ICE GENESIS Final Public Workshop
Snow Technostream

Airbus Helicopters
Rolls Royce
General Electric

Industrial Validation for snow

6-7 December 2023
Toulouse, France

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824310.

Content

1. Overview
2. Scope / Test cases
3. Results (AH / GE / RR)
4. Conclusions and way forward

A snow-covered plane stands at the Munich Airport.

(Karl-Josef Hildenbrand / picture alliance / Getty Images) https://www.foxweather.com/weather-news/germany-munich-snowstorm

Overview

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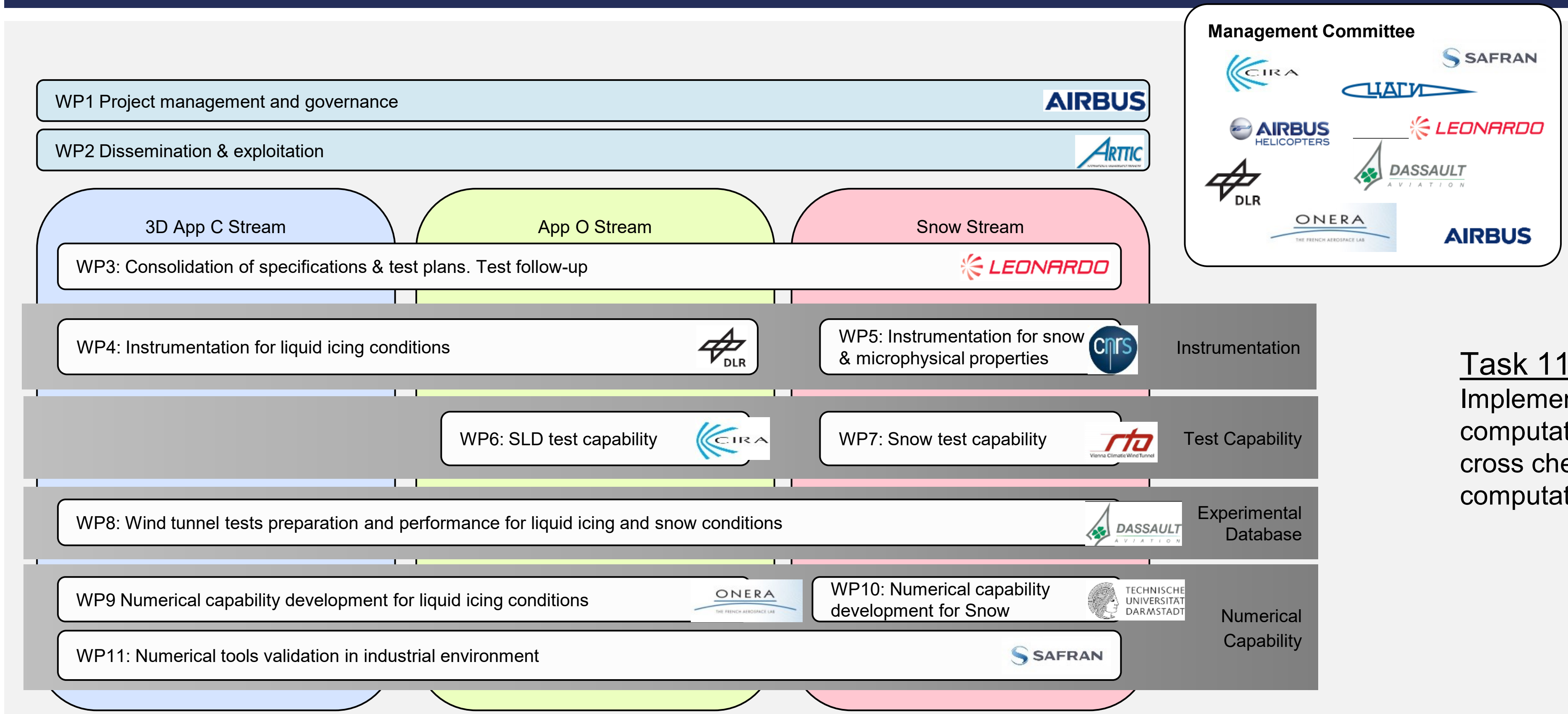
Overview



<u>Task 11.3 Objective</u>

Implement the snow models and learnings into the computational chains of the industrial partners & cross check the results from the different computational chains

<u>WP11 Tasks definitions :</u>

- Task 11.1 : Validation of App. C numerical capability in industrial environment.
- Task 11.2 : Validation of App. O numerical capability in industrial environment.
- **Task 11.3 : Validation of Snow numerical capability in industrial environment**

Test Cases

Data Base	Case	TAS (m/s)	SAT (°C)	MMD (µm)	TWC (g/m³)	LWR	Density (kg/m³)
NRC	**TR167**	**40**	**-2.4**	**1700**	**0.7**	**0.45**	**513**
	TR230	**40**	**-0.3**	**2400**	**1.1**	**0.45**	
	TR255	**40**	**-0.3**	**2000**	**2.2**	**0.45**	
	TR268	**40**	**-0.3**	**1100**	**1.4**	**0.45**	
RTA	TP07	40	-3	616.5	0.33	0.15	160
	TP08	40	-3	698.8	0.49	0.3	280
	TP09	40	-3	744.7	0.71	0.45	480
	TP11	**40**	**-3**	**NA**	**0.38**	**0.3**	**280**
	TP12	**40**	**-3**	**NA**	**0.61**	**0.45**	**480**
	TP19	**40**	**-3**	**697.4**	**0.44**	**0.3**	**280**
	TP20	**40**	**-3**	**740.9**	**0.58**	**0.45**	**480**
	TP22	**40**	**-3**	**747.8**	**0.41**	**0.3**	**280**
		40	-3	NA	0.23	0.15	160
CSTB	Run403	46	-3.2	96	5.08	0.33	
	Run405	46	-5.2	96	3.22	0.12	
	Run407	46	-7.2	96	3.21	0.15	
	Run903	94	-3.2	96	3.73	0.36	
	Run905	94	-5.2	96	3.04	0.22	
	Run907	94	-7.2	96	2.93	0.23	

- 3 Data bases used during the ICE GENESIS (CSTB, RTA & NRC)
- 4 more test cases with heated airfoil, snow updated simulations currently in progress
- **Green Test** cases are additional

General Electric

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Snow Numerical capability

GE Aerospace

Overview of ICE GENESIS implementation on Ge's simulation chain

Solver Framework at GE	Update solver with findings & models from D10.2	Data used for validation
Eulerian Modelling		
• Particle Transport – FENSAP drop 3D • Particle Impact – FENSAP drop 3D • Ice Accretion (ICAT tool) • Erosion & Sticking Eff -> MUSIC HAIC ICI	• Sticking eff & Erosion coefficient from Onera as starting point but not used • In house tunning of ICI Onera sticking eff Model • In house tunning of ICI NRC Erosion model	NACA0012 Ice Thickness, Data from CSTB, RTA & NRC
Lagrangian Modelling snow		
Particle Transport (ANSYS CFX) →	Holzer and Sommerfeld model for drag with 3D descriptors from in situ data (Flight Test)	Terminal Velocity from MASC ground measurements
Particle Impact (ANSYS CFX) →	• Snow Break Up Threshold (TUDA) • Left Truncated break up distribution (TUDA) • Graupel Factor from AIT data base	• TUDA secondary re emitted particle test • AIT fragmentation
Melting (ANSYS CFX) →	P1 & P2 models of mNS model **Not addressed**	TUDA melting particle Results **Not addressed**

Snow Numerical capability

GE Aerospace

Fragmentation : CFX implementation

From D10.2 TUDA :

- **Break Up Threshold** in function of min **dendrite length** based on Hauk et al.
- Particle break up distribution for Aggregate particle

Graupel break up investigation based on AIT database (+50 particles)

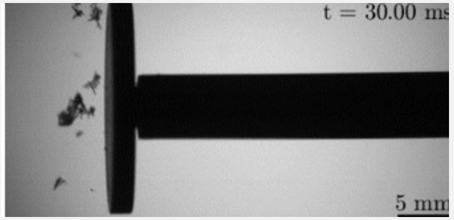
AIT data base shows graupels breaks “less” than aggregates

