ICE GENESIS Final Public Workshop

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.

Snow Models

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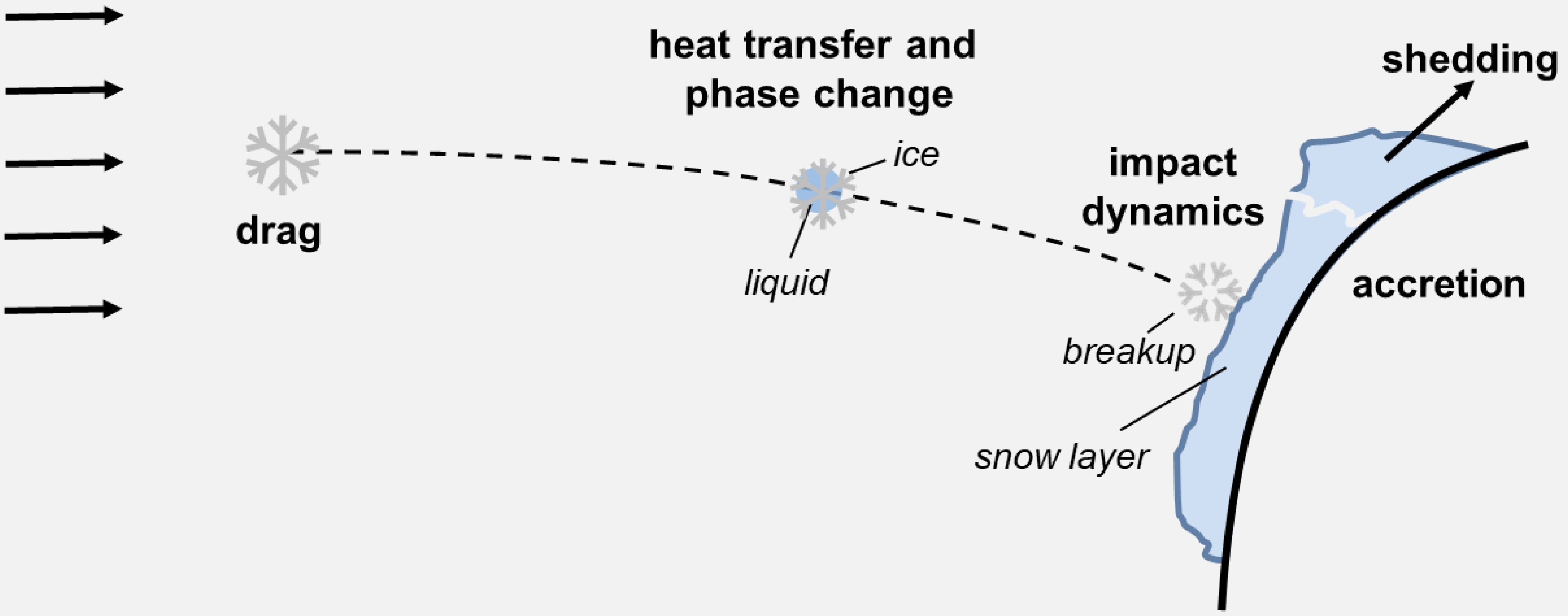
Physical description



- Partners involved: AIH, AIT, ONERA, POLIMI, TUDA + collaboration with WP5

Transport Models

AIH, ONERA, TUDA

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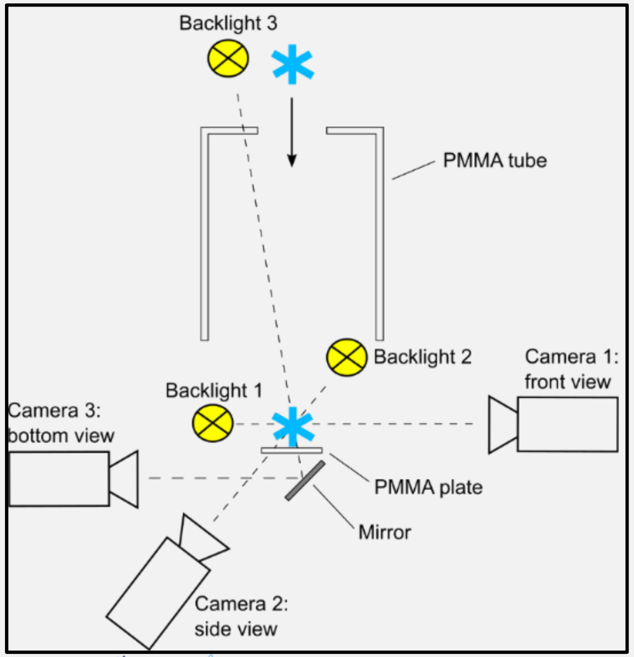
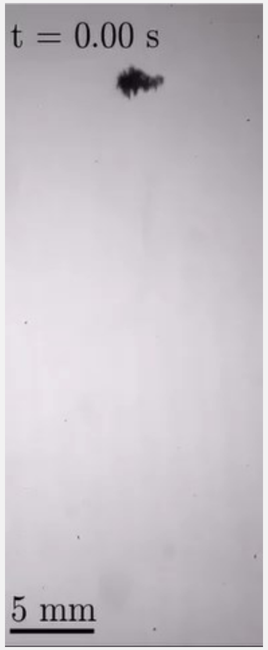
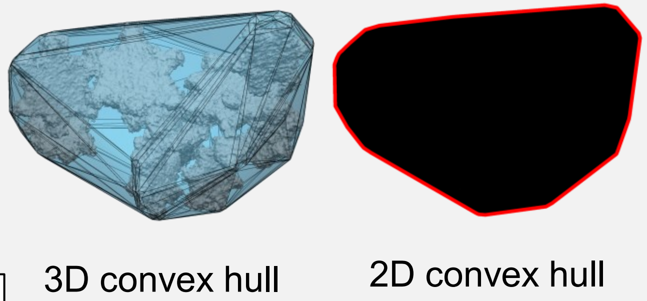
Snowflake Drag Model

