ICE GENESIS Final Public Workshop

6-7 December 2023
Toulouse, France

CIRA, ONERA, POLIMI, POLYMO, TUBS, TUDA, TUS

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.

SLD Models

CIRA, ONERA, POLIMI, POLYMO, TUBS, TUDA, TUS

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SLD Drop Impact

CIRA, CU, ONERA, TUBS, TUDA, TUS

ICE GENESIS

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Physical description

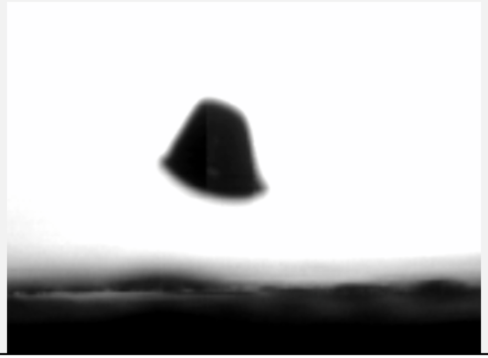
- Develop / extend the capabilities of the 3D solvers
  - Physical modelling
    - Based partially on academic experiments conducted in ICE-GENESIS
      - Database at disposal on different topics
    - Two main activities: Drop impact, Roughness
    - Liquid film activities have been drastically reduced
  - Numerical methods for Predictor-Corrector or Multi-Step approaches
    - Management of the displacement of the iced surface
    - Remeshing / automatic meshing strategies
    - Preliminary calculations have been performed
- Partners involved: CIRA, ONERA, POLIMI, POLYMO, TUBS, TUDA, TUS

SLD Droplet Deformation

- Objective: characterize the droplet deformation prior to impact
- Methodology
  - Phenomenon clearly observed during the academic ICE-GENESIS experiments
  - Influence on the spreading rate / splashing (β spreading parameter)
  - Characterization based on the radius of curvature

$$r/R_o = b\sqrt{t\,U_o/R_o} = \frac{b_o}{\sqrt{\kappa R_o}}\sqrt{t\,U_o/R_o}$$

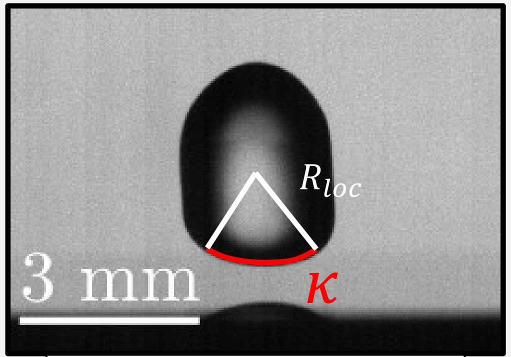
r wetted area radius, R_o impinging drop radius, U_o drop velocity



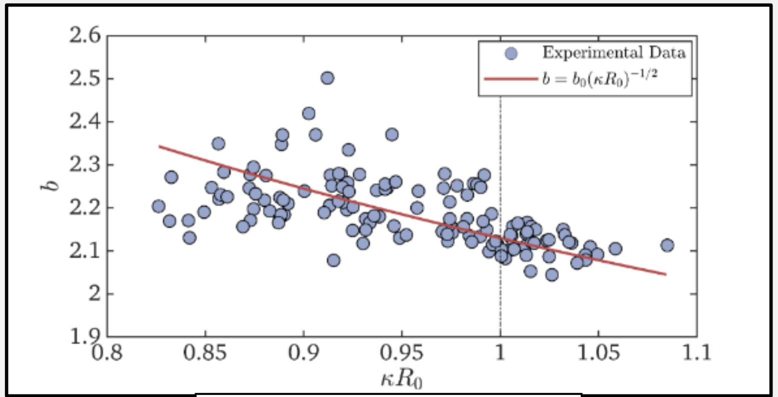
V_{air}=89m/s / T_{air} = 0°C / angle=0° / D_o = 1.236mm

  - Model adapted to the industrial solver $\kappa(U_0) = C_0 * [C_1 + C_2 \tanh(C_3 U_0)]$, $\kappa = \min(\kappa(U_0), 715)$