AIT data base used to derive constant factor to scale aggregate break up diameter distribution proposed by TUDA on D10.2

Fragmentation distribution implemented in CFX, validated with a simple flat plate model

Further Validation is planned with more complex engine model

Fragment Diam [mm] Aggregate	CFX D_out [mm]	Cumulative
0.087	0.070	0.25
0.130	0.126	0.5
0.198	0.232	0.75
0.383	0.370	0.95
0.650	0.490	0.99



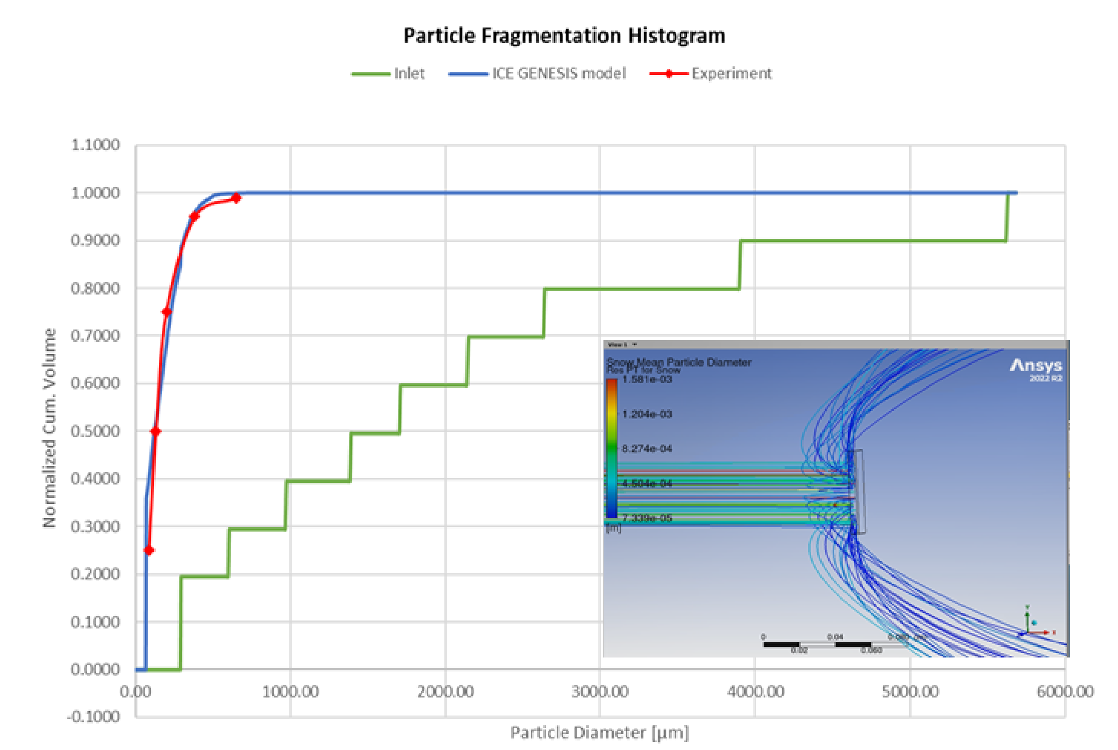


Figure from D10.2 Aluminum target impacting onto levitated snowflake (1 m/s impact vel)

Snow Numerical capability

GE Aerospace

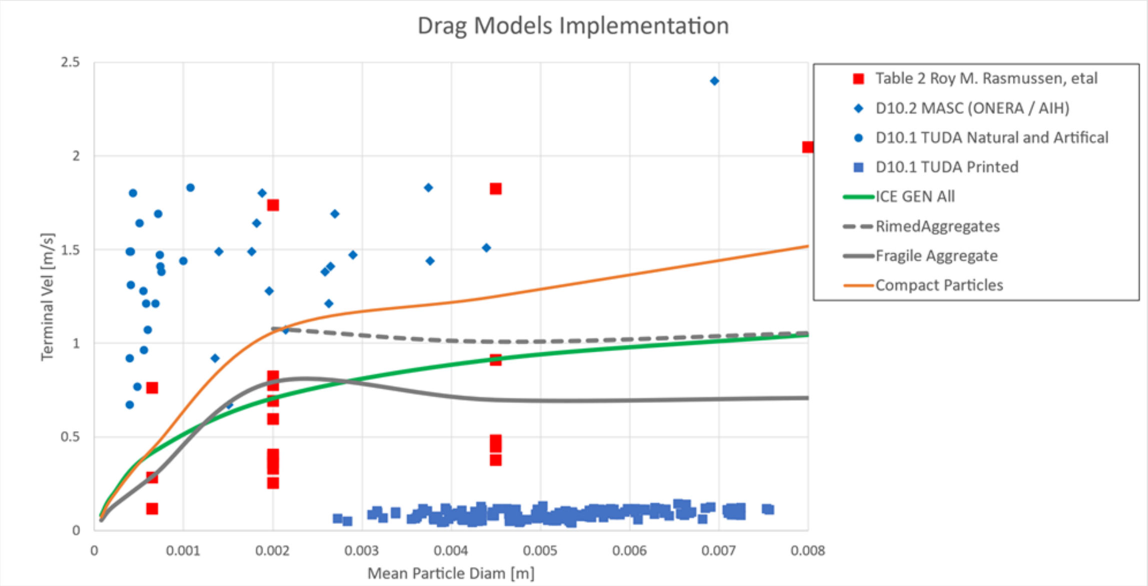
Drag : CFX implementation

Drag model:

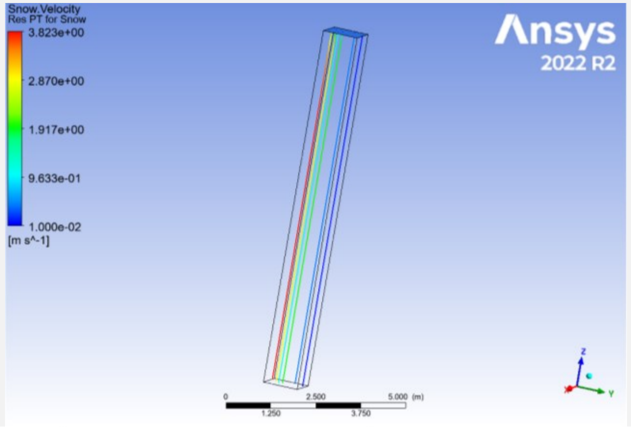
- Holzer and Sommerfeld model for drag with 3D descriptors from in situ data (Flight Test)
- Implementation in CFX studied with simple snowfall simulation for terminal velocity
- Flight models implemented (All Fligth data & Per Morphology)

Validation :

- D10.1 TUDA Natural and Artificial snow & D10.2 Multi Axial Camera for Aggregates are higher than simulated terminal velocity
- Data from Table 2 [1] with different morphologies are in range of simulation
- Full data set of MASCDB must be used to evaluate Terminal velocity



- **ICE GENESIS models implemented shows good trend, especially vs Table 2 [1]**
- **Further validation with MASCDB is required for other morphologies**



[1] "The Estimation of Snowfall Rate Using Visibility", ROY M. RASMUSSEN, JOTHIRAM VIVEKANANDAN, AND JEFFREY COLE, National Center for Atmospheric Research, Boulder Colorado, 1998

