Altitude Effects on Thermal Ice Protection System Performance; a Study of an Alternative Simulation Approach

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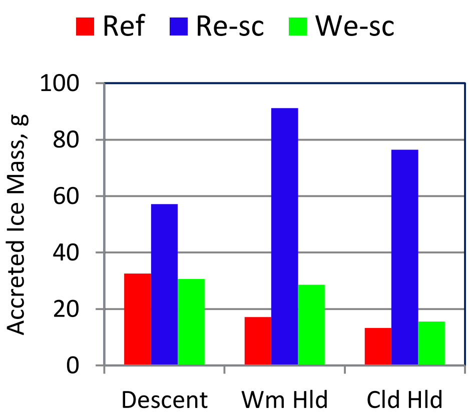
Presentation will include:



- Need for Study
- Initial test results
- Study Plan
- Development of alternate scaling method
- Flight scenarios
- Reference & Scaled test conditions
- Test Description & Results
- Summary

Need for Study

Aircraft efficiency ↑

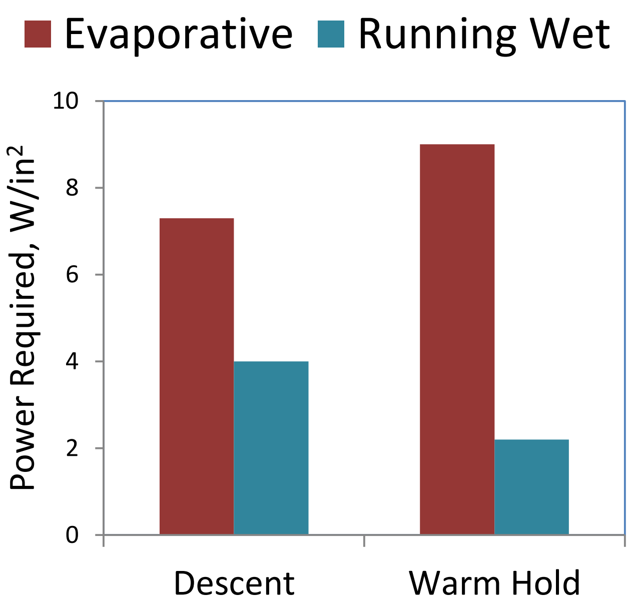
↳ Onboard power available ↓

↳ Thermal IPS power ↓

↳ Running wet vs. evaporative

↳ Develop and test thermal IPS at ground level icing facility

↳ NEED:
- Method to account for altitude effects
- Validation data for Computational tools

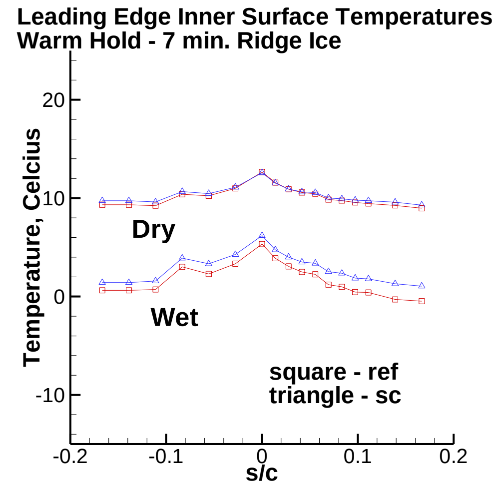


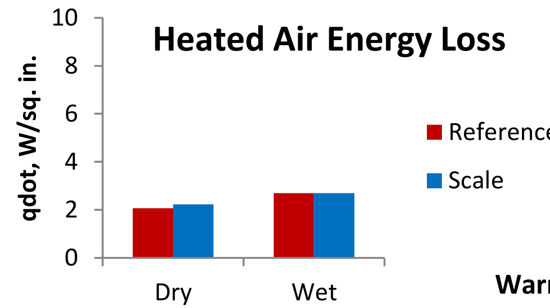
Example IPS power

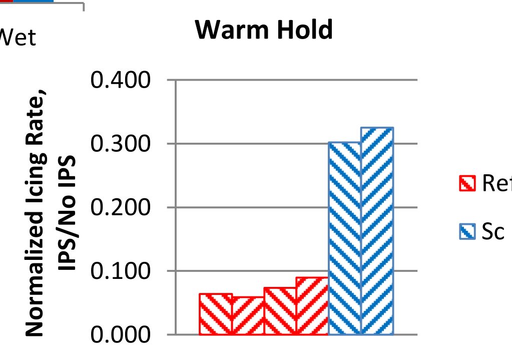
Initial Study & 2012 Test

- Objectives:
  - Study physics
  - Test altitude scaling method (Re)
- Outcomes
  - Heat transfer scaled well
  - Mass transfer did not
  - Water drops blown off surface?