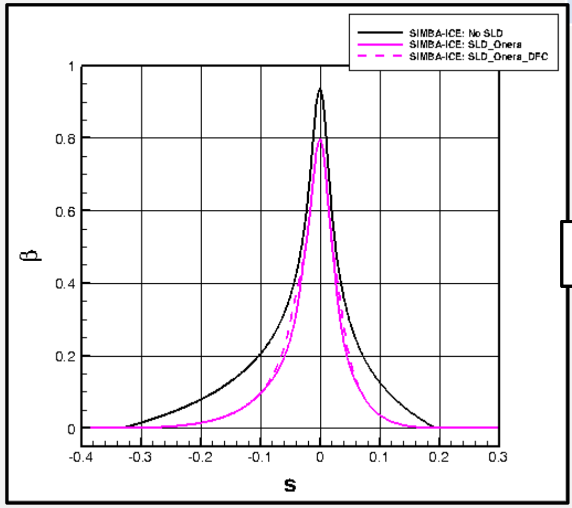
C_0	C_1	C_2	C_3
600	2	-1	0.28



Geometrical definition



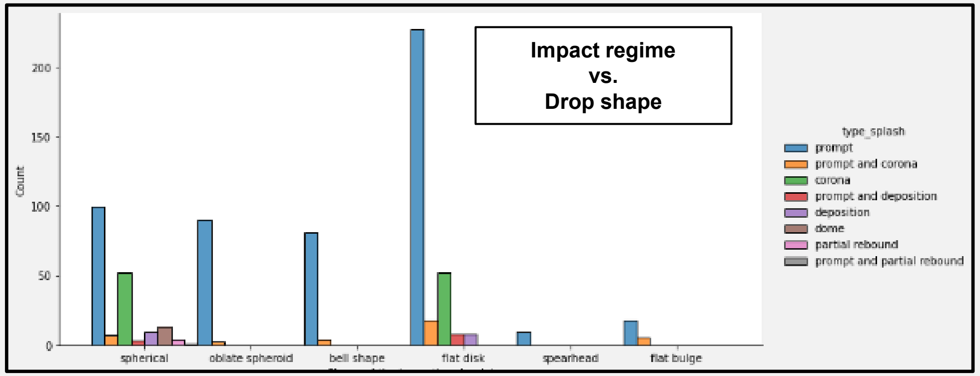
Curvature influence



Influence of the correction

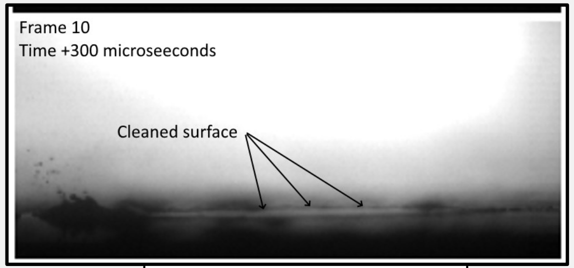
SLD Impact regime

- Objective: experimental characterization (surface, air temperature, impinging angle, …)
  - Most data correspond to corona or prompt splashing
  - Some unexpected features: cleaning, erosion, high-altitude effect => to be confirmed/explored



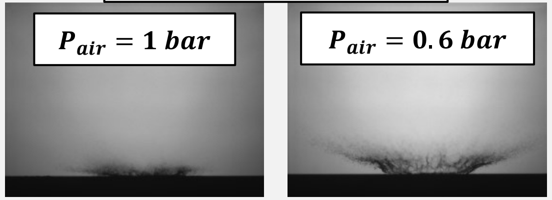
Impact angle effect

$V_{air} = 100\ m/s\,;\ T_{air} = -10°C$
$\theta = 40°$



Cleaning effect

Altitude effect

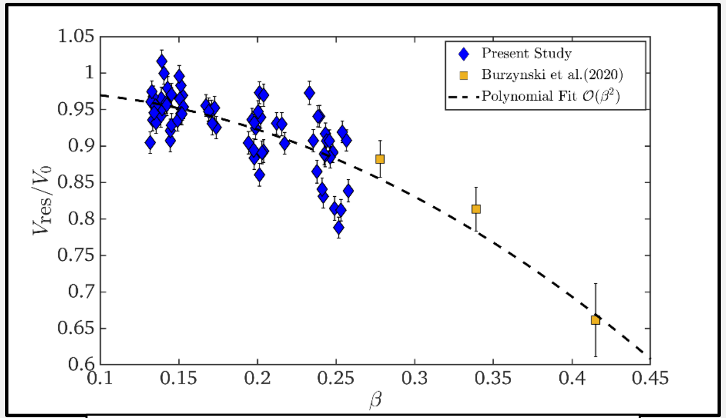


$D_0 \approx 325\ \mu m\,;\ V_{air} = 140\ m/s\,;\ T_{air} = 15°C$

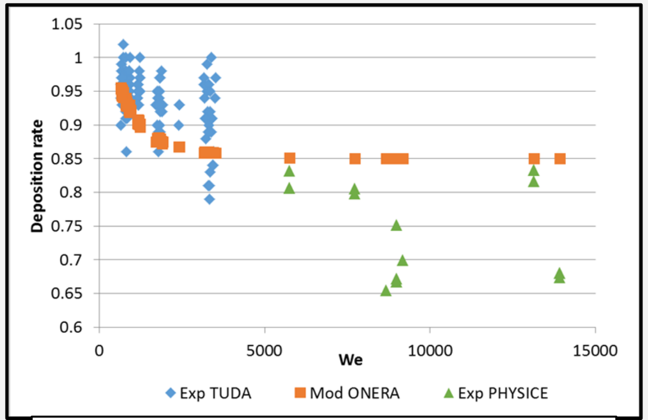
Erosion effect

SLD Mass Deposition

- Objective: improve our knowledge on the mass deposition modelling
- Methodology
  - Academic experiment to enforce the existing data at moderate Weber numbers
  - Preliminary validation of the existing models is satisfactory
  - Need of data at high Weber numbers is an open question



Experimental residual volume



Deposition rate vs. We number

ONERA model: $f\left(\widetilde{K}_n\right) = 1 - C_1 \frac{\widetilde{K}_n{}^2}{C_2^2 + \widetilde{K}_n{}^2}$

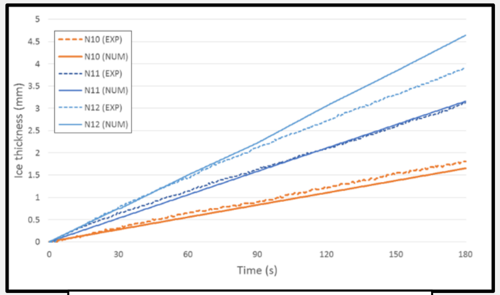
	Original	Modified
C_1	0.15	0.25
C_2	10	40

Wright model: $f_m = \frac{m_S}{m_0} = C_3[1 - sin(\theta_0)]\left[1 - e^{-0.0092(K_{L,n}-200)}\right]$

