Ice Accretion Measurements on an Airfoil and Wedge in Mixed-phase Conditions

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Presented at the SAE 2015 International Conference on Icing of Aircraft, Engines, and Structures
Prague, Czech Republic, June 22-25, 2015

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  - Wedge
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- Acknowledgements

Background / Introduction

- Ingestion of atmospheric ice crystals by aircraft engines can cause ice to accrete on internal components leading to rollback, flameout, mechanical damage, etc.

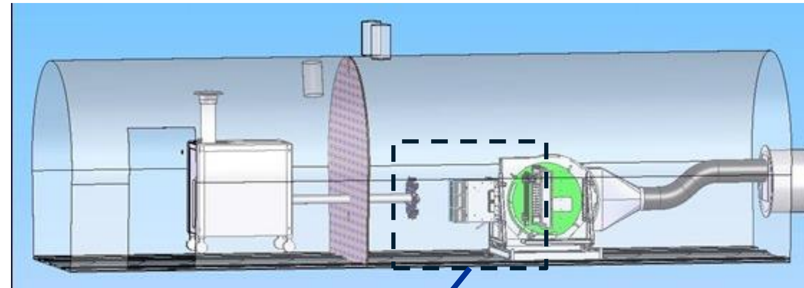
- Experiments underway to understand fundamentals of mixed-phase and ice crystal icing in jet engines
  - NASA & NRC collaborations have had 3 test entries:
    - Nov 2010
    - Mar 2011
    - Mar & Apr 2012

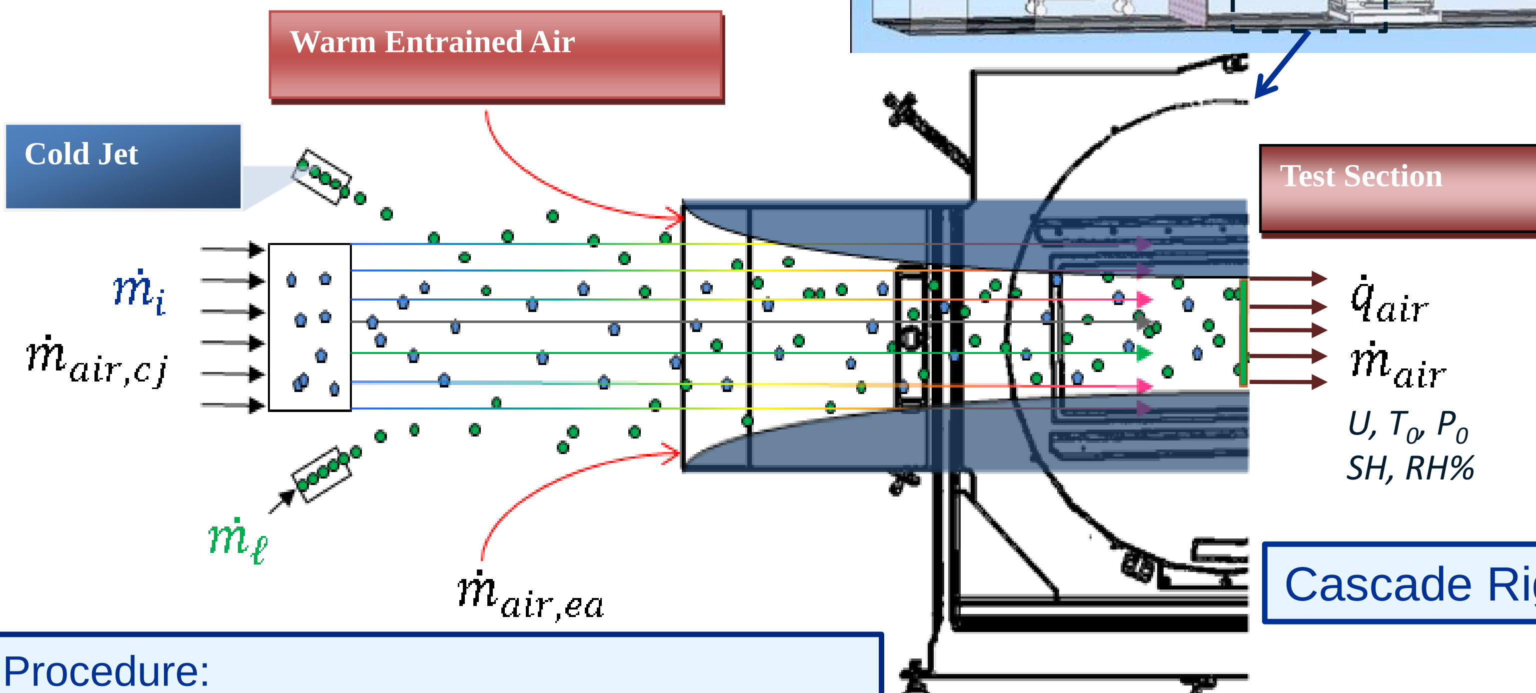
- Traditional methods of recording ice shapes (e.g. tracings and castings) were not easily adaptable to this experiment
  - Rely primarily on video imagery
    - First two test methods only captured 1D ice growth along leading edge
    - 2012 test entry produced first analyzable 2D shapes

- This paper presents the ice accretion shape and surface temperature measurements from the 2012 test entry
  - The measurements are intended to help develop models of the ice-crystal icing phenomenon associated with engine ice-crystal icing
  - However, the primary test objectives of the 2012 entry were to characterize facility and prove out imaging concepts so only limited test runs were dedicated for accretion

Experiment Overview

NRC's Research Altitude Test Facility (RATFac)





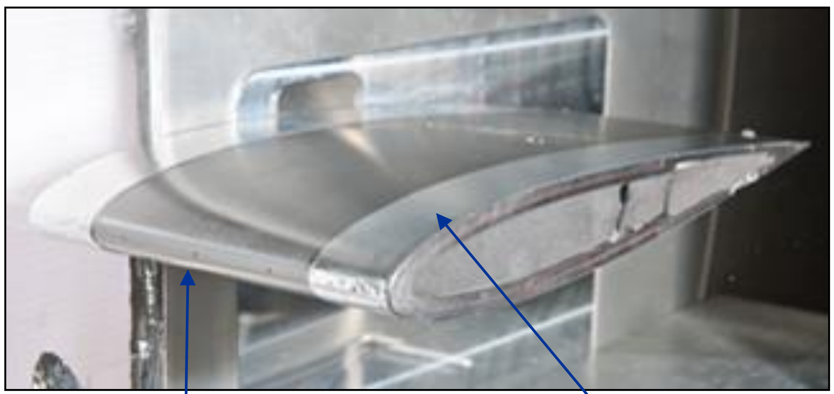
Cascade Rig

Test Procedure:

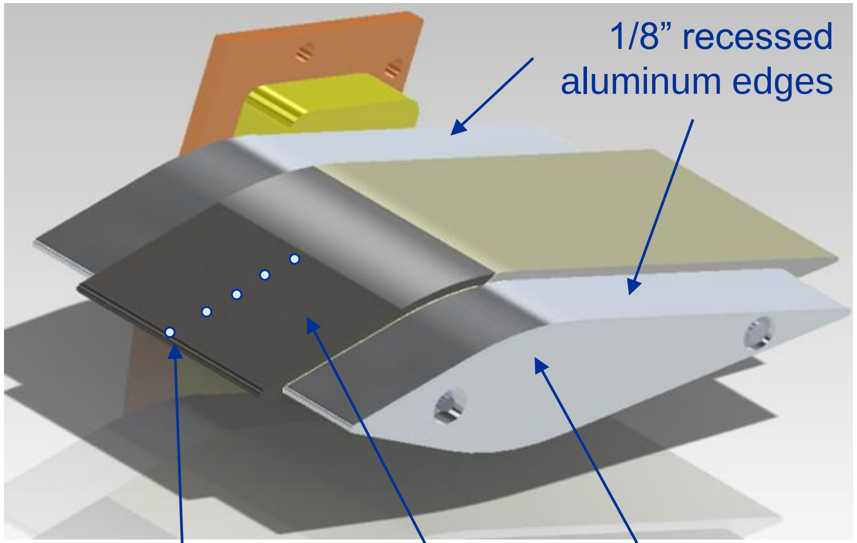
1. Set dry (cloud off) conditions
2. Turn on cloud for ~3-5 min for accretion test
3. Inserted SEA multiwire for LWC / TWC measurements