AIAA 2013-2934

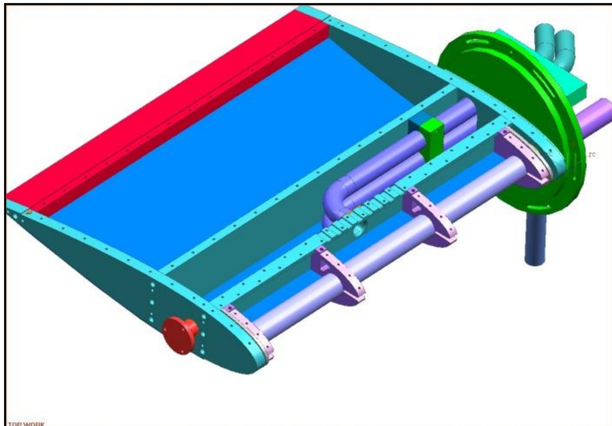


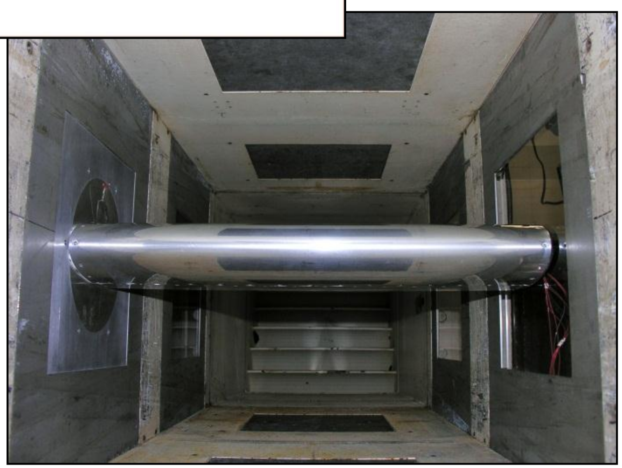




Study Plan

$$[\text{Icing Conditions}]_{\text{altitude}} = [\text{Icing Conditions}]_{\text{ground level}}$$





- Define scaling method (alt/grd)
- Altitude Icing Wind Tunnel (AIWT)
- NACA airfoil with Heated Air IPS
- Various icing scenarios
- IPS operated in running wet mode
- Compare results: ice accreted, surface temps, heat rejection
- Assess scaling method, insight on processes

Thermal IPS Scaling Method

Parameters matched:

- Reynolds number — $Re = \rho V d/\mu$, d=2xLE radius
- Water loading — $M_w = LWC \cdot V \cdot \beta$
- Impingement — $K_0 = f(Re_{droplet})$
- Recovery temperature — $T_r = T_s(1+r((\gamma-1)/2)M^2)$

Also matched: RHF, H_c, H_g, Nu, Sh, St, St_m

Not matched: ή, We

Alternate Thermal IPS Scaling Method

Parameters matched:

- Weber number $We = \rho_w \cdot V^2 \cdot d/\sigma$, d=2xLE radius
- Water loading $M_w = LWC \cdot V \cdot \beta$
- Impingement $K_0 = f(Re_{droplet})$
- Recovery temperature $T_r = T_s(1+r((\gamma-1)/2)M^2)$
- Model leading edge surface temperatures*

Not matched: Re, ή, RHF, H_c, H_g, Nu, Sh, St, St_m

*Requires two steps: Re match run (dry) followed by We match

Flight Scenarios for study

- Descent
- Cold Hold
- Warm Hold

Reference Conditions

Flight phase	Alt., m	V, kt	AOA, deg	T_s, °C	LWC, g/m^3	MVD, µm
Descent	3048	180	0	-14	0.35	20
Cold Hold	4572	180	0	-30	0.24	20
Warm Hold	4572	180	0	-9	0.50	20

Altitude Thermal Scaling Study

Reference and corresponding scale conditions

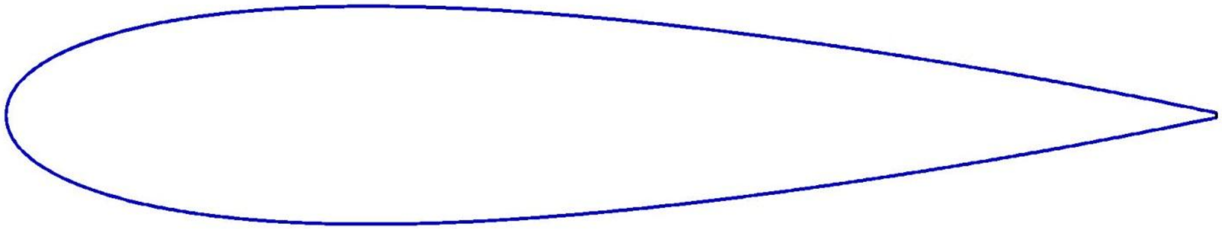
Flight phase	Alt. m	V kt	T_s °C	LWC g/m³	MVD µm	Re-2xr x10⁶	We-2xr x10⁶	M_w g/m²-s	K_0	T_r °C
Descent (ref)	3050	180	-14	0.35	19.6	1.58	4.30	20.3	1.37	-10
(Re sc)		130	-12	0.49	24.0	1.58	2.24	20.3	1.37	-10
(We sc)		180	-14	0.35	21.1	2.15	4.30	20.3	1.37	-10
Cld Hld (ref)	4570	180	-30	0.24	17.4	1.43	4.30	13.4	1.23	-26
(Re sc)		106	-28	0.41	24.2	1.43	1.49	13.4	1.23	-26
(We sc)		180	-30	0.24	19.5	2.35	4.30	13.4	1.23	-26
Wm Hld (ref)	4570	180	-8	0.54	17.7	1.26	4.30	30.3	1.24	-5
(Re sc)		106	-6	0.91	24.5	1.26	1.50	30.3	1.24	-5
(We sc)		180	-8	0.54	19.8	2.08	4.30	30.3	1.24	-5

