MUSIC-haic

3D MUltidisciplinary tools for the Simulation of In-flight iCing due to High Altitude Ice Crystals

SENS4ICE final meeting
November 29th 2023

Overview of MUSIC-haic main achievements

Presenter : Philippe Villedieu (ONERA)

MUSIC-haic in a nutshell

MUSIC-haic overall objective

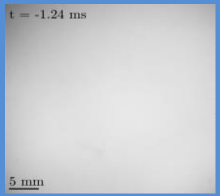
The overall objective of MUSIC-haic was to **develop and implement a validated Ice Crystal Icing (ICI) capability in existing industrial 3D multidisciplinary numerical tools** that can be used for both design and certification of new engines, probes and aircraft.

Start : Sept. 1rst 2018 - **End :** Feb. 28th 2023

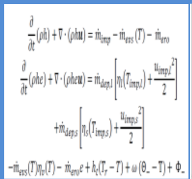
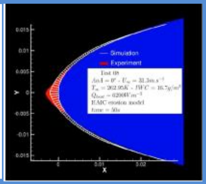
MUSIC-haic consortium : 13 partners (Universities, Research Centers, Engine & aircraft manufacturers, SMEs)

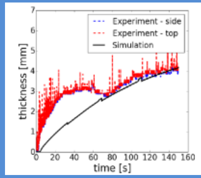
MUSIC-haic work-breakdown structure

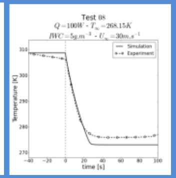
WP1
ICI experimental studies
(TUBS, TUDA, AIRBUS-CRT)
with a team of 4 PhD students

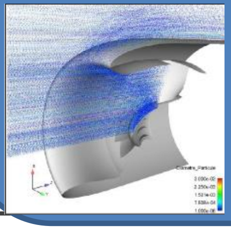
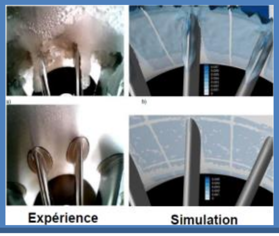
WP2
Model development and first assessment (2D benchmark)
(ONERA, TUDA, TUBS, CIRA)

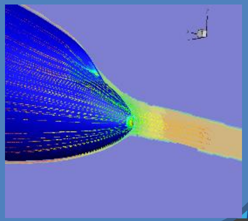







WP3
ICI models and & methods integration in 3D tools – 1st 3D benchmark
(ONERA, CIRA, Industry, ANDHEO)

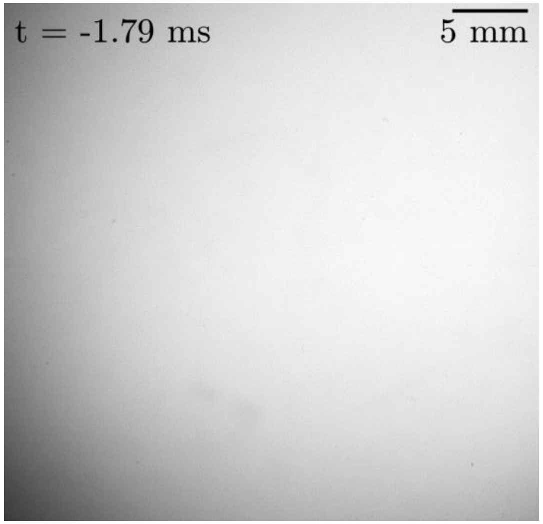


WP4
Industrial validation of the 3D Tools – 2nd 3D benchmark
(Industry, ANDHEO, ONERA, CIRA)


Result examples

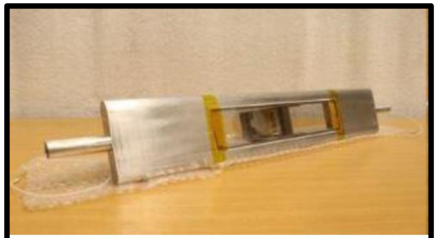
Main experiments performed in MUSIC-haic

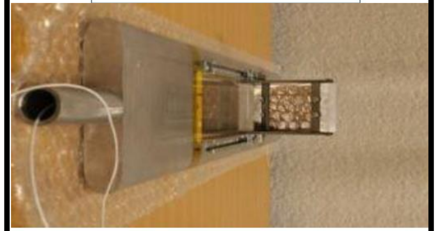
Experiment 1
Ice crystal impact experiments on a dry rigid surface
(TU Darmstadt, Airbus Munich)



Objectives :
- **Better characterize size and velocity distributions of the fragments.**
- Complement the existing databases (T. Hauk, M. Vergas)

Experiment 2
Heated flat plate accretion experiment
(TU Braunschweig)