Test Articles

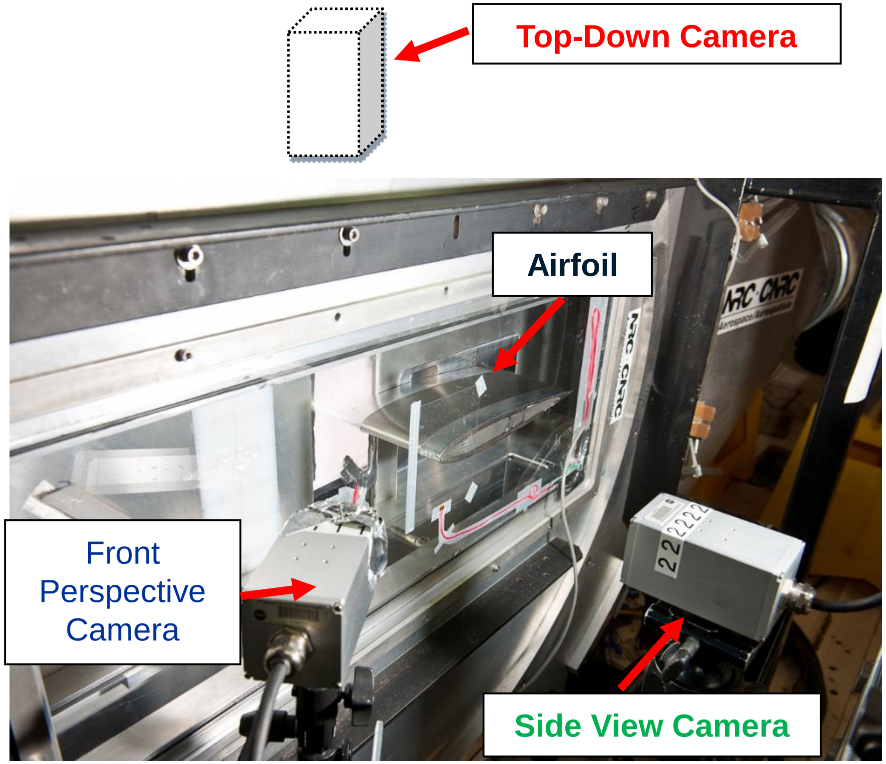
NACA 0012 Airfoil



Wedge Airfoil



Camera Setup – 2012

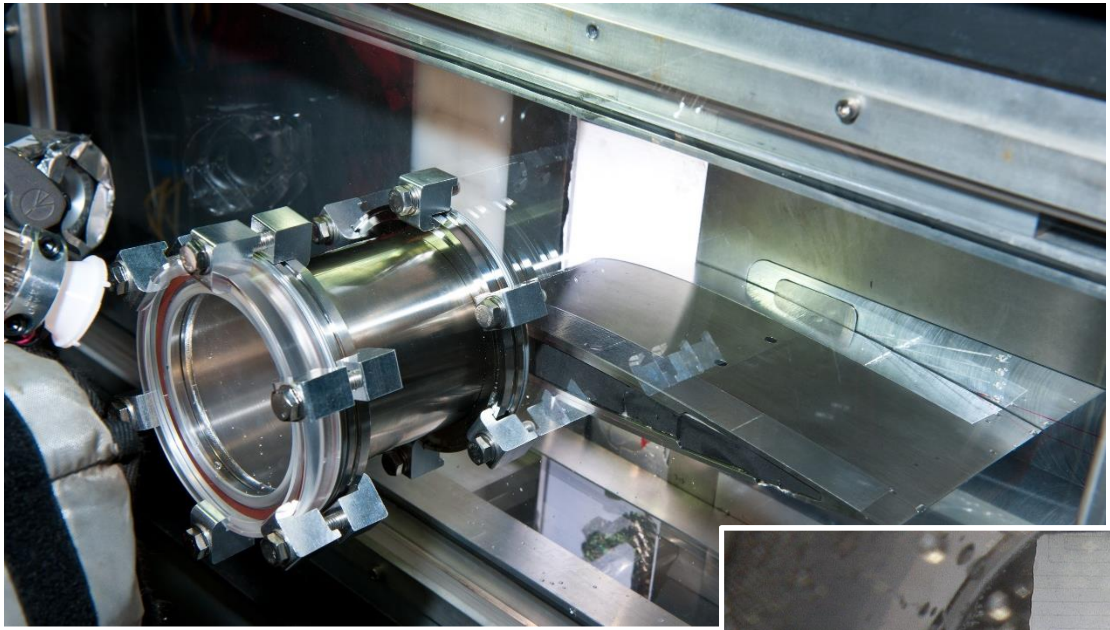


Test 824

Test 1003

Side view could not be analyzed from NACA 0012 cases due to obscurations

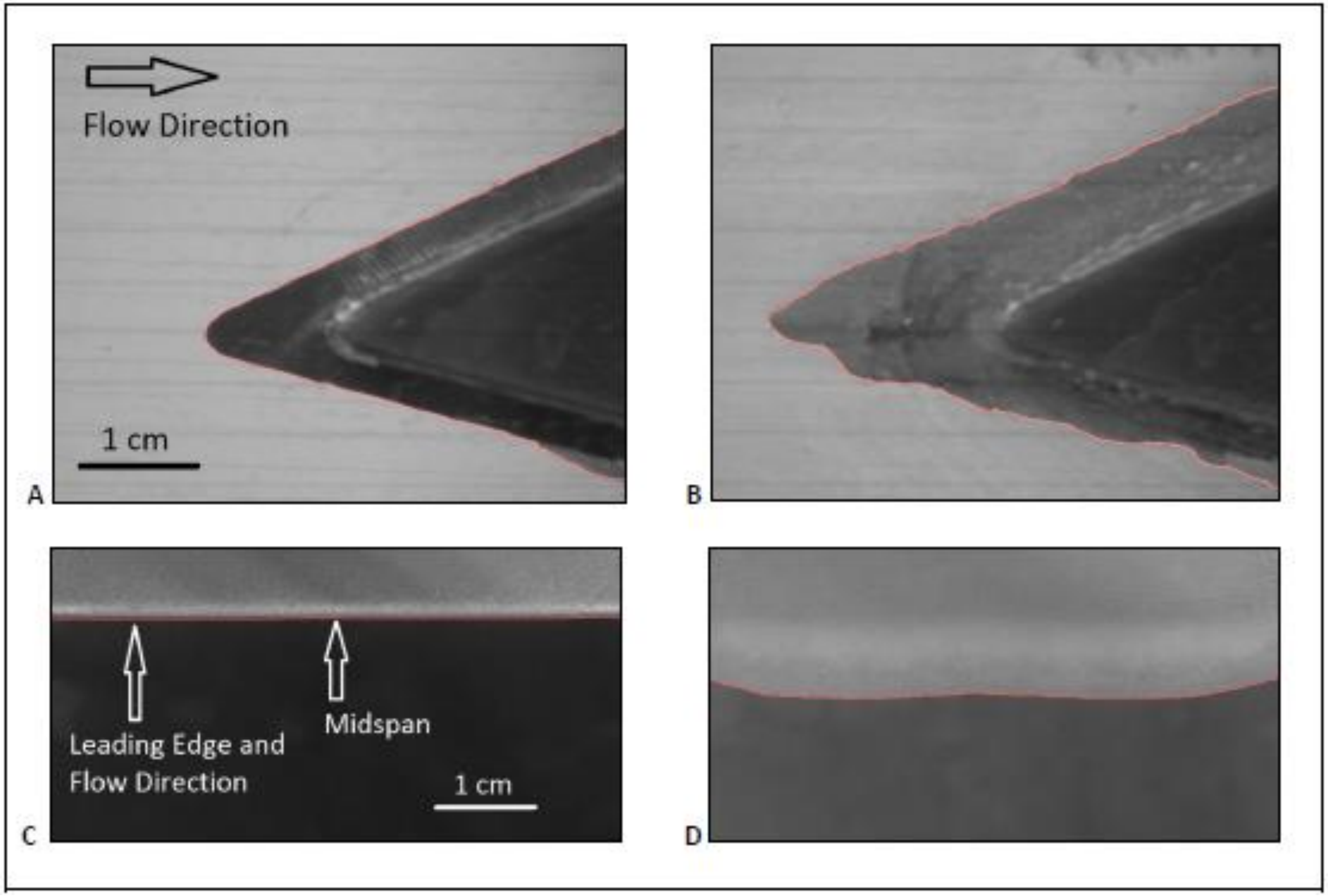
Optical View Port Tests



View though window

Analysis

Clean | Iced



Test Conditions – NACA 0012

- P_0 = 6.5 or 4.0 psia (~45 & 28 kPa)
- U = 85 or 135 m/s
- T_0 = ~6 to 19 °C (cloud off)
  - Decreased with cloud on
- Wet bulb: -5°C < T_{wb} <4
