WP9 - Numerical capability development for liquid icing conditions

AIRBUS SAS
BOMB
CIRA
CU
DASSAV
ONERA – O. Rouzaud
POLIMI
POLYMO
SAFRAN
TUBS
TUDA
TUS

ICE GENESIS

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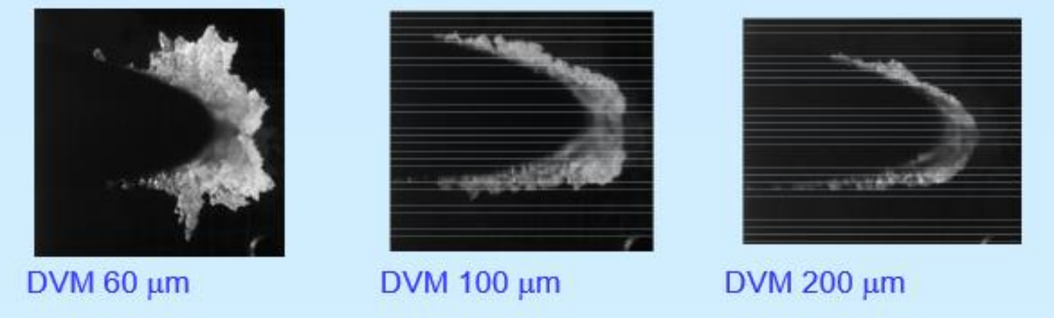
Context

- Objectives: **improve and validate current 2D/3D numerical tools** with respect to **Appendix C** and **Appendix O** conditions, so that they can be used for both design and certification of aircraft, rotorcraft and engines
- Why is it so important to work on SLDs?
  - Because large droplets do not behave as smaller droplets: more inertial, more energetic, …
  - Need for adapted or specific physical models



- Why is it so important to work on the numerical tools?
  - To improve the overall performances of the industrial solvers in 3D
  - To improve the solution by itself

* Appendix C is associated to clouds / "small" cloud droplets

* Appendix O is associated to Freezing Drizzle and Freezing Rain conditions / Supercooled Large Droplets (SLD)

Work plan

- Decomposition into 4 Tasks
  - Task 9.1: Basic experiments to provide missing data for model development
  - Task 9.2: Model improvements and implementation in 2D tools for calibration and preliminary validation
    - Phenomena under consideration: drop impact, ice roughness, ~~liquid film runback~~
    - More or less academic experiments performed in different labs (CU, ONERA, TUDA, TUBS)
    - Improvement or development of new physical models (CIRA, ONERA, POLIMI, TUBS, TUDA, TUS)

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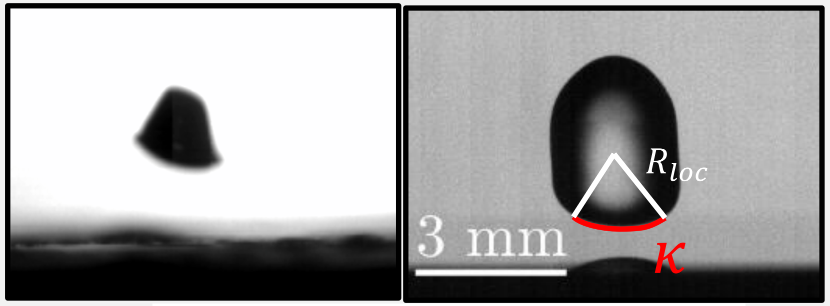
  - Task 9.4: Improvement of 3D ice accretion numerical methodologies (CIRA, ONERA, POLIMI, POLYMO)
    - Working on numerical models for meshing (automatic meshing, remeshing) for 3D test cases

||

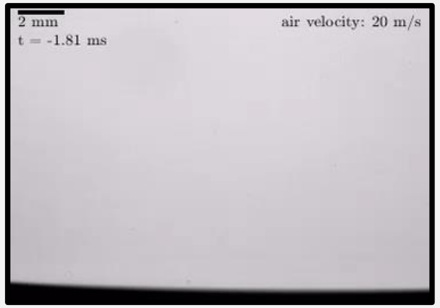
  - Task 9.3: Model integration in 3D numerical tools and preliminary validation
    - Combining physical models and numerical methods to answer Ice Genesis WP9 objectives
    - Towards the industrial configurations of WP11

