



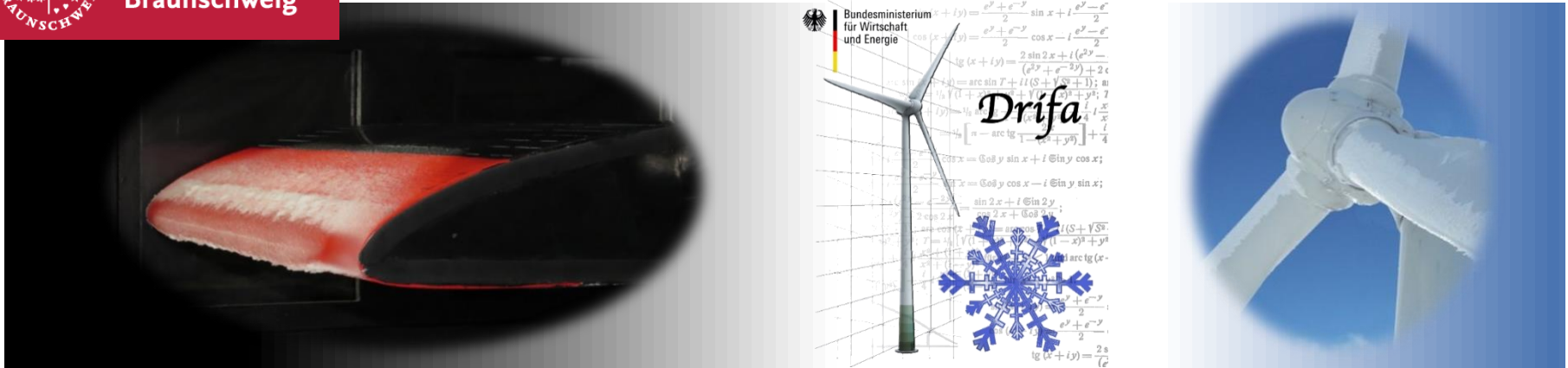
Technische
Universität
Braunschweig

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Bundesministerium
für Wirtschaft
und Energie

aufgrund eines Beschlusses
des Deutschen Bundestages



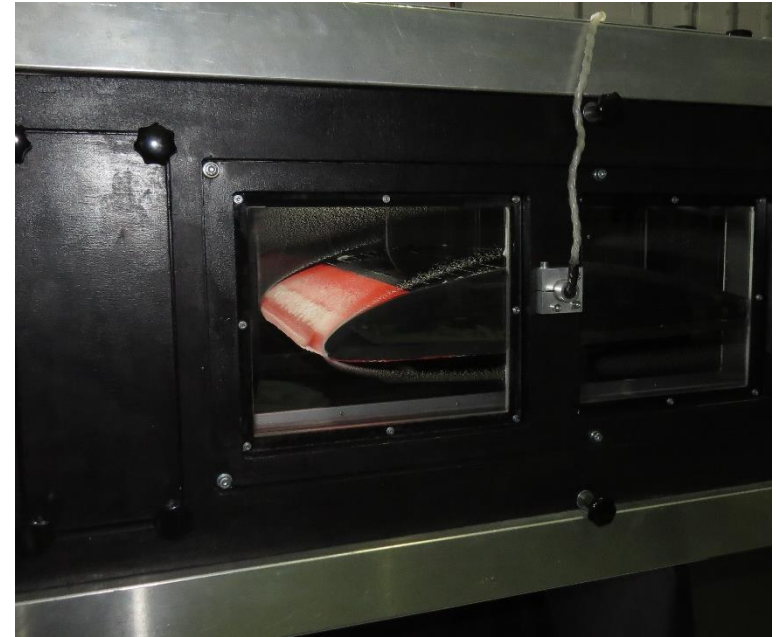
Industrial Research on the Design of Wind Turbines for Icing Conditions

Inken Knop, Stephan Bansmer (TUBS)