- Objective: develop/extend a drag model adapted for the various snowflake particles
- Methodology
  - Based on some academic experiments performed during ICE GENESIS with natural/synthetic snowflakes
  - Choice of simplified geometries
  - Preliminary assessment and down selection of the models using 2D solvers
  - Implementation and assessment on 3D solvers

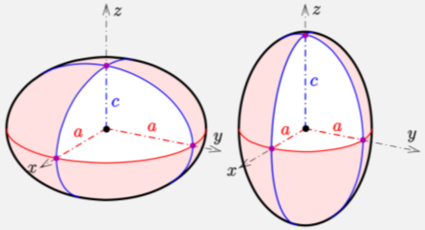




Free fall test case



Convex approximation



Spheroid approximation

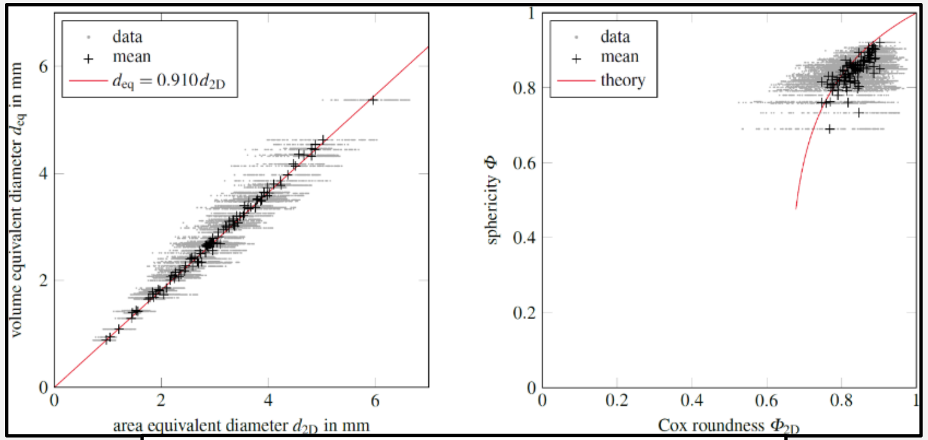
Snowflake Drag Model

- Assessment and down-selection of the model
  - Comparison vs. experimental data

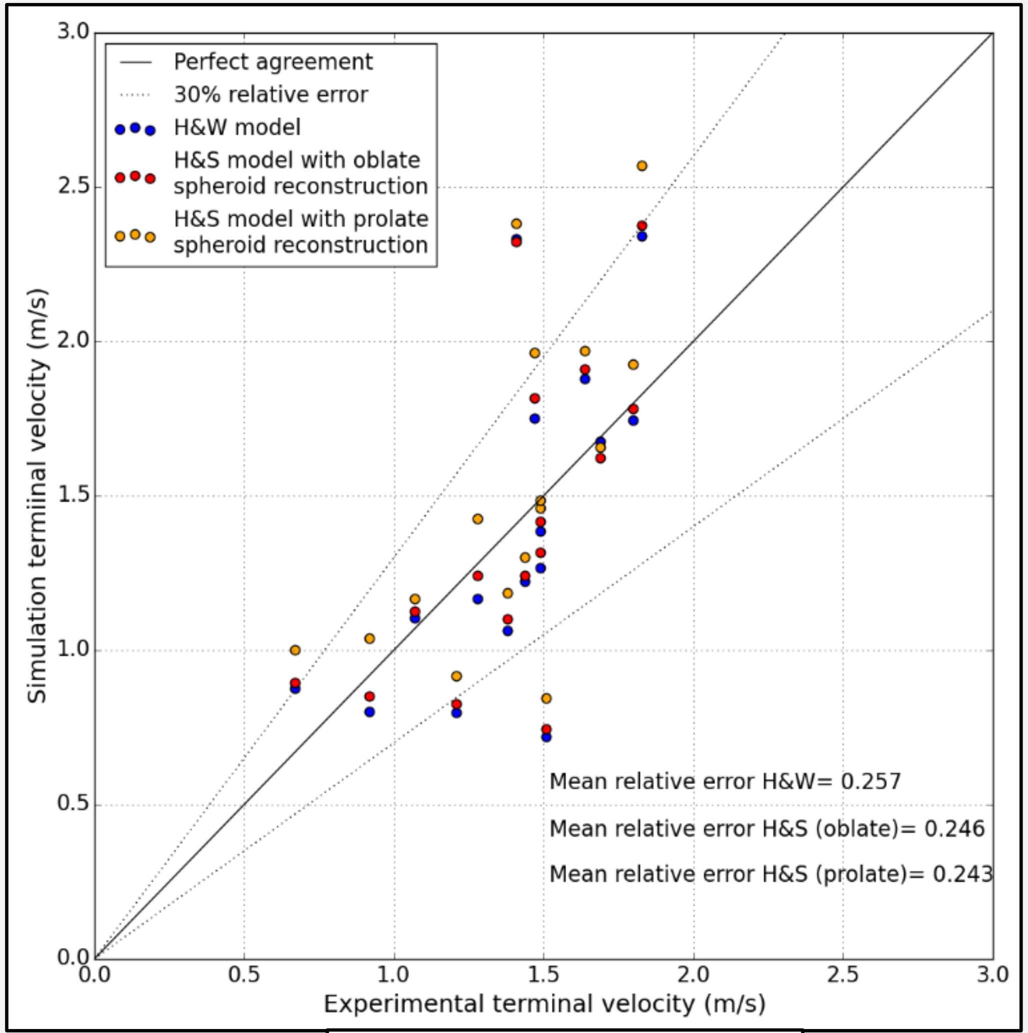
    => Down-selection of the Hölzer-Sommerfeld model

    +

    Oblate spheroid description
  - Relevancy of the 2D geometric parameters wrt their 3D counterparts