Frontal View with ITO Glass


Rear View with Mirror Rails

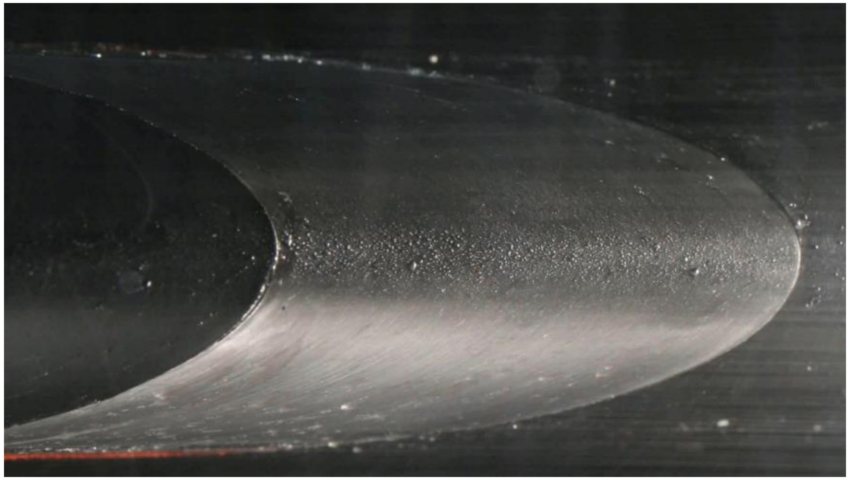
Objectives :
- **Better understand accretion inception phenomena**
- Better understand the influence of the wall heat flux compared to the influence of Twb
- Characterize the initial wall temperature drop

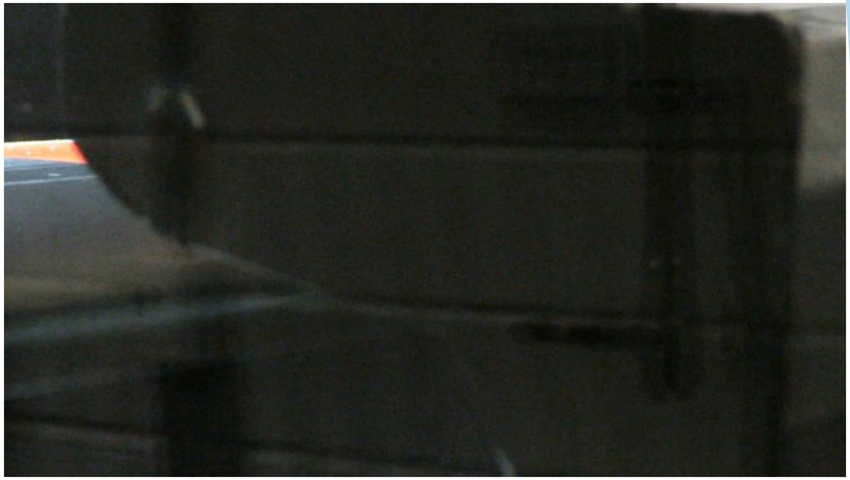
Experiment 3
Heated NACA0012 accretion & shedding experiment
(TU Braunschweig, Airbus Munich)

Objectives :
- **Investigate accretion and shedding phenomena on a heated wall model**
- Create a large database for model calibration and validation.

Experiment 3 : Accretion & Shedding experimental study

Creation of a new very large database devoted to both accretion and shedding on a heated NACA0012 model with several dozen test points





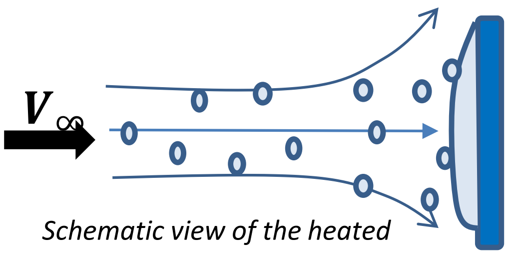
Non-heated, $V_{flow} = 30\,\frac{m}{s}, \boldsymbol{T_{wb} = +2.5}$℃$, IWC = 4.3\,\frac{g}{m^3}$
Video Sped up × 10

Heat Flux = 6200 $\frac{\boldsymbol{W}}{\boldsymbol{m^2}}, V_{flow} = 40\,\frac{m}{s}, \boldsymbol{T_{wb} = +2.0}$℃$, IWC = 15.1\,\frac{g}{m^3}$
Video Sped up × 10

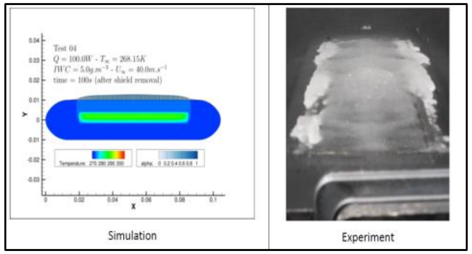
New models

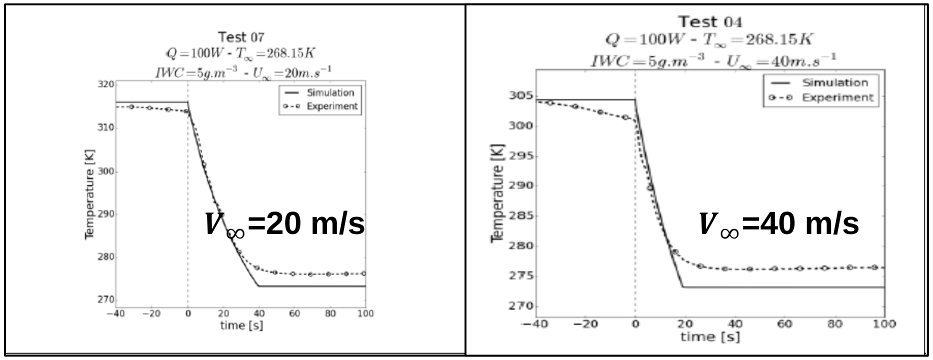
Main new achievements

- Capability to **capture the wall temperature drop** during the initial transient phase
- **New sticking efficiency model** valid for both adiabatic and heated wall
- **Improved ice crystal accretion model** (transient phase, heated & unheated walls …)