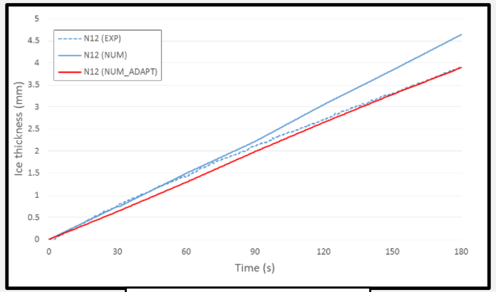
	Original	Modified
C_3	0.7	0.8

SLD Accretion

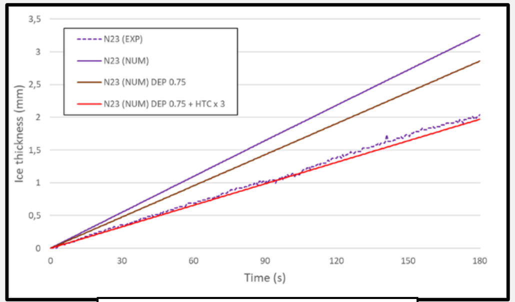
- Objective: assess the mass deposition model and its modifications in a 2D solver
- Methodology
  - Experimental characterization on a quasi-cylinder and the HMDI airfoil
  - Modifications may play a role but are not sufficient => minor improvement
    Heat transfer seems also to play a role
  - No modelling of the erosion phenomenon at the present time



Velocity influence (-10°C)