Snow Numerical capability

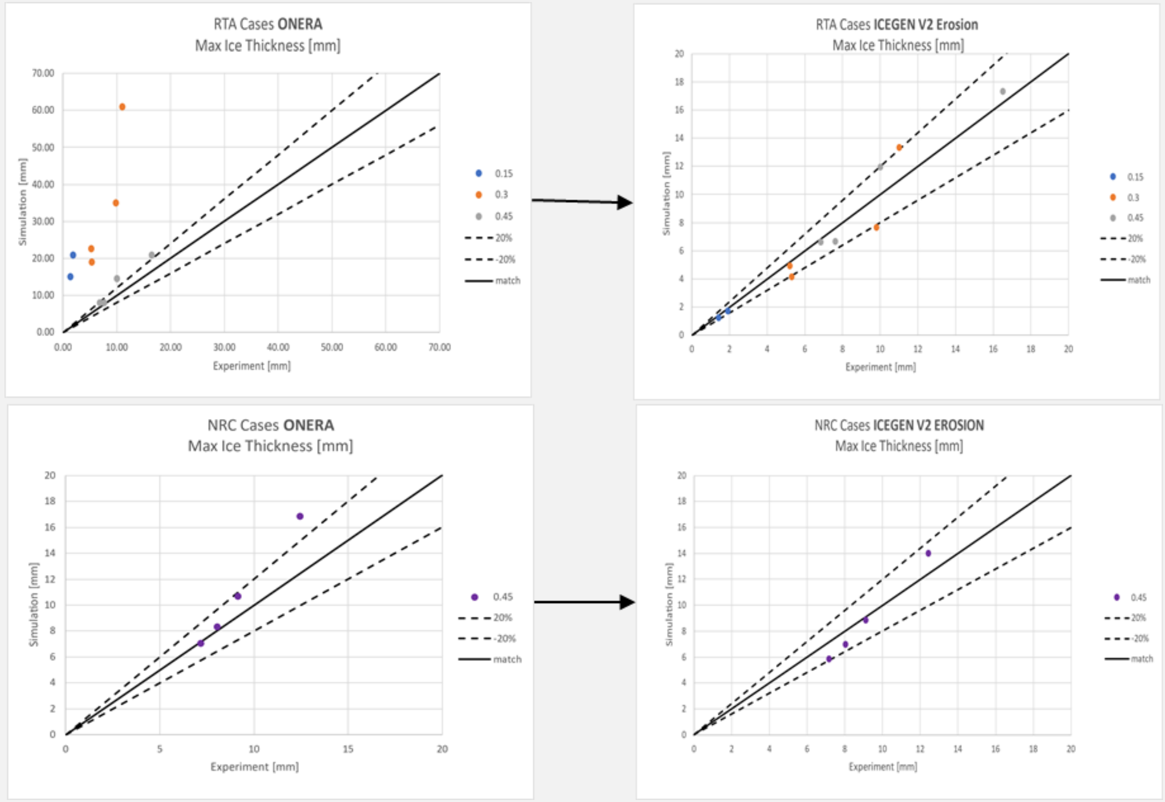
Sensitivity studies FENSAP drop 3D

- Particle types
- Density of snow particle for CSTB data base
- Aspect Ratio to match test impingement limits
  - CSTB = 0.8
  - RTA = 0.6
- Aspect Ratio assumed for NRC at 0.6

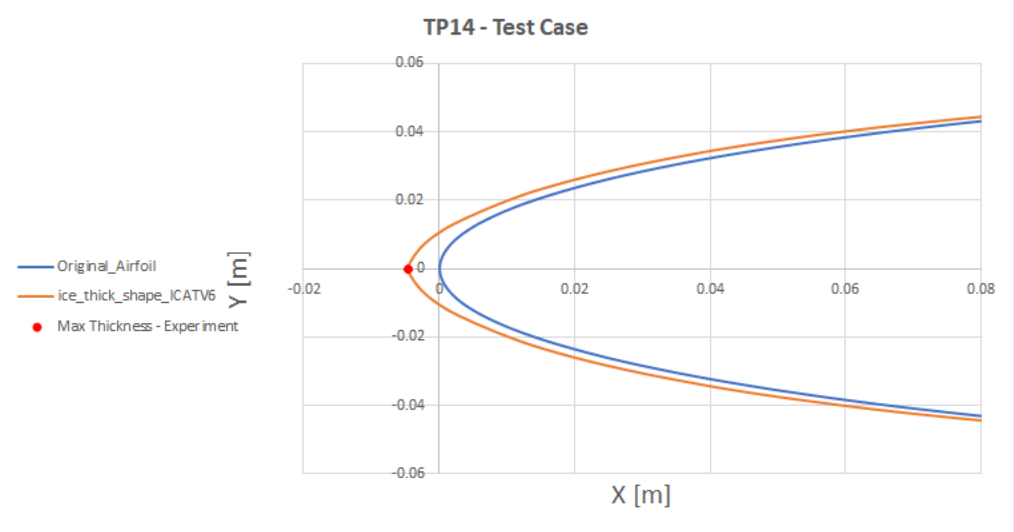
Sticking Efficiency & Erosion

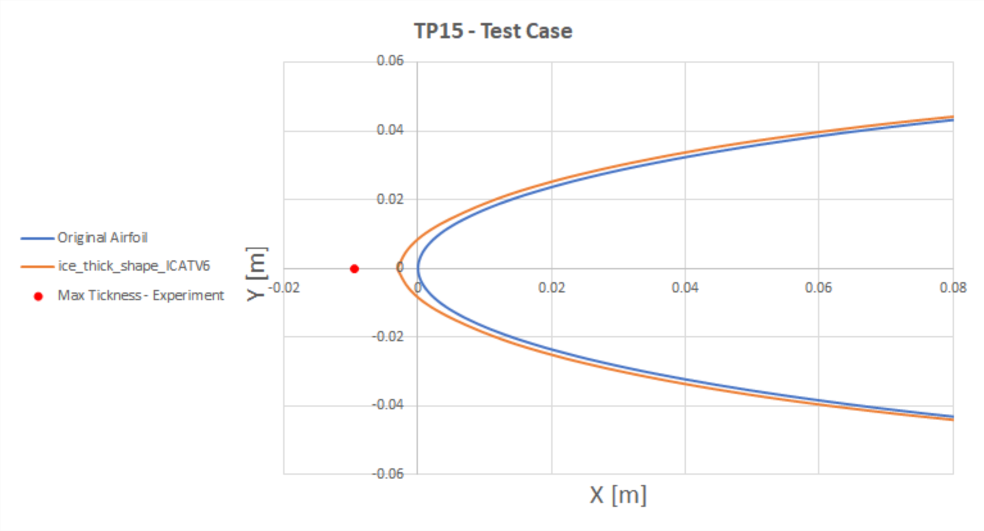
- Empirical Implementation
- Tune Sticking Efficiency and Erosion to match max ice thickness reported at each test case
- Sticking Efficiency & Erosion = fnc (Melt Ratio)
- CSTB data max ice thickness not included in tunning exercise but simulations executed afterwards showed overall reduction on error at max ice thickness

RTA &NRC CASES (unheated)



Snow Numerical capability Heated Cases





Case	TAS (m/s)	SAT (°C)	MMD (µm)	TWC (g/m³)	LWR	Density (kg/m³)
NACA04	60	-4.3	250	0.62	0.45	480
TP13	40	-3	619.4	0.32	0.15	160
TP14	40	-3	702.2	0.43	0.3	280
TP15	40	-3	764.2	0.61	0.45	480

- In the absence of heating power of heaters, the surface temperature was used to compute wall heat flux.
- To enable the use of Thermal conduction solver for more accurate modeling of heat flux in heated scenarios, heating power is required that is currently missing.
- ICAT snow model for heated scenarios is still a work in progress towards inclusion of heated cases in D11.3.

Rolls - Royce

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Snow Numerical capability

tools:
HYDRA system (in house tool)

- HYDRA – In house CFD solver
  - turbomachinery and external aerodynamics
  - Edge-based, 2nd order finite volume scheme, Implicit/Explicit with Multi-Grid.
  - Multi-Stage with mixing / sliding planes.
  - Water vapour transport and thermodynamic model.