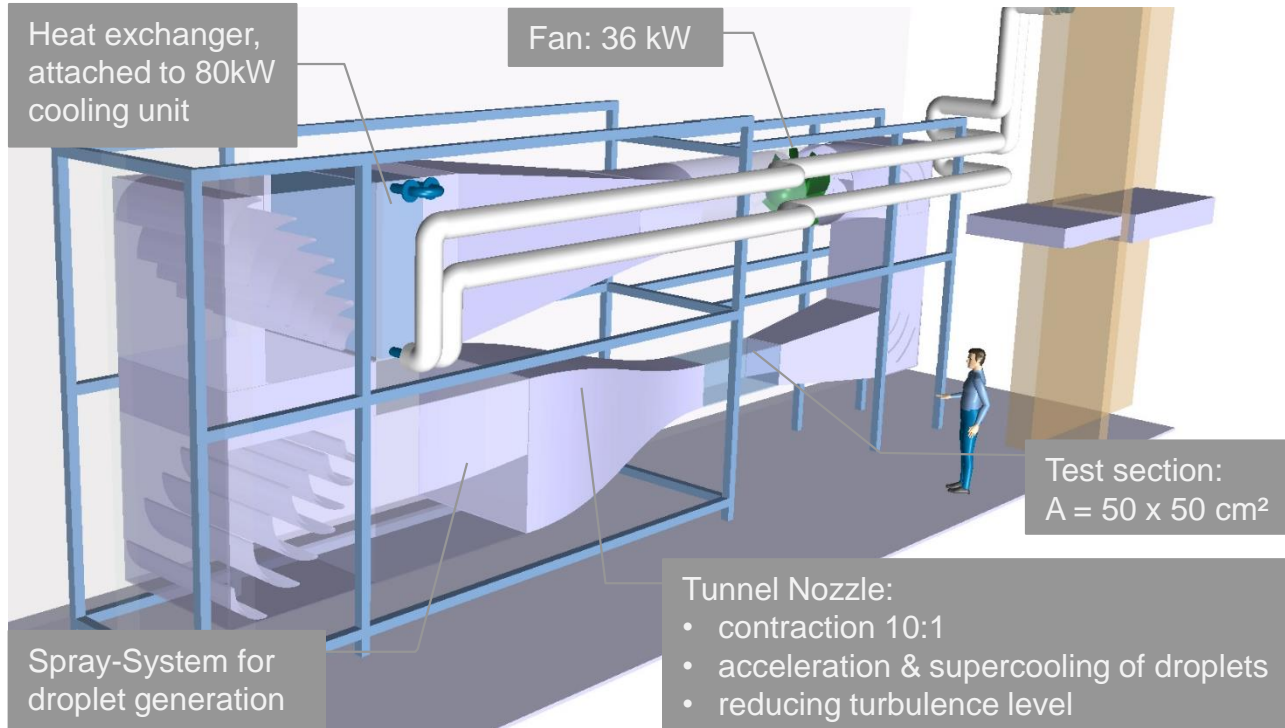
Khalid Abdellaoui, Muhanad Mahmoud, Andree Altmikus (WRD)

Goals in Research Project Drifa

- Experimental validation of commercial icing codes
- Numerical & experimental investigation of the influence of 2D /3D ice accretion on blade aerodynamics
- De-icing and anti-icing functionality of blade heating systems in wind tunnel experiments



Braunschweig Icing Wind Tunnel



Boundary Conditions:

$$U_{\infty} = 10 \text{ to } 40 \text{ m/s}$$

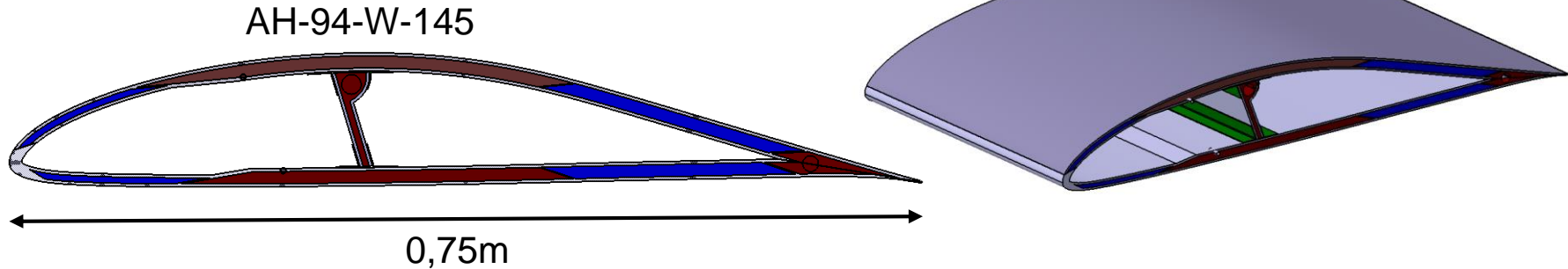
$$T = -20 \text{ to } +30 \text{ }^{\circ}\text{C}$$