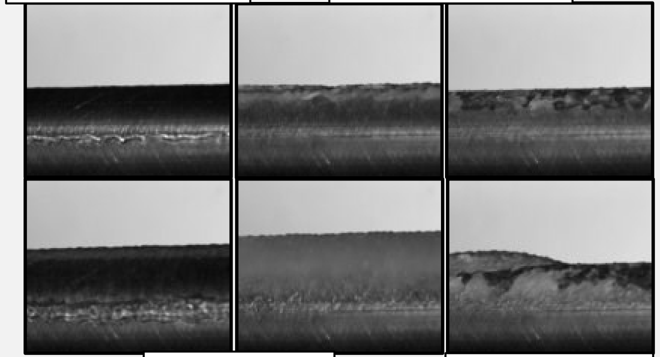


Modified model

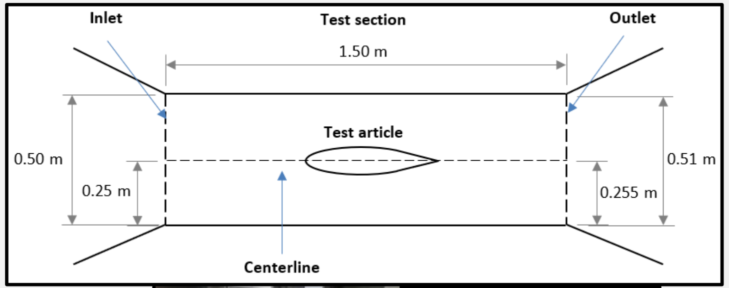


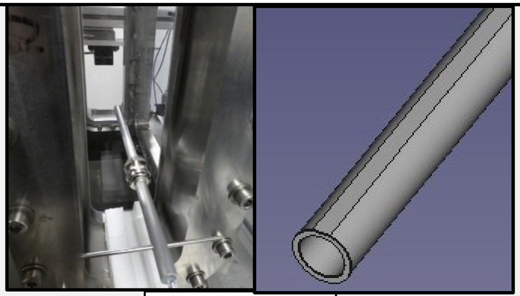
Modified model + htc

$V_{air} = 100\ m/s$ $V_{air} = 180\ m/s$



$T_{air} = -2°C$ $T_{air} = -10°C$

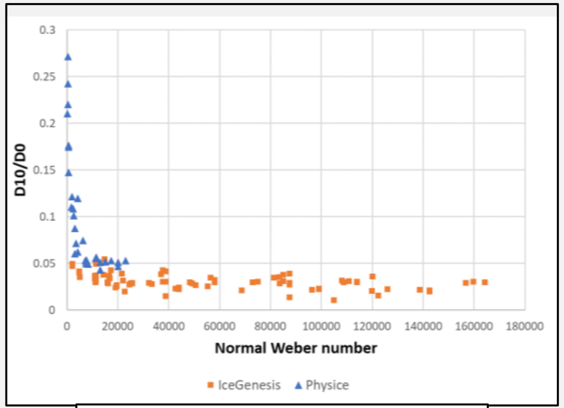




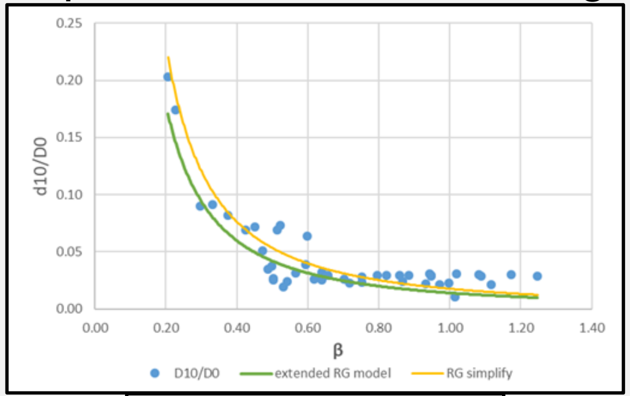
Set-ups

SLD Secondary Droplets

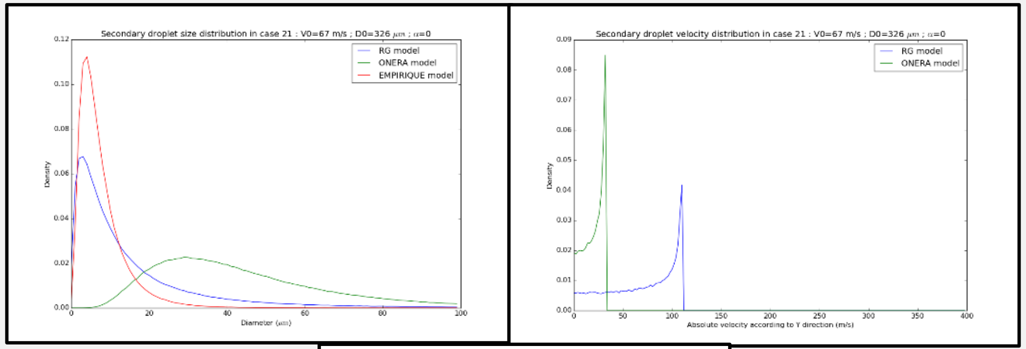
- Objective: improve the modelling of the secondary droplets at high We numbers
- Methodology
  - Based on an experimental characterization (quasi-cylinder) using PDPA measurement technique
    - Some influences have been studied experimentally (see comparison with previous data)
  - Approach based on Riboux-Gordillo (RG) and Burzinsky-Bansmer-Roisman model
    - Reference time defined as τ_D (Rayleigh-Taylor instability) + corrective factor
    - Probability Density Function of secondary droplets based on a log-normal law (D_10, D_32 RG) => improvement
    - Velocity based on the RG model => discrepancies between models
  - Further work is needed (to adapt the RG model, to design an adapted set-up, ...)



Ice Genesis vs. Physice data



RG model vs. experiments

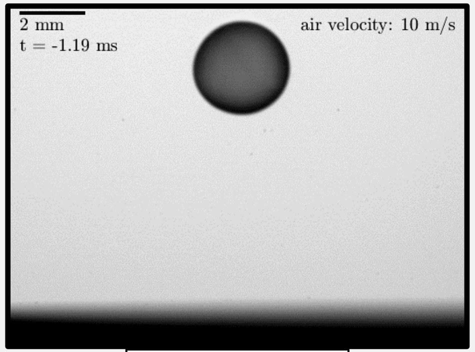


Model comparison (D and Vt)

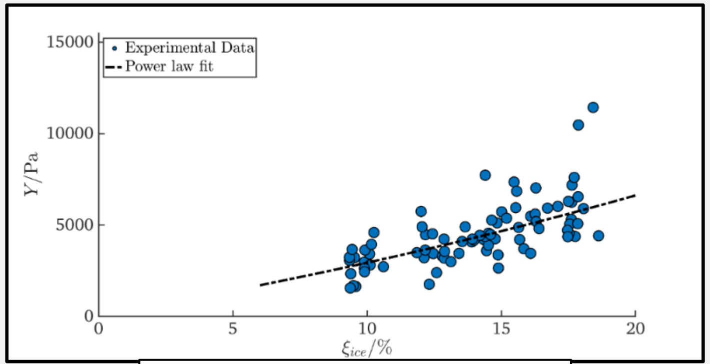
SLD Unexpected Features

- Met during the academic experiments => need further investigations
- High-altitude effect
  - Need to know if accretion at ambient conditions is more conservative than at high-altitude conditions
- Erosion effect
  - Modelling of this effect could be based or derived from our present knowledge on IC? Other topics?
- Dendritically Frozen Droplet
  - Observed during some academic experiments at TUDA and modelled with a plastic flow behaviour
  - Is it representative of real in-flight icing?

Erosion video



DFD impact



Yield strength vs. ice fraction

Roughness characterization

ONERA , TUBS

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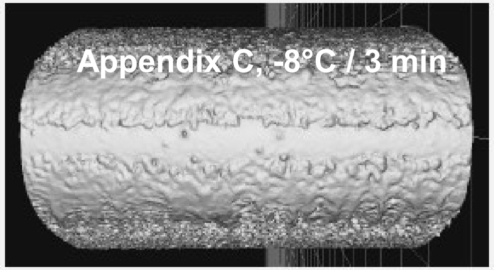
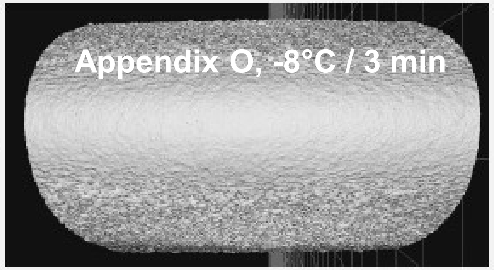
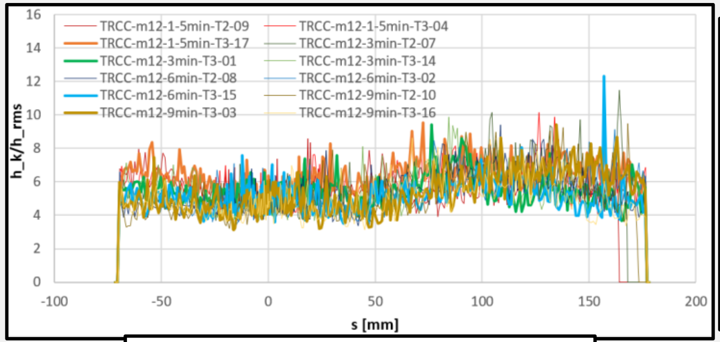
Roughness