Facility

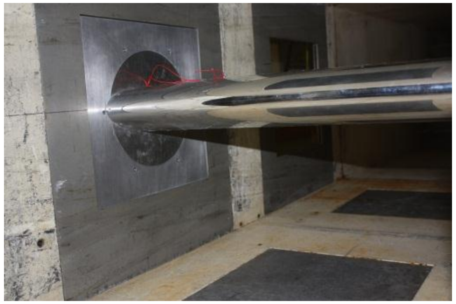
- NRC Canada Altitude Icing Wind Tunnel (AIWT)

- Test Section: 57 cm x 57 cm (22.5 in. x 22.5 in.)
- Airspeeds: 10 – 194 kts
- Air Temp: -35^{o}C to +40^{o}C
- LWC: 0.1 to 3 g/m^3
- MVD: 8 to 100 μm
- Altitude simulation: ground level to 9100 m

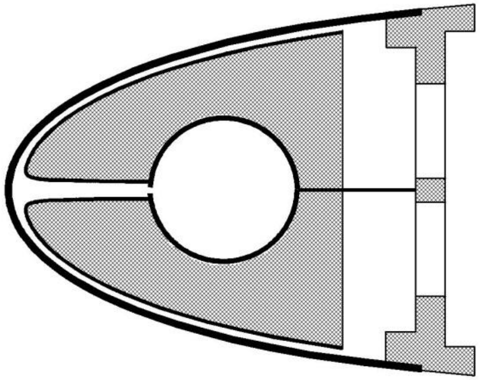
Model



NACA 0018, 45.7 cm (18 in.) chord



- Simple design to study fundamentals
- Aluminum skin on aluminum spar and rib frame

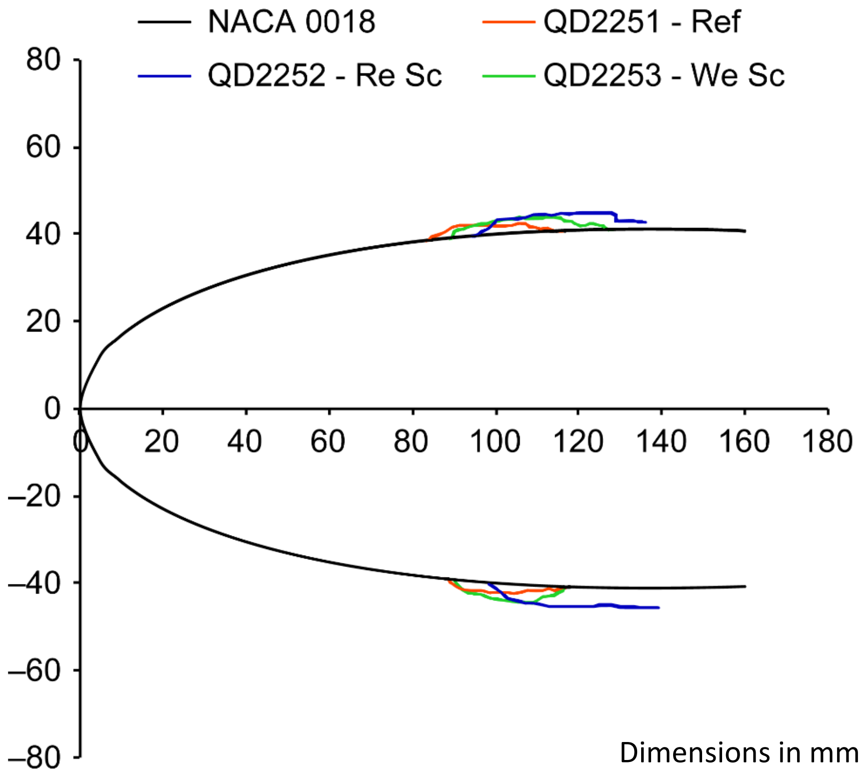


Heated Air IPS

- 2D flow
- Piccolo tube, single row of holes

Runback Ice - Descent

	Alt m	P_{alt} kPa	V kt	T_s °C	LWC g/m³	MVD µm	Tau s	Ice g
(Ref)	3048	69.7	180	-14.1	0.38	19.5	600	32.6
(Re-sc)	453	96.0	130	-12.4	0.50	24.3	600	57.2
(We-sc)	775	92.3	180	-14.2	0.36	21.5	600	30.6

