Ice Prediction Workshop 2
Test Case Descriptions

IPW Organizing Committee

February 7, 2023

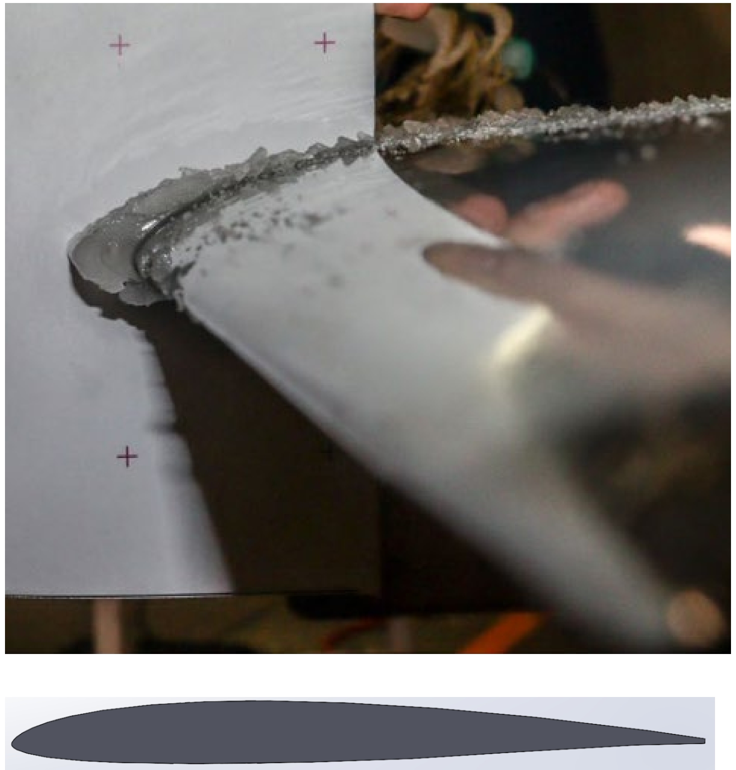
Revision log

- October 25, 2022
  - Initial version
- February 7, 2023
  - IRT cloud calibration data added for CRM65 cases simulation parameters
  - RG-15 AoAs changed to 4-degrees
  - RG-15 span changed from 590 to 580 mm
  - List of references

Configurations Summary

Case 1: CRM-65 Mid-span Hybrid (3D)

Case 2: CRM-65 Inboard Hybrid (3D)



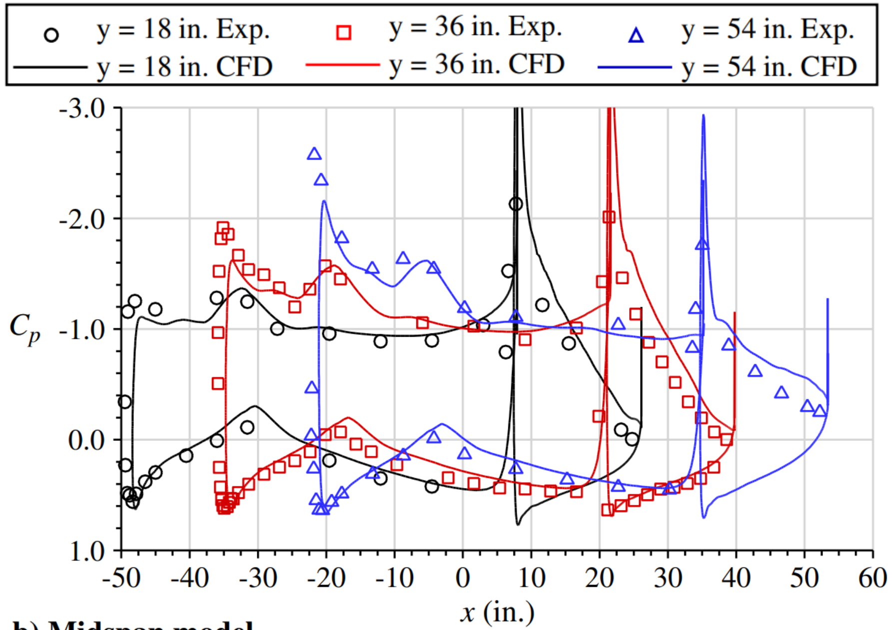
Case 3: RG-15 Low Speed Icing

Case list overview

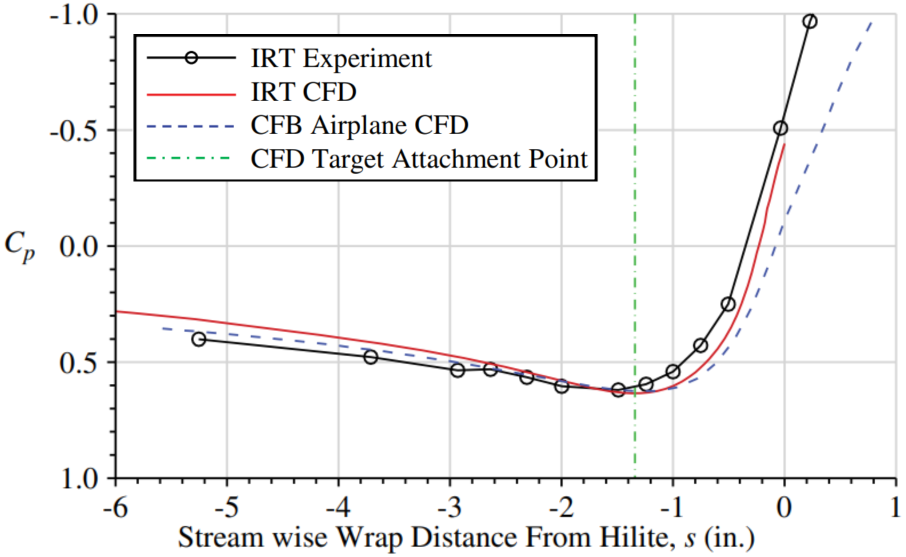
IPW-2 Case no.	Configuration	AoA	Speed	T_{static} (°C)	T_{total} (°C)	LWC (g/m³)	MVD (µm)	Icing Time (minutes)
1.1	CRM65 Mid-span	3.7	130 kts	-3.6	-1.4	1.0	25	29
1.2	CRM65 Mid-span	3.7	130 kts	-8.5	-6.3	1.0	25	29
1.3	CRM65 Mid-span	3.7	130 kts	-26.0	-23.8	1.0	25	29
2.1	CRM65 Inboard	3.7	130 kts	-3.6	-1.4	1.0	25	29
2.2	CRM65 Inboard	3.7	130 kts	-8.5	-6.3	1.0	25	29
2.3	CRM65 Inboard	3.7	130 kts	-26.0	-23.8	1.0	25	29
3.1	RG-15 Small wing	4	25 m/s	-2.0	-1.7	0.44	24	20
3.2	RG-15 Small wing	4	25 m/s	-4.0	-3.7	0.44	24	20
3.3	RG-15 Small wing	4	25 m/s	-10.0	-9.7	0.44	24	20

