2nd AIAA Ice Prediction Workshop

IPW

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Ice Shape Prediction Using ICEPAC

2nd AIAA ICE Prediction Workshop

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Contents

SIMULATION CODE DESCRIPTION

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[1] Son, C., Oh, S., and Yee, K., "Development of 2nd Generation Ice Accretion Analysis Program for Handling General 3-D Geometries," Journal of Computational Fluids Engineering, Vol. 20, No. 2, 2015, pp. 23–36.

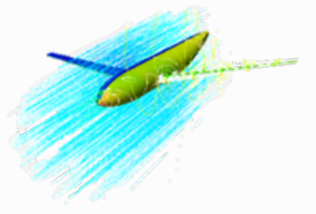
Icing simulation code

- **ICEPAC** (**I**ce **C**ontour **E**valuation and **P**erformance **A**nalysis **C**ode) developed by **Seoul National University** [1]
  - ✓ Consisting of four sequential modules based on **Eulerian method**

Aerodynamic

➢ Calculate the **flow-field**

- Solve **RANS** equation
- **Compute** U_a, ρ_a, τ_w, h_c



▲ **Pressure contour**

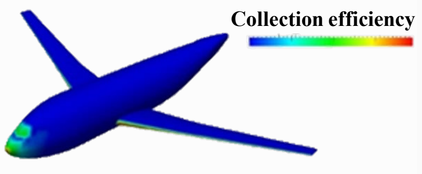
τ_w, Q_c

U_a, ρ_a

Droplet trajectory

➢ Determine **the droplet impingement rate**

- Solve droplet equation
- **Compute** U_d, ρ_d, β



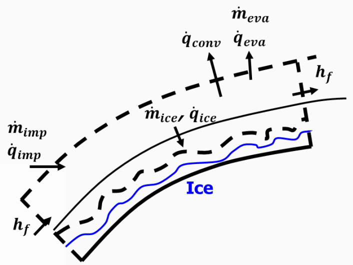
▲ **Collection efficiency** β **countour**

U_d, β

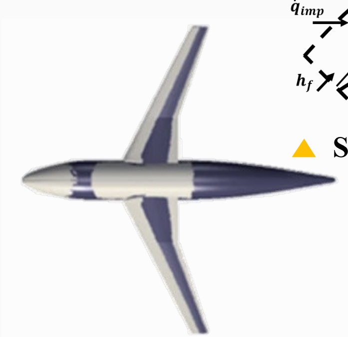
Thermodynamic

➢ Determine **the ice accretion rate**

- Solve **SWIM** equation
- **Compute** $h_f, \dot{m}_{ice}$



▲ **Schematic view of SWIM**



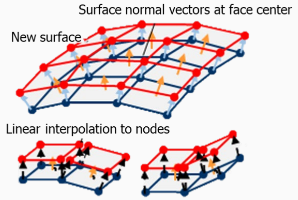
▲ $\dot{m}_{ice}$ **distribution on the surface**