$$\text{MVD} = 9 \text{ to } 48 \text{ } \mu\text{m}$$

$$\text{LWC} = 0.1 \text{ to } 2 \text{ g/m}^3$$

Reynolds number up to
 2.3×10^6

Wind Tunnel Model



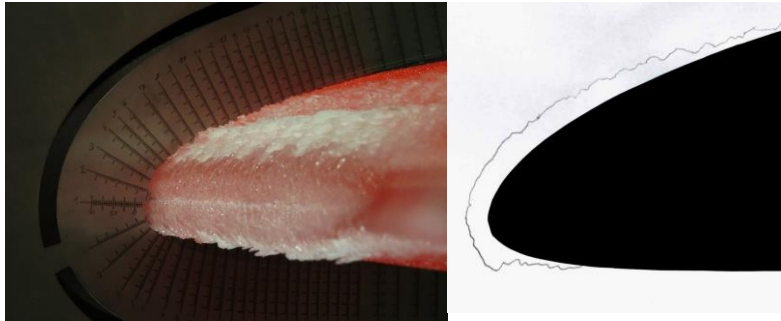
- Inner structure adapted to original rotor blades with
 - Fiberglass,
 - Balsa wood,
 - PET rigid foam
- Instrumented with 50 Pt1000 temperature sensors

Goal:

- Model as realistic as possible to avoid scaling difficulties

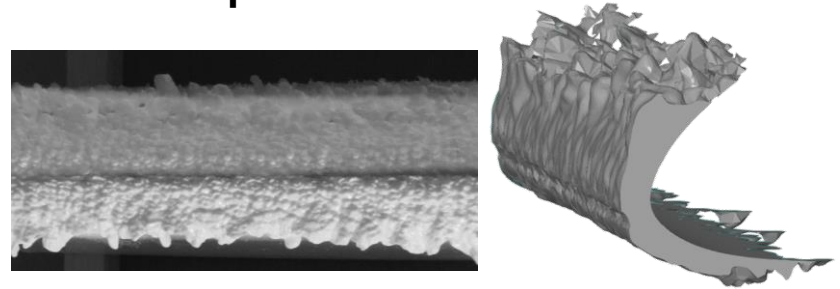
Experimental Ice Shape Generation

2D Ice Shape



- Melting a specific cut in the two-dimensionally iced area
- Tracing the mean ice contour
- Digitizing the drawing

3D Ice Shape

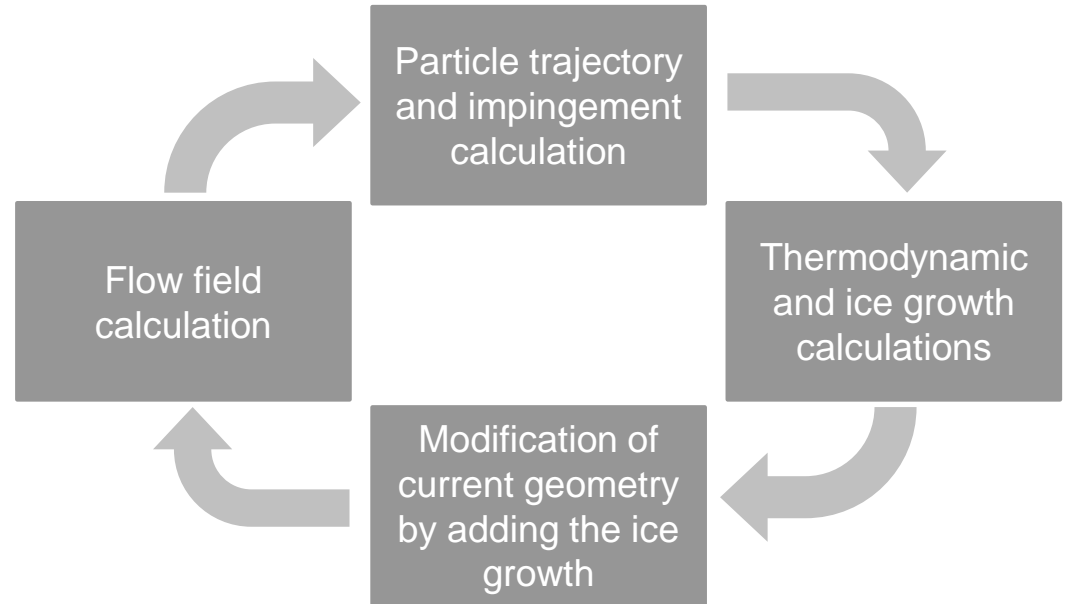


- Creating a negative from the ice shape with low viscosity platinum silicone
- Casting positive with two component polyurethane mixture
- 3D scan of positive for digitizing
- Average over two-dimensionally iced cross-section

Numerical ice shape generation

LEWICE (NASA)

- Based on Messinger-Model for mass and energy balances
- Time stepping procedure to “grow” ice accretion
- Validated for aircraft icing conditions with experimental ice shapes of the IRT at NASA