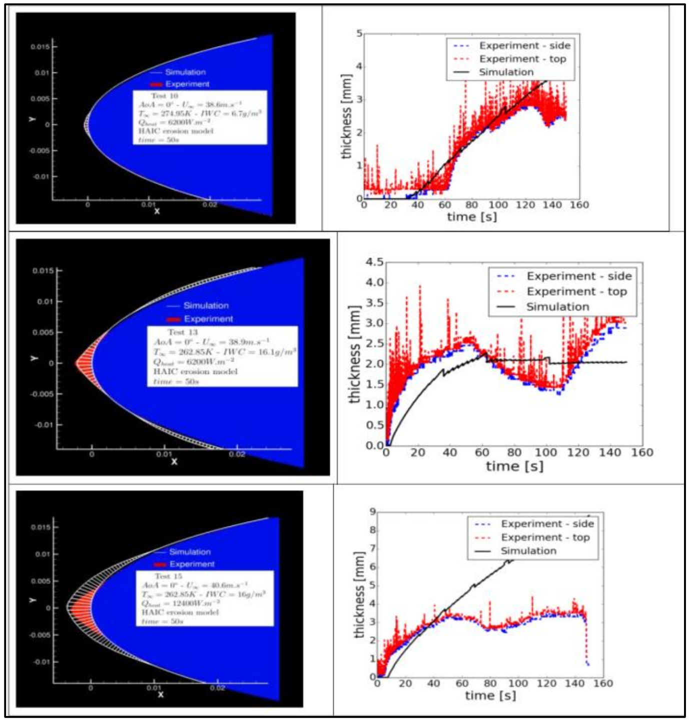


Schematic view of the heated flat plate experiment





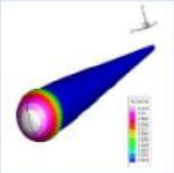
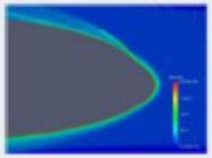
Influence of the air flow velocity on the wall temperature drop after the onset of the icing cloud



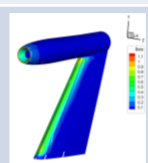
Experimental ice shapes (red) vs numerical ice shapes (white) at t = 50s

Time evolution of the tip ice thickness (side and top views).

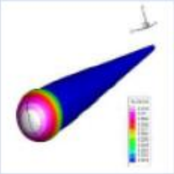
3D Tool validation – Level 1 test cases

Test case	Corresponding experiment	Schematic	Objective	Involved partners
TC1	CNRC crowned cylinder accretion experiment		Check correct implementation of accretion models in 3D tools including sticking efficiency and erosion rate models. Direct comparison with 2D tools	**ONERA, CIRA, DASSAV**
TC2	TUBS heated flat plate experiment		Same objective as TC1 + test of conjugate heat transfer capability (heated wall)	**ONERA, GE**
TC3	CNRC ICE-MACR small compressor rig		Capability to compute ICI in a representative engine configuration. Impact and accretion model validation.	**ANDHEO-ONERA, RR**
TC4	XRF1 geometry of a generic nose fuselage configuration		Capability to compute probe concentration factor. Influence of the impact model. Lagrangian vs Eulerian tools.	**ANDHEO-ONERA, AIRBUS, DASSAV**
TC6	Generic turbofan engine		Capability to compute ICI in a representative engine configuration. Comparison	**SAF-AE**
TC7	NACA12		Heated wall, Accretion modeling, Model implementation	**GE**

3D Tool validation – Level 2 test cases

Test Case	Description	Schematic	Objective	Involved partners
TC8	ICC database Simulation of some ALF502 icing tests		Engine application. Tool capability to model accretion, including heated wall cases	**RR, GE, SAFRAN, ANDHEO, ONERA**
TC9	In-service engine icing events. (Industry proprietary data)		Engine application. Tool capability to predict ICI risk	**RR, GE, SAFRAN**
TC10	Generic engine air duct		Assess capability of Eulerian trajectory solvers to compute internal flows	**DASSAULT**
TC12	HAIC flight tests (Airbus A330, Falcon20)		Probe application. Probe installation factors	**DASSAULT, AIRBUS, ANDHEO**
TC12	Pitot probe icing test		Probe application. Probe accretion and blockage	**CIRA**