- SS02 - 3D Lagrangian Tracker which handles multi-stage turbomachinery cases.
  - Lagrangian Tracker – currently using explicit Runge Kutta 4/5 scheme.
  - 2-way Coupling with CFD Hydra Model

Rolls-Royce Modelling Framework
(HYDRA system)

Rolls-Royce previous icing setup (HYDRA system)	**D10.2 Models and formulations used to update in-house modelling setup**
Flow calculations (HYDRA)	
Particle Transport (Lagrangian Model – SS02)	
Ice particle trajectories (Drag)	Holzer and Sommerfeld model for snow drag as per ONERA/AIH (D10.2 – 4.1.1.1)
Ice impact formulations	ONERA/TUDA ICI models (from HAIC/M-haic)
Heat and mass exchanges with surrounding gas	ICI model with updated bulk density & sphericity evolution for snow (4.1.2.1.3.1 First model proposed) (from ONERA HAIC)
Sticking efficiency	ONERA formulation (4.2.2.1)
Secondary re-emitted particles	ICI formulations (from ONERA HAIC/M-haic)
Ice accretion	Not addressed yet

Snow Numerical capability

HYDRA capability evaluation

- Effect on mesh type and mesh refinements
- Particle size (distribution) and bulk density
- Sensitivity of data to sticking and porosity

Table 3 Test conditions and LE growth rates for wet snow accretion points: unheated airfoil, AOA=0°, sea level, vol% water≈7% and TAS = 40 m/s

TR# XXX[3]	SAT[4]	Relative Humidity[5]	TWC @ (0,0)	Dv10	Dv20	Dv30	Dv40	Dv50[6]	Dv60	Dv70	Dv80	Dv90	Dv100 (Max Diameter)	Particle Count	LE growth rate @ X=0"	LE ice growth rate @ X=0", normalized to 1 g/m³
	°C	%	g/m³	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	[-]	mm/min.	mm/min.
167	-2.4	58.9	0.7	1.0	1.3	1.4	1.6	1.7	1.9	2.0	2.2	2.6	4.4	4782	0.74	0.83
230	-0.3	57.1	1.1	1.4	1.7	2.0	2.2	2.4	2.7	3.0	3.5	4.3	8.9	3904	0.79	0.76
255	-0.3	69.4	2.2	0.93	1.2	1.5	1.7	2.0	2.5	3.3	4.8	6.5	7.2	3690	1.18	0.82
268	-0.3	66.8	1.4	0.55	0.72	0.8	1.0	1.1	1.3	1.6	2.5	3.9	5.0	2041	0.69	0.57

NRC test cases

- Collection efficiency (ice + water deposition rate) after 8 to 12 mins
- 3D modelling, 1D extraction
- Parameter used
    - Density
        - Bulk density set to be to 517 kg/m³
        - Assumption is that all water and ice freezes at a combined density of 917 kg/m3 (ONERA model presumes a porosity of 0.5)
    - Aspect Ratio = 0.6
    - Sticking Efficiency & Erosion = Melt Ratio = 0.45
- 2D thin film solver (2D) for shallow water

Airbus Helicopter

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Snow Numerical capability

AIRBUS

IGLOO2D capability evaluation

- Mesh effect (structured / unstructured)
- Numerical parameter effect (multi-step, smoothing)
- **Ice density & Particle size effect**
- **Particle distribution effect**
- **Optimization of sticking / erosion model coefficients**

RTA	NRC	CSTB
TP07 (dry)	TR167	R403
TP08 (medium)	TR230	R405
TP09 (wet)	TR255	R407
TP11 (medium)	TR268	R903
TP12 (wet)		R905
TP13 (surface temp)		R907
TP14 (surface temp)		
TP15 (surface temp)		
TP19 (medium)		
TP20 (wet)		
TP21 (wet)		
TP22 (medium)		
NACA04 (surface temp)		

--- common test cases

--- not computed

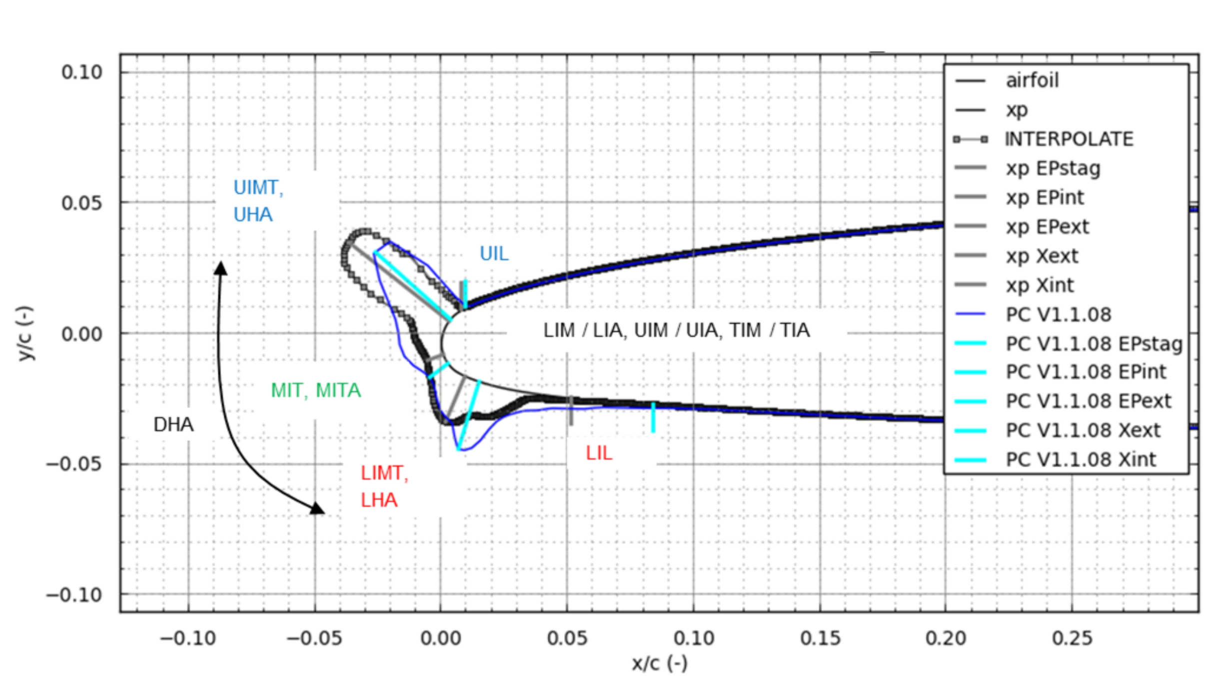
--- additional test cases

Snow Numerical capability

AIRBUS

Evaluation of the performances

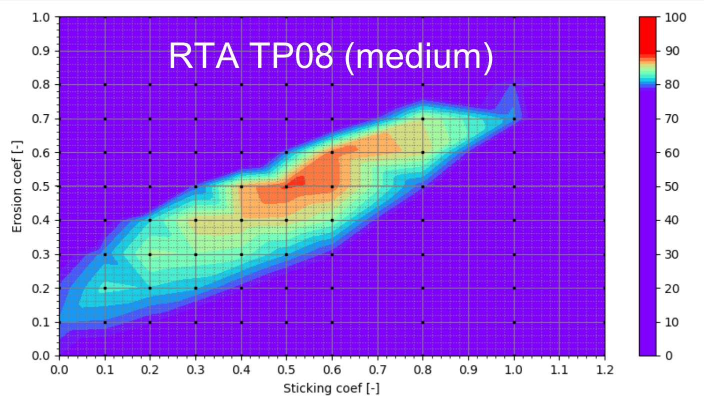
- The validation method is derived from NASA
- The geometrical characteristics usually considered for comparison with experimental ice shapes: ice accretion limits, horn angles, ice thickness, mass of ice
- For snow: ice accretion limits, ice thickness, mass of ice
- an ERROR can be defined for the considered parameters as well as a global SCORE representing how good the calculation is compared to the experimental results



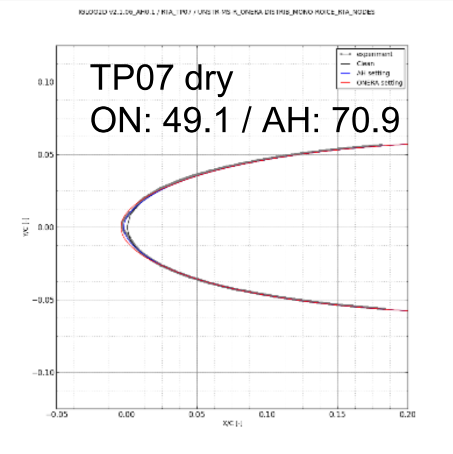
Snow Numerical capability

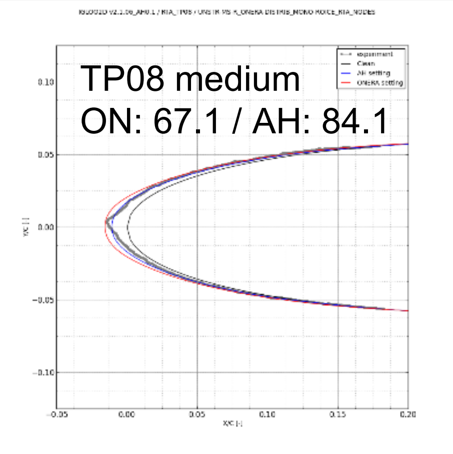
Optimization of sticking / erosion model coefficients