  - Injected steam set with cloud off
  - Measured humidity cloud off & on
- IWC_i = 7 g/m³ (no supplemental water)

Test	P_0 (psia)	U (m/s)	$T_{0,off}$ (°C)	$T_{0,on}$ (°C)	$T_{wb,off}$ (°C)	$T_{wb,on}$ (°C)
796	6.5	86.2	13.2	7.2	-0.3	-0.1
867	4.0	134.4	18.0	9.1	2.1	1.7

$$TWC_t = CF_{ice}IWC_i + CF_{noz}LWC_i - (GWC_{on} - GWC_{off})$$

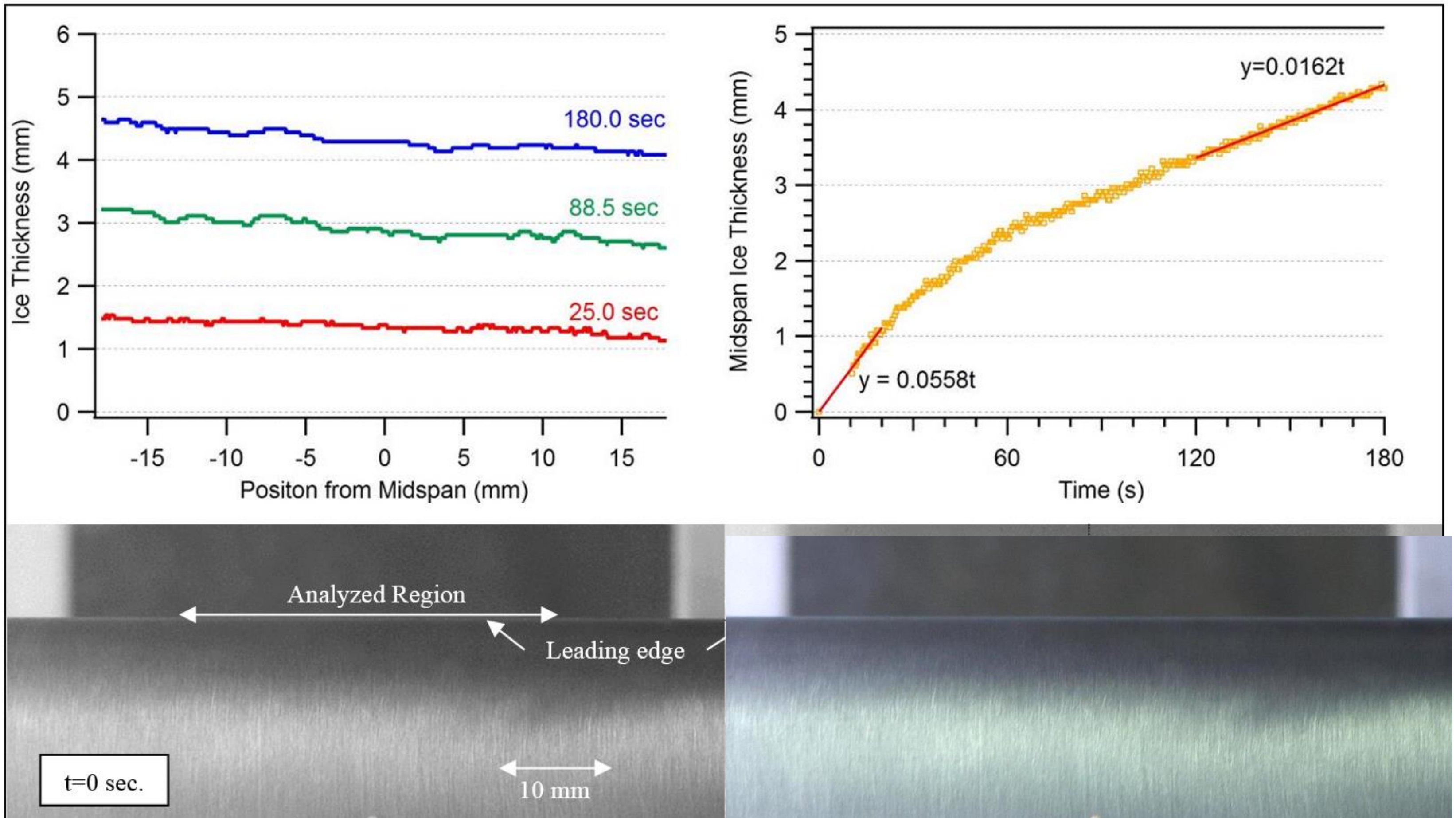
Water source	Velocity (m/s)	CF
LWC (nozzles)	all	CF_{noz} = 1.0
IWC (grinder)	85	CF_{ice} = 1.0
	135	$CF_{ice} =$ 1.2 @ $IWC =$ 15 g/m³; 1.5 @ $IWC =$ 3 g/m³