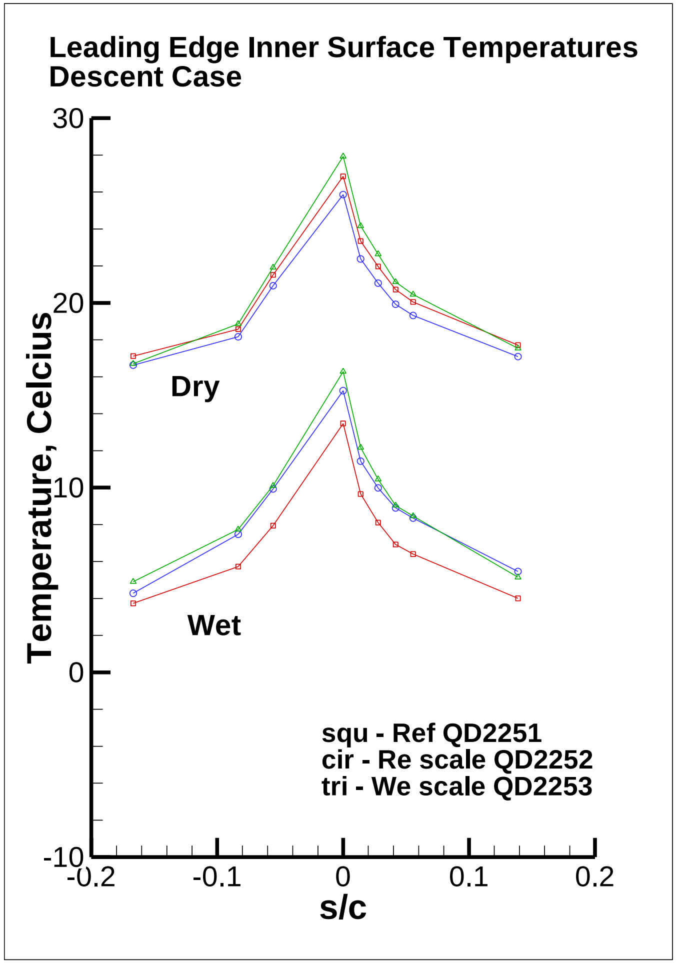


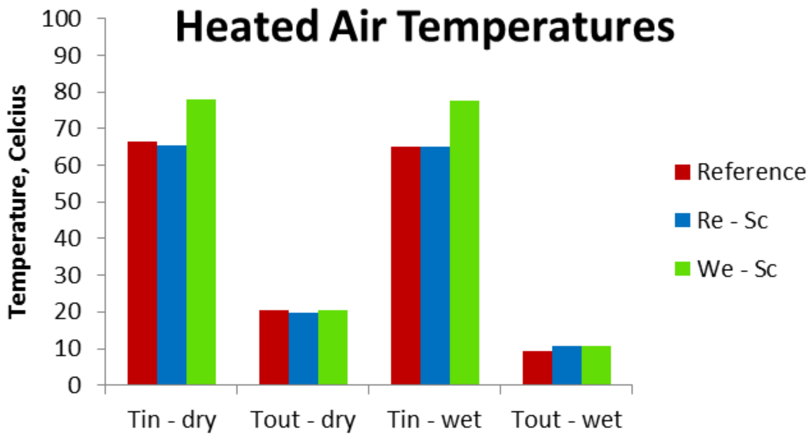
(Ref)

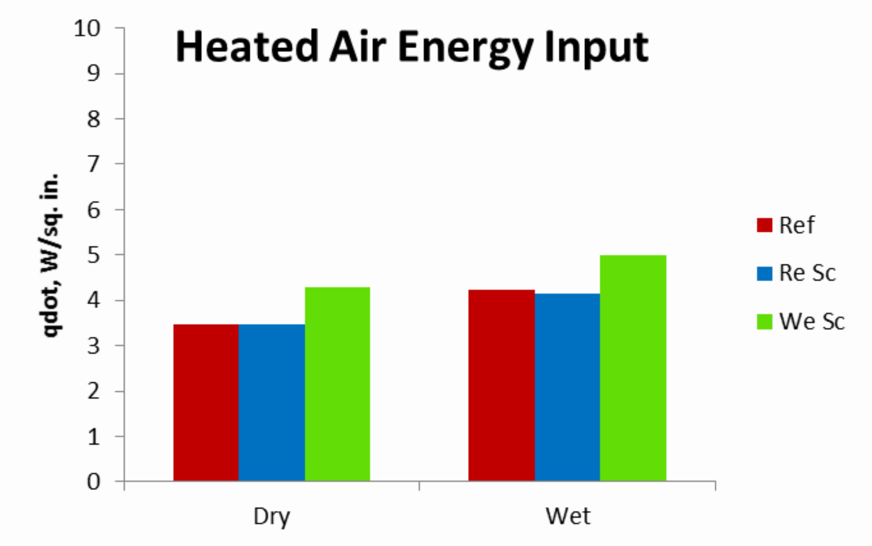
(Re - sc)

(We - sc)