Cases 1.1-1.3: CRM65 Midspan

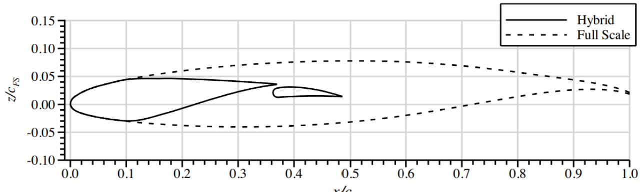
IPW-2 Case no	AoA (deg.)	Flap angle (deg.)	Speed (knots)	Speed (m/s)	T_{total} (°C)	T_{static} (°C)	P_{total} (kPa)	P_{static} (kPa)	MVD (µm)	LWC (g/m³)	Time (min.)	Freezing fraction	2015 ice mass (kg/m)	2021 ice mass (kg/m)	2022 ice mass (kg/m)
1.1	3.7	25.0	130	66.9	-1.4	-3.6	99.3	96.5	25	1.0	29.0	0.12	4.17	3.75	3.70
1.2	3.7	25.0	130	66.9	-6.3	-8.5	97.5	94.7	25	1.0	29.0	0.35	6.42	6.64	5.93
1.3	3.7	25.0	130	66.9	-23.8	-26.0	99.3	96.3	25	1.0	29.0	1.00	6.5	5.43	5.30



b) Midspan model



b) Midspan model



b) Midspan hybrid airfoil

- Workshop CAD and grids are provided with AoA and flap angle built-in
- Pressure coefficients are based on inlet static pressure and density: CFD results that set back pressure at tunnel exit should use converged inlet static pressure as reference when computing C_p .

References: *Broeren et al., "Ice-Accretion Test Results for Three Large-Scale Swept-Wing Models in the NASA Icing Research Tunnel", AIAA Aviation Forum, AIAA 2016-3733*
Fujiwara, Bragg, Broeren, "Comparison of Computational and Experimental Ice Accretions of Large Swept Wings", J of A, Vol 57, No 2, 2020

Cases 1.1-1.3: CRM65 Mid-span: Comparison of MCCS

IPW-2 Case no	AoA (deg.)	Flap angle (deg.)	Speed (knots)	Speed (m/s)	T_{total} (°C)	T_{static} (°C)	P_{total} (kPa)	P_{static} (kPa)	MVD (µm)	LWC (g/m^3)	Time (min.)	Freezing fraction	2015 ice mass (kg/m)	2021 ice mass (kg/m)	2022 ice mass (kg/m)
1.1	3.7	25.0	130	66.9	-1.4	-3.6	99.3	96.5	25	1.0	29.0	0.12	4.17	3.75	3.70
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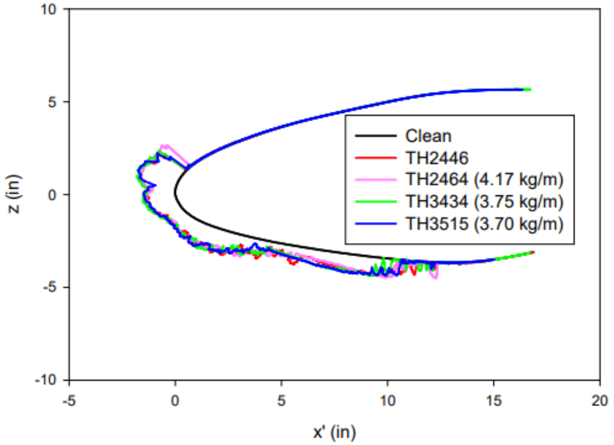
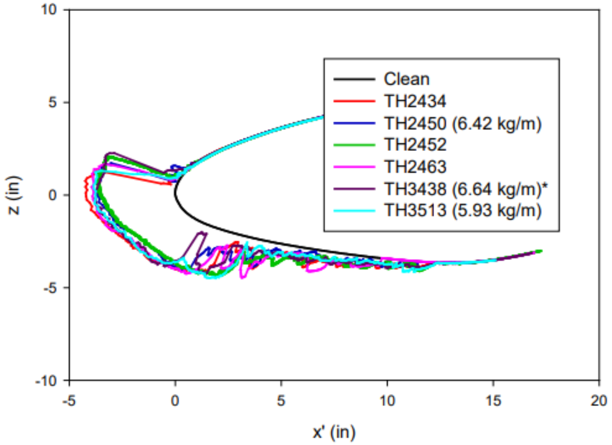
1.3	3.7	25.0	130	66.9	-23.8	-26.0	99.3	96.3	25	1.0	29.0	1.00	6.5	5.43	5.30