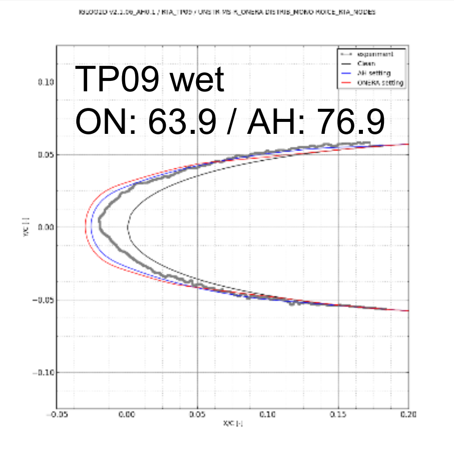
- ONERA setting (sticking = 1.28 / erosion = 0.65 ; AR =1)
- Node smoothing
- AH approach on RTA database
  - Mapping & preliminary optimization for dry, medium, wet snow
  - Global optimization pending
- Global improvement observed



SCORE	RTA	NRC	CSTB	ALL
ON setting	63.2	28.9	**26.5**	44.4
AH setting	**67.4**	**45.8**	19.0	**47.6**







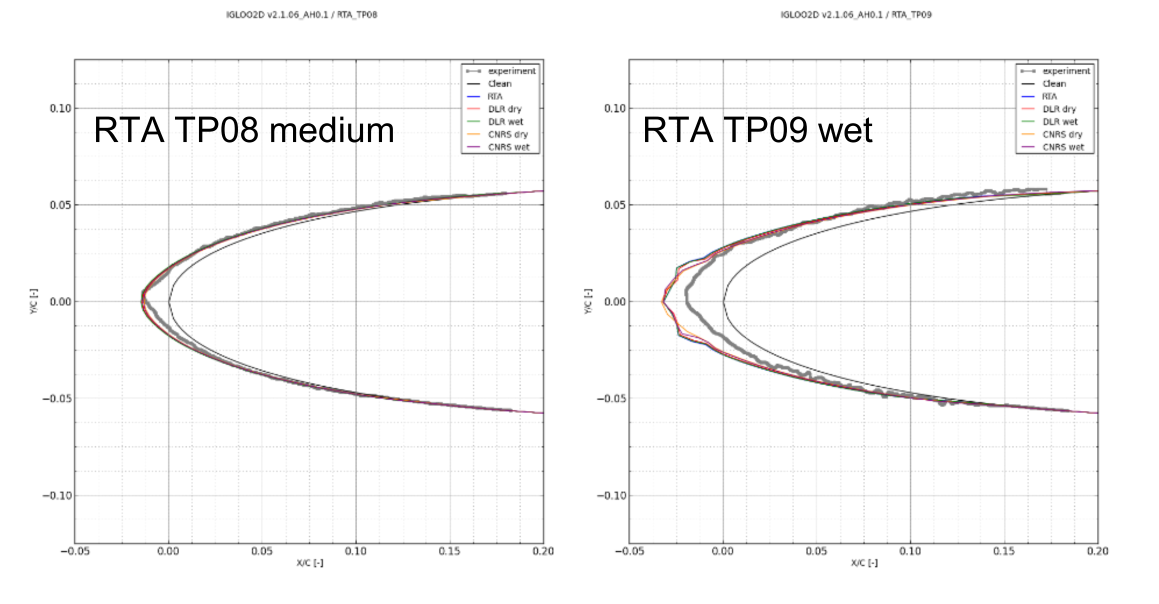
Snow Numerical capability

Ice density & Particle size effect

- AH setting (sticking = 0,5 / erosion = 0.5)
- No smoothing
- RTA database
  - RTA MMD and pice
  - CNRS MMD and Rogers 1974 $\rho_{ice(\frac{dry}{wet})}$
  - DLR MMD and Rogers 1974 $\rho_{ice(\frac{dry}{wet})}$

SCORE	RTA	CNRS dry/wet	DLR dry/wet
AH setting	**67.0**	64.1 / 62.8	67.3 / 66.8

- Limited influence of MMD and pice on RTA database



MMD_{RTA} = 699mic ; ρ_{RTA} = 280kg/m^3
MMD_{CNRS} = 332mic ; ρ_{CNRS_dry} = 512kg/m^3
MMD_{CNRS} = 332mic ; ρ_{CNRS_wet} = 917kg/m^3
MMD_{DLR} = 695mic ; ρ_{DLR_wet} = 268kg/m^3
MMD_{DLR} = 695mic ; ρ_{DLR_wet} = 917kg/m^3

MMD_{RTA} = 744mic ; ρ_{RTA} = 480kg/m^3
MMD_{CNRS} = 255mic ; ρ_{CNRS_dry} = 667kg/m^3
MMD_{CNRS} = 255mic ; ρ_{CNRS_wet} = 917kg/m^3
MMD_{DLR} = 614mic ; ρ_{DLR_wet} = 277kg/m^3
MMD_{DLR} = 614mic ; ρ_{DLR_wet} = 917kg/m^3

Snow Numerical capability

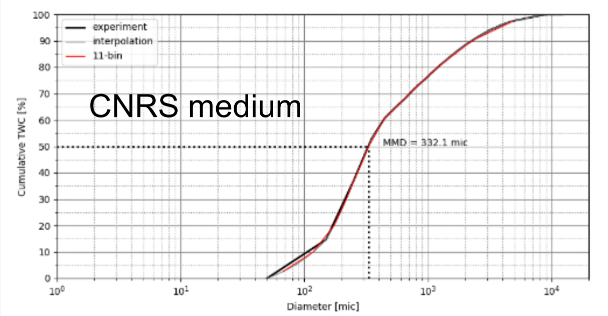
AIRBUS

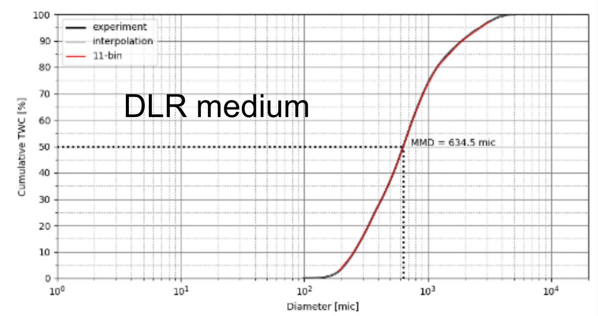
MSD effect

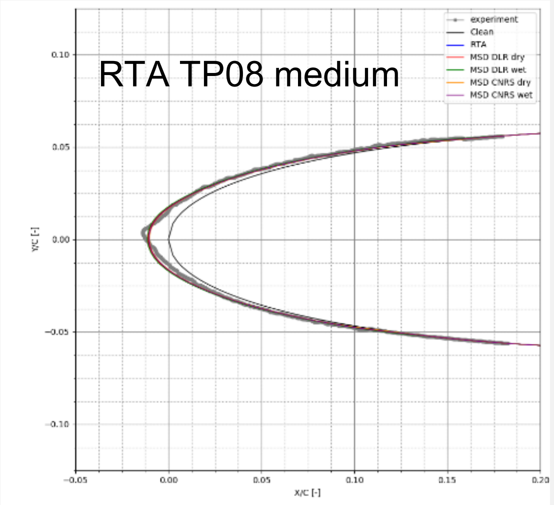
- AH setting (sticking = 0,5 / erosion = 0.5)
- Node smoothing
- RTA database
  - RTA ρice and MMD
  - CNRS MSD and Rogers 1974 ρice (dry/wet)
  - DLR MSD and Rogers 1974 ρice (dry/wet)