Runback Ice - Descent



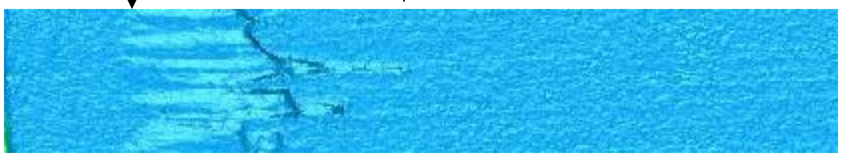




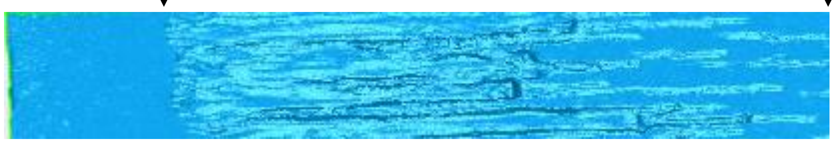
Runback Ice – Warm Hold

	Alt m	P_{alt} kPa	V kt	T_s °C	LWC g/m³	MVD µm	Tau s	Ice g
(Ref)	4572	57.2	180	-8.6	0.56	17.7	420	17.1
(Re-sc)	314	97.6	106	-6.1	0.83	24.5	420	91.2
(We-sc)	828	91.8	180	-8.4	0.56	19.8	420	28.6

Ice begins Ice ends



Ice begins Ice ends



Ice begins Ice ends

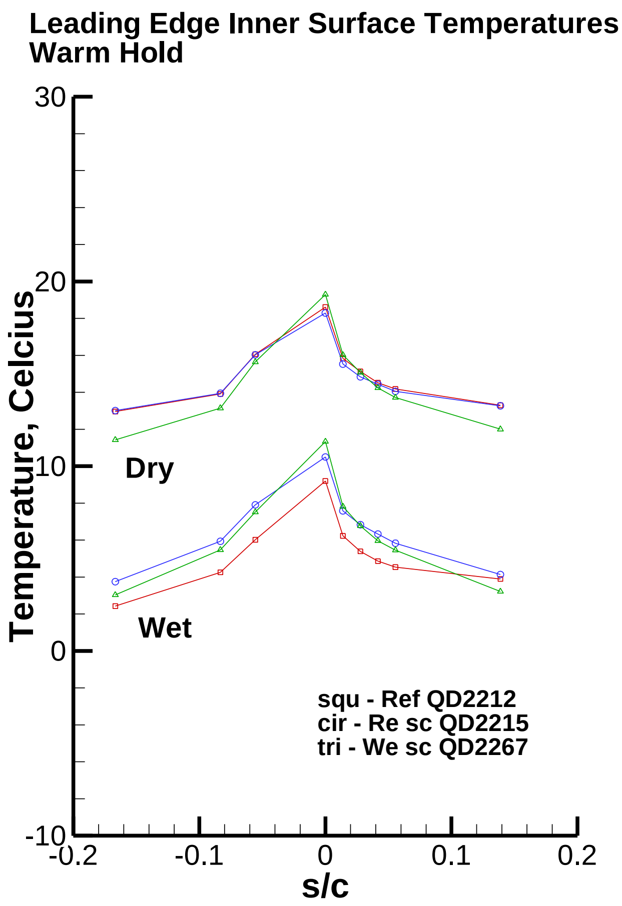
- No tracings

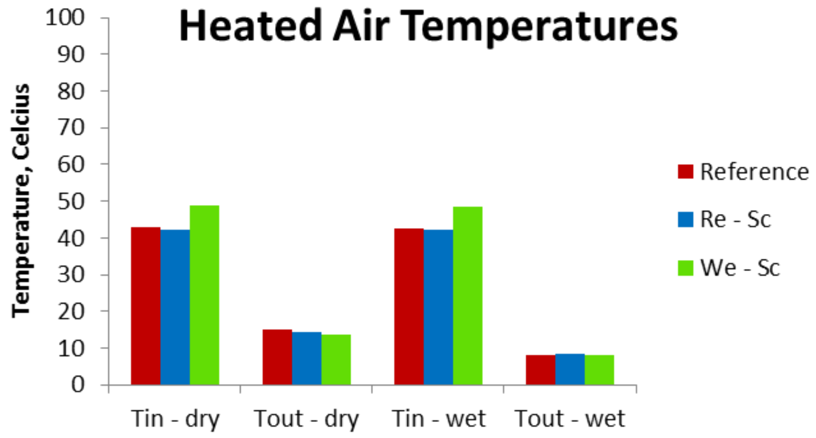
(Ref)

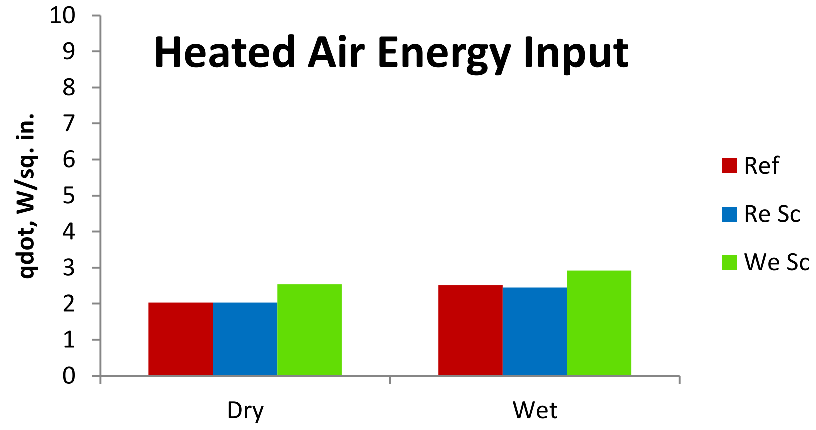
(Re - sc)