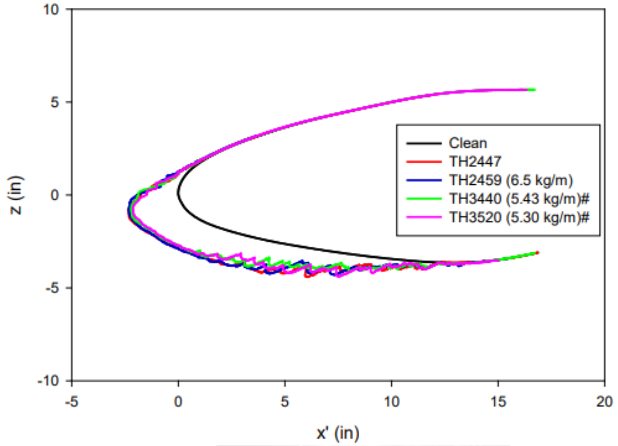
Test Condition 2



Test Condition 4



Test Condition 8



Case 1.1

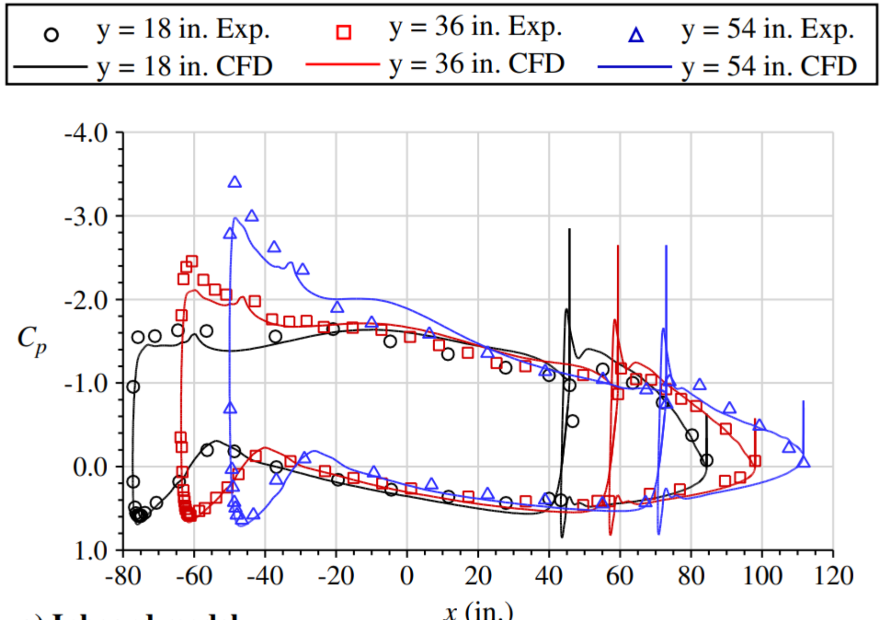
Case 1.2

Case 1.3

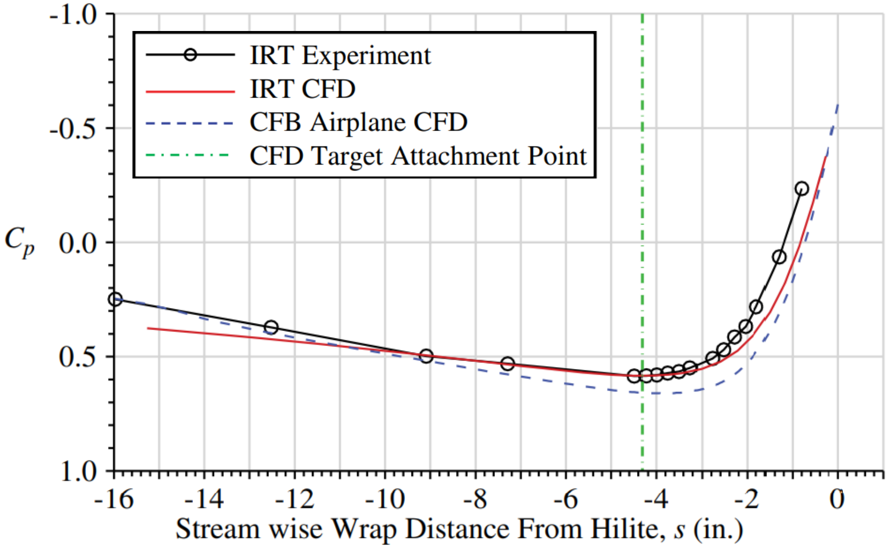
References: *Broeren et al.*, "Ice-Accretion Test Results for Three Large-Scale Swept-Wing Models in the NASA Icing Research Tunnel", AIAA Aviation Forum, AIAA 2016-3733
Fujiwara, Bragg, Broeren, "Comparison of Computational and Experimental Ice Accretions of Large Swept Wings", J of A, Vol 57, No 2, 2020

Cases 2.1-2.3: CRM65 Inboard

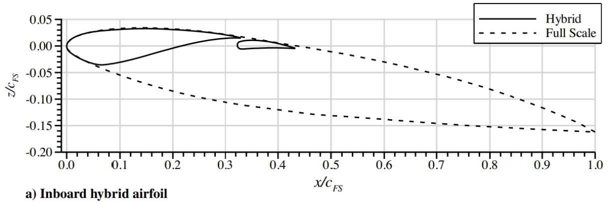
IPW-2 Case no	AoA (deg.)	Flap angle (deg.)	Speed (knots)	Speed (m/s)	T_{total} (°C)	T_{static} (°C)	P_{total} (kPa)	P_{static} (kPa)	MVD (µm)	LWC (g/m^3)	Time (min.)	Freezing fraction	2015 ice mass (kg/m)
2.1	3.7	13.8	130	66.9	-1.4	-3.6	99.3	96.5	25	1.0	29.0	0.12	4.92
2.2	3.7	13.8	130	66.9	-6.3	-8.5	100.7	97.8	25	1.0	29.0	0.35	8.22
2.3	3.7	13.8	130	66.9	-23.8	-26.0	99.3	96.3	25	1.0	29.0	1.00	7.90



a) Inboard model



a) Inboard model



a) Inboard hybrid airfoil

- Workshop CAD and grids are provided with AoA and flap angle built-in
- Pressure coefficients are based on inlet static pressure and density: CFD results that set back pressure at tunnel exit should use converged inlet static pressure as reference when computing C_p .