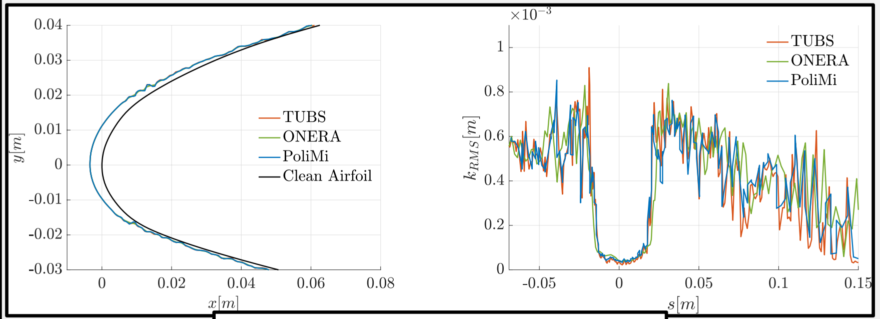
- Objective : develop tools to analyze the experimental roughness and propose a roughness model
- Methodology
  - Experiments performed on HMDI airfoil (c=0.5m Span=0.7m) for both Appendices C and O
  - Photogrammetry technique to characterize the roughness
- Analysis of the experimental data / assessment of the tools
  - Two methods: geometric definition/ Self-Organizing Maps
  - All the tools/methods provide similar results
  - Comparison extended to other approaches



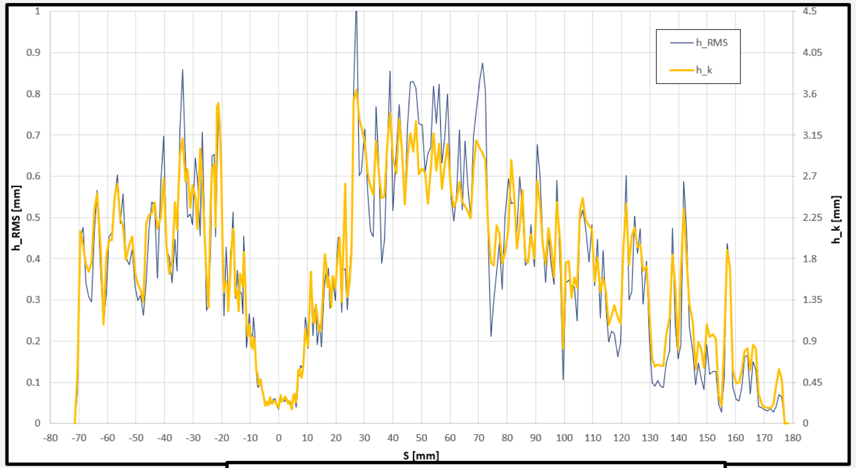




App. C, T = -12°C, t = 9 min



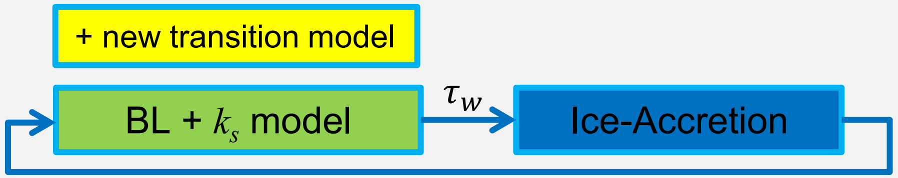
App. O, T = -8°C, t = 6 min



App. C, T = -12°C, t = 9 min

Roughness

- Modelling activities led by ONERA
  - Roughness plays a major role in the heat transfer at the wall... And possibly on the laminar-turbulent transition => development of a new model accounting for this transitional effect
  - Model writes as



$$e_b = \alpha_0 L {Re_\tau}^{\alpha_1} {We_\tau}^{\alpha_2} H_1(\theta, \Delta\theta) H_2(Re_b) \qquad k_s = \alpha_3 e_b$$

$$L = 1m \qquad \alpha_0 = \frac{\pi}{2} \qquad \alpha_1 = 0 \qquad \alpha_2 = -1 \qquad \alpha_3 = 1/3$$

$$H_1(\theta, \Delta\theta) = (\alpha_4(T_w + \alpha_5))^{\alpha_6} \quad \alpha_4 = -0.0108 \quad \alpha_5 = -275 \quad \alpha_6 = 1 \quad H_2(Re_b) = 1$$

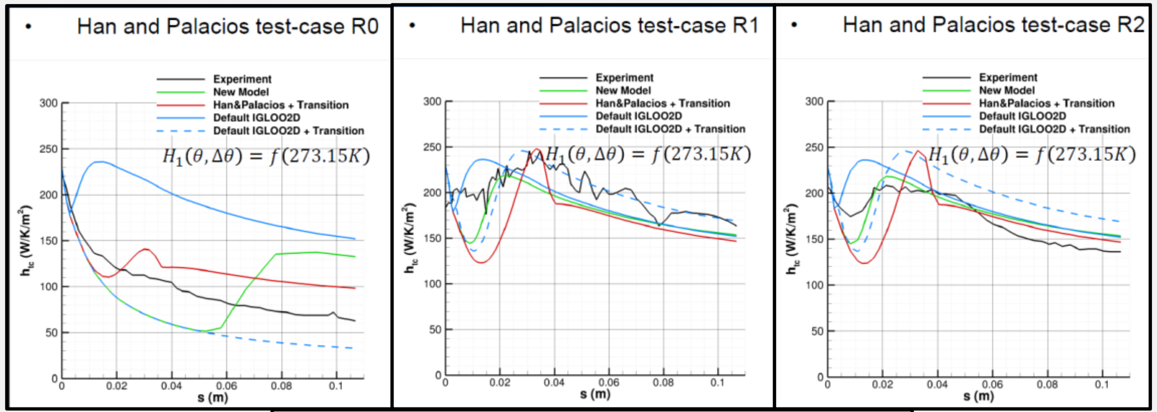
$$\gamma = 1 - e^{-\beta_1 \eta^{\beta_2}}$$

$$\beta_1 = 5 \quad \beta_2 = 3 \quad \eta = \frac{Re - Re_{on}}{\Delta Re} \quad Re_{on} = Re(Re_k = Re_{k,crit}) \qquad \Delta Re = 120000 \quad Re_{k,crit} = 600$$