(We - sc)

Runback Ice - Warm Hold



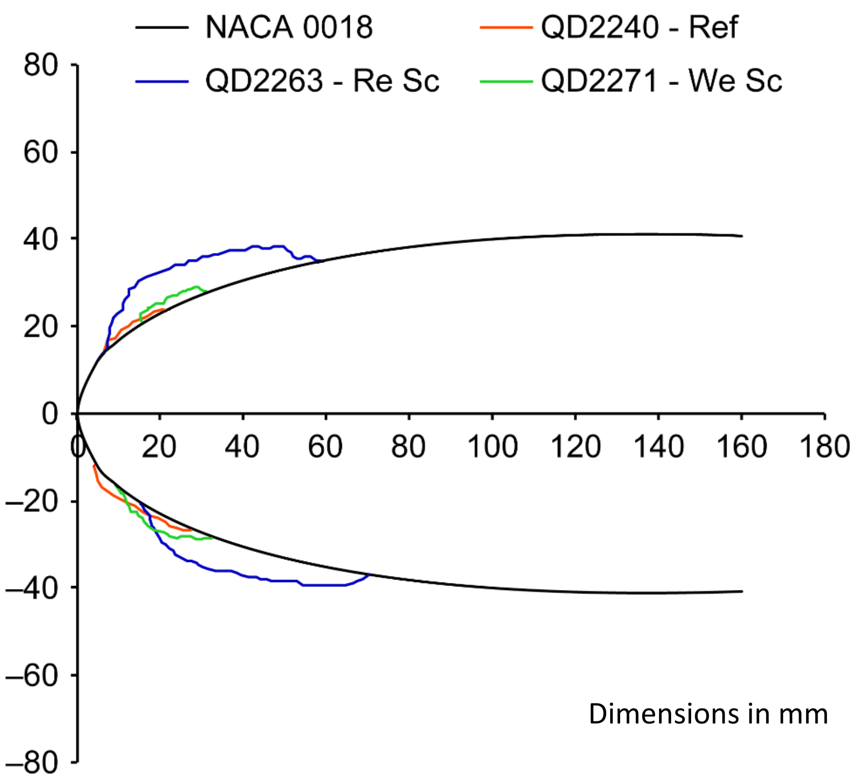




Runback Ice – Cold Hold

	Alt m	P_{alt} kPa	V kt	T_s °C	LWC g/m^3	MVD μm	Tau s	Ice g
(Ref)	4572	57.2	180	-30.0	0.24	17.4	600	13.3
(Re-sc)	390	96.7	106	-27.5	0.41	24.2	600	76.5
(We-sc)	781	92.3	180	-29.8	0.24	19.5	600	*15.5**