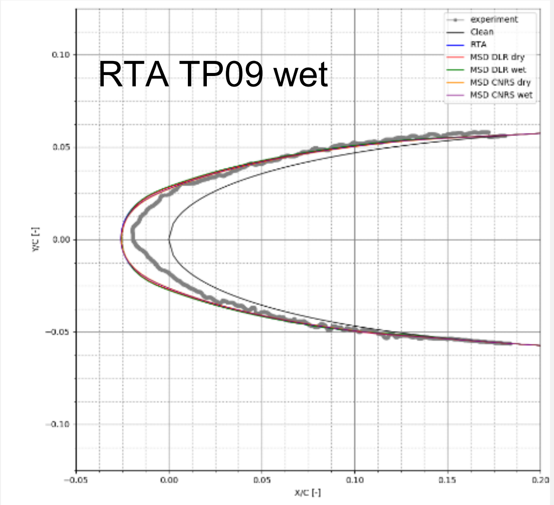
SCORE	RTA Monoclass	CNRS PSD dry/wet	DLR PSD dry/wet
AH setting	67.4	66.7 / 67.3	67.6 \ 68.0

- Limited influence of MSD (11-bin) on RTA database









Results

ICE GENESIS

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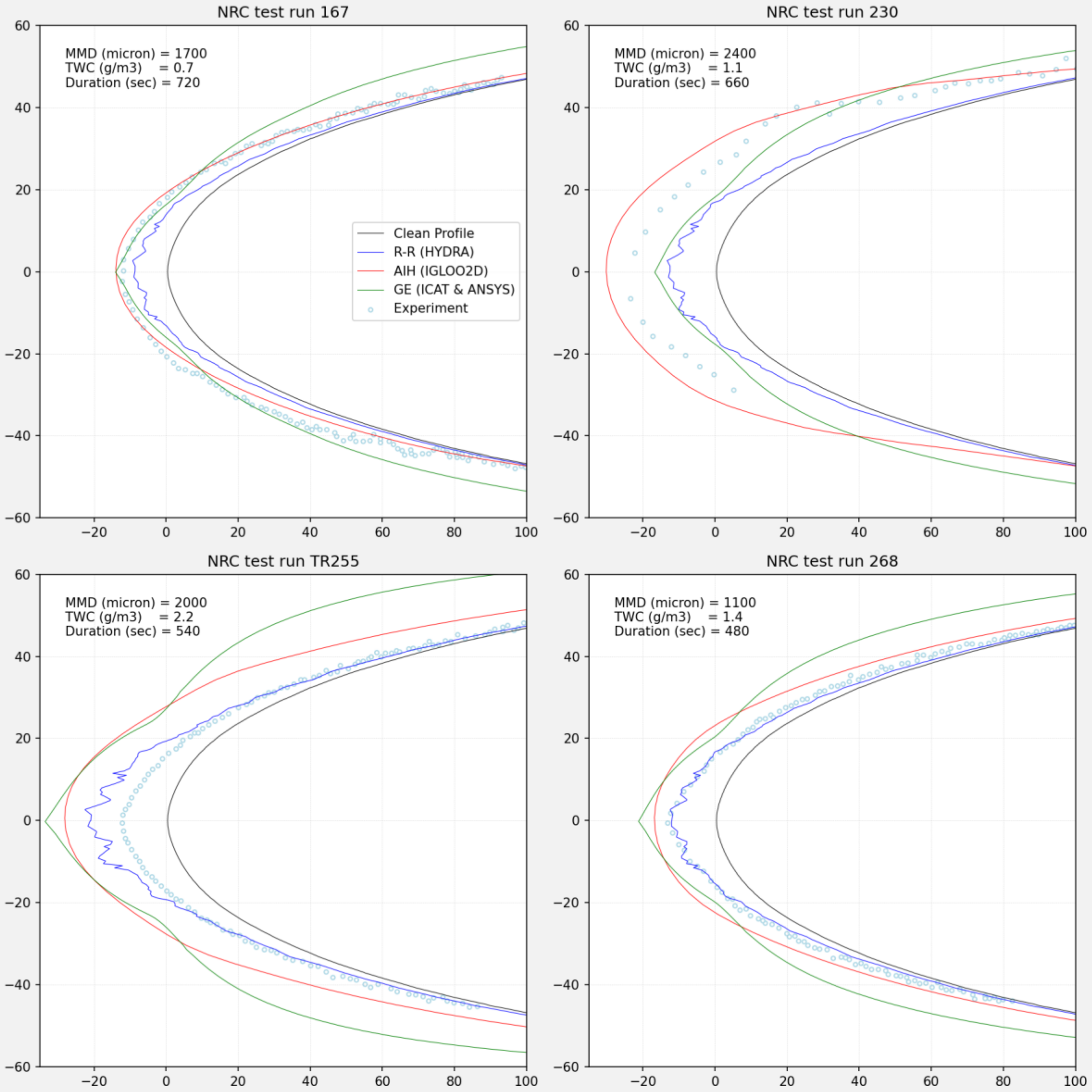
Simulation Comparison



Leading Edge Max Ice Thickness
- All Partners : Acceptable prediction on L/E for cases TWC<2.2
- All Partners : Overprediction of L/E max ice thickness on TWC > 2.2

Ice Accretion Limits (Upper and Lower)
- GE : not matching, further studies on AR and runback behavior
- AH & RR : good match

Ice Shape
- GE : not matching on TWC > 1
- AH & RR : Overall good match except on case TWC > 2.2

Conclusions

Conclusions

Prior to ICE GENESIS there was few resources that allowed a good capability on snow simulations. Current work shows the **significant improvement** based on extensive testing and modeling made on the ICE GENSIS framework.
All industrial partners have implemented on their simulation chain successfully learnings from the program

Next Steps

- Further optimization of sticking / erosion model coefficients needed
- Shattering, Bouncing, sticking, erosion, shedding, saltation phenomena to be further investigated
- Only 2D database for validation. Additional data covering a larger range for parameters of interest would be welcomed (LWR, RH, Speed,…)
- 3D application limited to functional assessment. Test on representative 3D industrial configurations to be performed

Back Up

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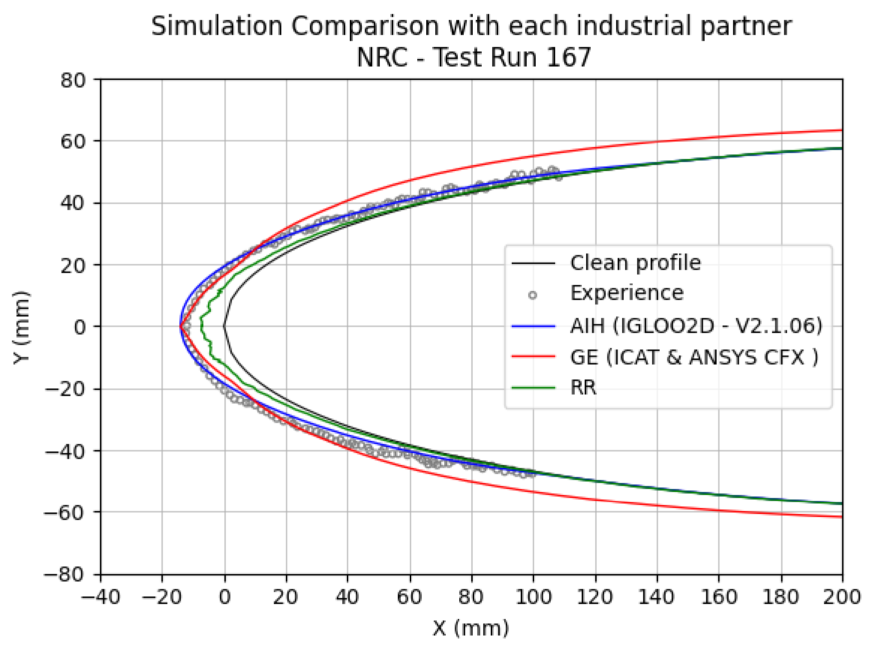
Simulation Comparison

AIH/GE/RR cross-comparison on NRC database – NRC TR167

- Good prediction of ice thickness at the L/E for both AIH and GE, slightly underprediction on RR
- Better overall prediction of the ice shape with AIH IGLOO2D simulation
- Behavior in line with approach used for optimizing sticking / erosion model coefficients