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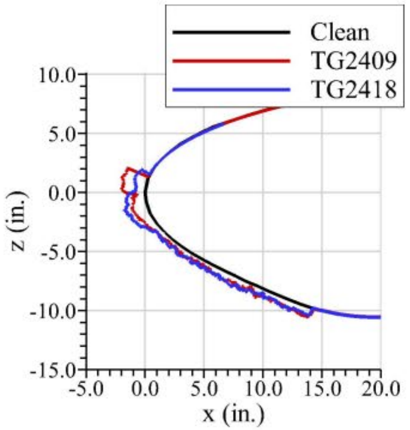
Fujiwara, Bragg, Broeren, "Comparison of Computational and Experimental Ice Accretions of Large Swept Wings", J of A, Vol 57, No 2, 2020

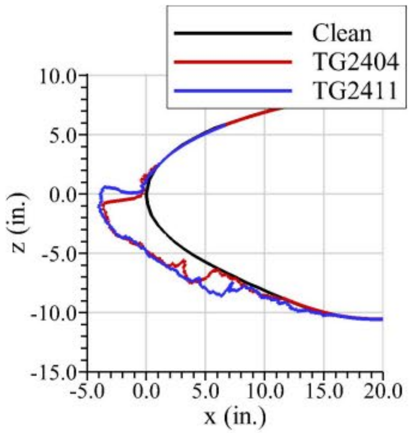
Cases 2.1-2.3: CRM65 Inboard: Comparison of MCCS

IPW-2 Case no	AoA (deg.)	Flap angle (deg.)	Speed (knots)	Speed (m/s)	T_{total} (°C)	T_{static} (°C)	P_{total} (kPa)	P_{static} (kPa)	MVD (μm)	LWC (g/m^3)	Time (min.)	Freezing fraction	2015 ice mass (kg/m)
2.1	3.7	13.8	130	66.9	-1.4	-3.6	99.3	96.5	25	1.0	29.0	0.12	4.92
2.2	3.7	13.8	130	66.9	-6.3	-8.5	100.7	97.8	25	1.0	29.0	0.35	8.22
2.3	3.7	13.8	130	66.9	-23.8	-26.0	99.3	96.3	25	1.0	29.0	1.00	7.90

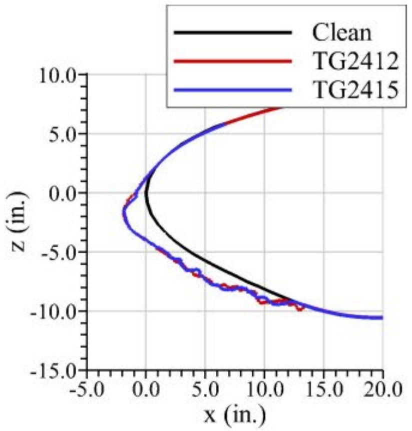
Test Condition 2



Test Condition 4



Test Condition 8



Case 2.1

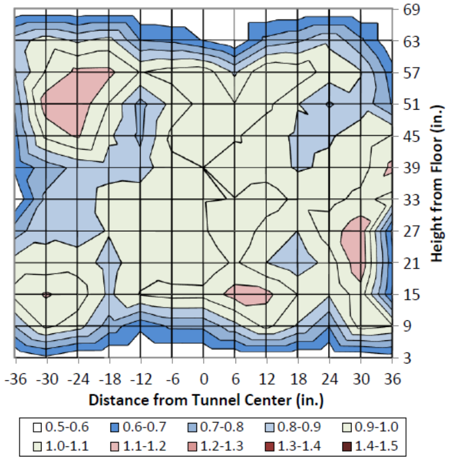
Case 2.2

Case 2.3

References: *Broeren et al.,* "Ice-Accretion Test Results for Three Large-Scale Swept-Wing Models in the NASA Icing Research Tunnel", AIAA Aviation Forum, AIAA 2016-3733
Fujiwara, Bragg, Broeren, "Comparison of Computational and Experimental Ice Accretions of Large Swept Wings", J of A, Vol 57, No 2, 2020

NASA Glenn Research Center Icing Research Tunnel Cloud Calibration data

- This data is provided as recommendation for setting numerical simulation parameters
- Below is the cloud uniformity map for MVD = 20 µm and V = 150 knots take from NASA TM 2015-218758. The contour levels are ice thickness on the grid normalized by the average of the center 12 locations. Note that the test section is 72-inches tall.



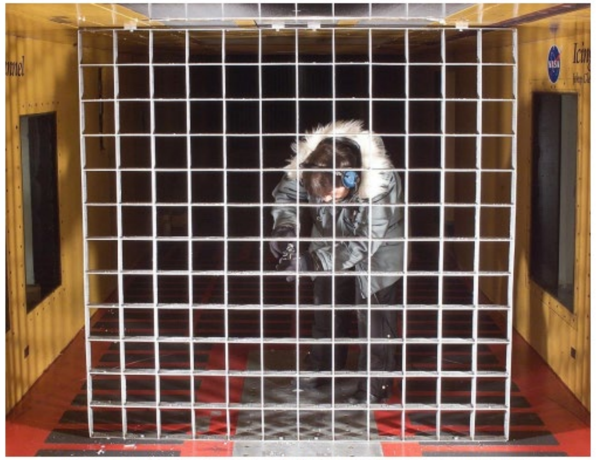
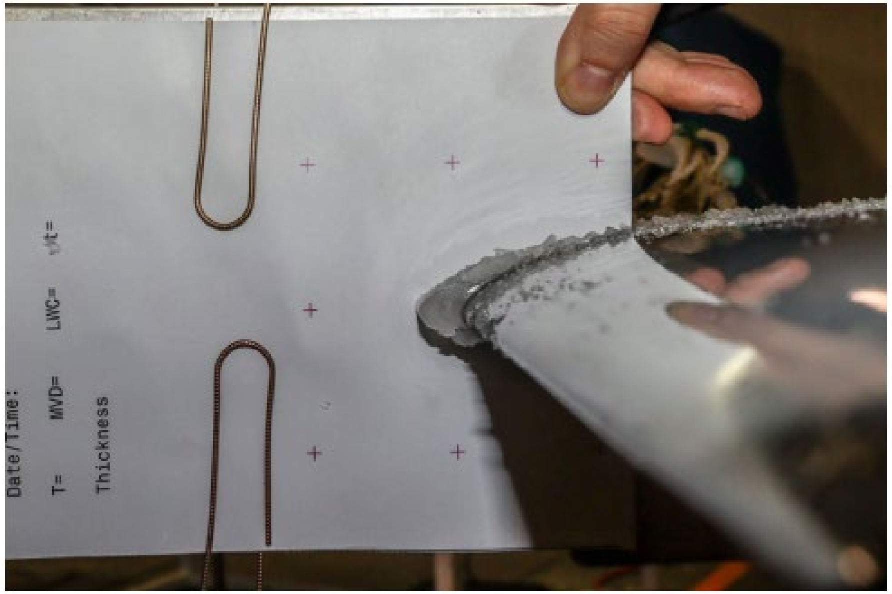