Geometric parameters comparisons



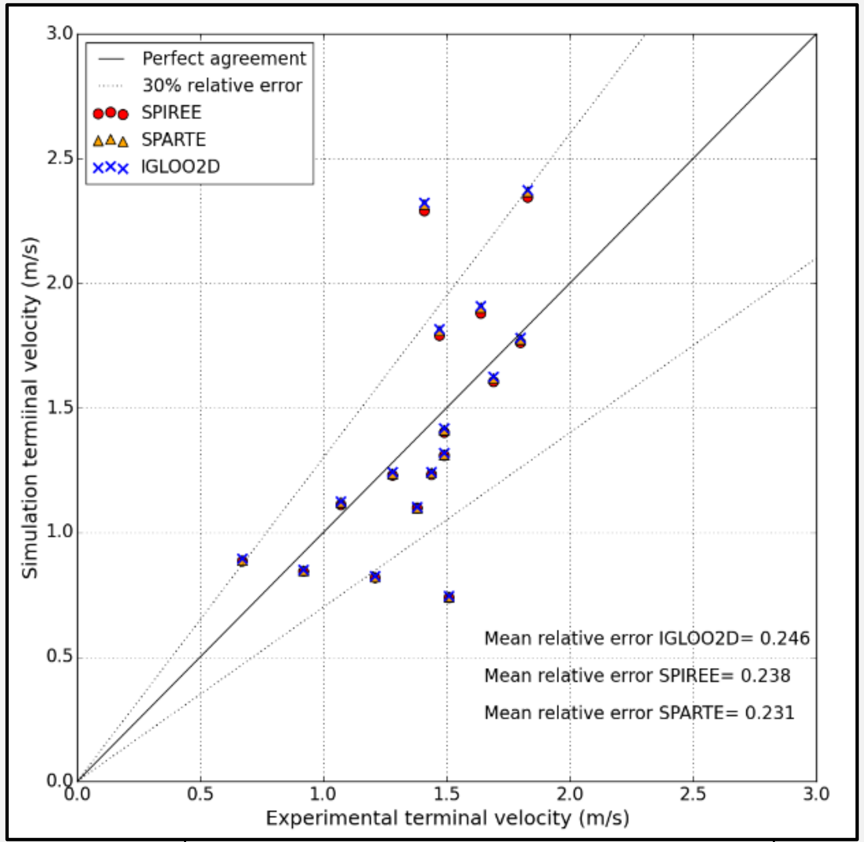
Drag model comparisons

Snowflake Drag Model

- Implementation and preliminary assessment into ONERA 3D solvers and ANSYS CFX
  - Lagrangian approach (AIT, ONERA) / Eulerian approach (ONERA)
  - Good agreement with the experimental data for all 3D solvers
  - Very good agreement between 2D and 3D results (ONERA)

N	Fall speed m/s	Mass mg	BL Mass mg	$d_{V,pro}$ mm	ρ_{pro} kg/m^3	ρ_{pro}(BL) kg/m^3	Φ_{pro} -	$\Phi^{\perp}_{pro}$ -	$d_{V,obl}$ mm	ρ_{obl} kg/m^3	ρ_{obl}(BL) kg/m^3	Φ_{obl} -	$\Phi^{\perp}_{obl}$ -	d_{max} mm	ρ_{max} kg/m^3	ρ_{max}(BL) kg/m^3	A_r -
1	0.67	0.063	0.105	1.042	117.0	180.0	0.95	1.05	1.248	64.8	103.2	0.93	1.51	1.505	38.1	62.4	0.34
2	1.83	1.480	0.924	2.571	192.5	100.2	0.95	1.02	3.098	102.1	56.2	0.93	1.51	3.745	55.2	32.4	0.45
3	2.40	16.790	3.907	4.977	265.0	61.1	0.96	1.08	5.880	158.4	36.7	0.95	1.51	6.953	95.4	22.2	0.43
4	1.47	0.576	0.532	2.340	97.2	83.8	0.98	1.47	2.599	65.9	58.1	0.97	1.82	2.898	45.6	41.3	0.47
5	1.49	0.132	0.155	1.143	174.1	195.5	0.98	1.11	1.263	131.1	145.9	0.98	1.35	1.396	99.2	109.3	0.57
6	1.44	0.546	1.217	3.018	40.4	83.6	0.98	1.14	3.369	28.3	59.5	0.98	1.42	3.763	19.9	42.7	0.56
7	1.07	0.170	0.314	1.653	75.1	135.8	0.98	1.09	1.882	51.8	93.2	0.97	1.42	2.144	35.9	64.3	0.49
8	1.80	0.298	0.236	1.493	184.6	138.2	0.97	1.26	1.672	124.2	95.2	0.97	1.56	1.880	86.7	68.3	0.52
9	0.92	0.047	0.085	0.862	188.0	265.7	0.92	0.82	1.075	83.3	127.5	0.90	1.25	1.352	40.8	66.8	0.51
10	1.38	0.243	0.528	2.109	54.7	108.5	0.98	1.12	2.330	38.1	78.0	0.98	1.37	2.583	27.1	57.6	0.56
11	1.69	0.459	0.515	1.994	113.1	125.0	0.97	1.04	2.317	75.6	82.6	0.96	1.39	2.697	51.6	55.7	0.47
12	1.28	0.157	0.191	1.300	168.5	168.0	0.94	0.92	1.591	81.8	87.4	0.92	1.40	1.957	41.2	47.5	0.42
13	1.49	0.134	0.148	1.127	227.4	199.8	0.93	0.87	1.407	109.4	100.4	0.91	1.37	1.766	54.3	52.2	0.57
14	1.64	0.349	0.246	1.487	203.4	143.1	0.98	1.10	1.644	150.9	106.1	0.98	1.35	1.818	112.0	78.7	0.59
15	1.41	0.578	0.582	2.150	178.1	111.2	0.98	1.13	2.386	130.9	81.7	0.98	1.39	2.648	96.2	60.0	0.59
16	1.51	0.266	1.201	3.195	18.5	71.4	0.95	1.15	3.728	10.3	42.5	0.94	1.58	4.391	6.1	27.4	0.36
17	1.21	0.150	0.482	2.017	38.9	114.3	0.97	1.10	2.296	24.1	74.9	0.96	1.43	2.628	15.8	51.7	0.45