Boundary Conditions Aircraft – Wind turbines

Variable	Validation Range Lewice 3.2	Our Experiments
Time	2 - 45 min	5 - 15 min
Chord	35,3 - 198,12 cm	75 cm
AoA	-4° - +7°	-4°, 0°, +4°
Velocity	56 - 146 m/s	10, 20, 30, 40 m/s
Reynolds Number	$2,26 \times 10^6$ - 13×10^6	$0,57 \times 10^6$ - $2,55 \times 10^6$
Mach Number	0,17 - 0,45	0,03 - 0,125
LWC	0,31 - 1,8 g/m ³	0,17 - 0,96 g/m ³
MVD	15 - 270 μm	14 - 48 μm
Temperature	-31,7 to -3,3°C	-20°C to -3°C

Experimental Results for Rime Ice Conditions

Temperature [°C]

-10

Liquid Water Content [g/m³]

0,260

Mean Volume Diameter [μm]

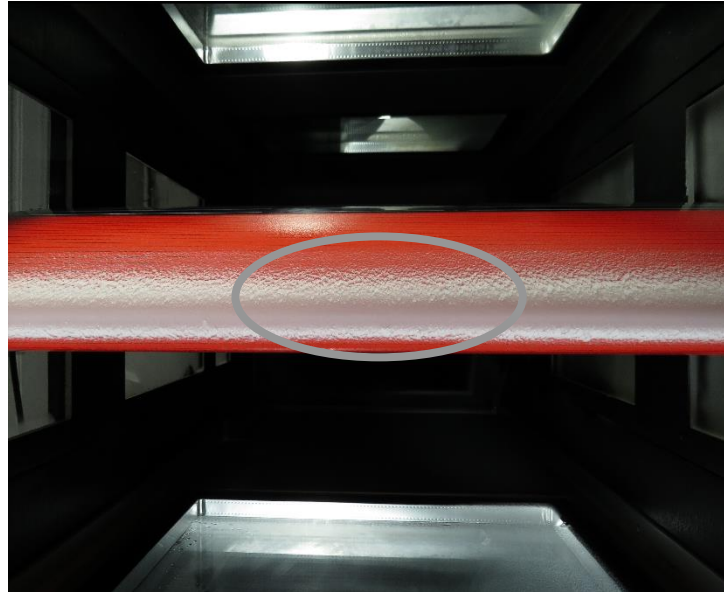
14

Velocity [m/s]

40

Icing duration [s]

900



Experimental Results for Rime Ice Conditions

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Liquid Water Content [g/m³]

0,260

Mean Volume Diameter [μm]