** Ice remaining after partial ice shed*

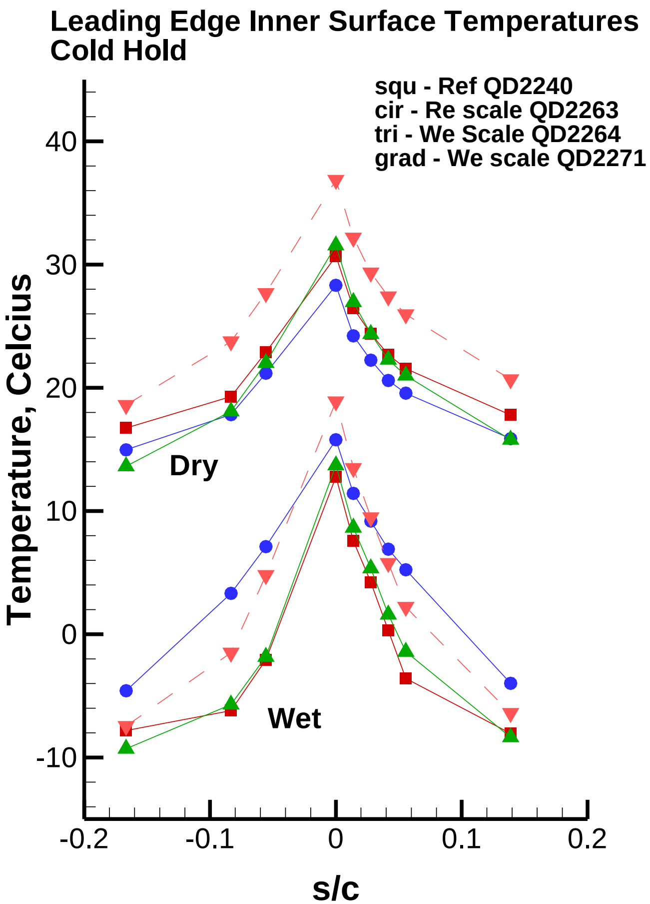


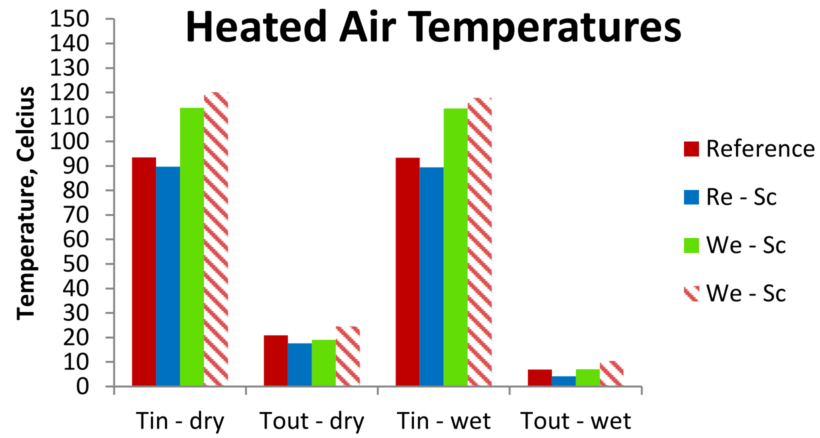
(Ref)

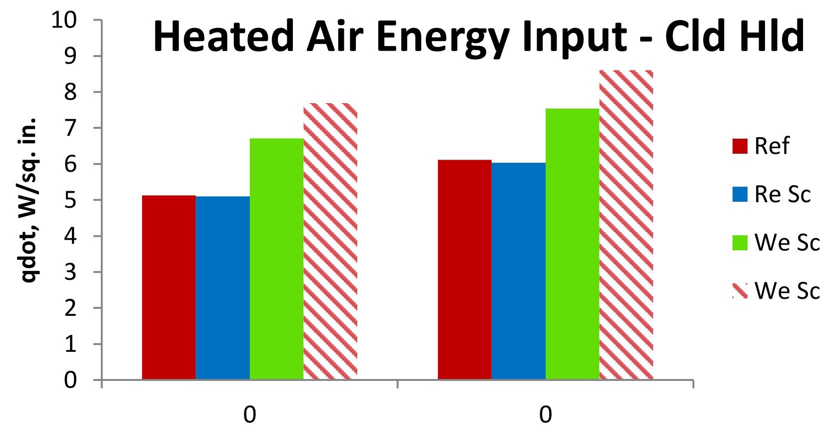
(Re - sc)

(We - sc)

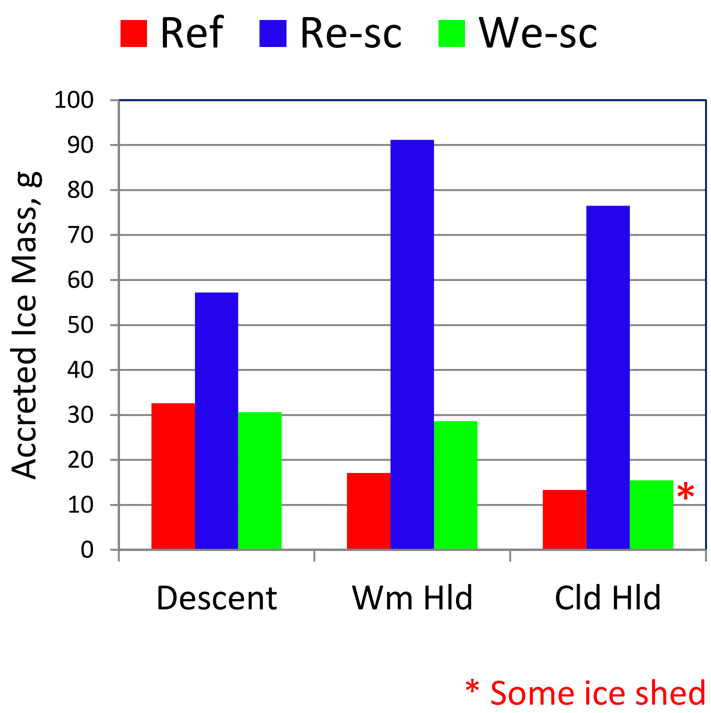
Runback Ice – Cold Hold







Runback Ice Mass



- More ice accreted for Re-scaled conditions
- Mass of ice accreted for We-scaled conditions more similar to that accreted at reference (altitude) conditions

Summary

- Surface temperatures and heat rejection rates matched well between reference and Re-scaled conditions
- Re-scaled conditions resulted in greater mass of ice accreted
- We-scaled conditions combined with T_{surf} matching resulted in ice accretions more similar in mass and location of ice
- Greater convective cooling with We-scaling does affect freezing of runback water
- Results indicate that surface water is being re-entrained in airstream
- The two-step, Re & We scaling method produced ice accretions more similar to those at the reference altitude conditions, but differences in convective cooling warrant further investigation
- Model of water shedding being investigated
- Joint report being written