3D Tool validation – Level 1 test cases

Test case	Corresponding experiment	Schematic	Objective	Involved partners
TC1	CNRC crowned cylinder accretion experiment		Check correct implementation of accretion models in 3D tools including sticking efficiency and erosion rate models. Direct comparison with 2D tools	**ONERA, CIRA, DASSAV**
TC2	TUBS heated flat plate experiment		Same objective as TC1 + test of conjugate heat transfer capability (heated wall)	**ONERA, GE**
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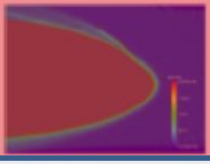
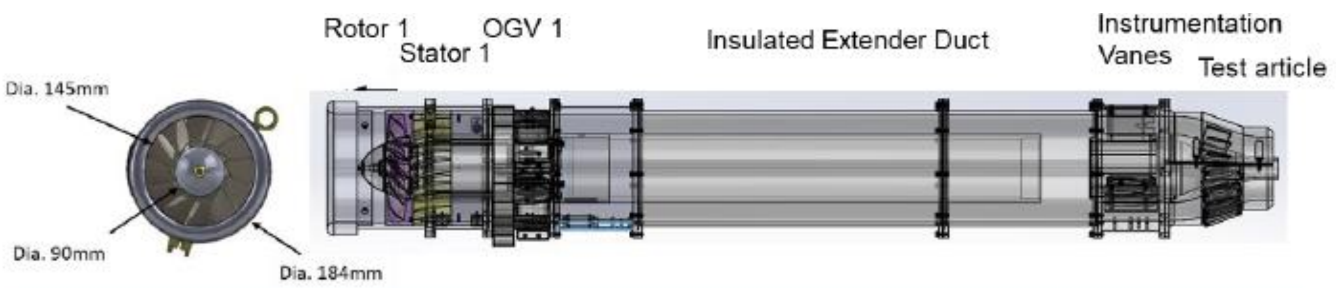
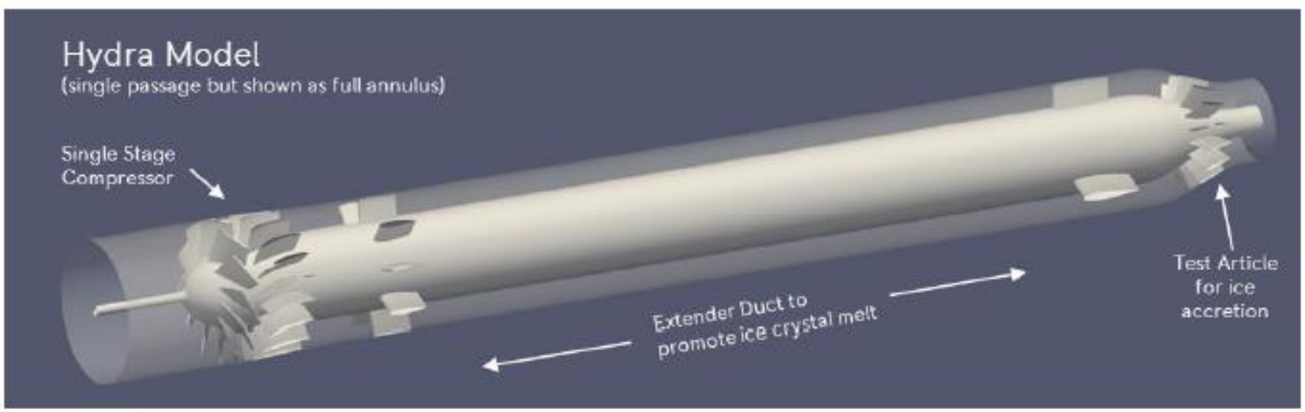
TC4	XRF1 geometry of a generic nose fuselage configuration		Capability to compute probe concentration factor. Influence of the impact model. Lagrangian vs Eulerian tools.	**ANDHEO-ONERA, AIRBUS, DASSAV**
TC6	Generic turbofan engine		Capability to compute ICI in a representative engine configuration. Comparison	**SAF-AE**
TC7	NACA12		Heated wall, Accretion modeling, Model implementation	**GE**