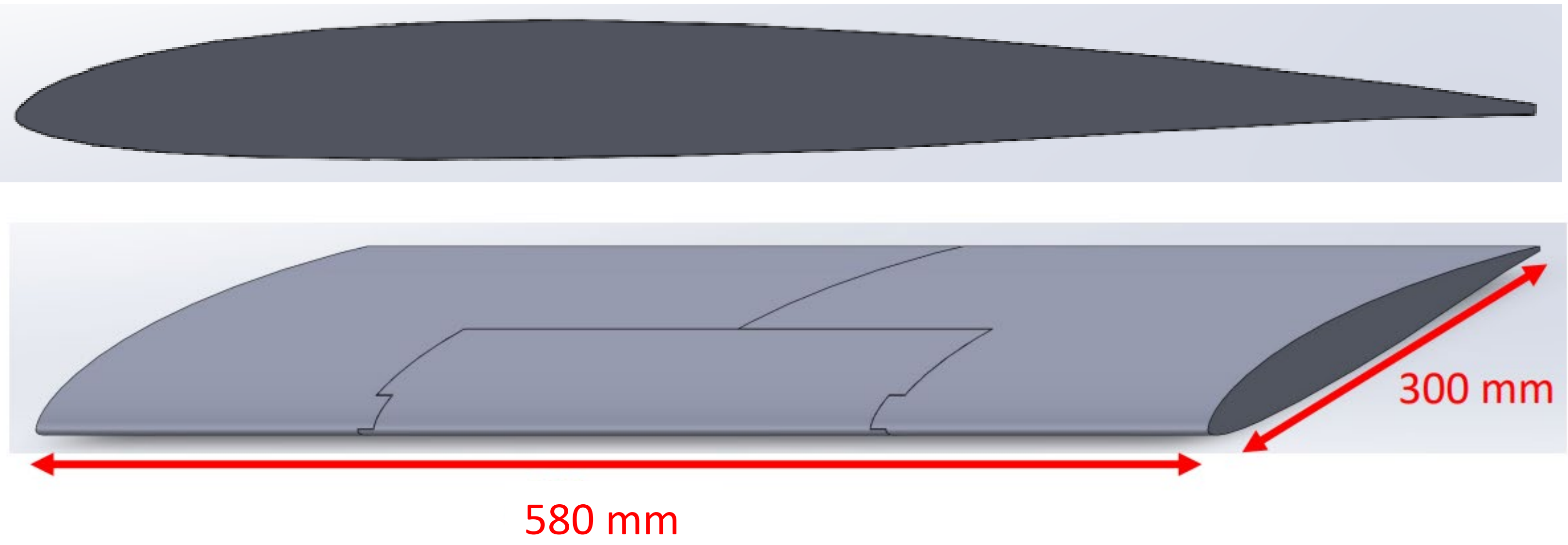
Figure 2.—A technician measures the thickness of ice accreted on the Grid.

- IRT distribution is different than Langmuir-D, and will be provided.

Cases 3.1-3.3: RG-15 Small Wing Low Speed Icing

IPW-2 Case no.	AoA (deg.)	Speed (m/s)	T_{static} (°C)	T_{total} (°C)	P_{static} (kPa)	MVD (µm)	LWC (g/m^3)	Time (min.)
3.1	4	25	-2.0	-1.7	101.3	24	0.44	20
3.2	4	25	-4.0	-3.7	101.3	24	0.44	20
3.3	4	25	-10.0	-9.7	101.3	24	0.44	20