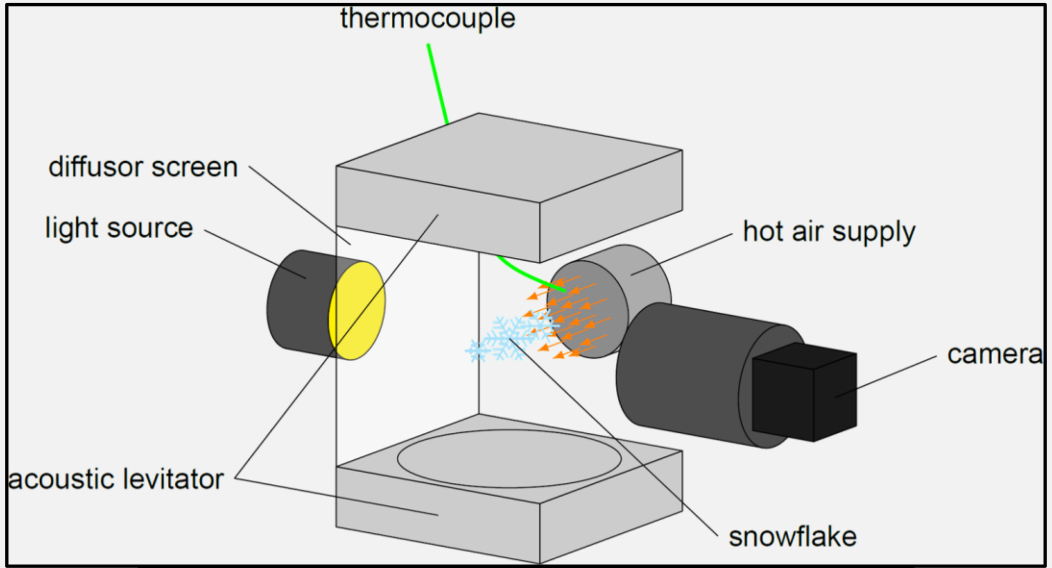
Assessment based on TUDA free fall experiments



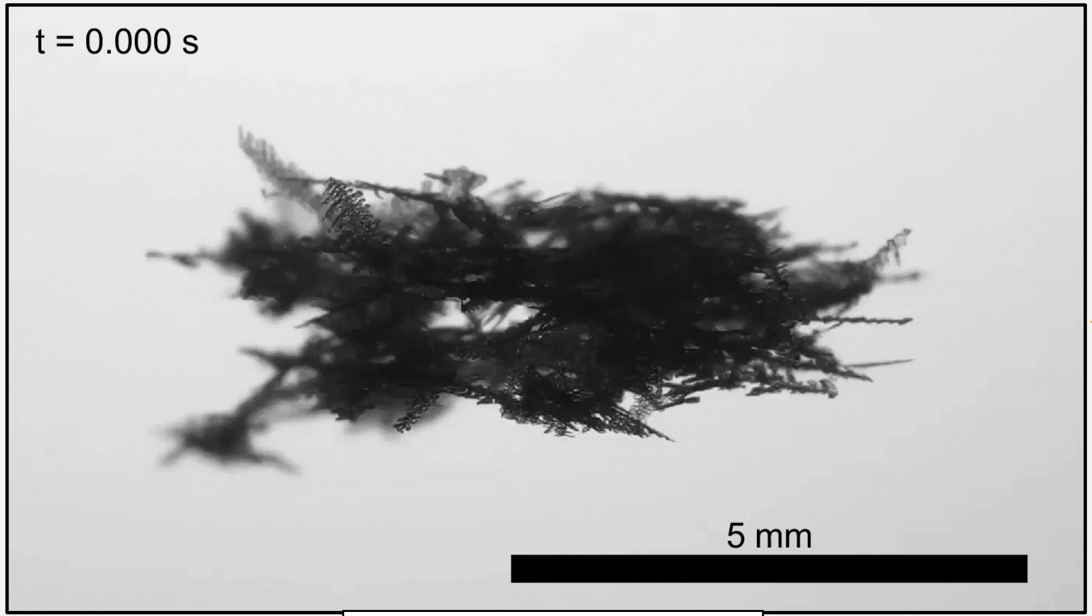
Free fall speed comparisons

Snowflake Melting Model

- Objective: develop/extend a melting model adapted for the various snowflake particles
- Methodology
  - Based on some academic experiments performed during ICE GENESIS
  - Preliminary assessment and down-selection of the models using 2D solvers
    - Mitra model, HAIC model (modified Nusselt-Sherwood / mNS)
  - Integration and assessment in 3D solvers