$\dot{m}_{ice}$

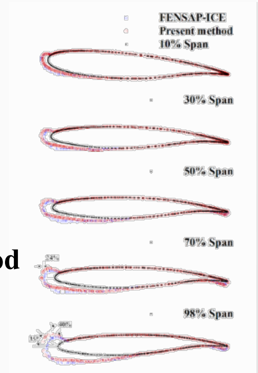
Ice Growth

➢ Update the geometry change due to icing

- **Compute Ice growth based on** $\dot{m}_{ice}$



▲ **Surface generation method**



▲ **Airfoil ice shape generation**

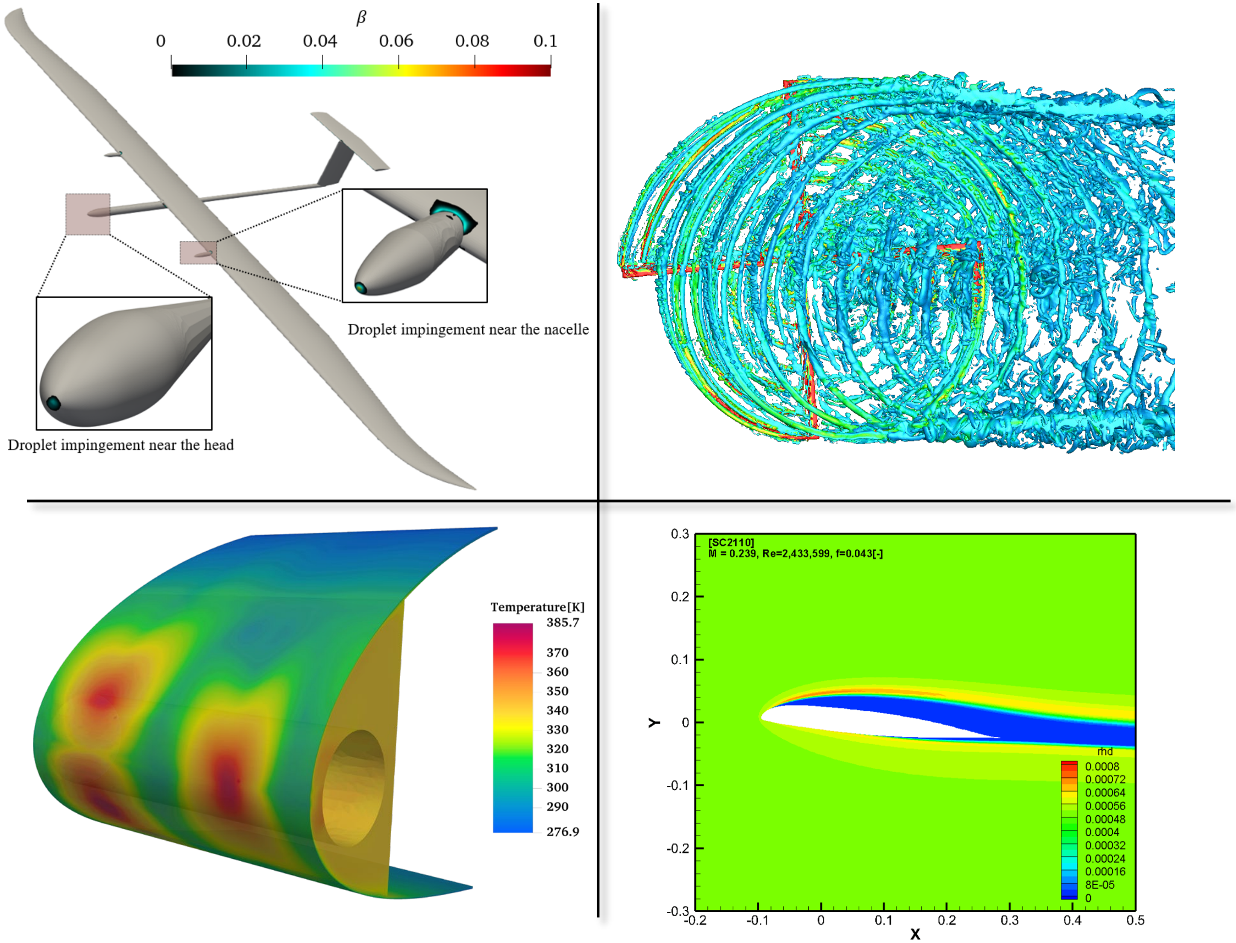
Quasai-steady assumption n times iteration

[2] Park, J.-S., "Optimal Latin-Hypercube Designs for Computer Experiments," Journal of Statistical Planning and Inference, Vol. 39, No. 1, 1994, pp. 95–111.
[3] Hong, Yoonpyo, Soo Hyung Park, and Kwanjung Yee. "Comparative Assessment of Local Accuracy of High-Order Spatial Schemes for Rotorcraft Aeroacoustics." AIAA Journal 61.1 (2023): 355-377.
[4] Fortin G., "Equivalent Sand Grain Roughness Correlation for Aircraft Ice Shape Predictions," SAE Technical Paper; 2019 Jun 10.

Icing simulation code

- **ICEPAC** (**I**ce **C**ontour **E**valuation and **P**erformance **A**nalysis **C**ode) developed by **Seoul National University**
  - ✓ Based on both structured and unstructured mesh
    - **OpenFOAM** (Unstructured) and **KFLOW** [2, 3] (Structured)

Codes	OpenFOAM	KFLOW
Grid types	• Unstructured 2D/3D	• Structured 2D/3D
Flow	• RANS → Upwind 2nd order → *SA*, $\gamma - Re_\theta$ transition, etc. • Roughness model → Fortin's ESGR model[4]	• RANS → Roe's FDS / HLLE+ / AUSMPW+ → *SA*, $\gamma - Re_\theta$ transition, etc. • Roughness model → Fortin's ESGR model
Droplet	• 2D/3D Eulerian → Upwind 1st order	• 2D/3D Eulerian → HLLC 2nd order
Thermo.	• SWIM	• SWIM
Application	• Icing on complex geometry • Anti-icing	• Rotor icing • Oscillating airfoil