Drop Impact – Experimental activities

Drop impact implies to characterize…



1 - Drop deformation

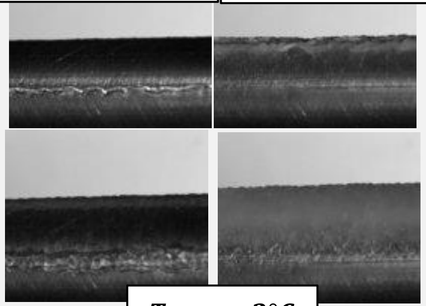


$V_{air} = 180\frac{m}{s}$; $T_{air} = -2, -10°C$; $\theta = 0°$

2 - Impact regime

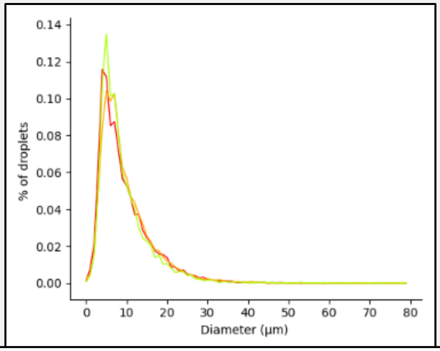
5 - Ice Accretion

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



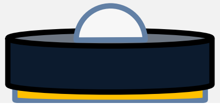
$T_{air} = -2°C$

4 - Secondary droplets

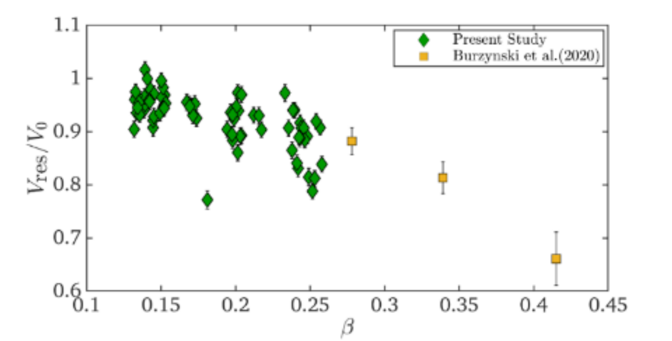


Temperature influence (5, -10, -20)
$V_{air} = 100\ m/s$

Melting drop

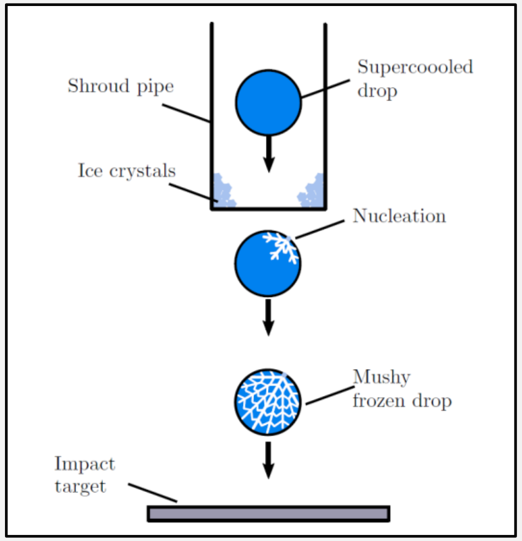


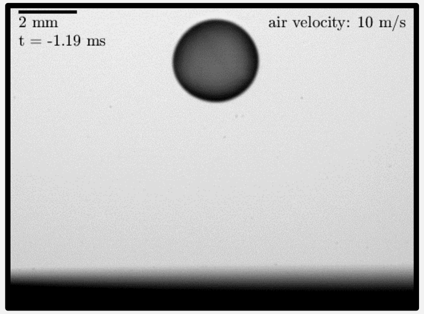
3 - Mass deposition



Drop Impact – Experimental activities

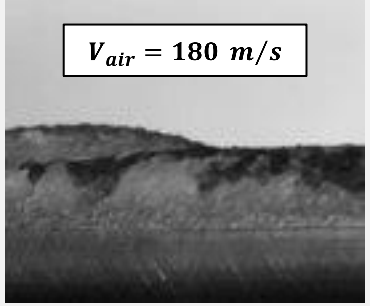
- And also new or unexpected phenomena





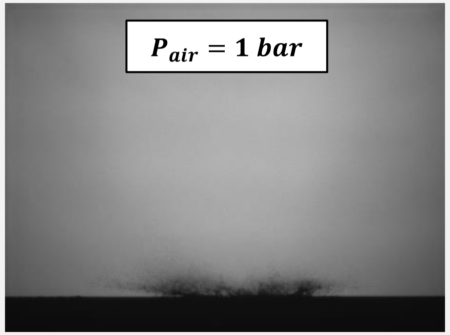
Dendritically frozen drop impact

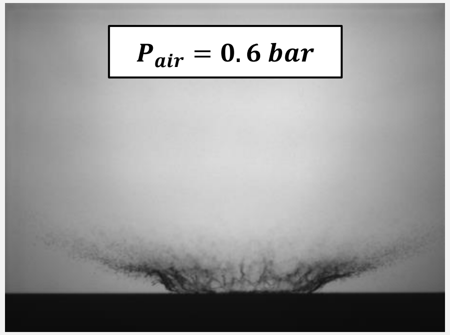
$T_{air} = -10°C$



Erosion phenomenon

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

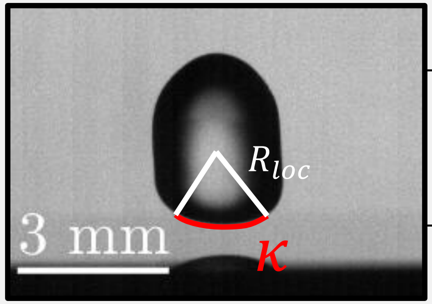




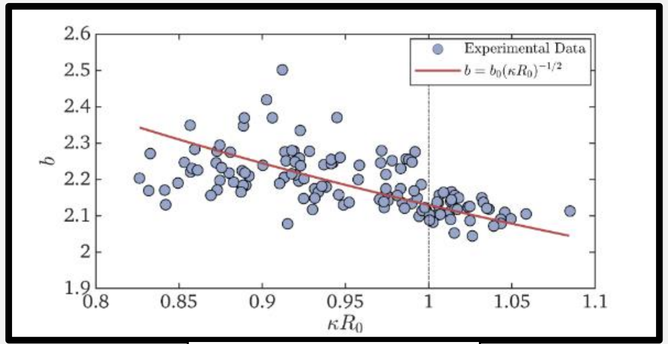
Altitude effect

Drop Impact – Physical modelling

- From very detailed models…
  - Droplet deformation prior to the impact
    - Spherical droplet: $r/R_o = b\sqrt{t\,U_o/R_o} \Rightarrow r^+ = b\sqrt{t^+}$
    - Analysis of the IG data provides: $b = b_o/\sqrt{\kappa\,R_o}$, b_o= 2.12



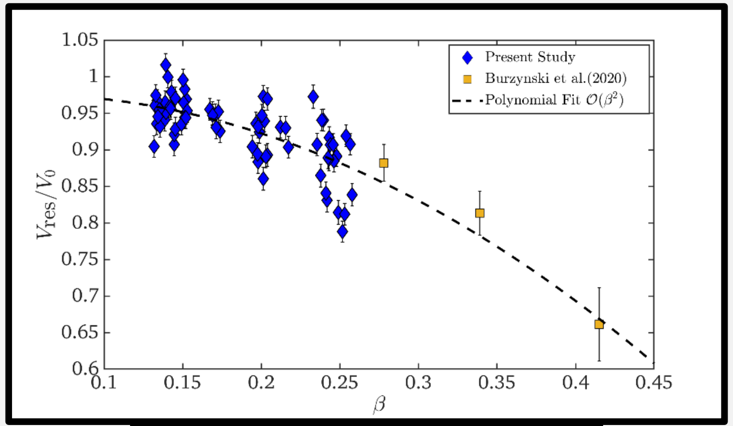
r radius of the wetted area
R_o radius of the impinging drop
U_o drop velocity



Curvature influence

⇒ influence on the splashing parameter β (Riboux-Gordillo model)

- Mass deposition
  - Depending on the splashing parameter β
  - Flight conditions may exceed $\beta > 0.4$ (what happens above 0.45?)
- Liquid film runback (not presented here)