Sketch of the experimental set-up

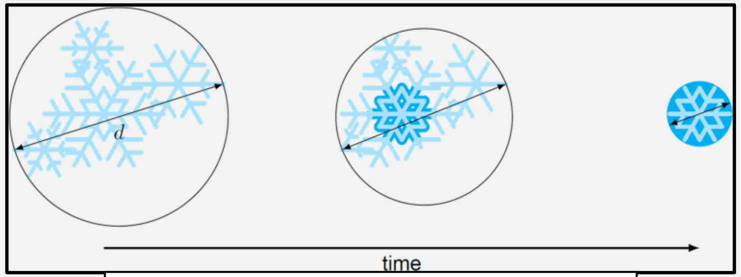


Snowflake melting

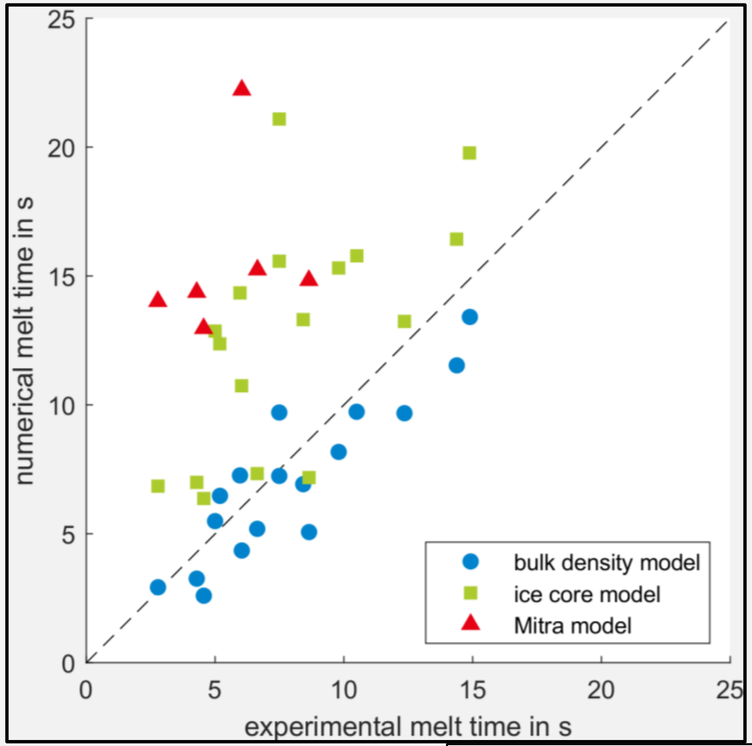
Snowflake Melting Model

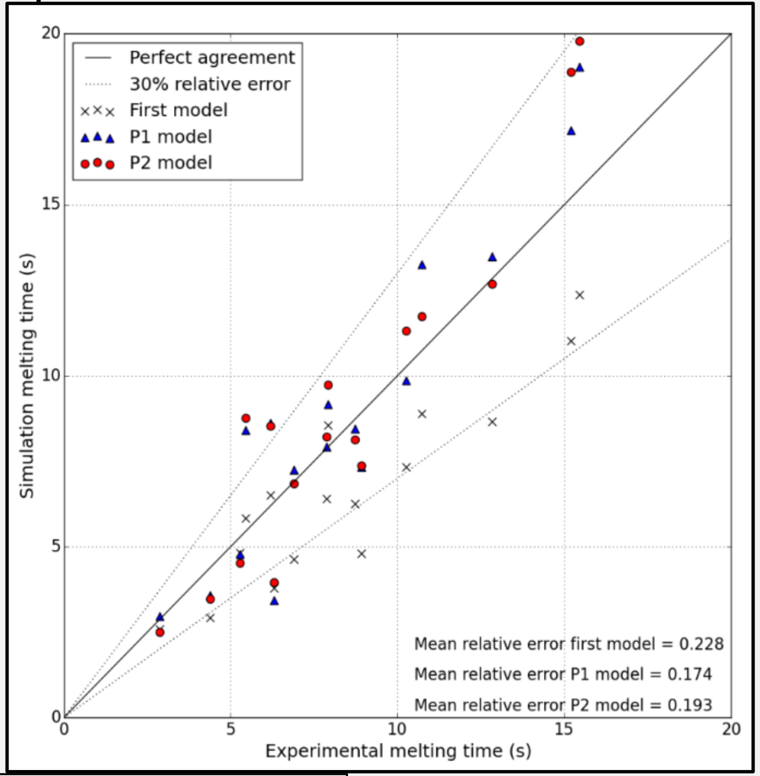
- Assessment and down-selection of the models
  - Comparison vs. experimental data

    => Down-selection of the modified-NS model + Oblate spheroid description



Melting evolution





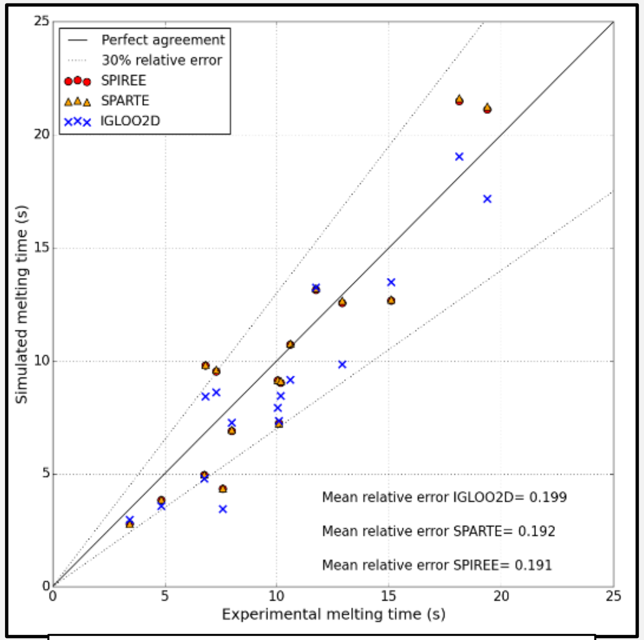
Melting time comparisons

Snowflake Melting Model

- Models tested: Modifications of the HAIC model (mNS) + oblate spheroid approximation
  - Rather good agreement with the experimental data
  - Rather good agreement between 2D and 3D results
  - Discrepancies between the numerical results due to differences between the thermophysical properties

	Runs	T_a °C	v_a $\mathrm{m\,s^{-1}}$	RH -	m_{p_0} mg	T_{p_0} °C	$t_m \approx t_{circ}$ s	$\rho_{p_0}^{bulk}$ $\mathrm{kg\,m^{-3}}$	C_{i_0} -	$\Phi_{\star_0}$ -
Dense aggregates	TUDA Run13	26.0	0.5	26	1.666	-14.0	15.5	112	0.24	0.91
	TUDA Run25	27.4	0.6	35	2.041	-12.5	15.2	120	0.21	0.86
	IAG Run18	28.4	1.0	6	0.723	-7.0	12.8	145	0.36	0.93
	IAG Run27	33.1	0.9	4	0.318	-4.0	6.9	144	0.35	0.88
	IAG Run38	32.4	0.9	1	0.240	-7.0	8.9	132	0.28	0.98