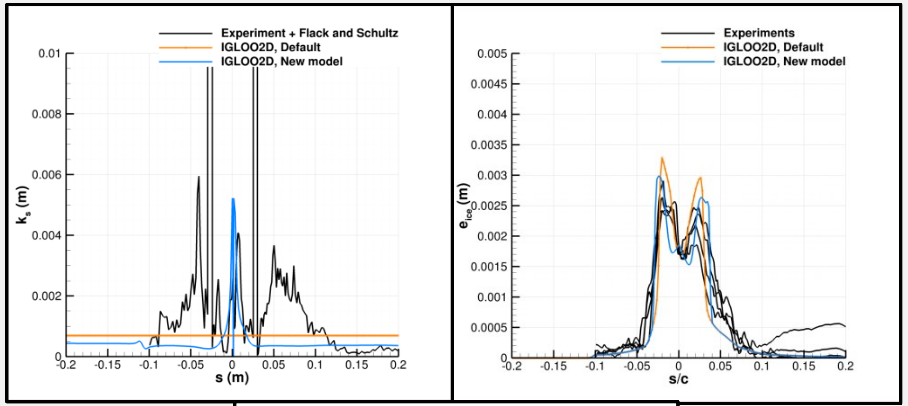
  - New model based on an optimization of three critical parameters (red) using an AI approach

Roughness

- Assessment of the model wrt to Han-Palacio's database (10-3=7 test cases / App. C)
  - Heat Transfer Coefficient behaviours are most of the time improved but roughness heigths are not satisfactory
- Assessment of the model with TUBS database
  - Comparison on the roughness height and ice thickness for both Appendix C and Appendix O
    - Roughness height is not well reproduced while ice thickness is quite nice
- Further work
  - Investigate a larger number of test cases + study the influence of App. O
  - Improve the set of representative parameters of the model?



Comparisons of Heat Transfer Coefficient



App. C / T = -8°C, t = 3 min

Numerical Methods

CIRA, ONERA , POLIMI
POLYMO, TUS

ICE GENESIS

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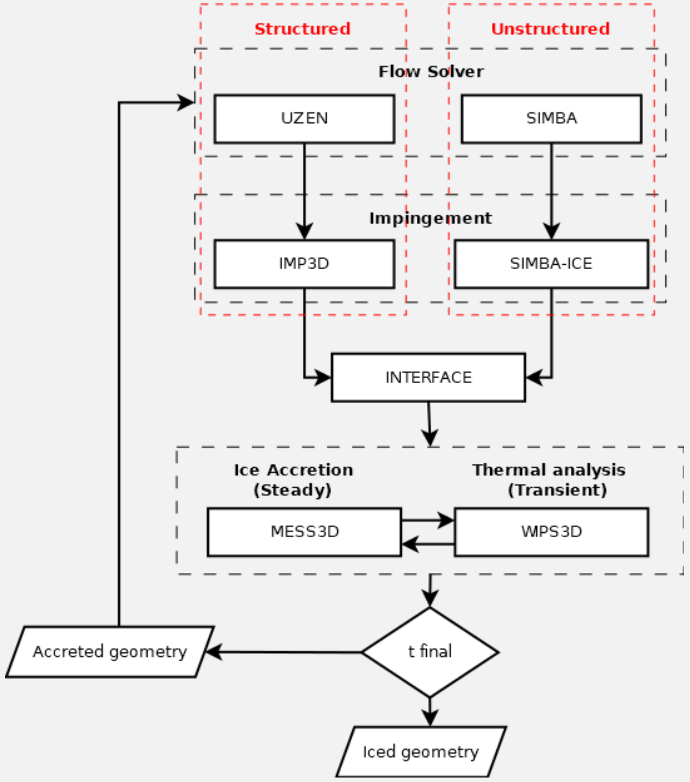
Numerical methods - 3D solvers

- Objective: extending the capabilities of the 3D solvers for Liquid Icing Conditions
- Methodology
  - Developing numerical methods for Predictor-Corrector / Multi-step calculations + Integrating SLD models
    - Need to consider the displacement of the iced surface
    - Need to consider the re-meshing/automatic meshing of the new geometry
    - Need to check the overall performances (CPU time, solution, …)
  - Assessing the 3D solvers



Numerical methods - 3D solvers

Definition of common test cases

- Baseline calculation: NACA23012 2D extruded cases (Ice Prediction Workshop database)

Run	V [m/s]	T [C]	P [Pa]	MVD [μm]	LWC [g/m³]	AoA [°]	Time [s]	Remarks
Case 241	103	-23°	92528	30	0.42	2°	300	Rime ice
Case 251	103	-12.6°	91700	21.5	1.64	2°	400	Monomodal SLD
Case 252	103	-12.6°	91700	21.5	1.64	2°	400	Bimodal SLD