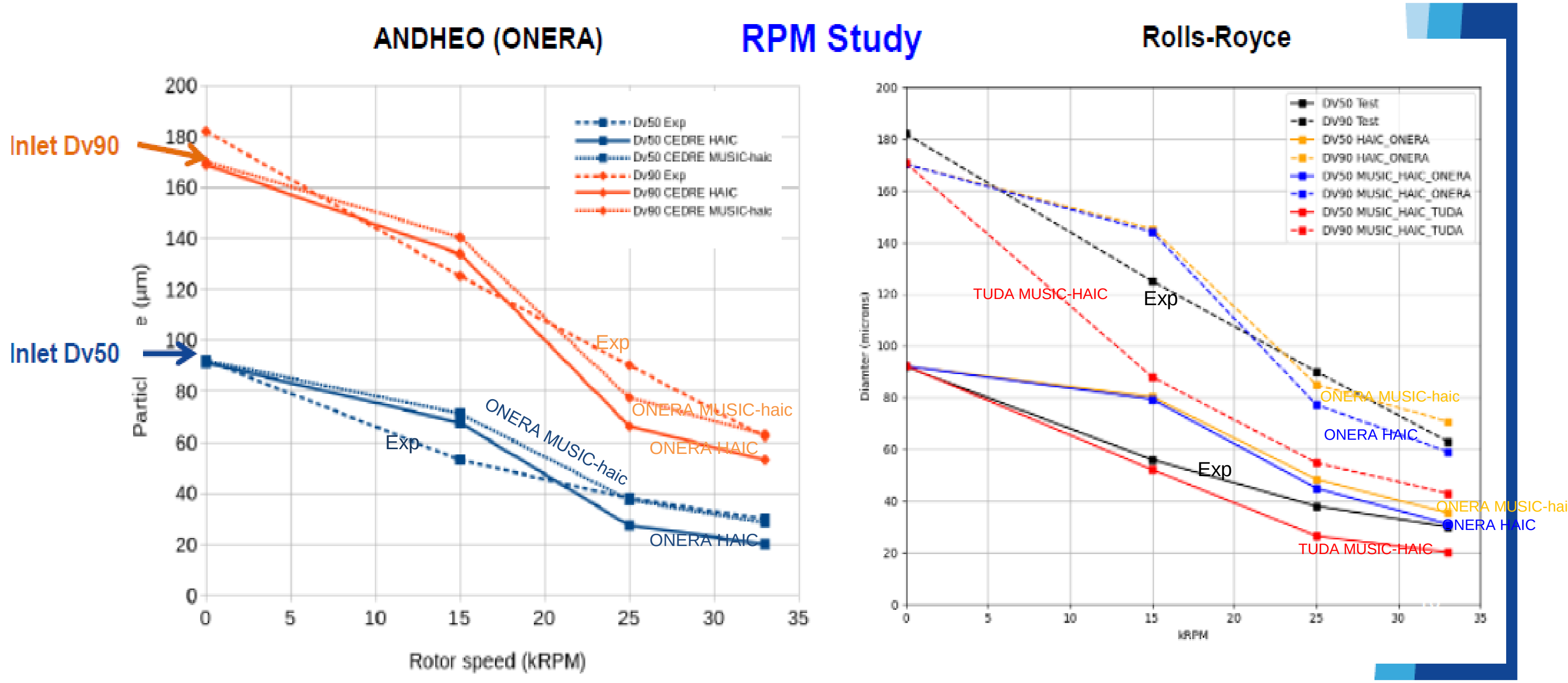
Test Case 3 : NRC's ICE-MACR

- NRC's ICE-MACR Rig tested in May 2019
- **Single Stage configuration** as reported AIAA 2020-2823
- Simulation of **3 different runs** : #131.01 (no icing) , #132.01 (light icing), #132.02 (severe icing)
- Influence of rotor speed on particle fragmentation.
- **Computations performed by ANDHEO using CEDRE and by RR using HYDRA-SSO2**





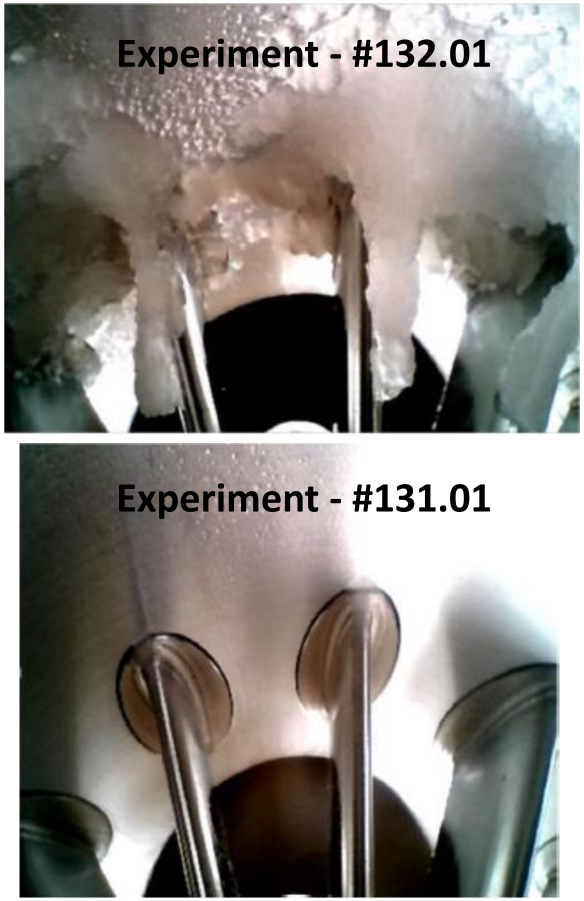
Influence of the rotor speed on particle fragmentation



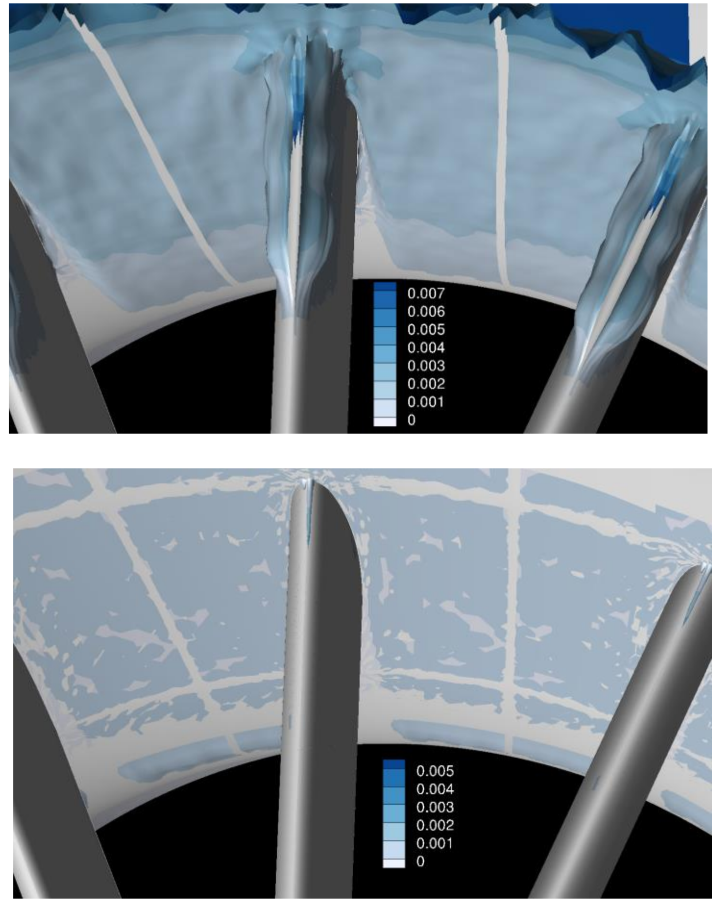
- ONERA’s HAIC and MUSIC-haic fragmentation models provide similar results. **Quite good agreement with the experimental results for both DV50 and DV90.**
- TUDA’s model tend to predict lower values for both DV50 and DV90.
- Similar trends between ONERA’s tool and RR’s tool but RR results tend to be higher → Could be due to excluded smallest particles in SS02.