	Runs	T_a °C	v_a $\mathrm{m\,s^{-1}}$	RH -	m_{p_0} mg	T_{p_0} °C	$t_m \approx t_{circ}$ s	$\rho_{p_0}^{bulk}$ $\mathrm{kg\,m^{-3}}$	C_{i_0} -	$\Phi_{\star_0}$ -
Light aggregates	TUDA Run26	24.4	0.6	41	1.578	-14.7	10.7	76	0.32	0.93
	TUDA Run27	28.0	0.7	36	1.711	-14.0	8.7	43	0.20	0.88
	TUDA Run28	25.6	0.6	38	1.575	-16.1	10.3	43	0.14	0.92
	TUDA Run36	26.6	0.7	38	0.449	-14.2	2.9	23	0.20	0.69
	TUDA Run37	28.6	0.6	34	2.046	-14.4	7.9	30	0.15	0.76
	TUDA Run38	28.2	0.6	35	0.487	-13.5	4.4	30	0.17	0.77
	TUDA Run39	28.2	0.5	36	1.652	-13.0	6.2	39	0.18	0.85
	TUDA Run40	27.2	0.6	35	1.187	-15.4	5.5	53	0.18	0.77
	TUDA Run51	28.3	0.7	32	1.059	-13.1	6.3	14	0.09	0.78
	TUDA Run71	25.2	0.5	33	2.057	-16.6	7.9	21	0.12	0.92
	TUDA Run72	26.5	0.6	30	0.964	-15.8	5.3	17	0.14	0.82



Melting times comparison

Accretion Models

AIH, ONERA, TUDA

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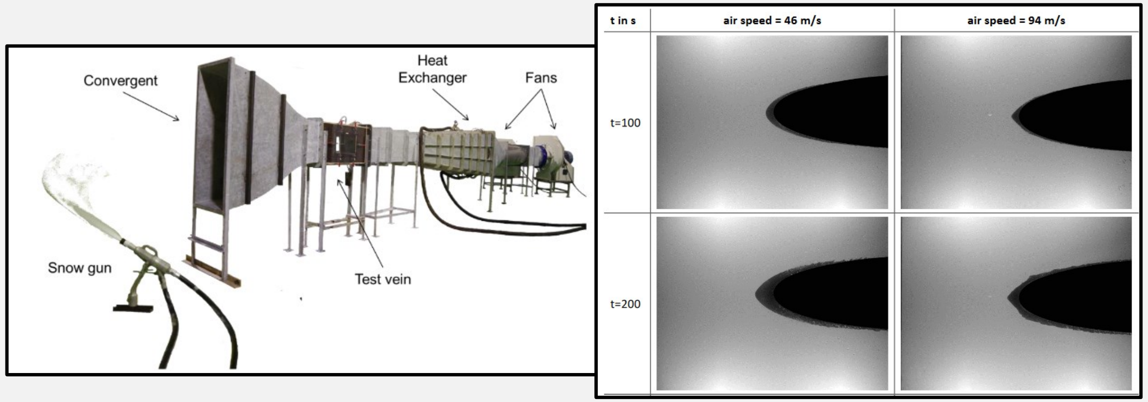
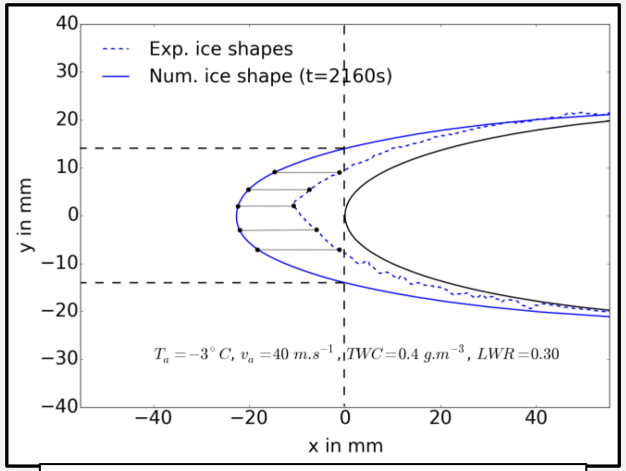
Snowflake Accretion Model

- Objective: assess the HAIC accretion models (sticking & erosion) for the snow particles
- Methodology
  - Based on some IWT experiments performed during ICE GENESIS => CSTB, RTA
  - Optimization-based approach on some (3) coefficients of the sticking/erosion models
    - Using 2D configurations
    - Severity function based on the experimental and numerical ice shapes for each case
    - Optimization process (Trust Region Reflective algorithm)
    - Values of the coefficients defined on a case-by-case analysis or considering several test cases together