▲ Simulation analysis approach

Results & Discussion

Results & Discussion

■ Case 1 & 2 : CRM-65 hybrid (3D)

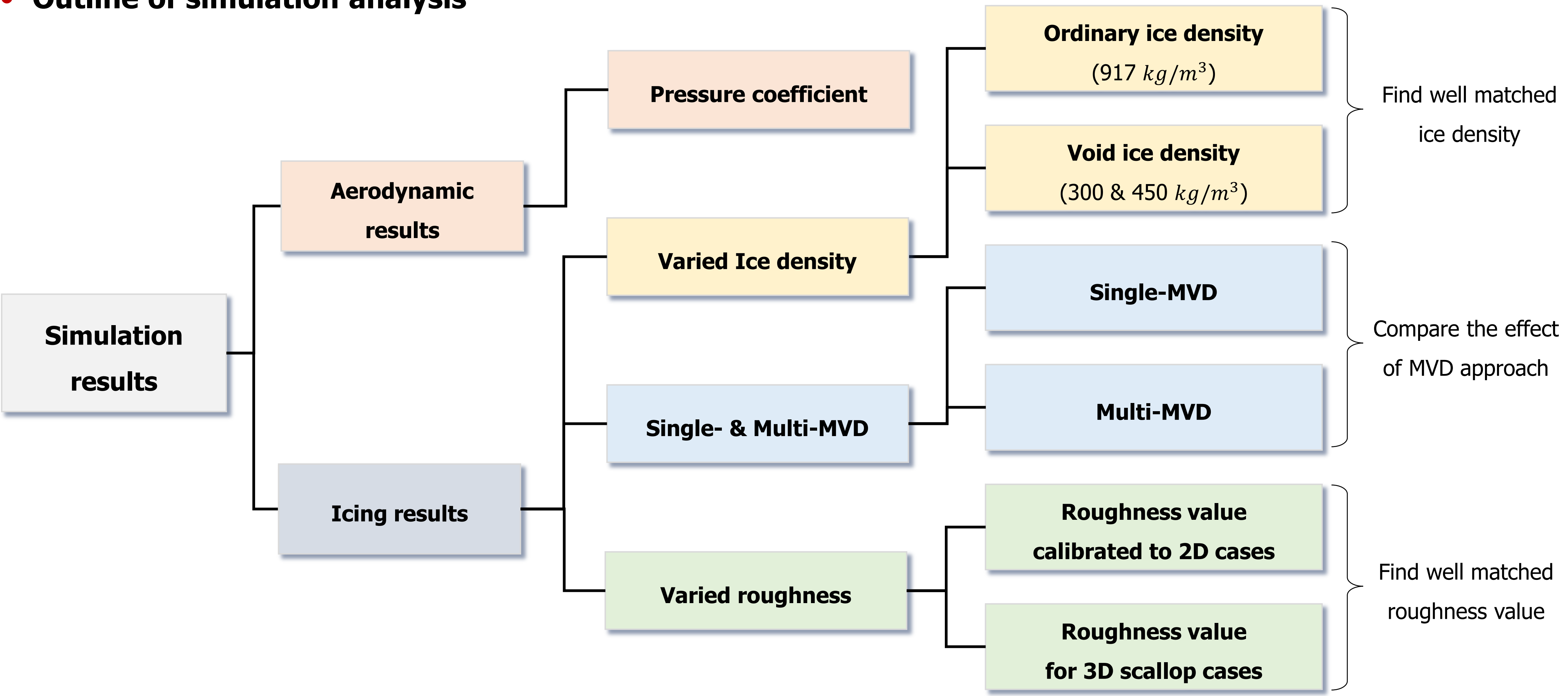
Case 1: CRM-65 Mid-span Hybrid (3D)

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

Results & Discussion

Case 1 & 2 : CRM-65 hybrid (3D)