MUSIC-haic
No. 767560

Ice accretion prediction



CNRC experiments



3D numerical simulations

Good qualitative agreement in terms of occurrence, location and surface extension of ice accretion.

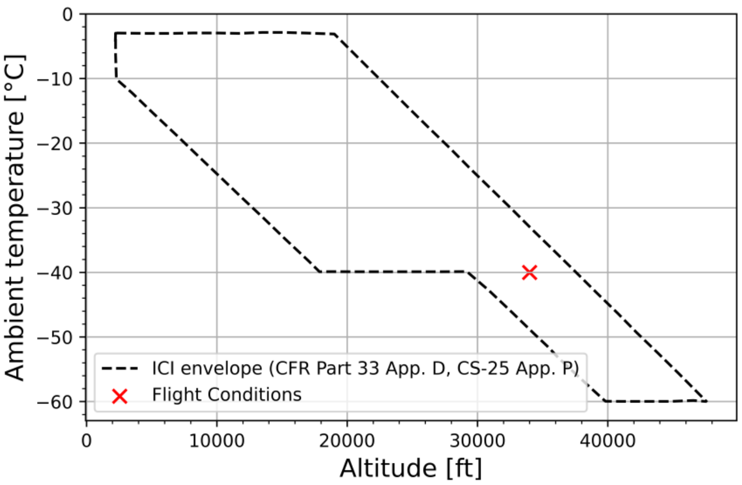
Test Case 4 : XRF1 A/C Nose + fuselage

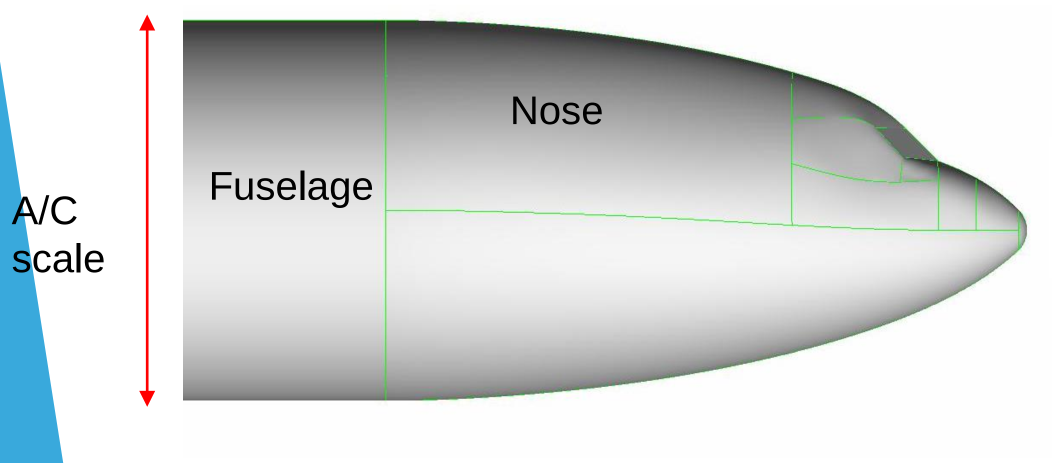
Flight conditions			
Pressure (Pa)	Angle of Attack (°)	Mach	Temperature (K)
25,000.	2.05	0.78	233.15

Ice cristal caracteristics		
MMD (µm)	IWC (g/m3)	Sphericity Φ
336.5	1.15	0.578 / 0.8

Particle aspect ratio << 1

Particle aspect ratio close to 1





Heider & Levenspiel drag coefficient model :

$$C_d = \left[\frac{24}{Re_p}\left(1 + a\,Re_p^b\right)\right] + \frac{c}{1 + d\,Re_p^{-1}}$$

$$a = exp(2.3288 - 6.5481\Phi + 2.4486\Phi^2)$$
$$b = 0.0964 + 0.5565\Phi$$
$$c = exp(4.905 - 13.8944\Phi + 18.4222\Phi^2 - 10.2599\Phi^3)$$
$$d = exp(1.4681 + 12.2584\Phi - 20.7322\Phi^2 + 15.8855\Phi^3)$$

