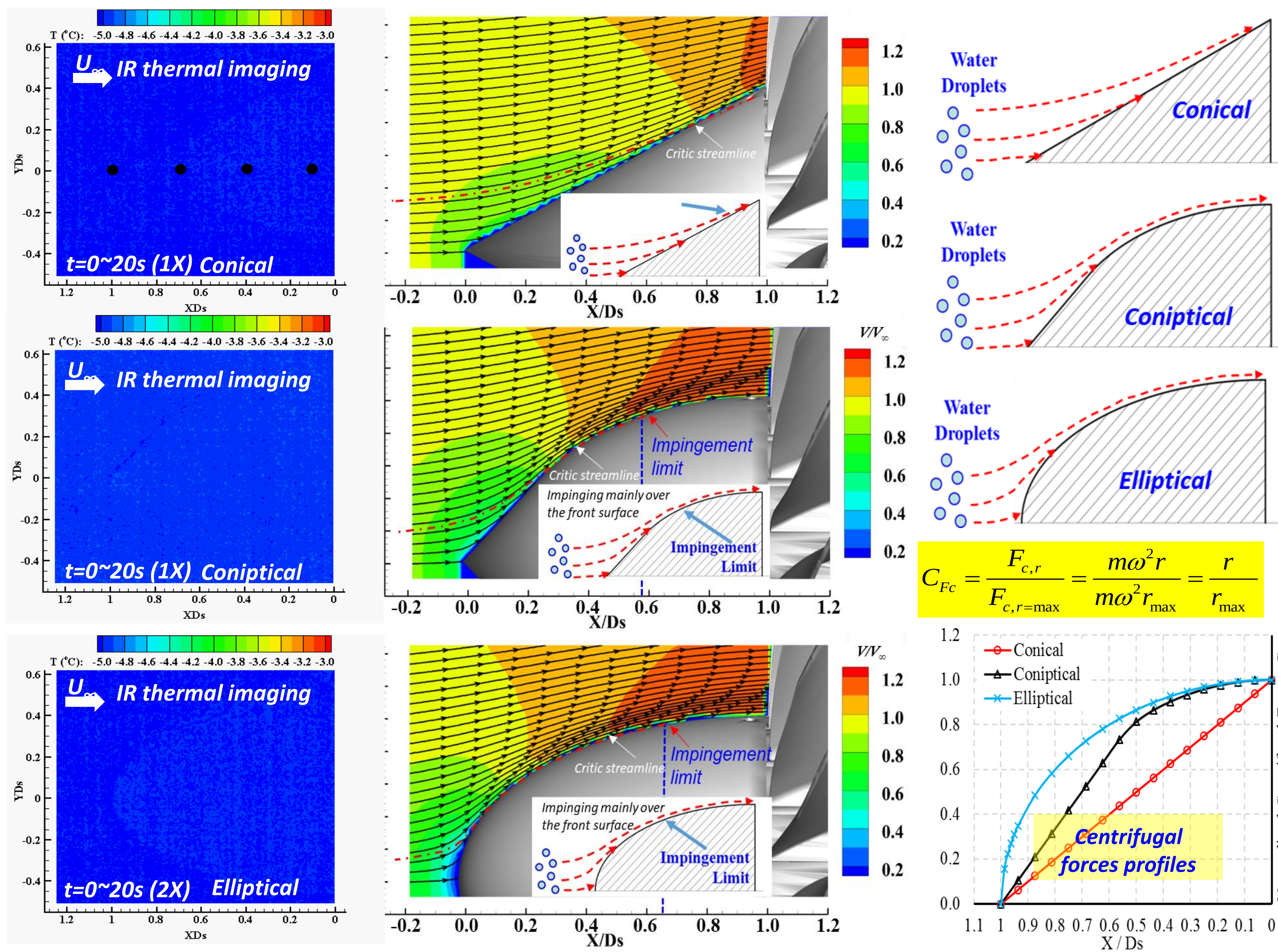


Intermittent maximum atmospheric icing conditions from 14 CFR Part 25 Appendix C[1]

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/m³)	0.1 ~ 2.0	0.6 ~ 2.4
Advanced Ratio, J	1.80	1.80

❑ 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.*

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  - ***Current Graduate Students:*** *ZC Zhang; R. Veerakumar; HY Hu; NH Han; LQ Tian; M. Siddique; F. Al-Masri (MS)*
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Hu Lab's Summer BBQ Party on 08/14/2019

Thank You Very Much For Your Time!
Questions?

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