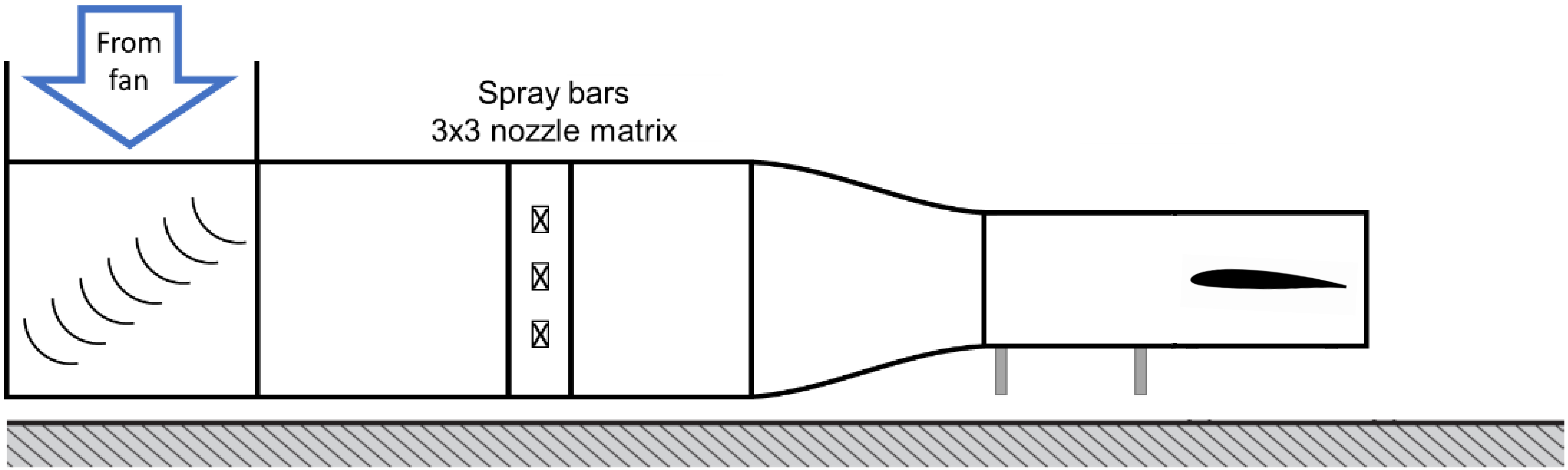
Reference: *NTNU UAV Icing Lab*

Cases 3.1-3.3: RG-15 Small Wing Low Speed Icing

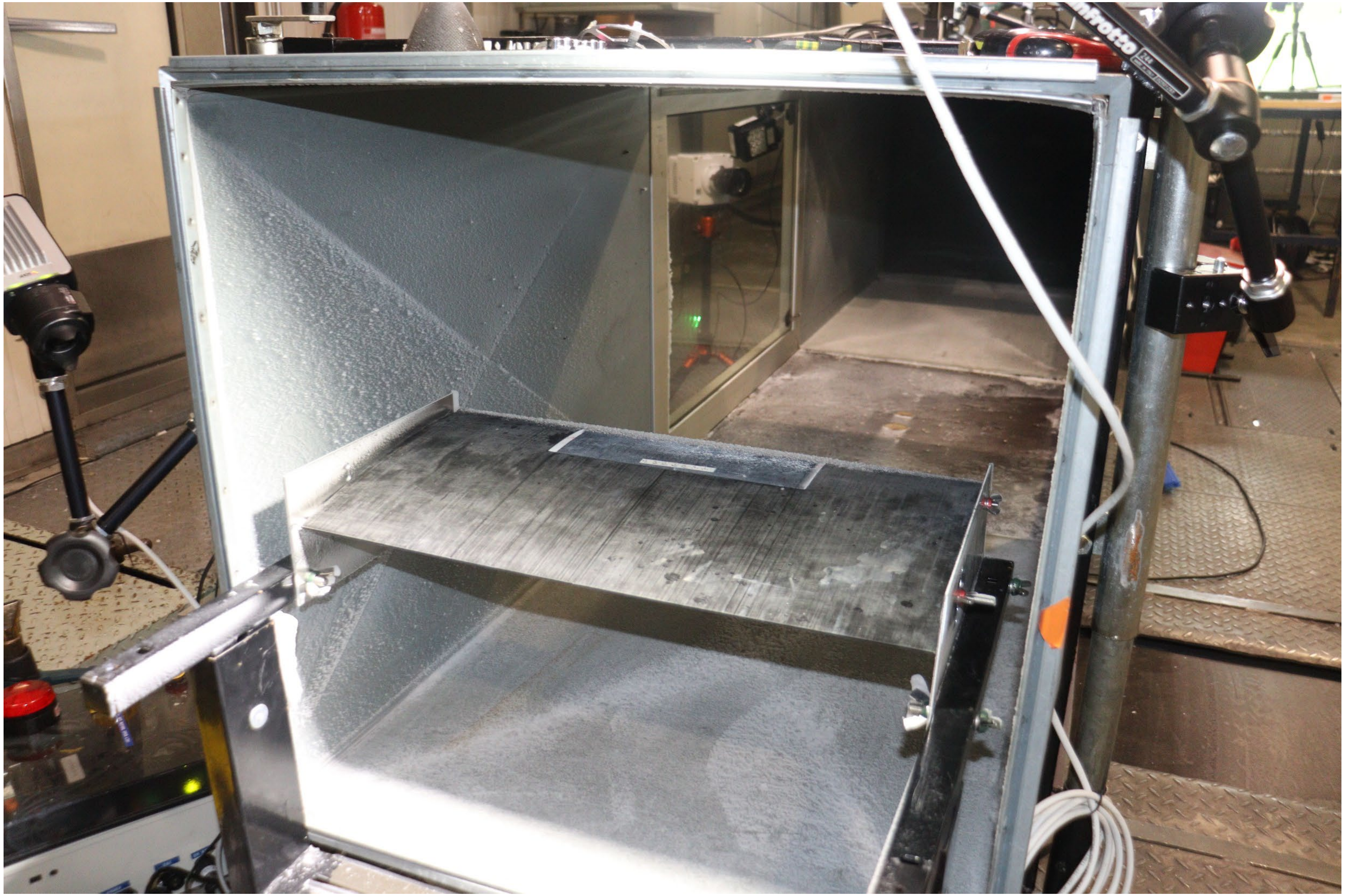
Airfoil	RG-15
Span	0.58 m
Chord	0.30 m
Airspeed	25 m/s
Angle of attack	4 $^\circ$
Liquid water content (LWC)	0.44 g/m^3
Mean volume diameter (MVD)	24 microns*
Duration	20 min
Static temperature (glaze, mixed, rime)	$[-2, -4, -10]$ $^\circ$C
Reynolds numbers	$[5.7, 5.8, 6.0]\times10^5$
Relative Humidity	95–100%
Pressure	101.3 kPa

*Monodisperse. A more detailed droplet spectrum will be supplied at a later stage.