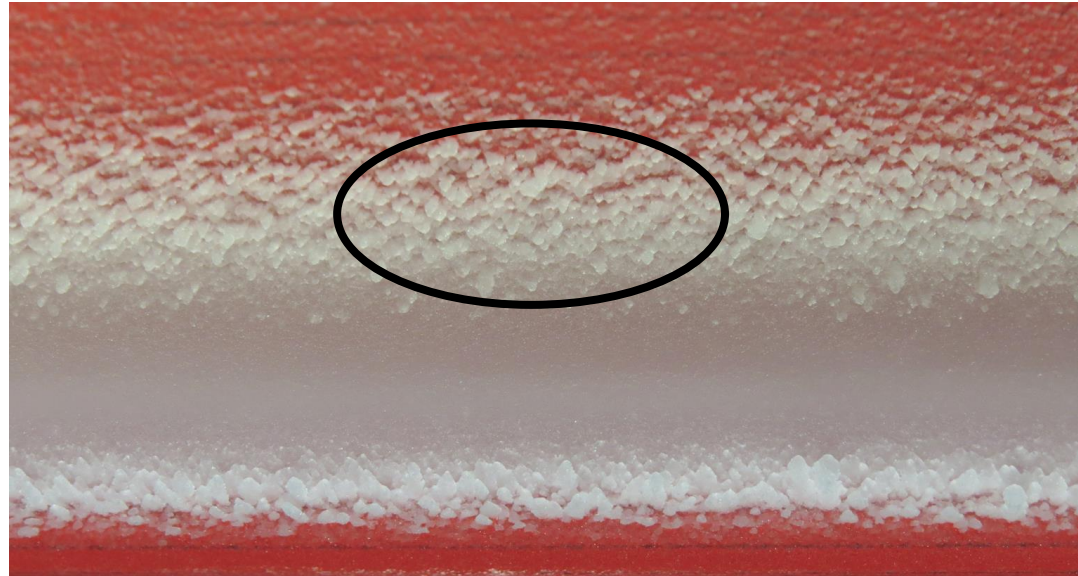
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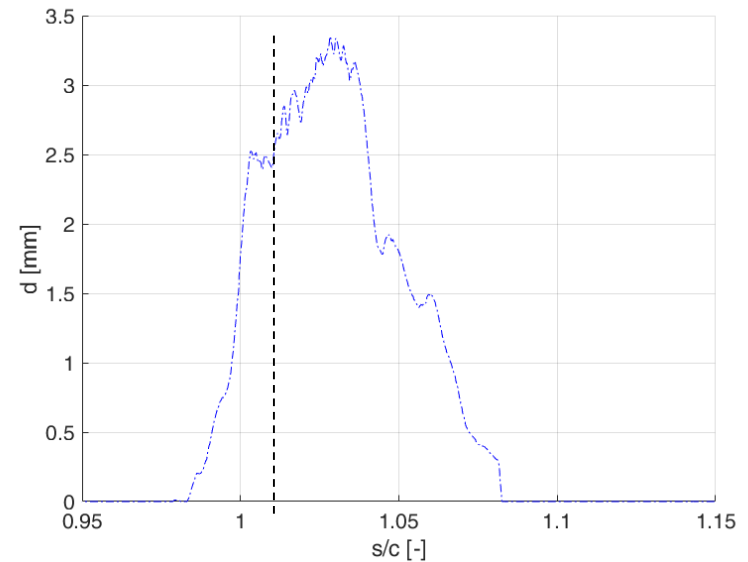
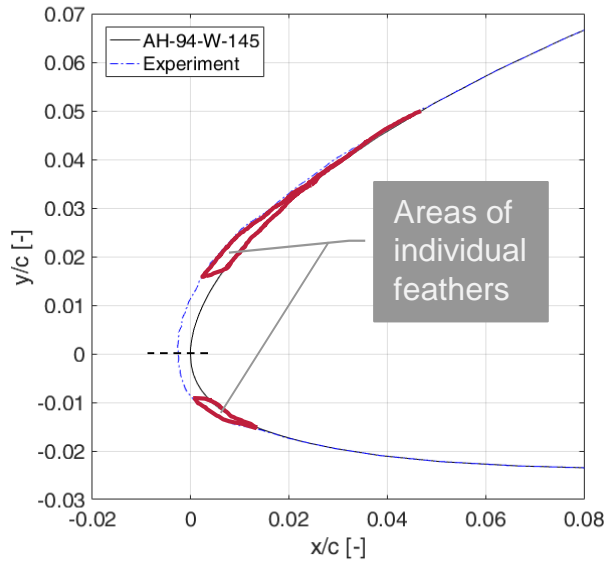
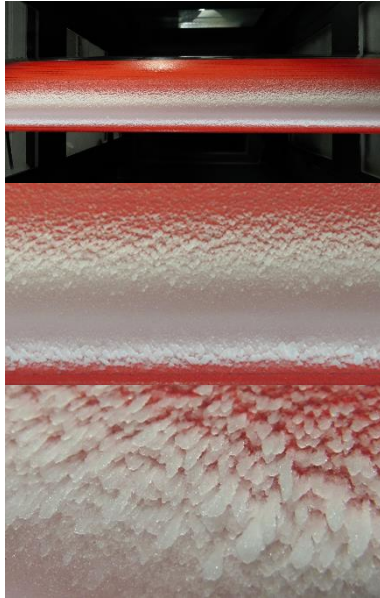
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Velocity [m/s]

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Icing duration [s]

900



Computational Results for Rime Ice Conditions

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-10

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Mean Volume Diameter [μm]