Residual volume on the surface

Drop Impact – Physical modelling

- To applied ones used in the industrial solvers
  - Droplet deformation => how to define the radius of curvature κ?
  - Mass deposition
    - Adaptation of the Trontin-Villedieu and the Wright models on the impact function
    - Application to an accretion experimental test case (Ice Genesis database)
  - Secondary droplets
    - Approach based on Riboux-Gordillo and Burzinsky-Bansmer-Roisman models
    - Description of the spray by a log-normal law defined by parameters estimated from RG

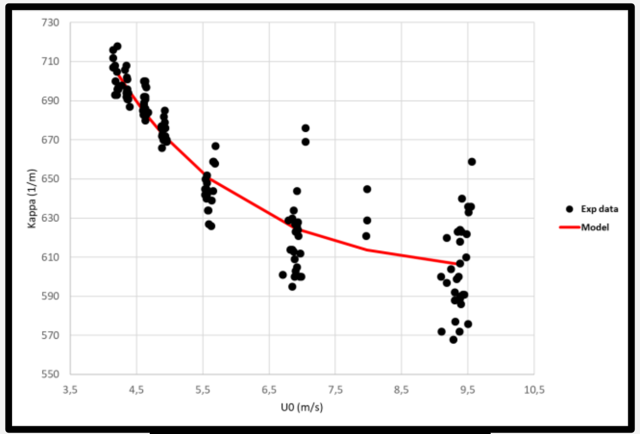
$$\kappa(U_0) = C_0 * [C_1 + C_2 \tanh(C_3 U_0)]$$

$$\kappa = \min(\kappa(U_0), 715)$$

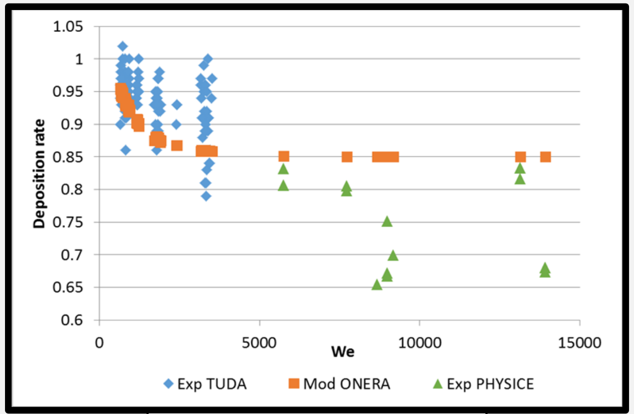
ONERA model: $f(\widetilde{K}_n) = 1 - C_1 \frac{\widetilde{K}_n^2}{C_2 + \widetilde{K}_n^2}$

Wright model:

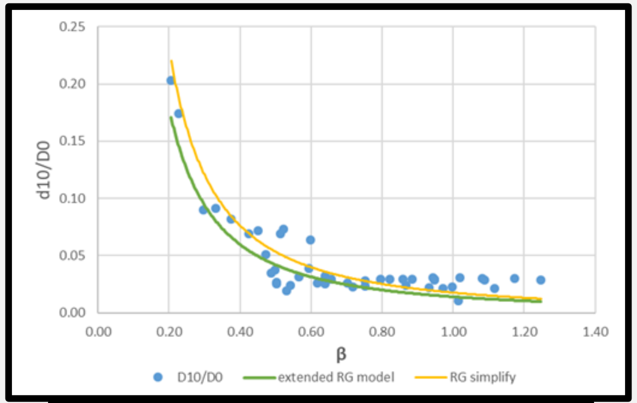
$$f_m = \frac{m_S}{m_0} = C_3[1 - sin(\theta_0)][1 - e^{-0.0092(K_{L,n}-200)}]$$



Droplet deformation



Mass deposition



Mean diameter vs. splashing parameter

Experimental activities – Ice Roughness

- Objective: investigate influence of icing conditions on the characteristics of ice accretion roughness
- Experiments performed in TUBS Icing Wind Tunnel
  - HMDI airfoil: Span=0.5m, Chord=0.7m, non-symmetrical airfoil based on NASA CRM
  - Operating conditions encompassing both App.C and App. O

    $V_{air} = 40\ \mathrm{m/s}$; $AoA = 0°$; $T_\infty = -5$ to $-16\ °C$; $Reynolds\ number\ Re \approx 2e6$

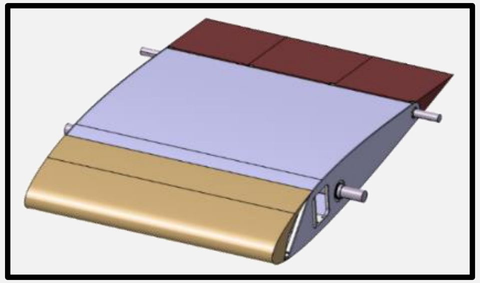
    $\mathrm{MVD}_\infty \approx 19\mu\mathrm{m}$ (App. C) & $70\mu\mathrm{m}$ (App. O) ; $\mathrm{LWC}_\infty \approx 0.88\mathrm{g/m^3}$ (App. C) & $0.56\mathrm{g/m^3}$(App. O)

    Accretion time $\mathrm{t} = 1.5, 3, 6, 9$ min

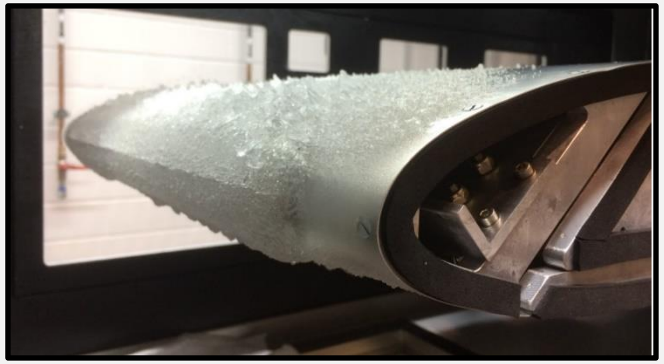
    Experiments include several levels of $\eta_{f,0}$