  GE: ice thickness at the L/E

  AH: ice thickness at the L/E, ice accretion limits, total, upper and lower ice surface



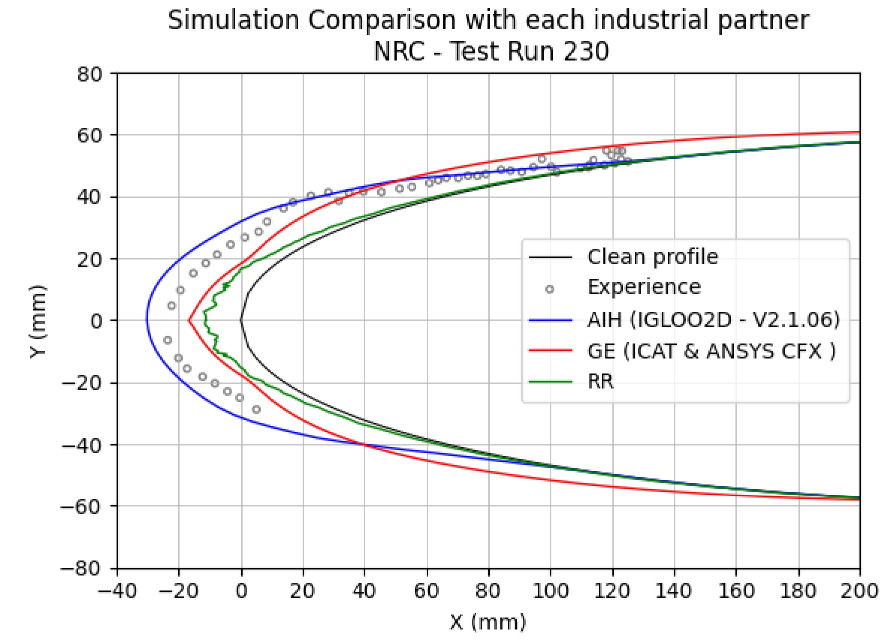
Simulation Comparison

AIH/GE/RR cross-comparison on NRC database – NRC TR230

- **Acceptable prediction of ice thickness at the L/E** for both AIH and GE
- Better overall prediction of the ice shape with AIH IGLOO2D simulation
- Behavior in line with approach used for optimizing sticking / erosion model coefficients

GE: ice thickness at the L/E

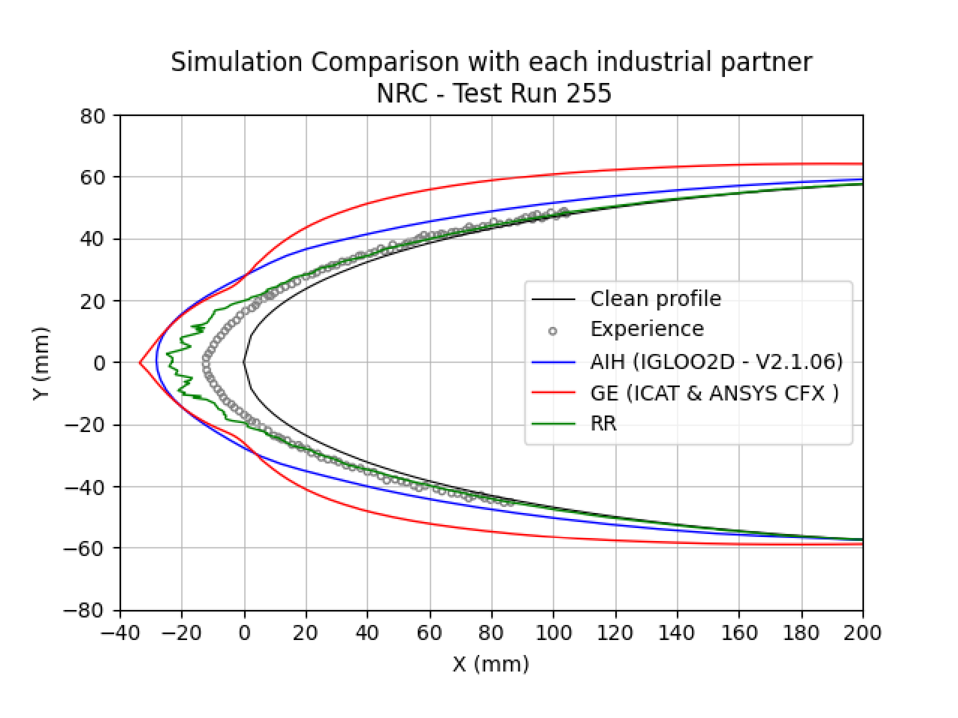
AH: ice thickness at the L/E, ice accretion limits, total, upper and lower ice surface



Simulation Comparison

AIH/GE/RR cross-comparison on NRC database – NRC TR255

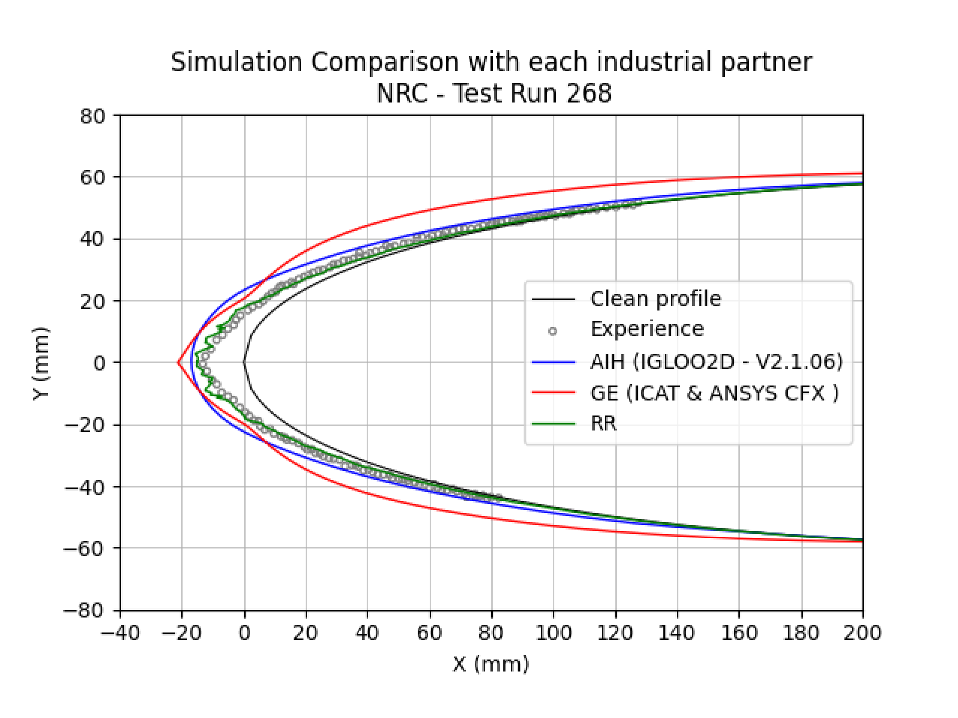
- Over-prediction of ice thickness at the L/E for both AIH and GE



Simulation Comparison

AIH/GE/RR cross-comparison on NRC database – NRC TR268

- Acceptable prediction of ice thickness at the L/E for both AIH and GE
- Better overall prediction of the ice shape with AIH IGLOO2D simulation
- Behavior in line with approach used for optimizing sticking / erosion model coefficients
  - GE: ice thickness at the L/E
  - AH: ice thickness at the L/E, ice accretion limits, total, upper and lower ice surface