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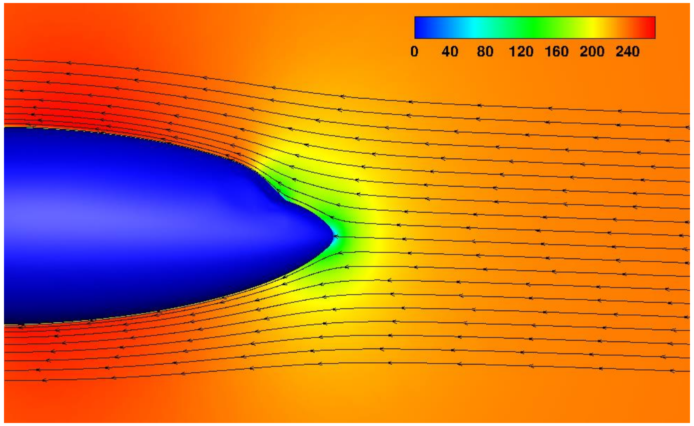
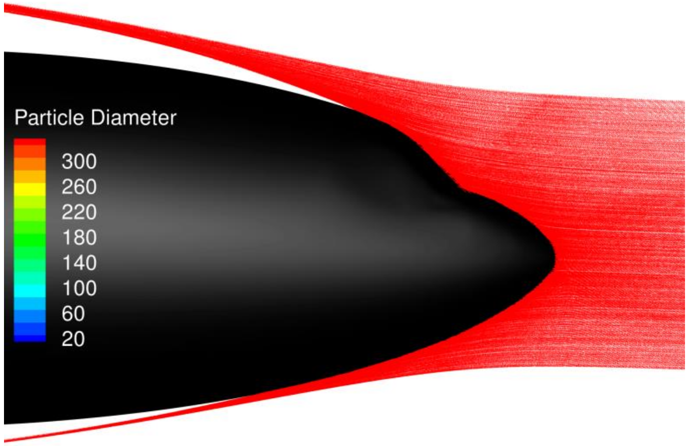
Influence of inertial effects and fragmentation phenomena on ice particle trajectories

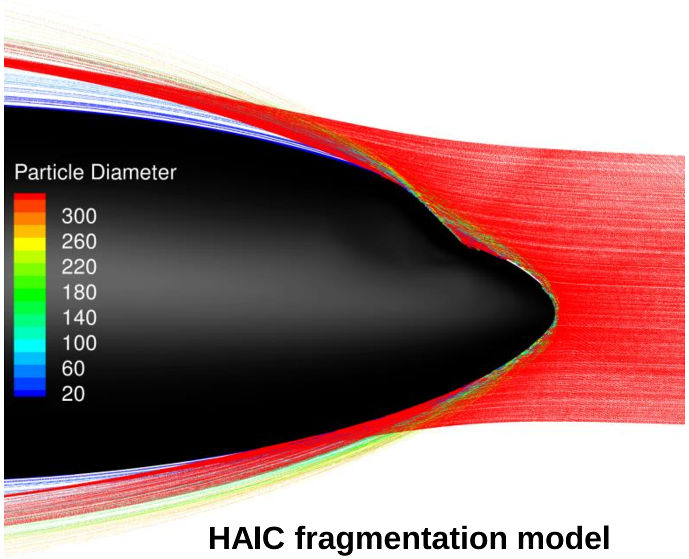
(Symmetry plane results for Φ= 0.578)