    Combinations of $\eta_{f,0}$ and A_c not investigated before

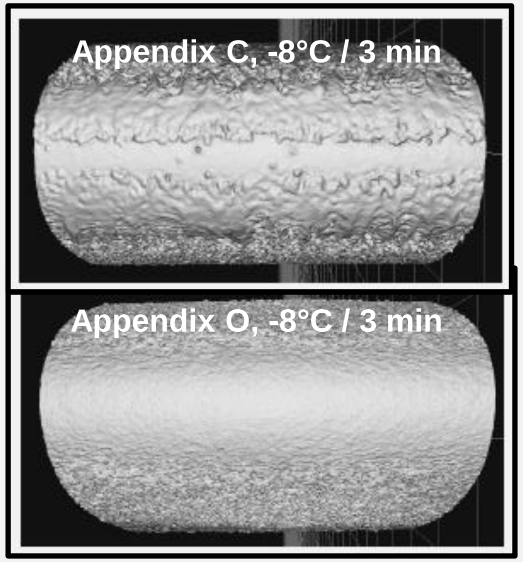
    Insight on effects of non-symmetric airfoils



Airfoil sketch



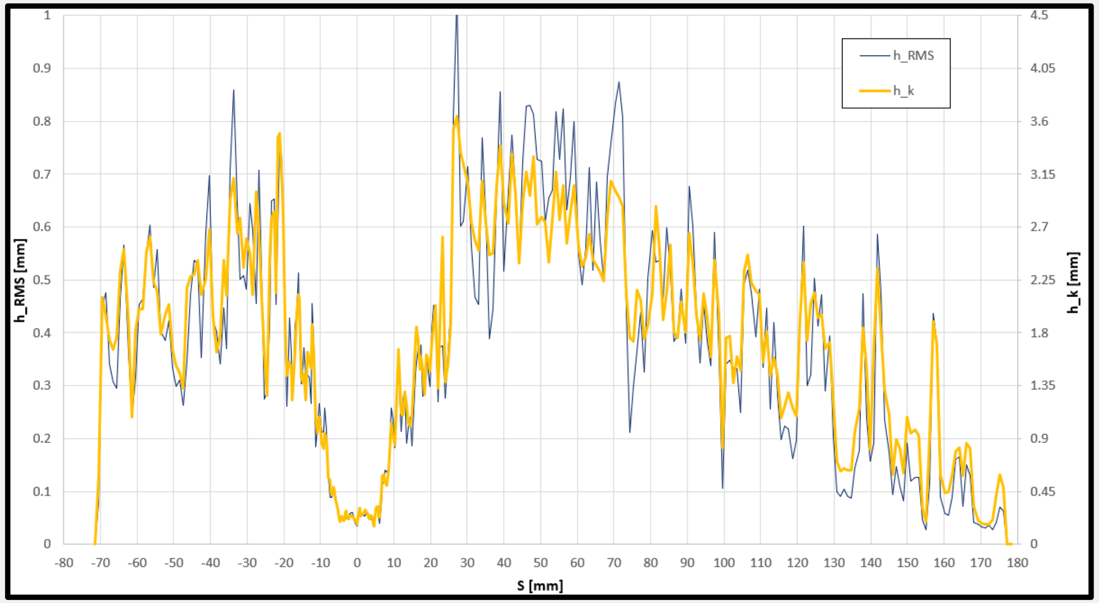
Iced airfoil in the test section



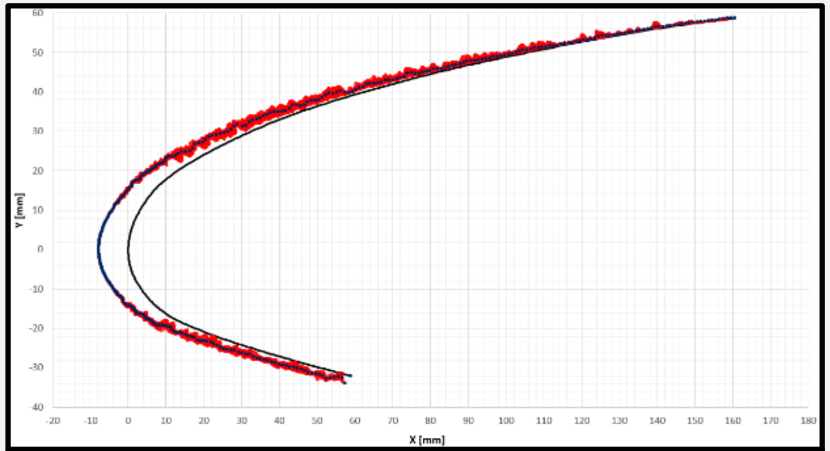
Accreted ice
Front view

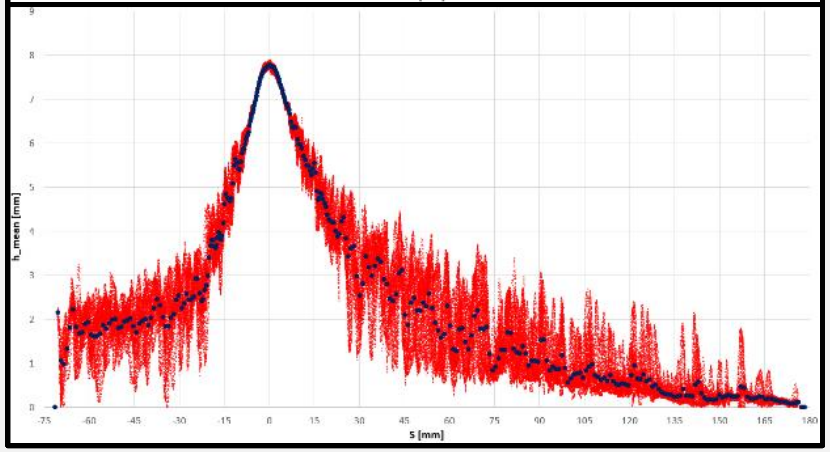
Ice Roughness – Experimental activities

- How to analyse the ice roughness?
  - Digitalization of the ice shape (photogrammetry method)
  - Development of tools for statistical analysis
  - **Post-processing of the experimental data**
  - Assessment of the tools



h_K (orange) and h_{RMS} (blue) vs. curvilinear abscissa





Top view: clean and iced airfoil

Bottom view: $h_{mea}n$ (slices in red, mean in black dot)

Ice Roughness – Experimental activities

How to analyse the ice roughness?