$$MR = \frac{\max(LWC_{m,083}, LWC_{m,021})}{TWC_t}$$

Test	$LWC_{m,083}$ (g/m³)	$LWC_{m,021}$ (g/m³)	$TWC_{m,HP}$ (g/m³)	GWC_{off} (g/m³)	GWC_{on} (g/m³)	TWC_t (g/m³)	MR (%)
796	0.67	0.51	3.58	1.84	3.21	5.54	12
867	0.92	1.29	4.85	3.35	4.01	9.13	14

NACA 0012 Result – Test 796

$U = 85\ \text{m/s},\ P_0 = 6.5\ \text{psia},\ T_{wb0} = -0.1\ °\text{C},\ IWC_i \cong 7\ \text{g/m}^3$

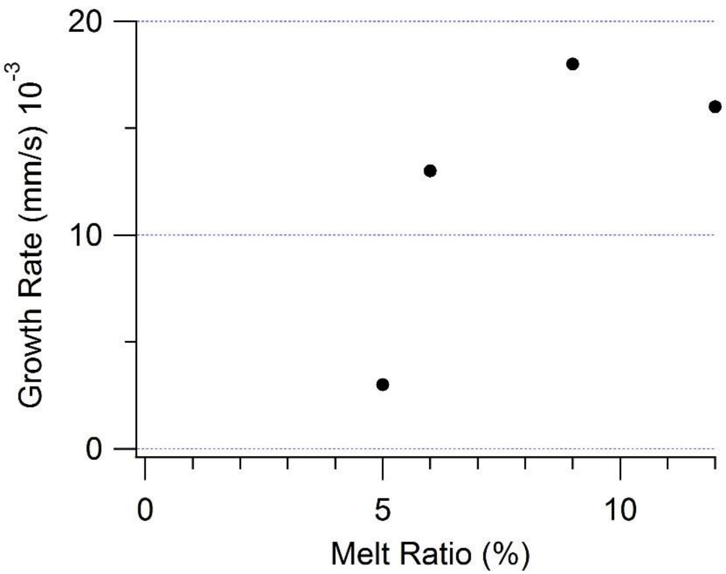


24X playback

Variation of growth rate with MR

Parameter	Value
U	85 m/s
P_0	6.5 psia
IWC_i	7 g/m^3
T_{WB}	0 to -1 °C

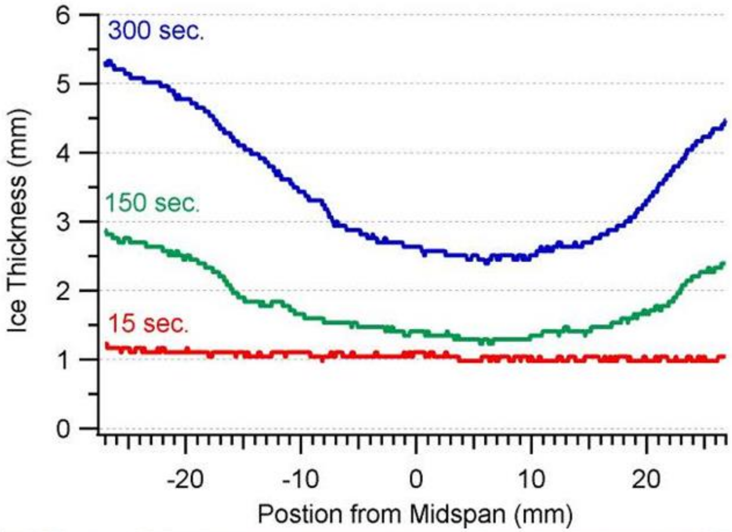
Scans 824, 802, 834, 796

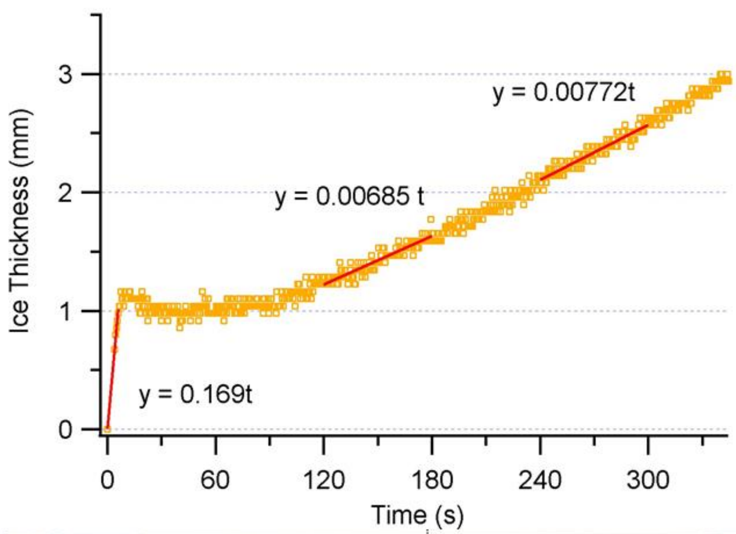


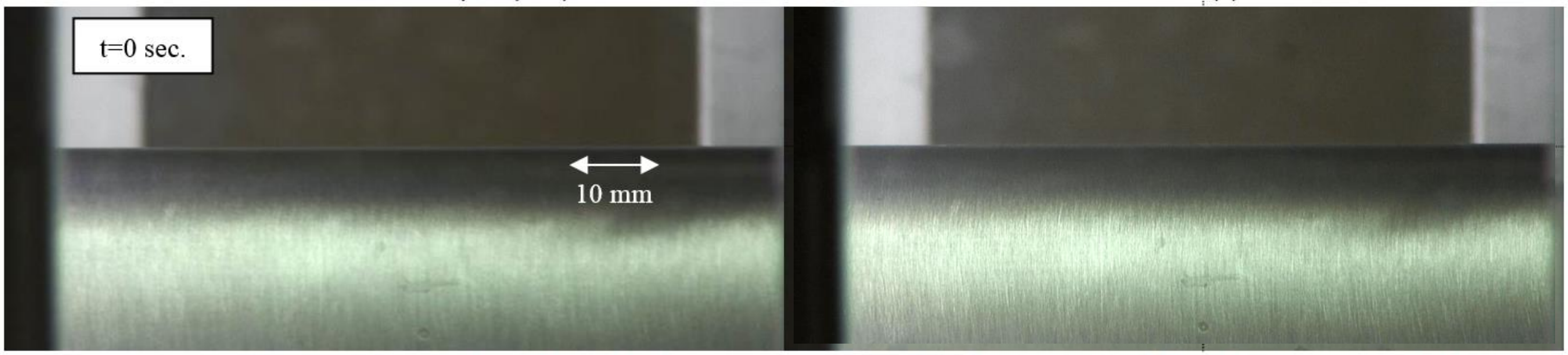
$\dot{r}$ increases then decreases with MR

NACA 0012 Result – Test 867

U = 134 m/s, P_0 = 4.0 psia, T_{wb0} = 1.7 °C, $IWC_i \cong 7$ g/m^3, MR = 14%







Only case with substantial ice growth at 135 m/s from available data

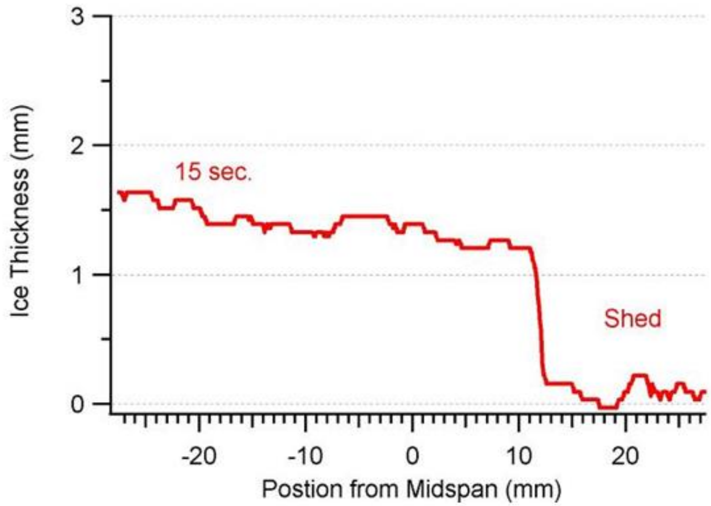
24X playback

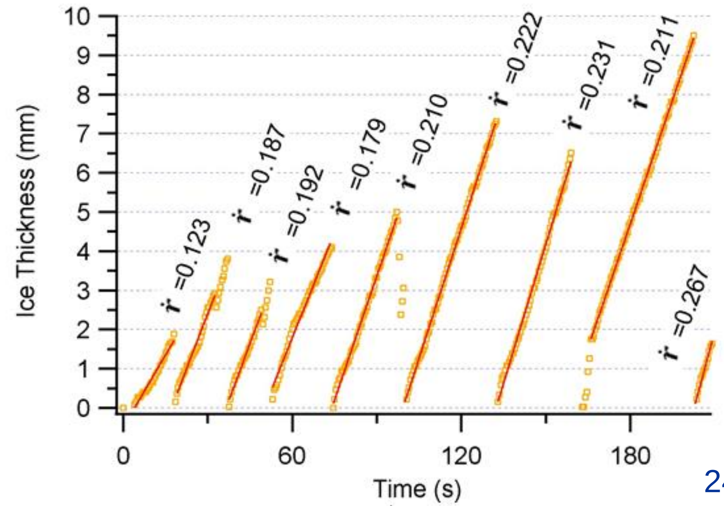
Test Conditions – Wedge

- P_0 = 6.5 or 10.0 psia (~45 & 69 kPa)
- U = 85 m/s
- T_0 = ~8 to 21 °C (cloud off)
  - Decreased with cloud on
- Wet bulb: 1°C < T_{wb} <5
  - Adjusted incoming stream and measured humidity
- IWC_i = ~7, 8.5, or 17 g/m^3
  - One case with supplemental water (1003)

Wedge Result – Test 901

$U = 87$ m/s, $P_0 = 6.5$ psia, $T_{wb0} = 2.5$ °C, $IWC_i \cong 16.7$ g/m^3, MR=13%