Icing wind tunnel setup

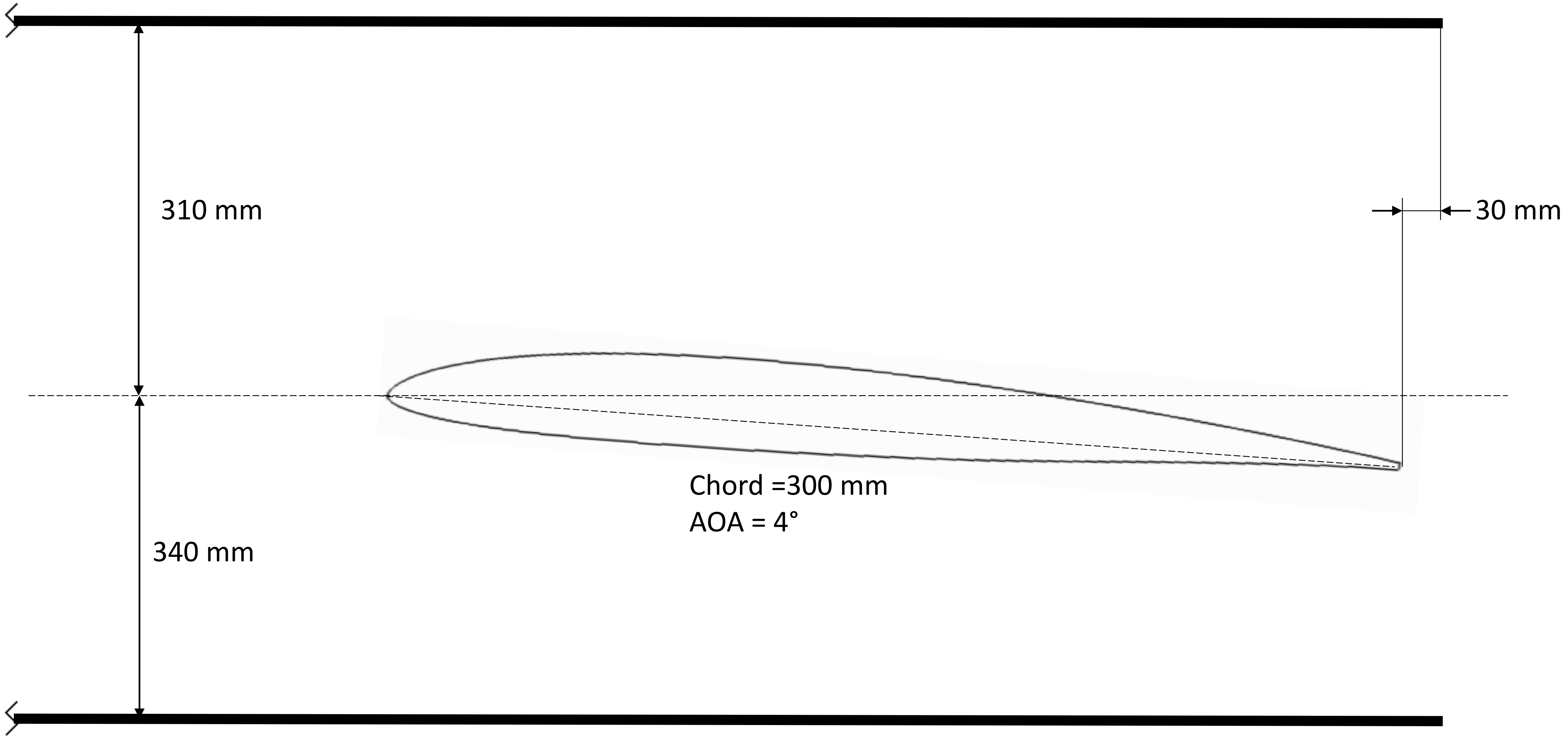


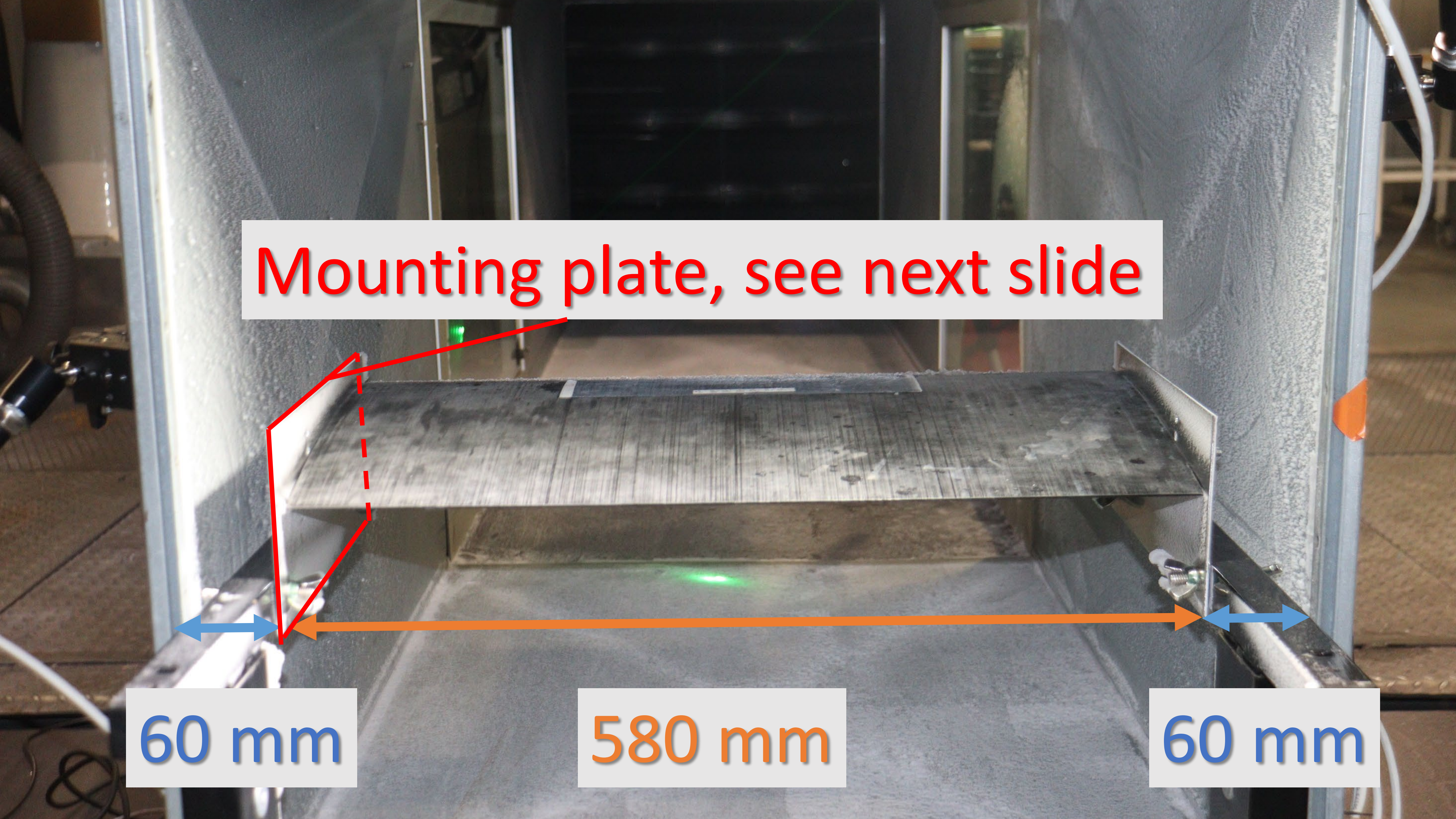
Cases 3.1-3.3: RG-15 Small Wing Low Speed Icing