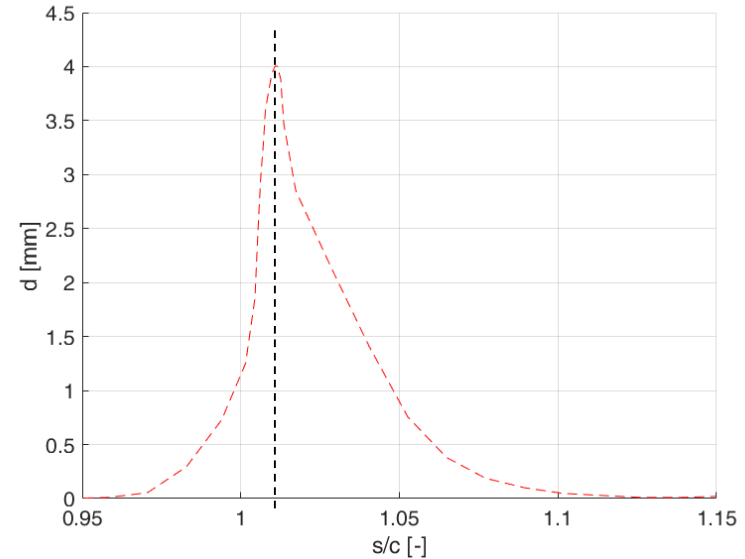
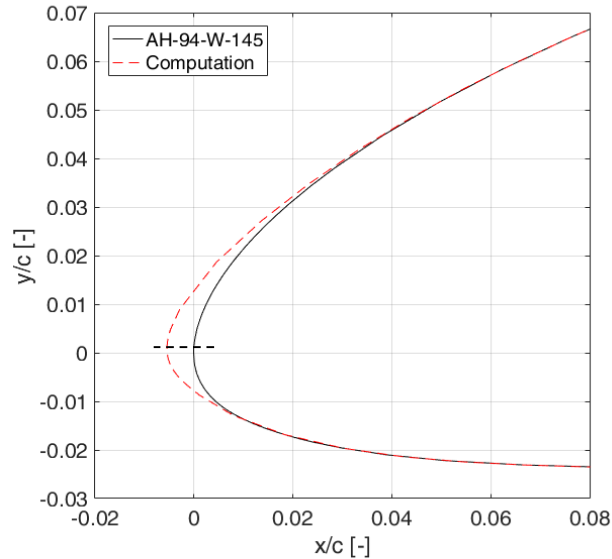
14

Velocity [m/s]

40

Icing duration [s]

900



Experiment vs. Computation for Rime Ice Conditions

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Liquid Water Content [g/m³]

0,260

Mean Volume Diameter [μm]

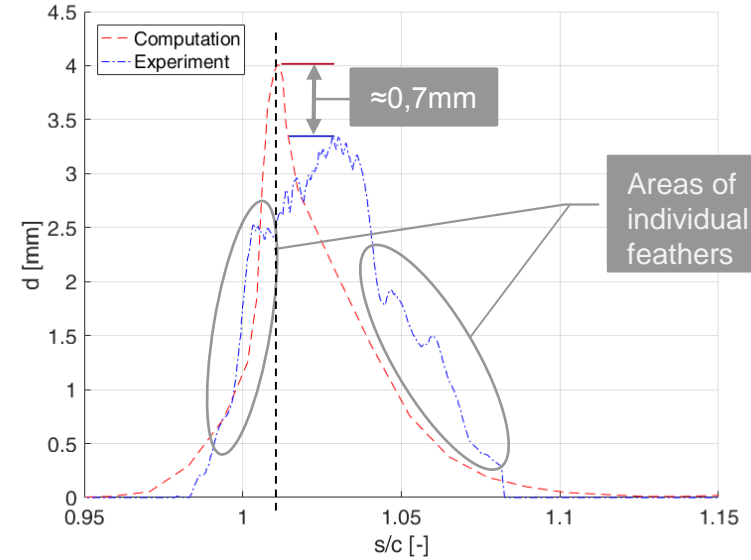
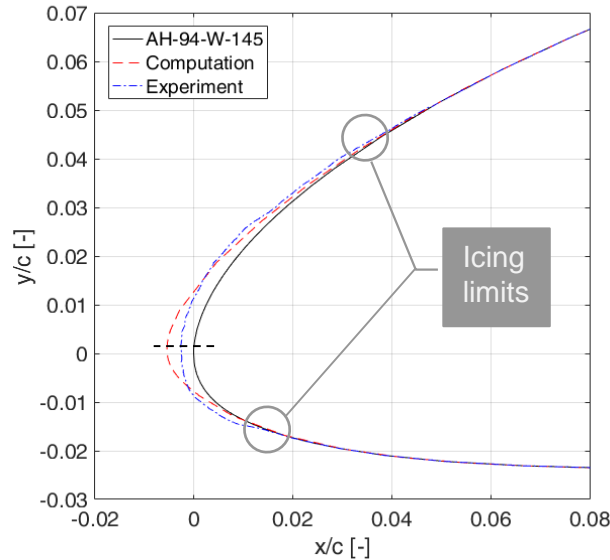
14

Velocity [m/s]

40

Icing duration [s]

900



Experimental Results for Glaze Ice Conditions

Temperature [°C]

-5

Liquid Water Content [g/m³]

0,962

Mean Volume Diameter [μm]

30

Velocity [m/s]

40

Icing duration [s]

900



Experimental Results for Glaze Ice Conditions

Temperature [°C]

-5

Liquid Water Content [g/m³]

0,962

Mean Volume Diameter [μm]

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Velocity [m/s]

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Icing duration [s]

900



Experimental Results for Glaze Ice Conditions

Temperature [°C]

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Liquid Water Content [g/m³]