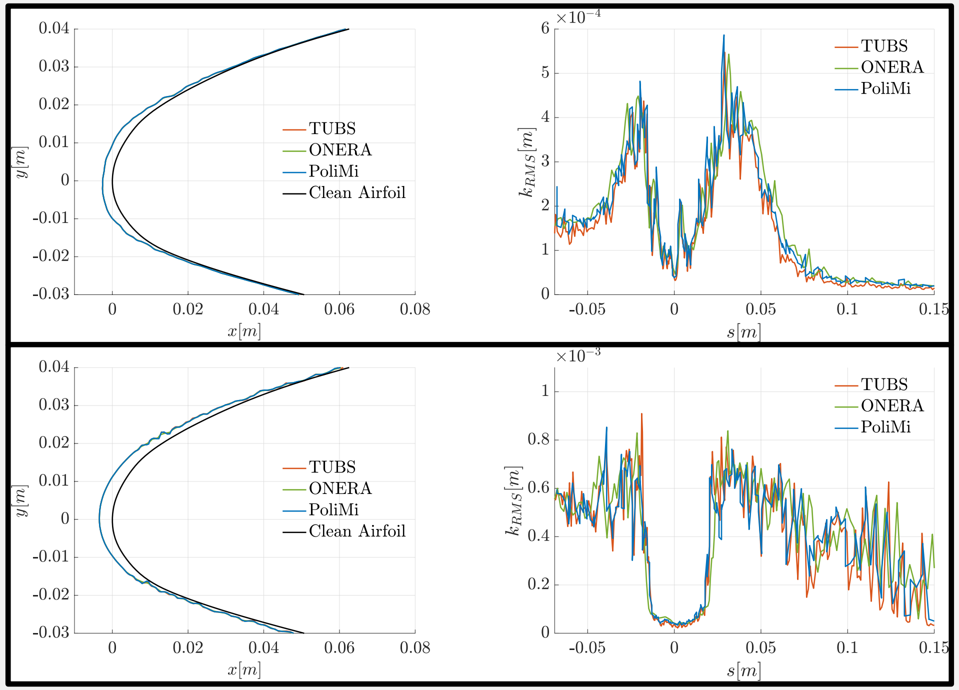
- Digitalization of the ice shape (photogrammetry method)
- Development of tools for statistical analysis
- Post-processing of the experimental data
- **Assessment of the tools**

App. C

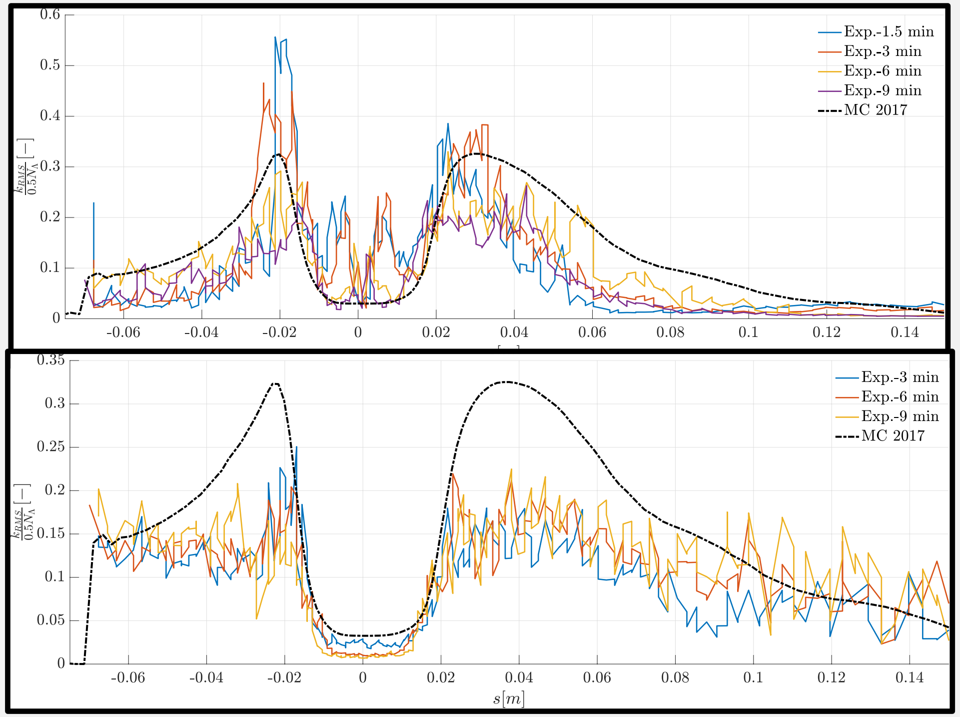
T = -12°C ; t = 3 min

App. O

T = -8°C ; t = 6 min



Ice shape (left) / kRMS (right)

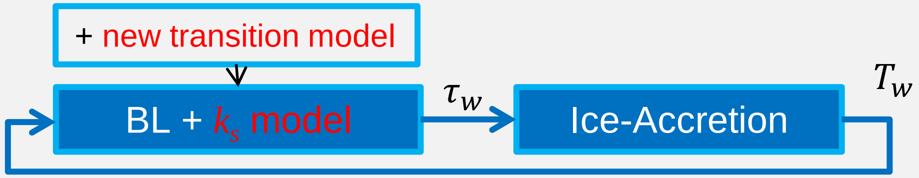


Rq comparison with McClain’s model

T= -8°C / Top view App.C / Bottom view App.O

Ice Roughness – Physical modelling

- Model based on Fortin's bead model (roughness height) and Abu-Gahnnam & Shaw model (transition)



- Roughness height model

  Bead size: $e_b = \alpha_0 L Re_\tau^{\alpha_1} We_\tau^{\alpha_2} H_1(\theta, \Delta\theta) H_2(Re_b)$