CSTB experiments

RTA experiments

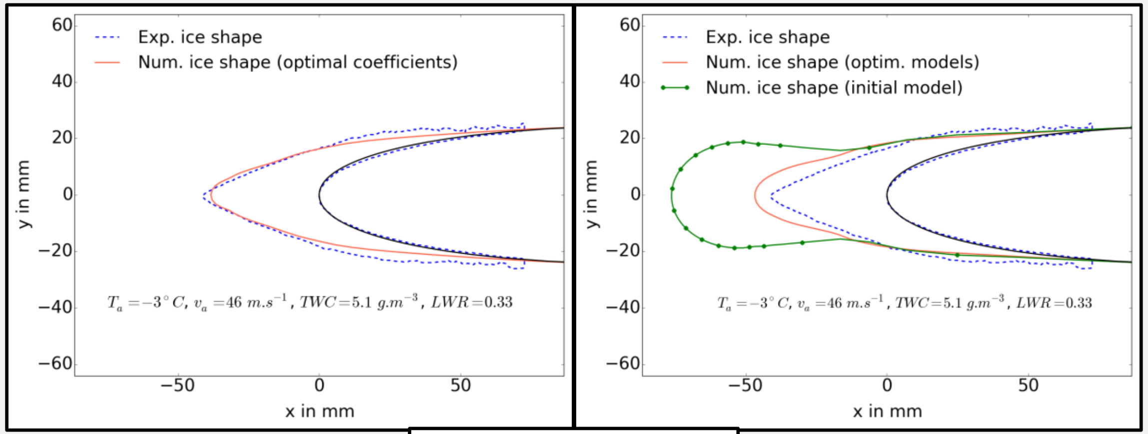


Numerical vs. exp. ice shape

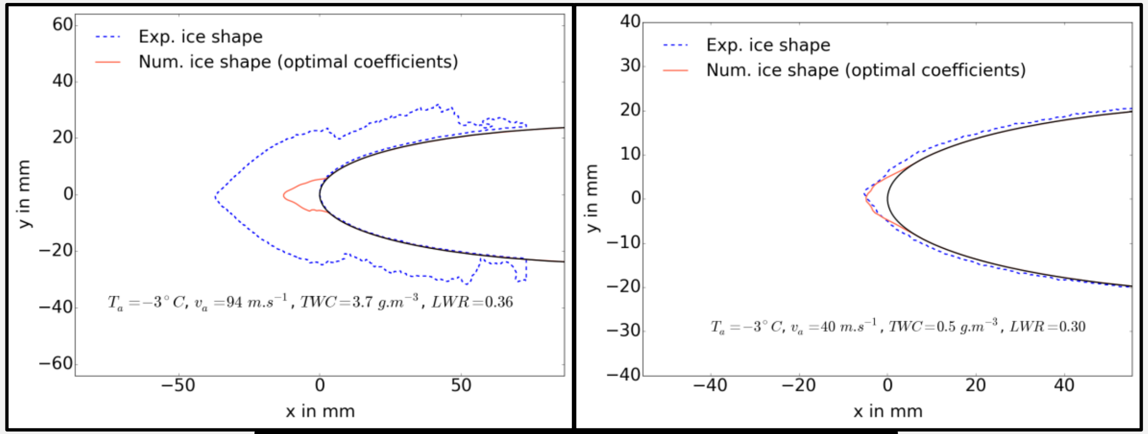
Snowflake Accretion Model

- Some comparisons
  - The optimization provides some improvements on the numerical results but is not fully satisfactory
  - Need for a better optimization ... and/or a better modelling

	CSTB	RTA
Specific coef.	6 cases	9 cases
Arithmetic average	5 cases	9 cases



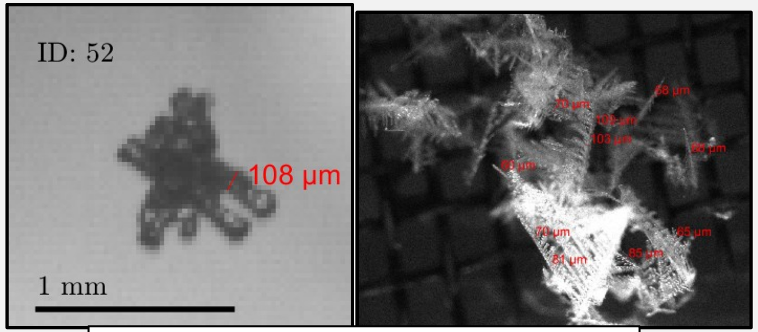
CSTB – Run 403



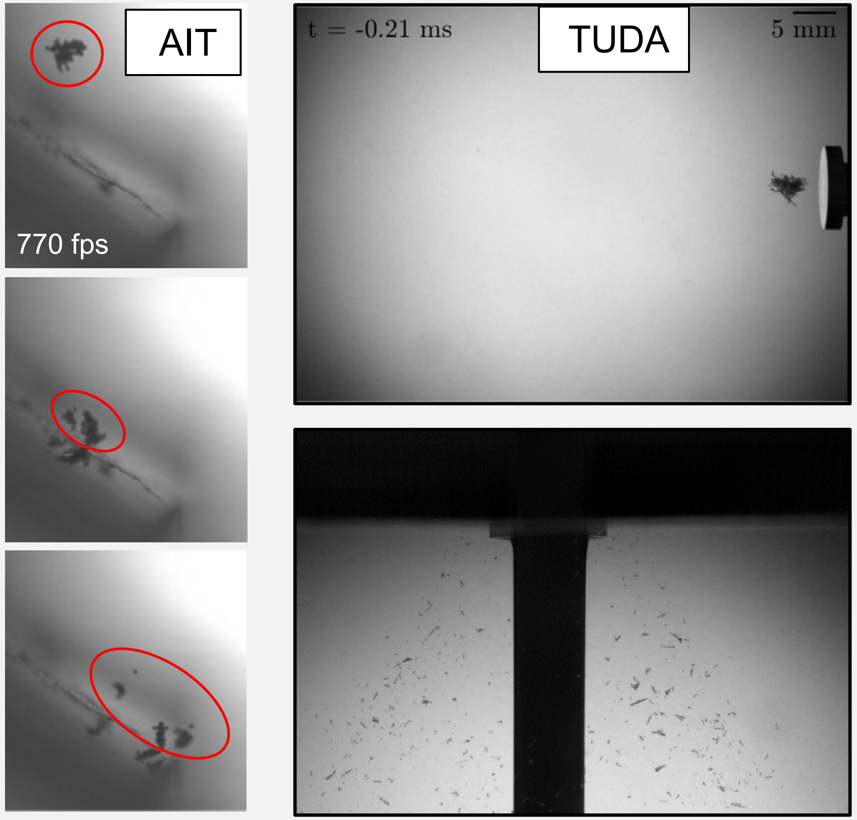
CSTB (left) and RTA (right) cases

Shattering Model

- Objective : characterize the break-up threshold and the Particle Size Distribution after Break-up
- Methodology
  - Based on TUDA and AIT experimental data
    - Snowflake impacts onto a clean solid substrate
    - Snowflake impact at 11 m/s, 19 experiments (TUDA)
    - Natural snowflakes sucked through a constriction, 112 impacts (AIT)
  - Break-up threshold
    - Considering previous results from HAIC model
    - Need to define a characteristic length scales
- No implementation in the 3D numerical tools at that point



Snow particles dimensions



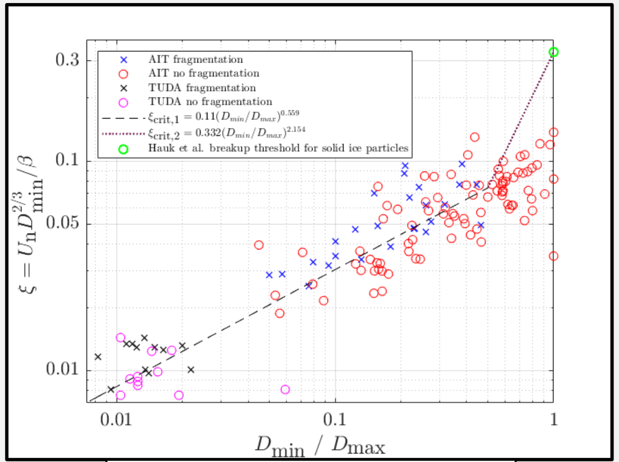
Break-up sequences

Shattering Model

- Break-up threshold
  - Parameter of interest $\xi = \frac{U_n D_{\min}^{\frac{2}{3}}}{\beta}$

$$\xi_{\text{crit},1} = 0.110 \left(\frac{D_{\min}}{D_{\max}}\right)^{0.559} \quad \text{for } 0.008 < \frac{D_{\min}}{D_{\max}} < 0.5,$$