0,962

Mean Volume Diameter [μm]

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Velocity [m/s]

40

Icing duration [s]

900



Experimental Results for Glaze Ice Conditions

Temperature [°C]

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Liquid Water Content [g/m³]

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Mean Volume Diameter [μm]

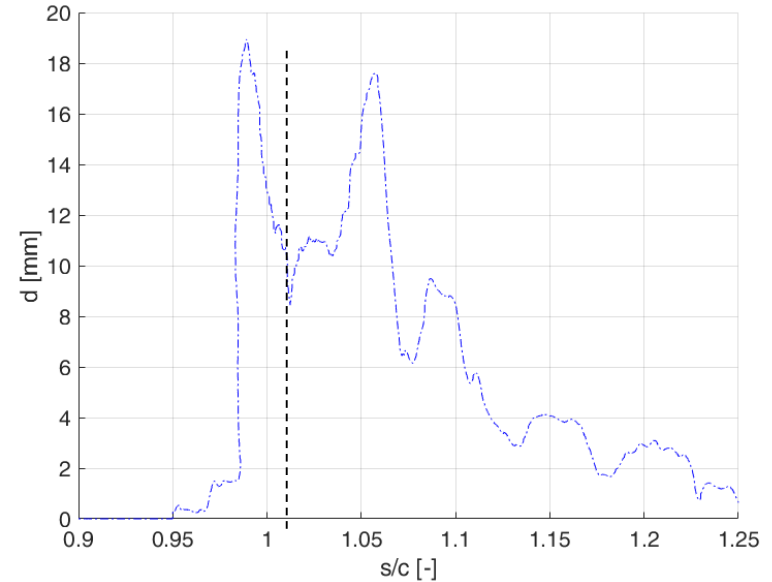
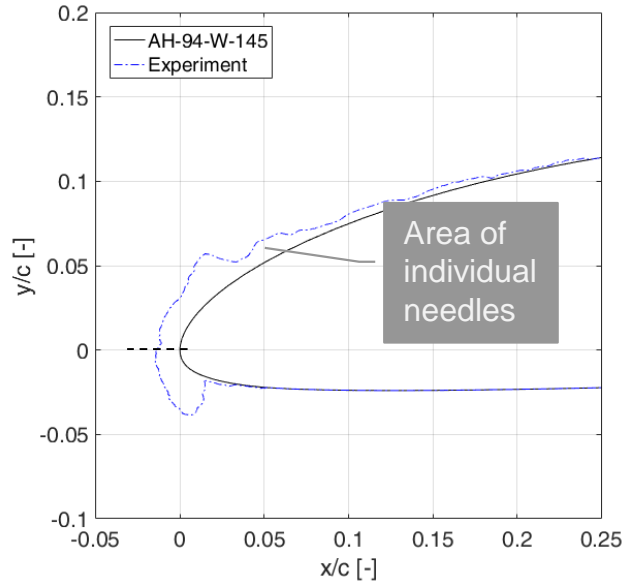
30

Velocity [m/s]

40

Icing duration [s]

900



Computational Results for Glaze Ice Conditions

Temperature [°C]

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0,962

Mean Volume Diameter [μm]

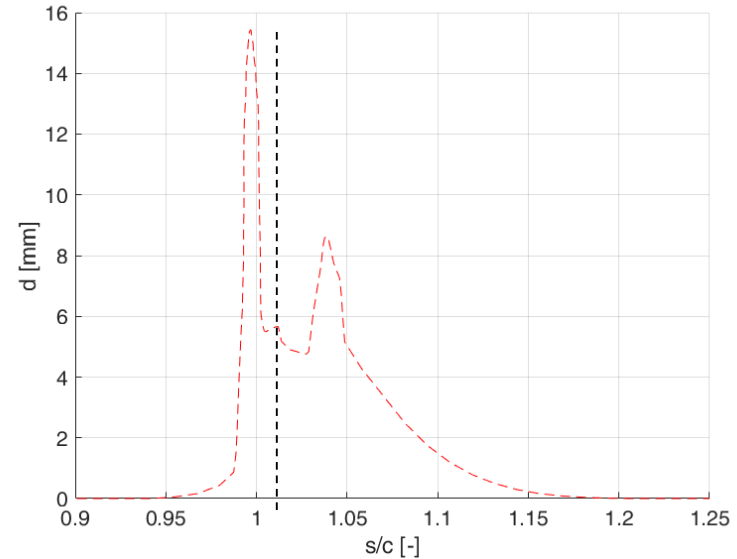
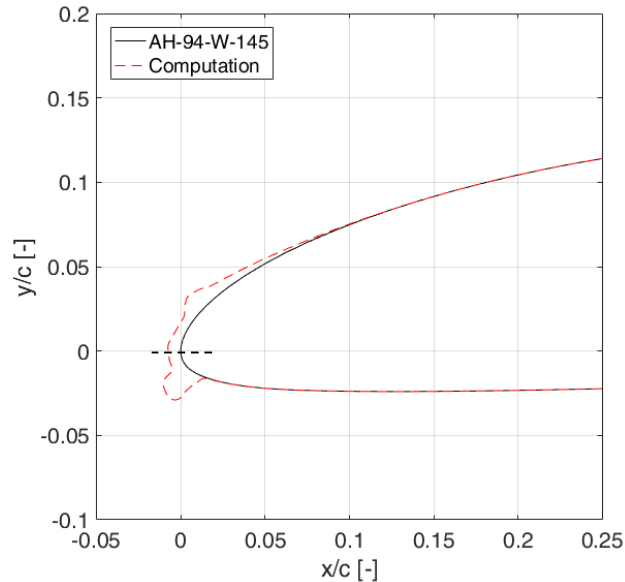
30