  $k_s = \alpha_3 e_b$

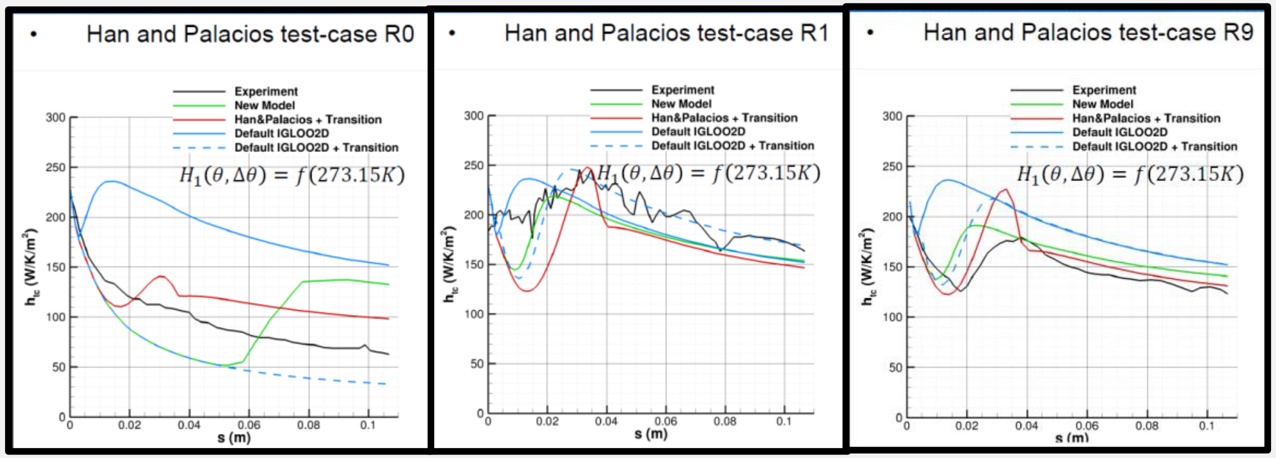
- Transition model

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

- Optimization process to determine the best values α_3 of and η using an IA approach
  Performed on 3 of the Han & Palacio's Heat Transfer Coefficient (htc) database

Physical modelling – Ice Roughness

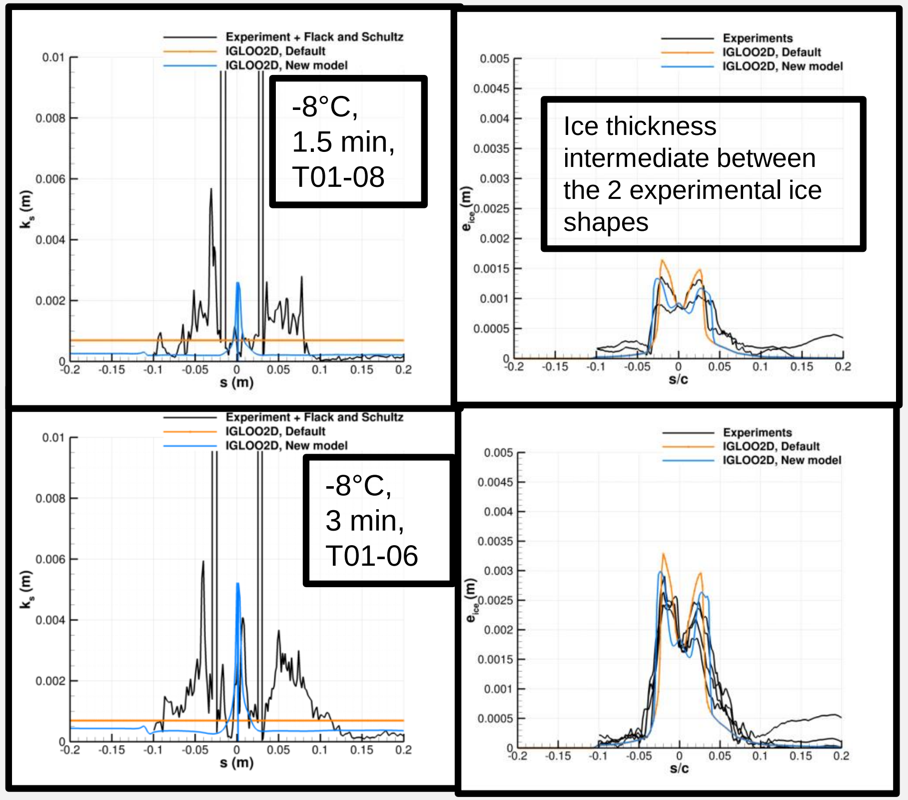
- Assessment of the model based on
  - Roughness height characteristics (TUBS database)
  - Impact of the roughness height on measured data (htc - Han & Palacio's database, ice shape - TUBS database)



Heat transfer coefficient comparisons

▼

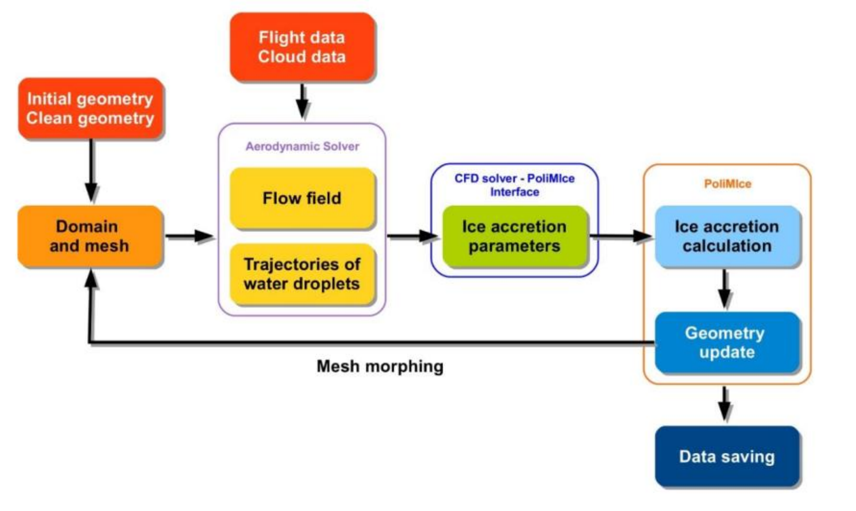
Good agreement for most of the cases



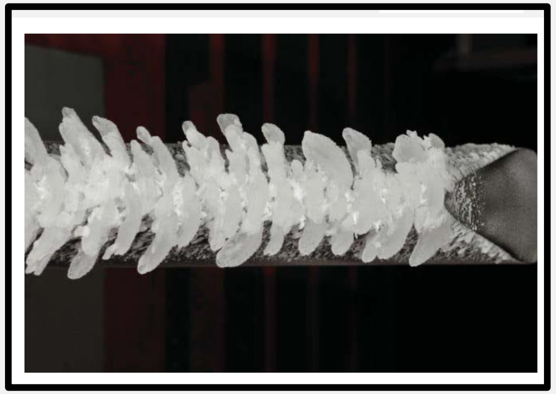
Roughness height (left) / Ice thickness (right) comparisons