Snow Numerical capability

GE Aerospace

Sensitivity studies FENSAP drop 3D
- Particle types
- Density of snow particle for CSTB data base
- Aspect Ratio to match test impingement limits
  - CSTB = 0.8
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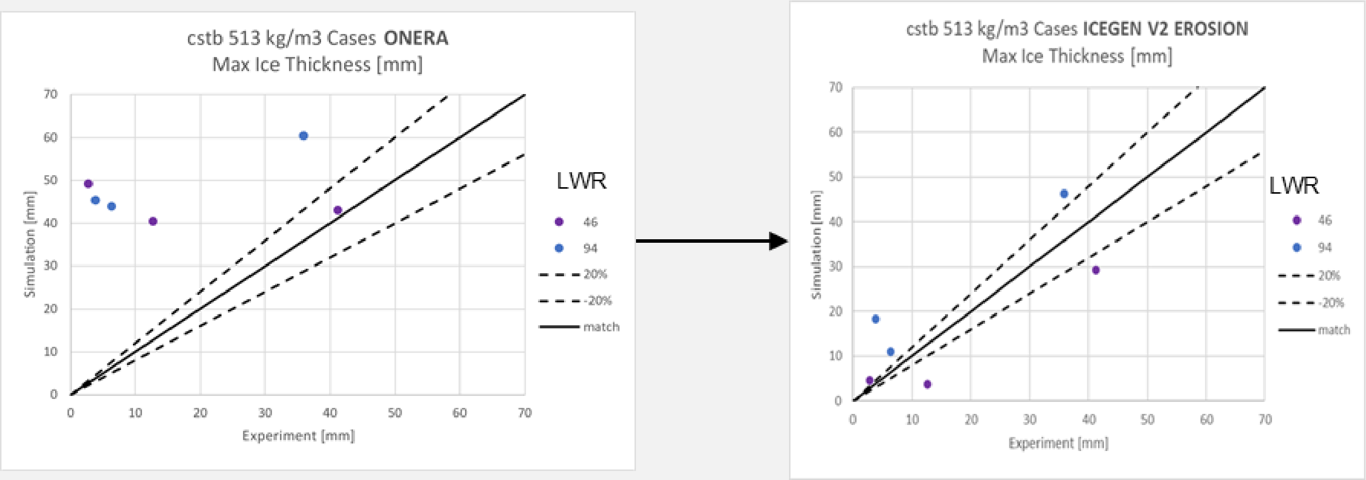
- Aspect Ratio assumed for NRC at 0.6

Sticking Efficiency & Erosion
- Empirical Implementation
- Tune Sticking Efficiency and Erosion to match max ice thickness reported at each test case
- Sticking Efficiency & Erosion = fnc (Melt Ratio)
- CSTB data max ice thickness not included in exercise

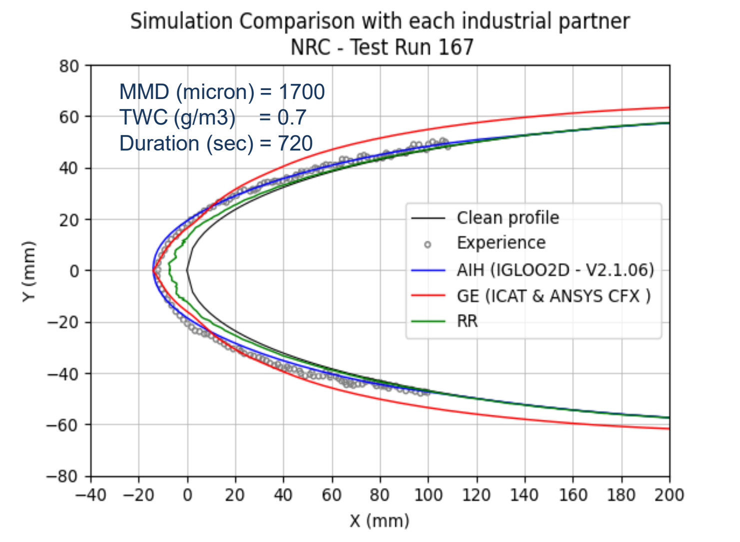
CSTB CASES (unheated)

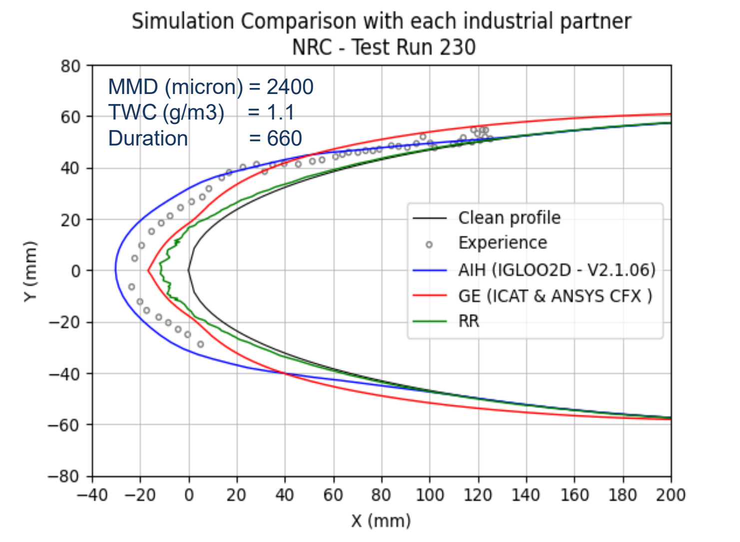


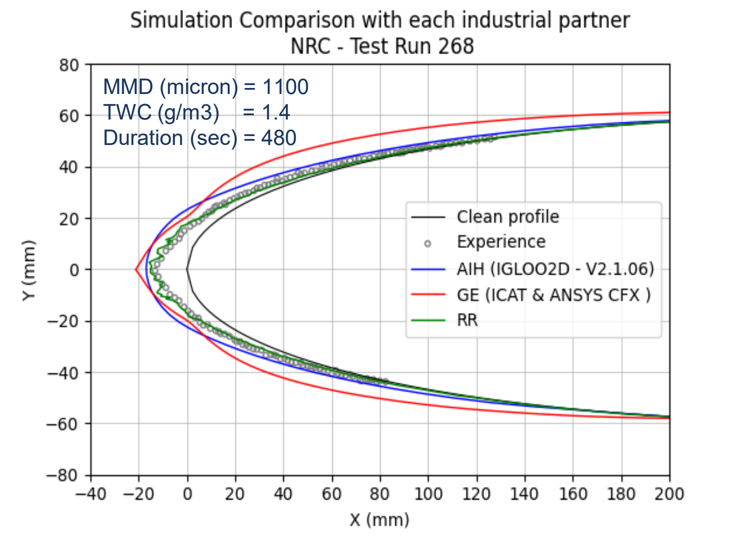
CSTB data simulated with updated model and density = 513 kg/m3, data is still off but showing good trend

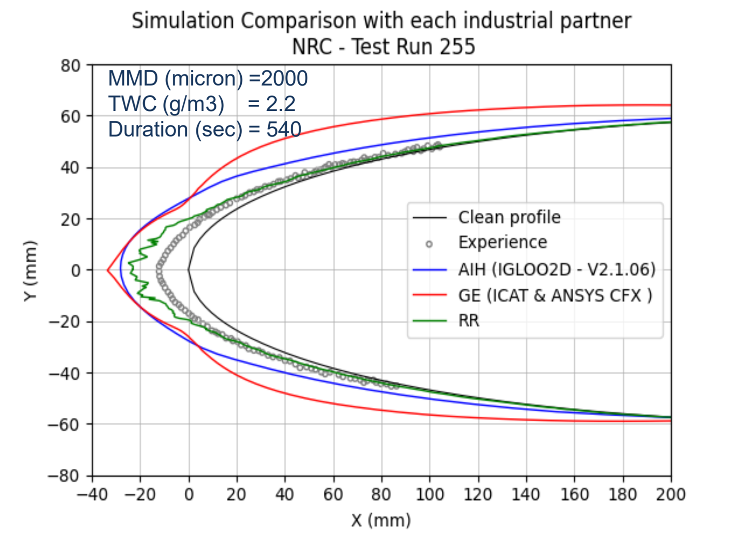
Simulation Comparison

AIRBUS ROLLS ROYCE GE Aerospace









Leading Edge Max Ice Thickness
- All Partners : Acceptable prediction on L/E for cases TWC<2.2
- All Partners : Overprediction of L/E max ice thickness on TWC > 2.2

Ice Accretion Limits (Upper and Lower)
- GE : not matching, further studies on AR and runback behavior
- AH & RR : good match

Ice Shape
- GE : not matching on TWC > 1
- AH & RR : Overall good match except on case TWC > 2.2