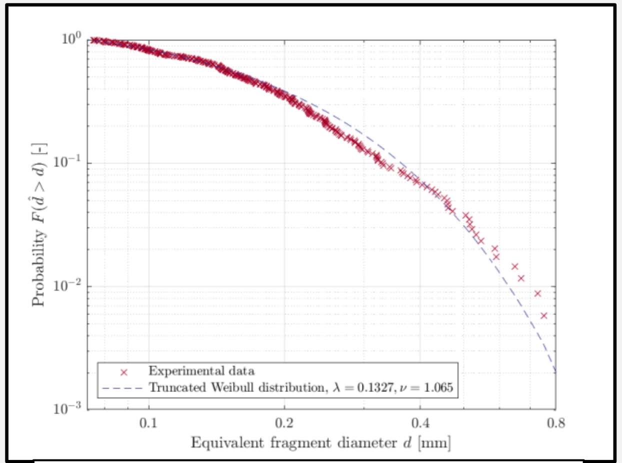
$$\xi_{\text{crit},2} = 0.3315 \left(\frac{D_{\min}}{D_{\max}}\right)^{2.154} \quad \text{for } \ 0.5 < \frac{D_{\min}}{D_{\max}} < 1$$



Break-up Threshold

- Particle Size Distribution after impact
  - Using a Kalman multi-object tracking algorithm (@Matlab)
  - Truncated Weibull density function

$$f(d) = \frac{\nu}{\lambda} * \left(\frac{\nu}{\lambda}\right)^{\nu-1} * \exp\left(-\left(\frac{d}{\lambda}\right)^{\nu}\right) \quad \text{if } \ d > 0.073 \text{ mm}$$



PSD of the fragment diameter

3D numerical assessment

AIT, ONERA, POLIMI

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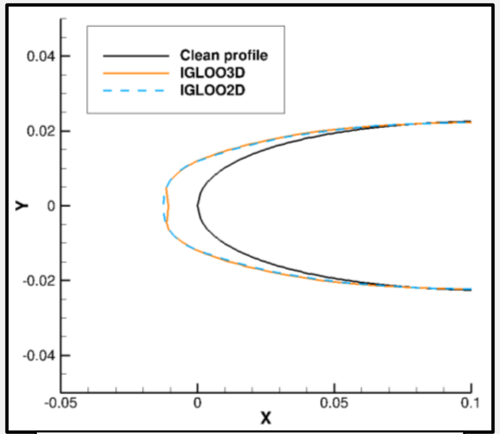
Preliminary Validation in 3D solvers

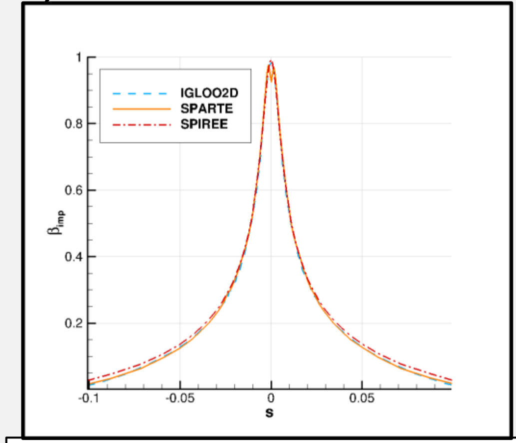
- Academic validations have been presented previously (drag & melting models)
- Considering 2D-extruded cases with the 3D solvers (RTA database)
  - Hölzer & Sommerfeld drag model / mNS melting model
  - Accretion based on ONERA IGLOO3D/MESSINGER3D solver
  - Same Heat Transfer Coefficient as in the 2D calculation
  - Predictor calculation with a monodisperse distribution
- To be tested more extensively in WP11

Exp	V_∞ (m/s)	T_∞ (°C)	MMD (µm)	TWC (g/m³)	LWR	Density (kg/m³)	Duration (s)
TP08	40	-3	698.8	0.49	0.3	280	600

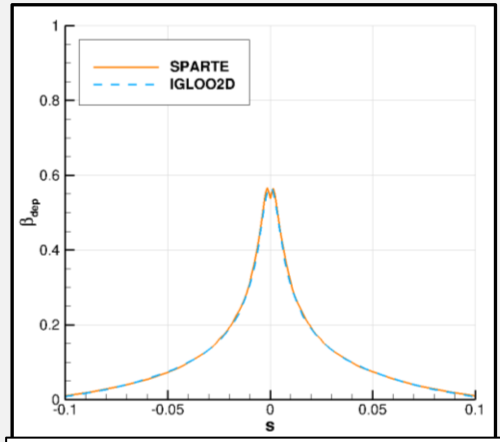
Operating conditions



Ice shape



Impact collection efficiency



Deposit collection efficiency

Conclusion & Way Forward

AIH, AIT, ONERA, POLIMI, TUDA

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Conclusion & Way Forward

- A set of basic experiments to understand snow physical phenomena and support modeling activities

- A first set of snow transport and snow accretion models derived from HAIC / MUSIC-HAIC showing commonality between ice crystals and snow icing physics
- Snow models implemented in 2D and 3D icing tools and preliminary validation

- **Achievements within ICE GENESIS provides already major improvement compared to the state of the art especially wrt transport model. Preliminary 2D/3D capability available and ready for further assessment on representative industrial configuration.**

- Still, improvements needed
  - Snow accretion : improvement of sticking / erosion modeling
  - Other phenomena: shedding, saltation