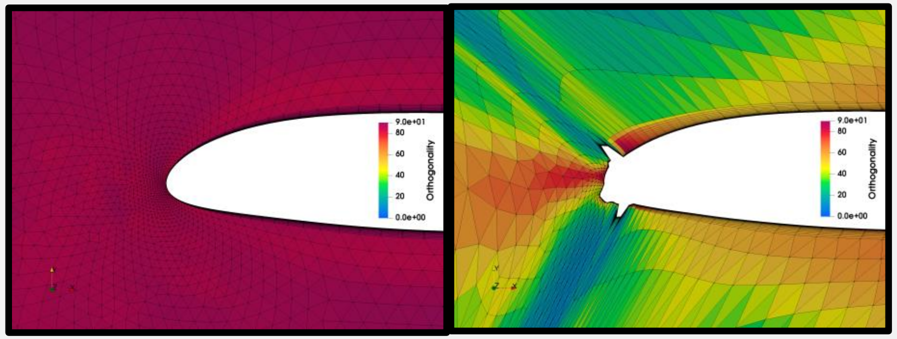
Numerical methods - Introduction

- Objective: develop efficient numerical methods to handle 3D simulations
  - Aiming at **Predictor-Corrector or MultiStep approaches**
  - Considering mesh adaptation to account for ice surface growth



3D ice shape





Mesh displacement

  - But
    - On physical grounds, 3D ice shape can be quite complex, 3D ice ≠ 2D ice
    - On numerical/modelling grounds, need to deal with mesh displacement, ice density modelling, mass conservation, …

Numerical methods - Results

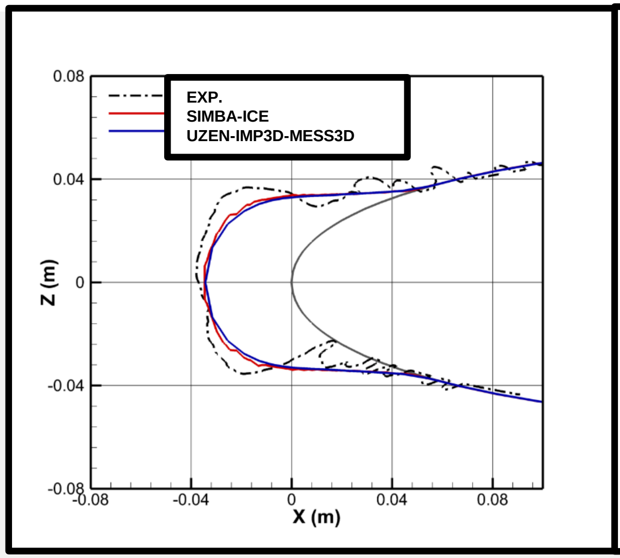
- Several candidate methods have been developed by the partners:
  - 3D Multi-step Immersed Boundary Method, Lagrangian displacement of surface mesh for ice accretion only (CIRA)
  - 3D Predictor-Corrector plus remeshing, with Lagrangian displacement (ONERA)
  - 3D Multi-step on conformal meshes with level-set and remeshing (POLIMI)
  - 3D Multi-step on conformal meshes with Lagrangian (POLYMO)
  - Very preliminary approaches for mass conservation are available
- Definition of Numerical benchmark tests for T9.4
  - Baseline calculation: NACA23012 2D extruded cases (Ice Prediction Workshop database)

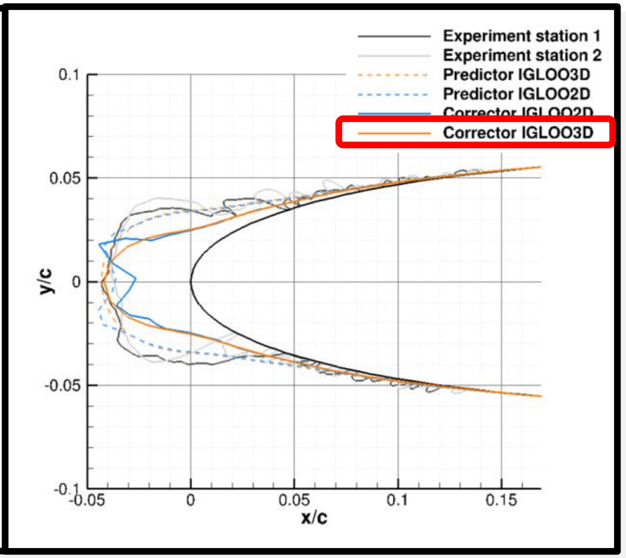
Run	V [m/s]	T [C]	P [Pa]	MVD [µm]	LWC [g/m³]	AoA [°]	Time [s]	Remarks
Case 241	103	-23°	92528	30	0.42	2°	300	Rime ice
Case 251	103	-12.6°	91700	21.5	1.64	2°	400	Monomodal SLD
Case 252	103	-12.6°	91700	21.5	1.64	2°	400	Bimodal SLD