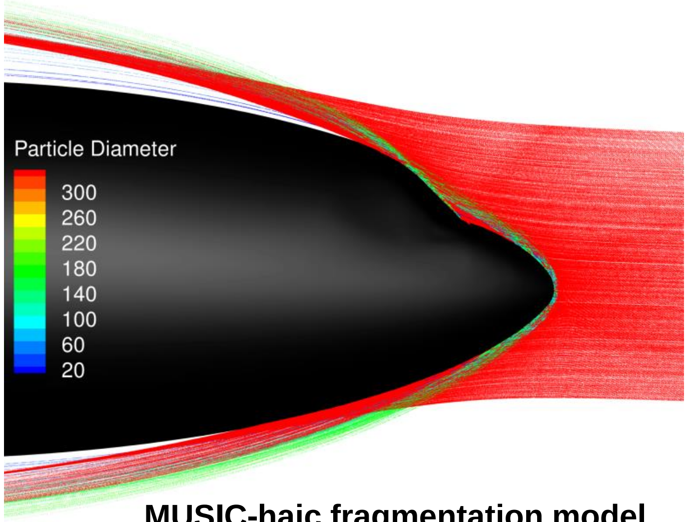
Stremlines and axial air flow velocity



Full Deposition model



HAIC fragmentation model

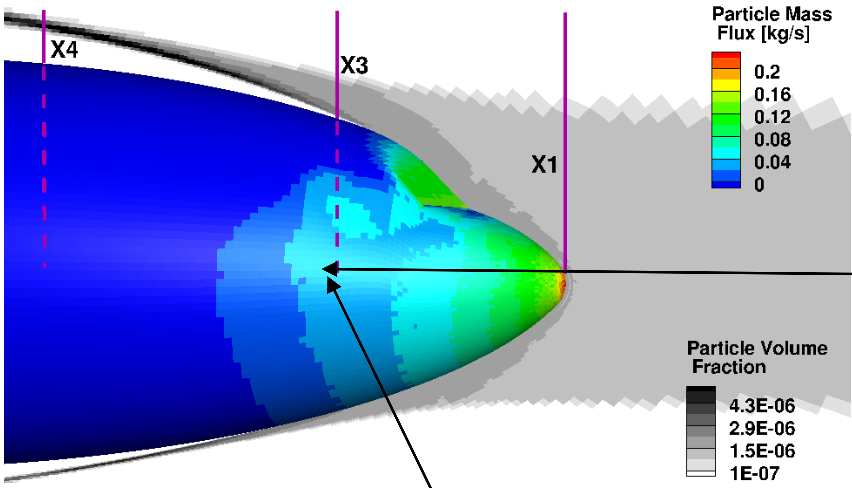


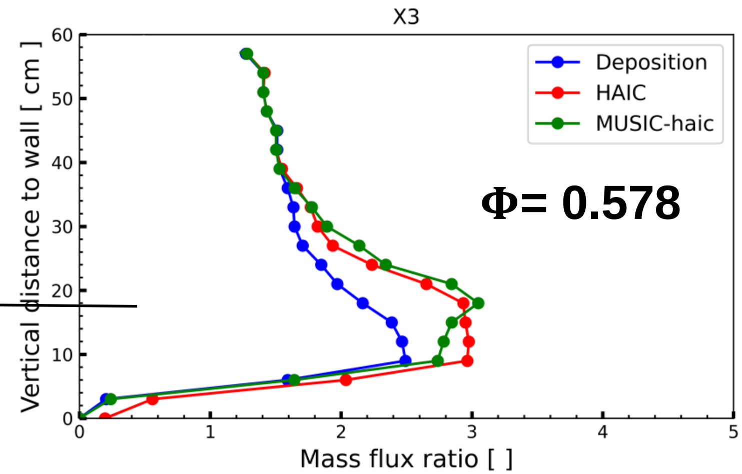
MUSIC-haic fragmentation model

MUSIC-haic
No. 767560

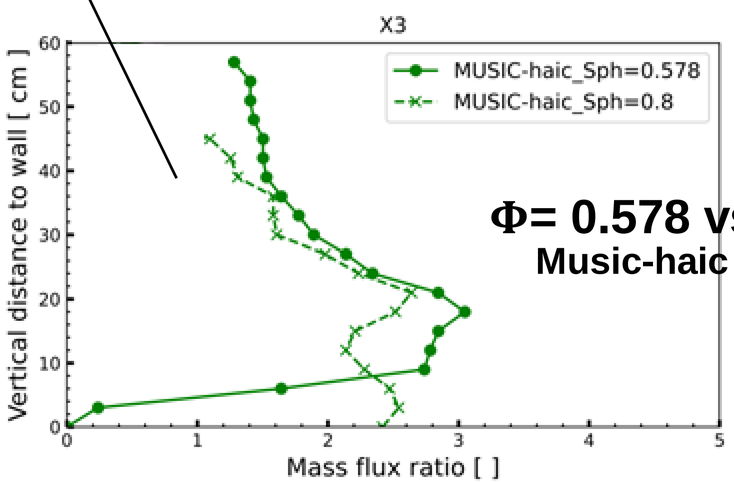
Influence of fragmentation on the local particle mass flux
(Results for Φ= 0.578 and Φ= 0.8)

Particle mass flux ratio : $\frac{M_{Flux_{loc}}}{M_{Flux_{\infty}}} = \frac{TWC_{loc}}{TWC_{\infty}} \times \frac{|U_{loc}|}{|U_{\infty}|}$ `loc`: local conditions





Φ= 0.578



Φ= 0.578 vs Φ= 0.8
Music-haic model

Conclusion & Perspectives

Conclusions

- ✓ Even if TRL6 has not been reached, **all the industrial partners are now equipped with a 3D ice crystal icing numerical capability**
- ✓ Very **promising results on** the ability of the new tools to **predict accretion zones in engines** (and the associated risk level) and to **calculate probe installation factors**.
- ✓ **Lot of new experimental results** that will be very useful for further model improvement and validation.

Summary of new capabilities of 3D industrial numerical tools in terms of targeted measurable results

Application	Targeted measurable results	Status at the end of MUSIC-haic
Engines (RR, GE, SAF-AE)	**Quantify the fan and discharge device extraction efficiency** (Result#1)	**This capability is now available (TRL5/6) in all engine tools**
	Identify the most likely zones of the engine core for ice crystal accretion to occur (Result#2)	**This capability is now available (TRL5/6) in all engine tools**
	Predict the accretion rate in these zones (including the ice erosion effect) (Result#3)	**This capability is now partially available in ONERA's (SAF-AE) and GE's tool. It is still under development in RR's tool.**
	Estimate the maximum mass of the shed ice debris (Result#4)	**This capability is not yet available but large experimental databases have been produced.**
Probes, including their installation on the aircraft (AIRBUS, DASSAULT)	**Predict probe installation factor** (Result#5)	**This capability is now available (TRL5) in DASSAV's and Airbus tools**
	Predict, for given aerothermal conditions, the **critical ice water content (IWC) leading to the probe inlet obstruction** (Result#6)	**This capability is not yet available, but the building blocks to achieve it have been developed.**

Perspectives for future research projects

Despite the progress made in MUSIC-haic, not all the objectives could be achieved and some gaps remain, including in particular:

- **experimental data**: need for additional tests at **higher speed and with smaller particles** (possibility to collaborate with CNRC and NASA)
- **modelling** : need to **improve / extend / further validate some models** (sticking efficiency, erosion rate, liquid water and heat transport in accretions ...)
- **numerical methods:** need to **consolidate thermal coupling algorithms** and to **implement the numerical strategy** proposed in MUSIC-haic **to treat shedding phenomena**
- **validation of tools:** need to **continue the validation of 3D tools** by continuing to explore existing databases (MUSIC-haic, CNRC for altitude and high speed influence, ICC, HAIC flight tests, proprietary data …)