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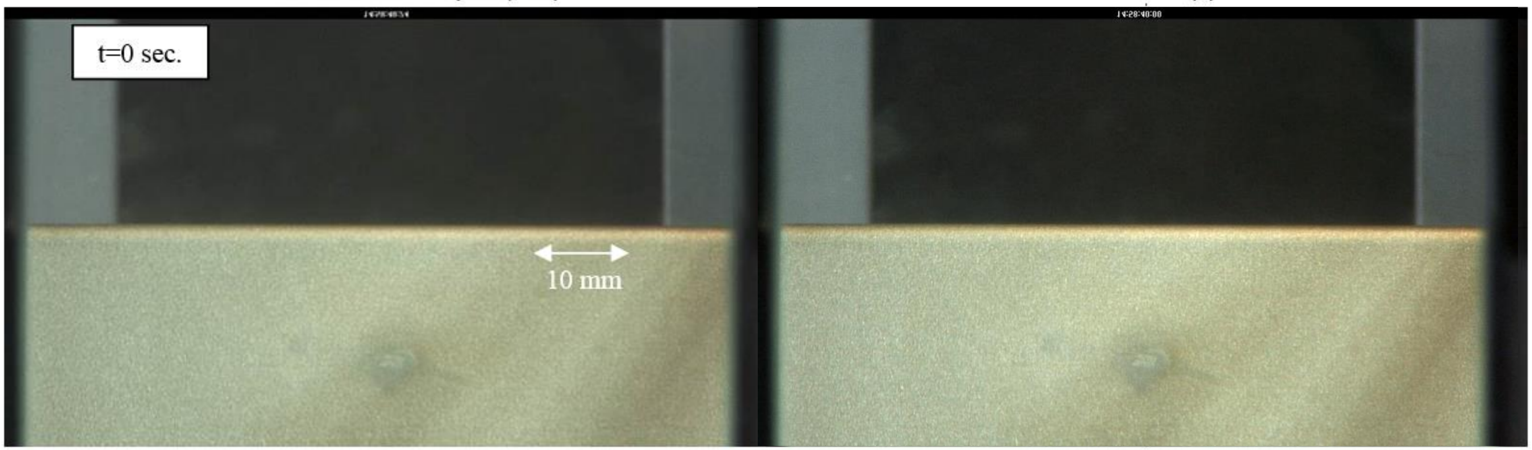
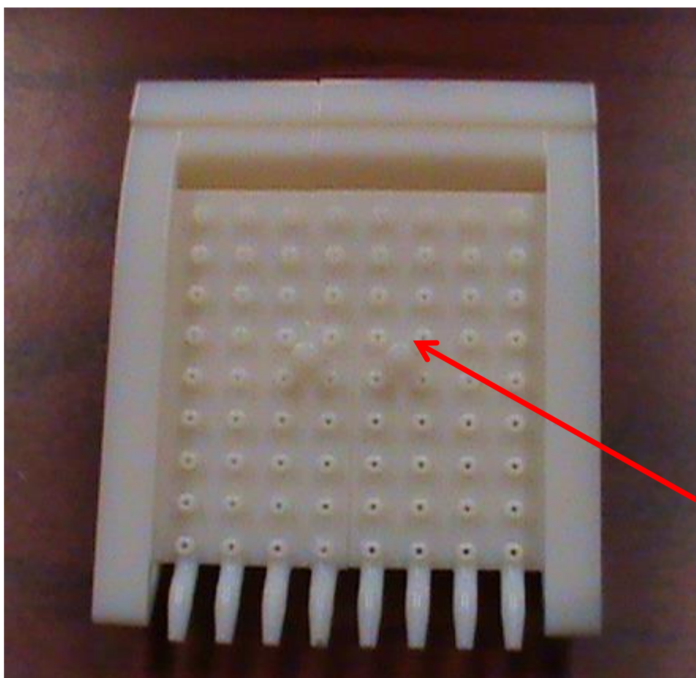
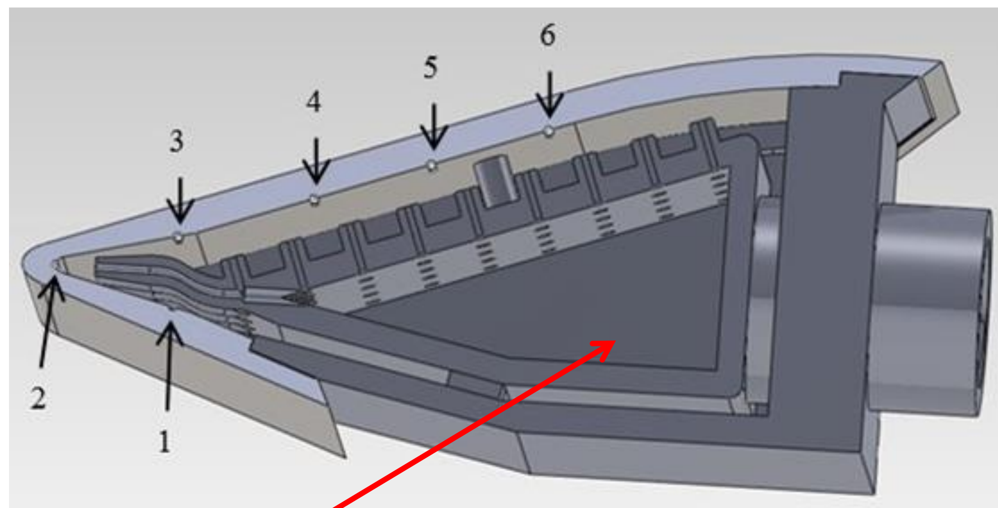


Similar test (883) with $IWC_i \cong 7$ g/m^3 (MR = 16%) did not show ice accretion

Wedge Heating-Cooling System

- Heating/cooling achieved by spraying heated/cooled water/antifreeze on back of 1/8” thick Ti 6Al-4V icing surface through ~ 100 1/32” holes