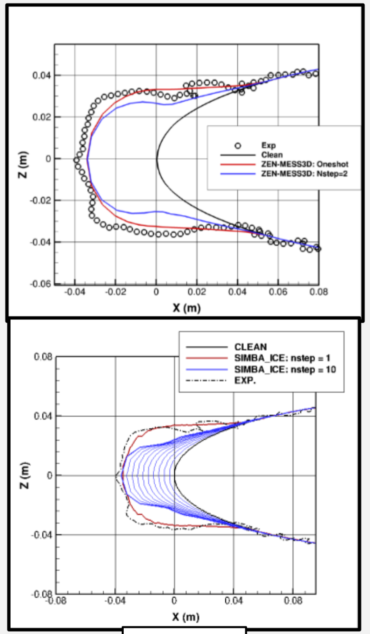
- Benchmark tests: 30° swept NACA0012 (Ice Prediction Workshop database)

Case 361	103	-16°	92321	34.7	0.5	0°	1200	Rime ice
Case 362	103	-7°	92321	34.7	0.5	0°	1200	Glaze ice

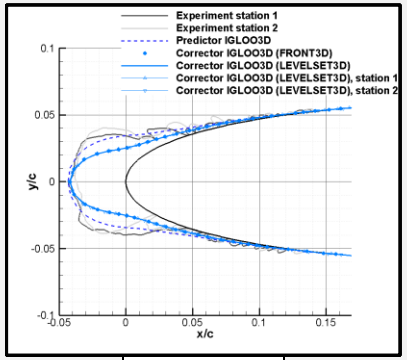
- Yellow cases used for the TRL4 validation held in December 2022 (CIRA)

Numerical methods - 3D solvers

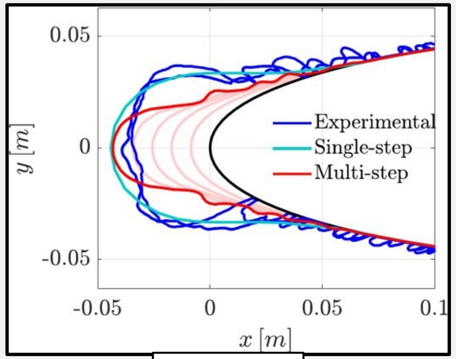
- Results from TRL4 – Appendix C conditions
  - Case 361
    - Bilan



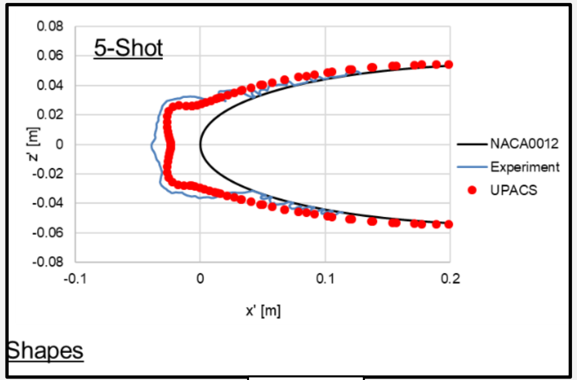
CIRA



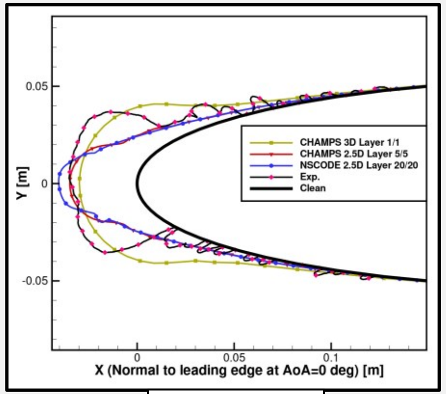
ONERA



POLIMI



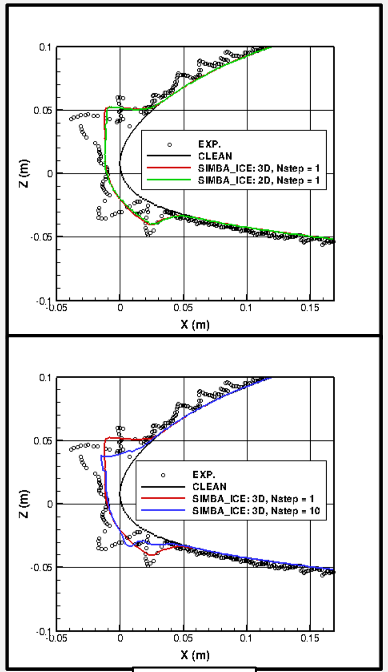
TUS



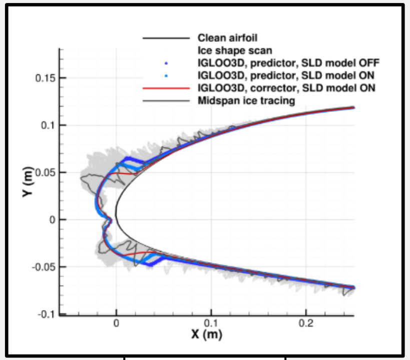
POLYMO

Numerical methods - 3D solvers

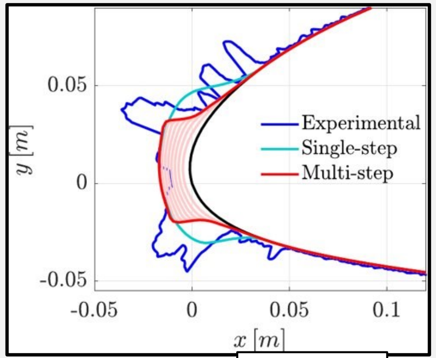
- Results from TRL4 – Appendix O conditions
  - Case 252 – Straight wing
    - Bilan