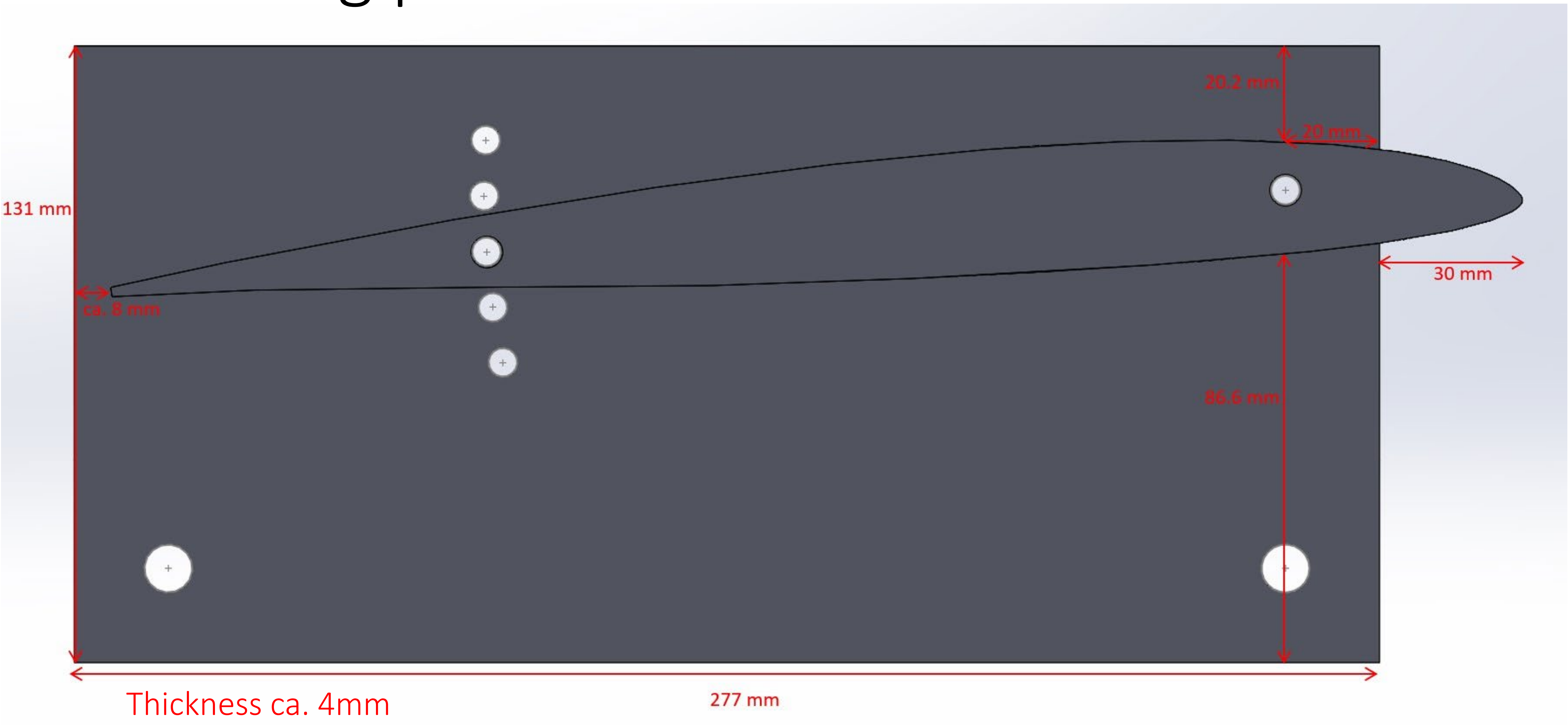
Cases 3.1-3.3: RG-15 Small Wing Low Speed Icing

Tunnel cross-section




Mounting plate, see next slide
60 mm
580 mm
60 mm

Mounting plates



References

- Broeren, A., Potapczuk, M., Lee, S., Malone, A., Paul, B., Woodard, B. “Ice-Accretion Test Results for Three Large-Scale Swept-Wing Models in the NASA Icing Research Tunnel”, AIAA-2016-3733, doi: 10.2514/6.2016-3733
- Yadlin, Y., Monnig, J., Malone, A., Paul, B., “Icing Simulation Research Supporting the Ice-Accretion Testing of Large-Scale Swept-Wing Models”, NASA/CR—2018-219781
- Fujiwara, G., Bragg, M., Broeren, A., “Comparison of Computational and Experimental Ice Accretions of Large Swept Wings”, Journal of Aircraft Vol. 57, No. 2, March–April 2020
- Steen, L., Ide, R., Zante, J., Acosta, W., “NASA Glenn Icing Research Tunnel: 2014 and 2015 Cloud Calibration Procedures and Results”, NASA/TM—2015-218758
- Broeren, A., Lee, S., Bragg, M., Woodard, B., Radenac, E., Moens, F., “Experimental and Computational Icing Simulation for Large Swept Wings”, NASA/TP-20210023843
- Hann, R., Müller, M., Lindner, M., Wallisch, J., UAV Icing: “Experimental validation data for predicting ice shapes at low Reynolds numbers”, Technical Paper, International Conference on Icing of Aircraft, Engines, and Structures, accepted manuscript, 2023.