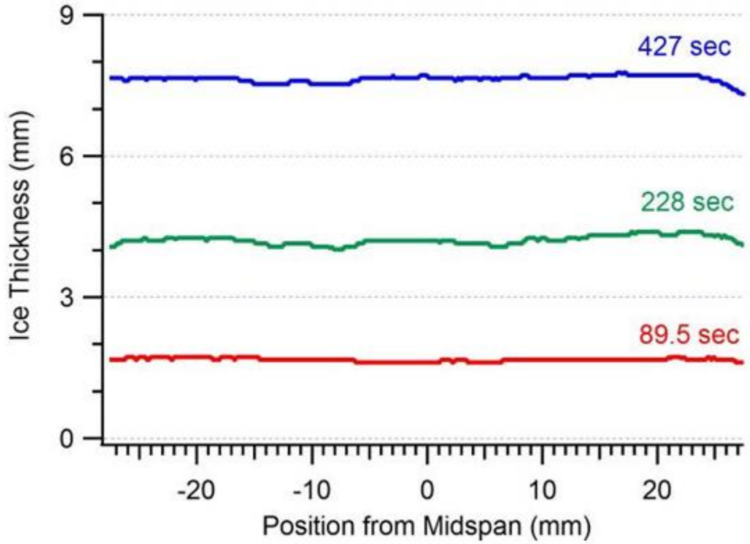


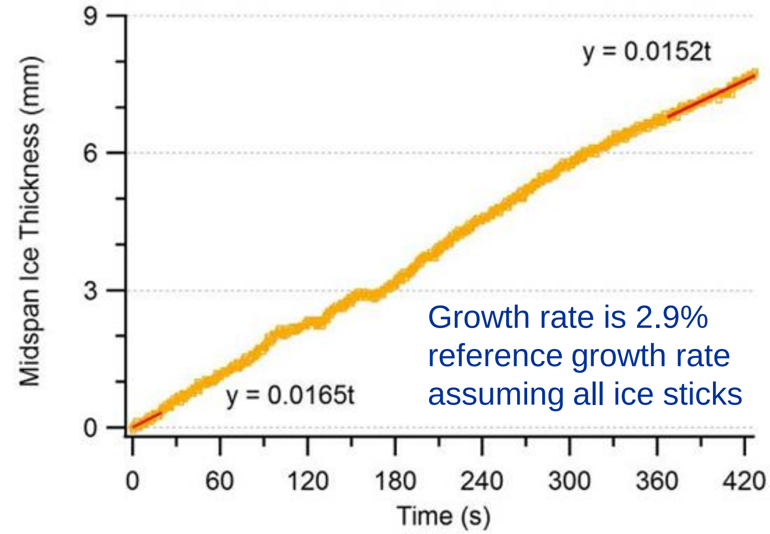


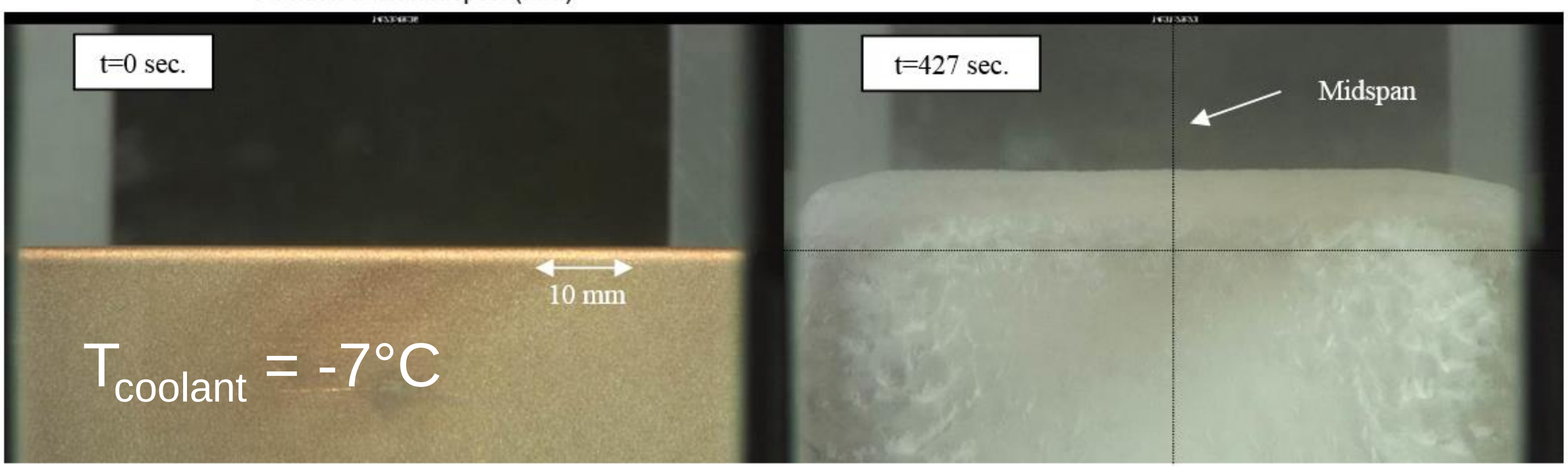
Plenum

Cooled Wedge Result – Test 982

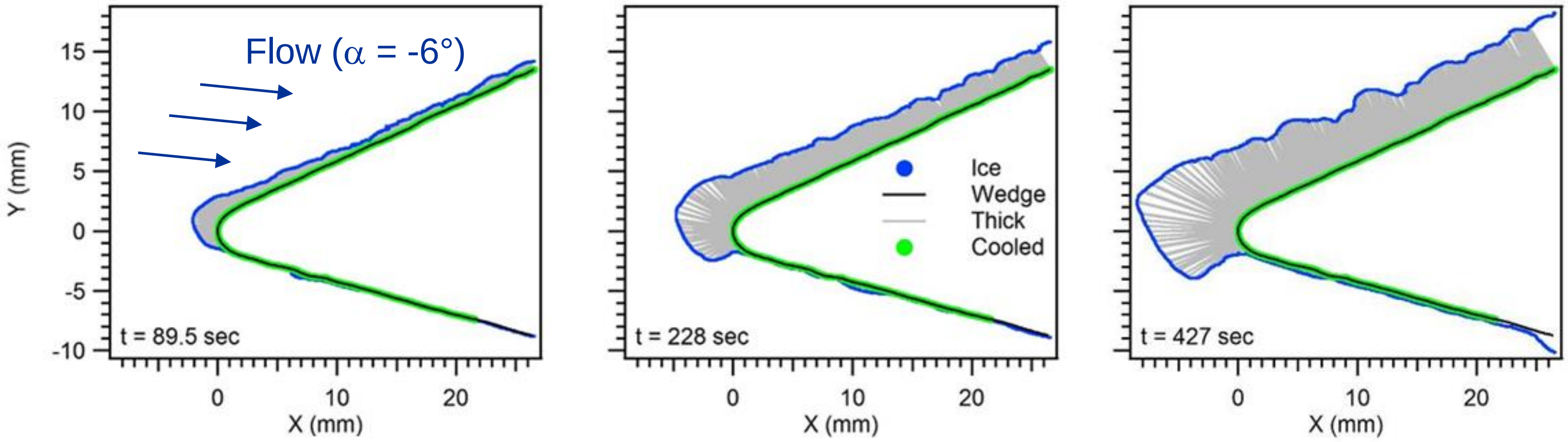
$U = 86$ m/s, $P_0 = 10$ psia, $T_{wb0} = 1.2$ °C, $IWC_i \cong 16.7$ g/m^3

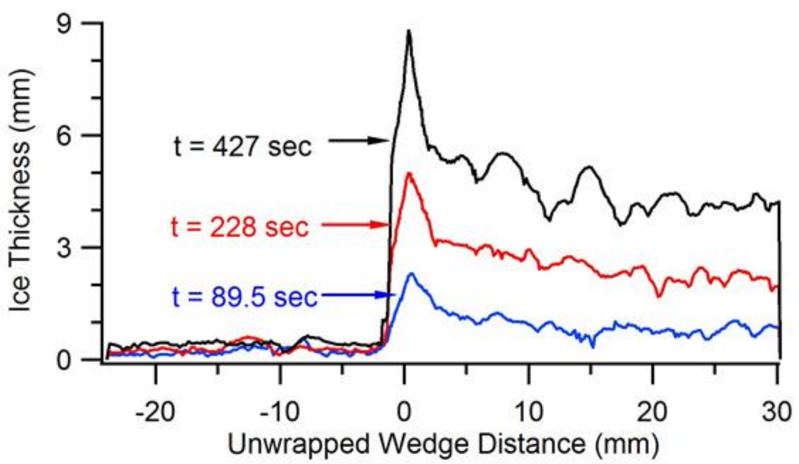


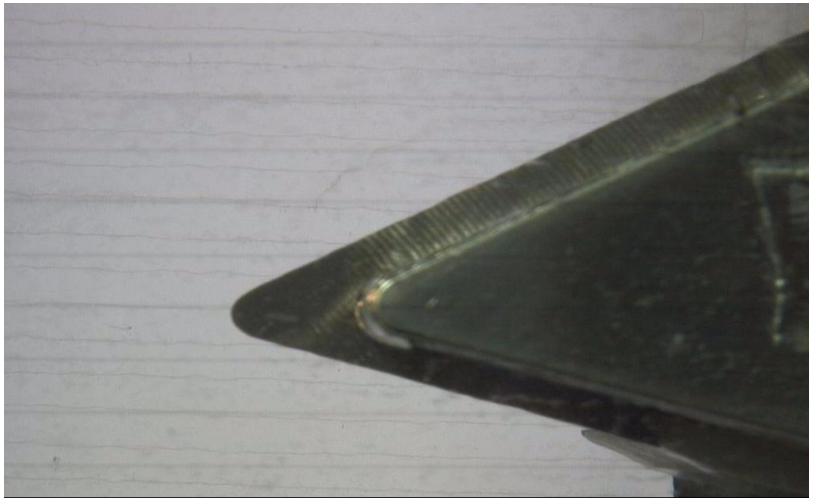




Cooled Wedge Result – Test 982 (Side Profile Measurements)