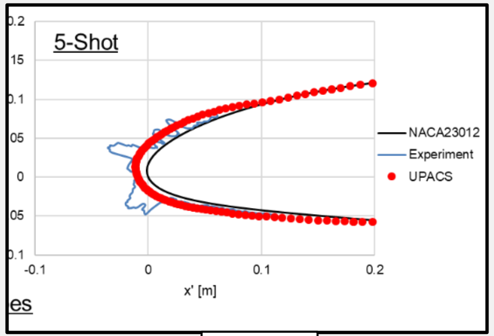
CIRA



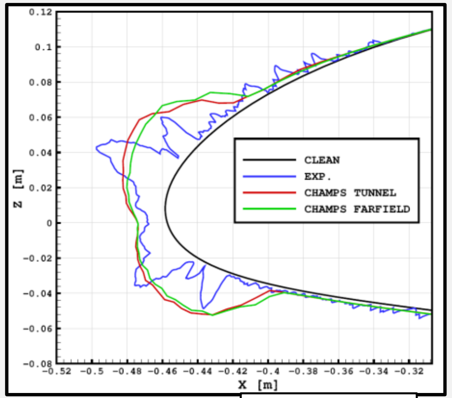
ONERA



POLIMI



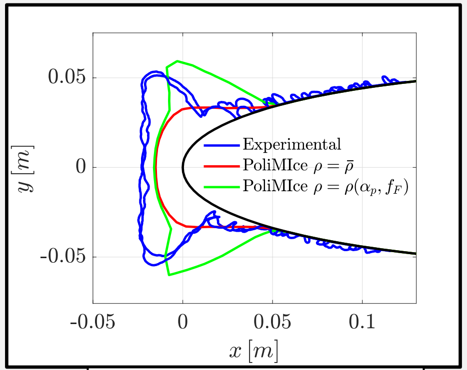
TUS



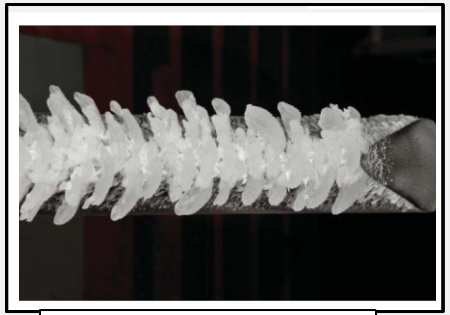
POLYMO

Numerical methods - 3D solvers

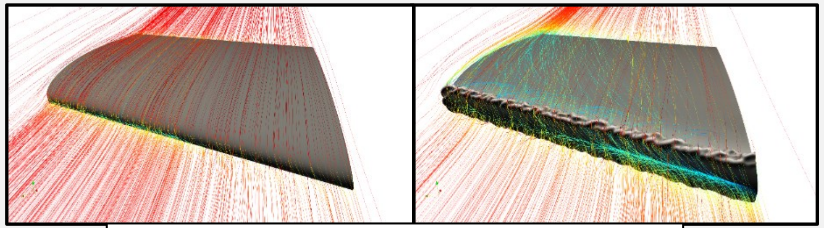
- Some general comments
  - All of the numerical approaches have been implemented and tested
    - Not an automatic process at the moment (skills, experience needed)
    - Internal geometries are much more complicated to handle
    - Computational time can be a question (CIRA data : 1 layer 15h / 10 layers 120h)
  - Rime ice conditions can be captured accurately in 3D
  - Accretion models, including density, limit accuracy in glaze ice conditions
  - Some numerical issues
    - Grid convergence, volume conservation, mass conservation (ice density)
    - Swept wing effect
    - ...



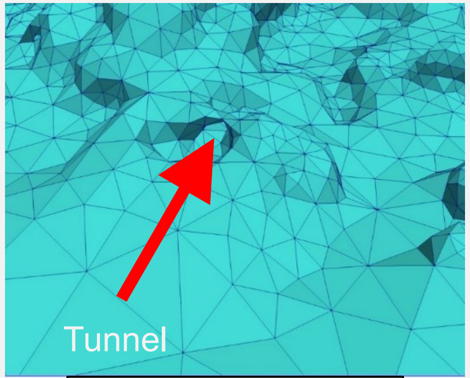
Ice density effect



Ice density variation



Effect of unsteadiness in ice accretion



Geometrical issues

Partial conclusions on WP9

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POLYMO
TUS

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Partial conclusions

- Experimental & modelling parts
  - Progress
    - New database
    - Minor improvements on the mass deposition model
    - New law for the PSD of the secondary particles
    - New features observed experimentally
  - Further investigations needed
    - Mass deposition (single-drop impact at high velocities, spray vs. drop impact)
    - Secondary droplets (defining a new set-up, progress on a new model,...)
    - Roughness modelling
    - Erosion? Altitude effect? DFD?

Partial conclusions

- Numerical method part
  - Progress
    - Multi-Step / Predictor-Corrector implemented and tested in the 3D tools
    - Operability has been demonstrated on airfoil/wing configuration
    - Methods not automatic and requiring a certain experience to be used
    - Computational time could be an issue
    - Industrialization will be the key
  - Further investigations
    - More experience needed when using the Predictor-Corrector/Multi-Step methods
    - Improvement of the methods (robustness, best pratices, ...)