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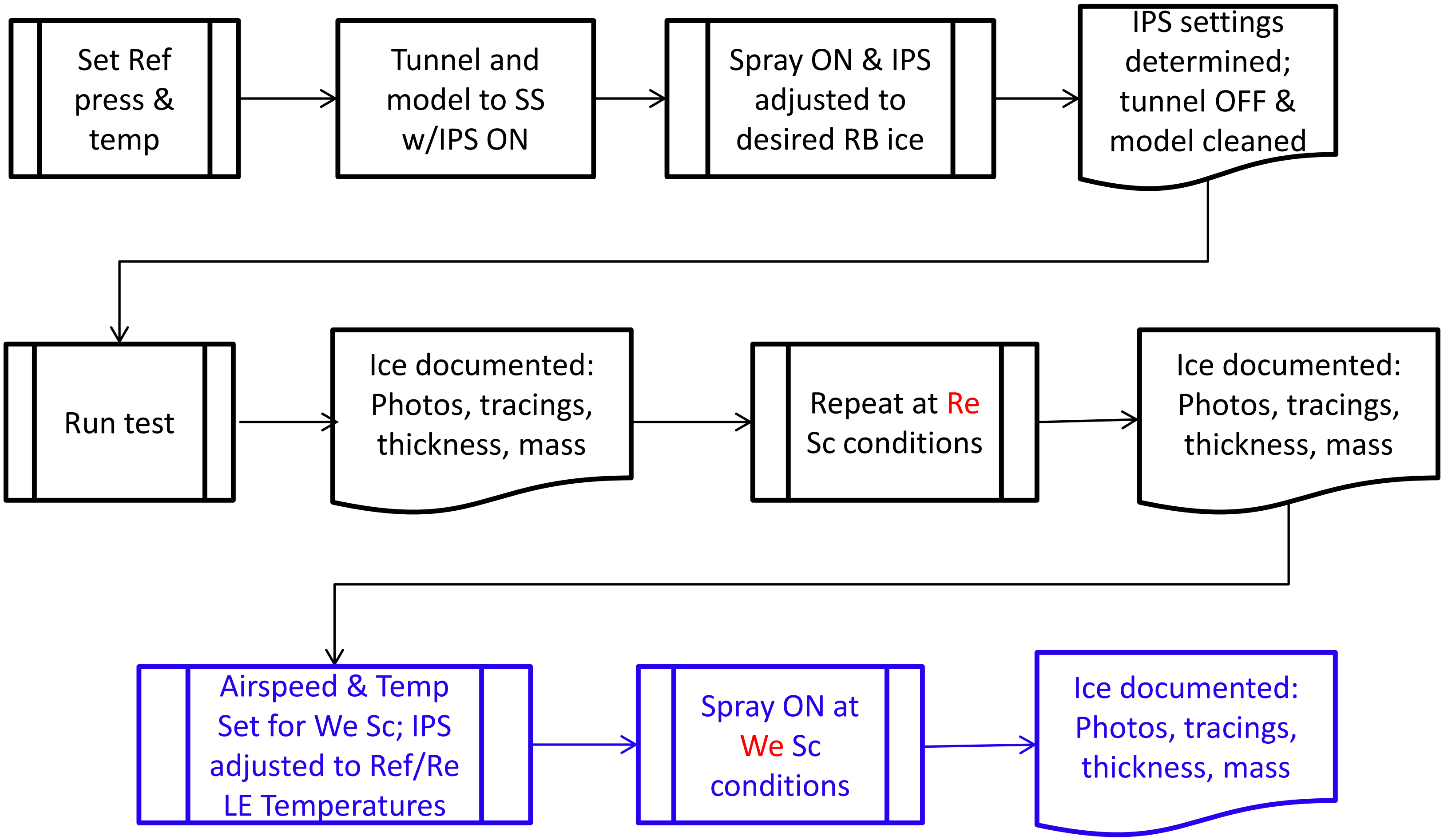
Backup Slides

Test Procedure



Nomenclature

c = model chord (18 in./45.7 cm)
d = twice the model leading edge radius
H_c = convective heat transfer coefficient
H_g = convective mass transfer coefficient
IPS = ice protection system
K = inertia parameter
K_0 = modified inertia parameter
LWC = liquid water content
M = Mach number
MVD = median volumetric diameter
M_w = water loading
Nu = Nusselt number
qdot = power density
r = recovery factor
Re = Reynolds number
$Re_{(droplet)}$ = Reynolds number based on droplet diameter
Re sc = Reynolds number scaled conditions
Ref = Reference conditions
RHF = Relative Heat Factor
s = surface distance
Sh = Sherwood number
St = Stanton number
St_m = Stanton number for mass transfer
T_r = recovery temperature
T_s = static temperature
V = true air speed
We = Weber number
We sc = Weber number scaled conditions

β = collection efficiency at stagnation
γ = ratio of specific heats for air
H = freezing fraction
μ = air viscosity
ρ = air density
ρ_w = water density
σ = surface tension, water-air