24X playback

Summary (1 of 2)

- This paper presents measurements of ice accretion shape from ice-crystal icing experiments conducted at the NRC RATFac
  - Data provided for development of ice-crystal accretion models
  - Select surf. temperature measurements available in paper
- Used two different models: NACA 0012 and wedge
  - Several wedge tests included actively cooled surface
- Tested at different U, T, and P
  - Only a limited set of permutations
  - NACA 0012 tests used only injected ice particles which naturally melted in the warm airflow (no supplemental LWC)

Summary (2 of 2)

- The ice accretion measurements included:
  - leading-edge thickness (both models)
  - 2D cross-section profile (wedge & 1 NACA 0012 case)
- NACA 0012
  - In some cases, initial growth rate, $\dot{r}$, higher than at end of test
  - Results suggest that $\dot{r}$ increases then decreases with MR
  - 135 m/s case showed less growth near midspan compared with root & tip
- Wedge
  - With adiabatic model, observed weakly adhered rapid accretions with shedding at T_{wb} above freezing
  - With active surface cooling, ice accretion without shedding occurred and the growth rate increased with *MR*
  - Accretions grew generally parallel to the icing surface

Acknowledgements

- This work was performed under an agreement between NASA and the National Research Council of Canada
- Financial support:
  - Atmospheric Environment Safety Technologies (AEST) project under NASA's Aviation Safety Program
  - National Research Council
  - Federal Aviation Administration
  - Transport Canada
- Special thanks are extended to Dr. Ron Colantonio, Mr. Jim MacLeod, and Mr. Thomas Bond for their support of the work
- Finally, the authors would like to thank Mr. Chris Lynch for his excellent imaging work during the experiments

Question

Ice Accretion Measurements on an Airfoil and Wedge in Mixed-phase Conditions

BACKUP

Test Conditions – NACA 0012

Test	Figure	P_0 (psia)	U (m/s)	V_{edge} (VAC)	$T_{0,off}$ (°C)	$T_{0,on}$ (°C)	$T_{wb,off}$ (°C)	$T_{wb,on}$ (°C)	HR_{off} (g/kg)	HR_{on} (g/kg)	LWC_i (g/m^3)	IWC_i (g/m^3)	GWC_{off} (g/m^3)	$LWC_{m,083}$ (g/m^3)	$LWC_{m,021}$ (g/m^3)	$TWC_{m,HP}$ (g/m^3)	GWC_{on} (g/m^3)	TWC_t (g/m^3)	MR (%)	$\dot{r}_{initial}$ (mm/s)	$\dot{r}_{120-180}$(mm/s)
796	6	6.5	86.2	0	13.2	7.2	-0.3	-0.1	3.4	5.9	0	6.91	1.84	0.67	0.51	3.58	3.21	5.54	12	0.056	0.016
802	7	6.5	85.7	60	13.1	7.5	-0.9	-0.7	2.8	5.1	0	6.95	1.42	0.33	0.29	2.47	2.61	5.76	6	0.14	0.013
818	N/A	6.5	84.4	0	5.8	0.8	-4.6	-4.4	2.0	4.0	0	7.05	1.18	0.19	0.20	2.57	2.19	6.04	3	0	0
824	8	6.5	85.8	0	10.8	6.0	-1.6	-1.0	3.0	5.3	0	6.94	1.62	0.29	0.27	2.68	2.73	5.82	5	0.10	0.0033
OPTICAL VIEW PORT TESTS																					
834	9	6.5	85.7	0	13.6	7.3	-0.1	-0.1	3.5	5.9	0	6.94	1.80	0.51	0.39	2.75	3.02	5.72	9	0.14	0.018
843	N/A	6.5	135.5	0	13.4	7.8	-0.5	-0.6	3.1	5.1	0	6.96	1.75	0.58	0.59	4.72	2.38	9.15	6	0	0
849	11	6.5	135.4	0	13.1	9.0	3.6	3.4	7.2	8.6	0	6.97	4.19	0.96	1.40	5.43	4.73	9.24	15	0.18	N/A
855	N/A	3.9	137.4	0	18.7	6.9	-3.3	-3.3	2.8	7.1	0	6.87	0.91	0.58	0.60	4.41	1.74	8.94	7	0	0
861	N/A	4.0	133.8	0	17.4	7.6	-1.4	-1.4	5.5	9.1	0	7.05	1.90	0.64	0.68	4.32	2.59	9.10	7	0	0
867	10	4.0	134.4	0	18.0	9.1	2.1	1.7	9.6	12.8	0	7.02	3.35	0.92	1.29	4.85	4.01	9.13	14	0.17	0.0069

Test Conditions - Wedge

Test	Figure	P_0 (psia)	U (m/s)	$T_{coolant}$ (°C)	$T_{0,off}$ (°C)	$T_{0,on}$ (°C)	$T_{wb,off}$ (°C)	$T_{wb,on}$ (°C)	HR_{off} (g/kg)	HR_{on} (g/kg)	LWC_i (g/m^3)	IWC_i (g/m^3)	GWC_{off} (g/m^3)	$LWC_{m,083}$ (g/m^3)	$LWC_{m,021}$ (g/m^3)	$TWC_{m,HP}$ (g/m^3)	GWC_{on} (g/m^3)	TWC_t (g/m^3)	MR (%)	$\dot{r}_{initial}$ (mm/s)	$\dot{r}_{360-420}$(mm/s)
883	N/A	6.5	87.1	Adia	19.9	10.6	3.5	2.5	4.2	6.9	0	6.84	2.14	0.88	0.80	3.18	3.42	5.56	16	Trace	Trace
889	N/A	6.5	87.4	Adia	20.8	12.7	5.2	4.4	5.9	8.3	0	6.81	2.95	1.12	1.21	3.22	4.14	5.62	21	0	0
901	15	6.5	86.9	Adia	20.5	8.3	3.5	2.5	4.0	7.9	0	16.68	2.04	1.85	2.15	5.71	3.87	14.84	13	0.123	0.202 *
982	16	10.1	85.7	-7	8.5	5.6	1.1	1.2	2.9	4.2	0	8.43	2.40	0.76	0.52	3.30	3.43	7.40	10	0.017	0.015
996	17	10.0	83.9	-5	8.2	4.3	3.2	2.1	4.9	5.6	0	8.61	3.88	1.28	1.03	3.62	4.32	8.17	16	0.048	0.021
1003	18	10.0	84.1	-5	8.2	3.8	1.9	1.4	3.8	5.2	1.87	8.60	3.01	1.98	1.74	4.92	4.24	9.24	21	0.049	0.032