  - **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

Numerical methods – Results



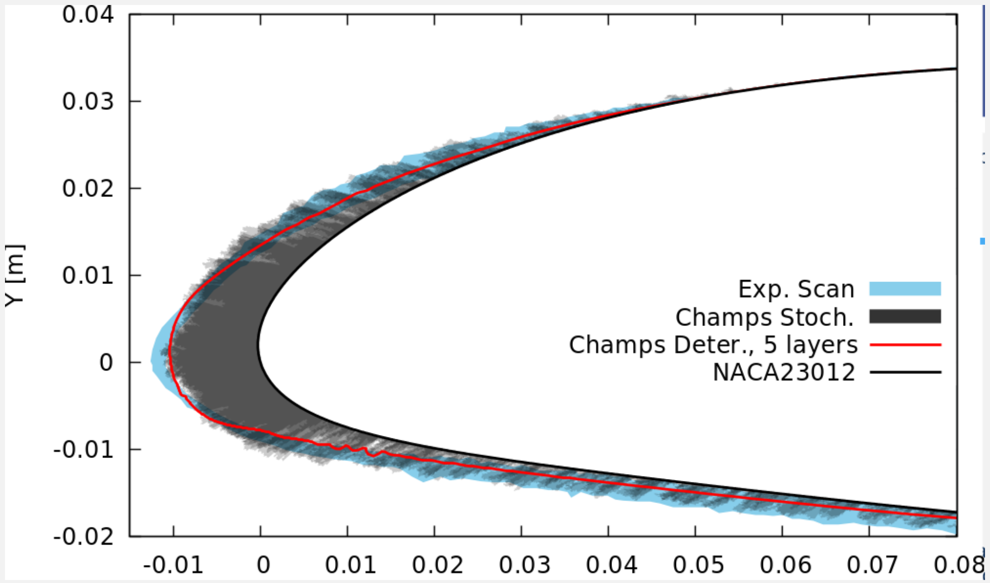


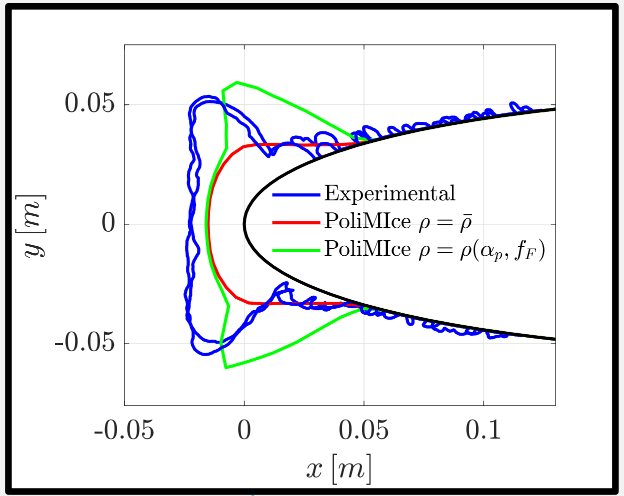
Case 361 – Rime ice (CIRA, ONERA)

- Correctly captured in 3D

Case 241 – Rime ice (POLYMO)

- Stochastic approach vs. Deterministic approach





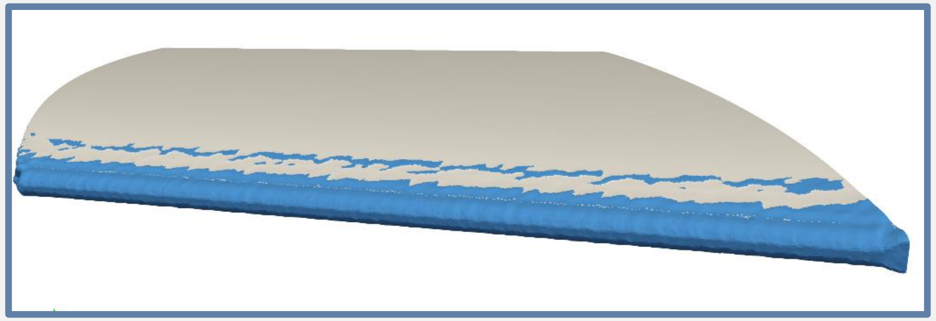
Case 362 – Glaze ice (POLIMI)

- Less correctly captured in 3D
- Ice density plays a role

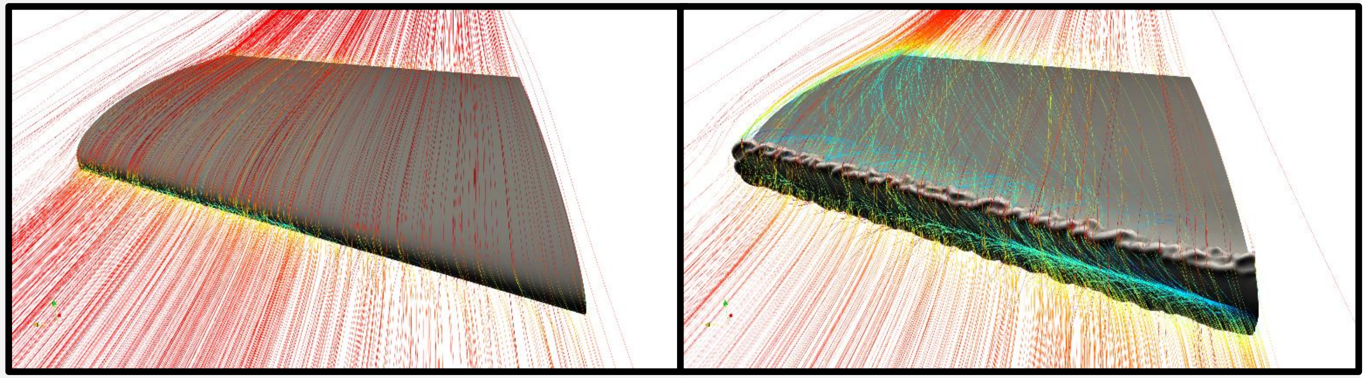
Numerical methods – Some more results

Observations

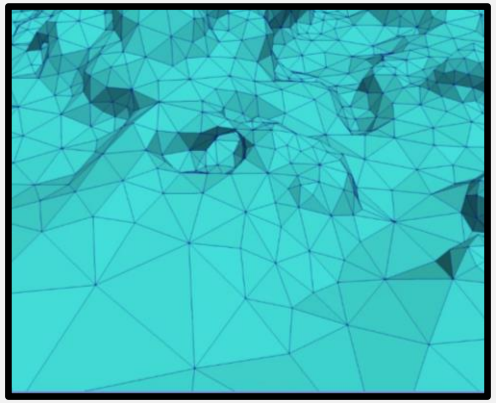
- Physics of 3D ice accretion results in non-negligible numerical difficulties
- Unsteady ice accretion is important to describe the whole process
- Models are still not satisfactory (e.g. ice density)



Multi-connected ice shapes (ice in blue)



Collection efficiency coefficient: single step (left), multistep (right)



Mesh issues with very refined grid leading very small ice structures

Conclusions & Perspectives

- Main achievements on the experimental and modelling parts so far
  - Academic experiments performed on two important topics for SLD: drop impact and roughness
  - Roughness
    - Experimental methodology clearly defined
    - Ongoing activity to build a model to account for roughness & transition
  - Drop impact
    - Insights gained thanks to some experiments or some complex/basic models but…
    - Improvements of the existing models are not that conclusive
  - New phenomena to be possibly investigated (Dendritically Frozen Drop, erosion, drop deformation)
  - High-altitude effects to be investigated
- Main achievements on the numerical part so far
  - Extension of the capabilities of the 3D tools ongoing (Predictor-Corrector, Multistep)

THANK YOU

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