Velocity [m/s]

40

Icing duration [s]

900



Experiment vs. Computation for Glaze Ice Conditions

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0,962

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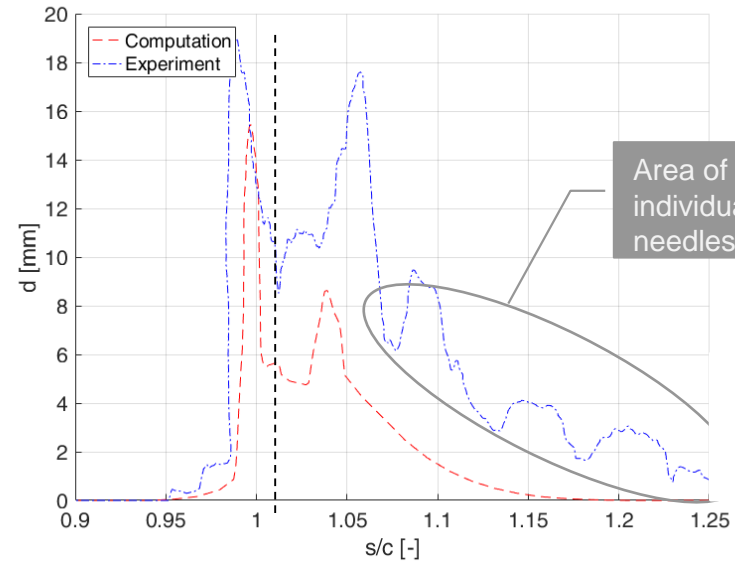
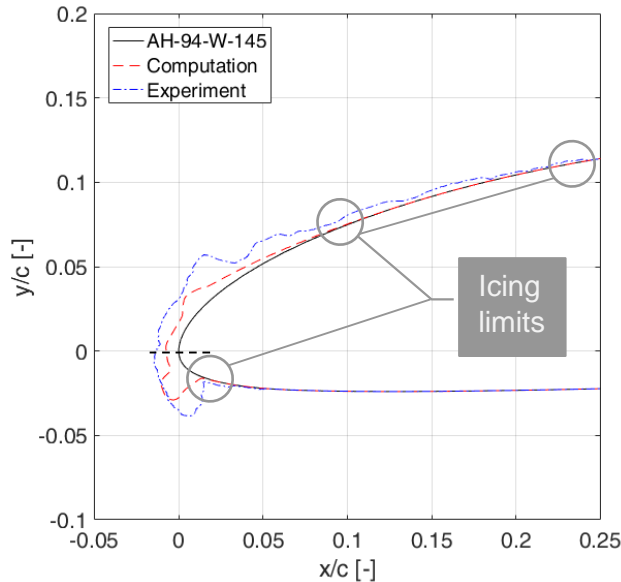
30

Velocity [m/s]

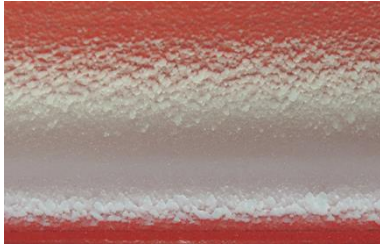
40

Icing duration [s]

900



Summary: Computation vs. Experiment



Rime Ice Conditions



Glaze Ice Conditions

- ✓ Position of maximal thickness
- ✓ Absolute value of maximal thickness
- ✓ Icing limits
- Small deviations in areas with single feathers

- ✓ Icing limits
- Position of maximal thickness (horns)
- Absolute value of maximal thickness
- Large deviations in areas with single needles