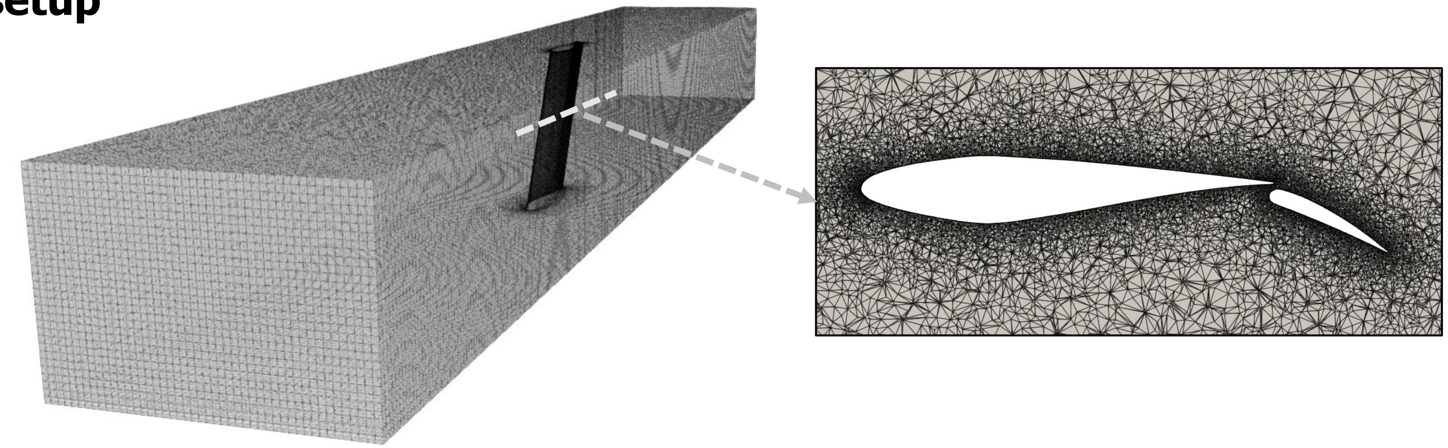
- **Outline of simulation analysis**



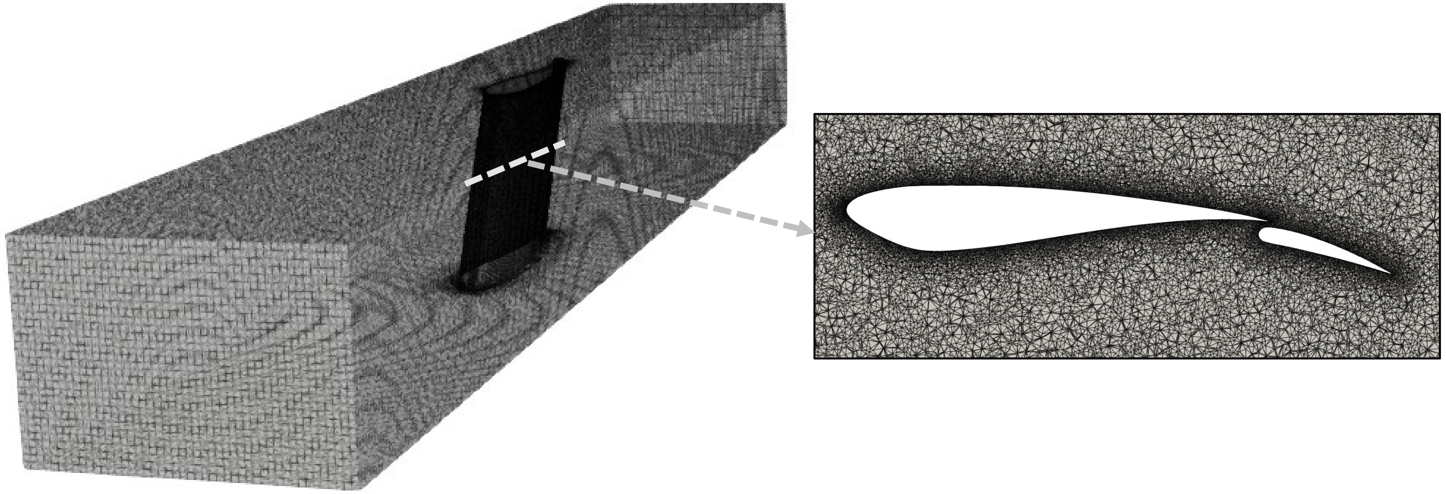
▲ Outline of presenting Ice shapes

Case 1 & 2 : CRM-65 hybrid (3D)

- **Computational grid and numerical setup**
  - ✓ Computational grid
    - Using no-gap configuration
    - **Unstructured mesh**
      - **Composed of 12 million volume cells**
      - y+=1 at wall
  - ✓ Numerical setup
    - Spatial Discretization
      - Upwind 2nd order
    - Temporal Integration
      - PIMPLE algorithm
    - Turbulence model
      - Modified SA model
    - Roughness model
      - Fortin's ESGR model



▲Grid configuration of Mid-span hybrid wing



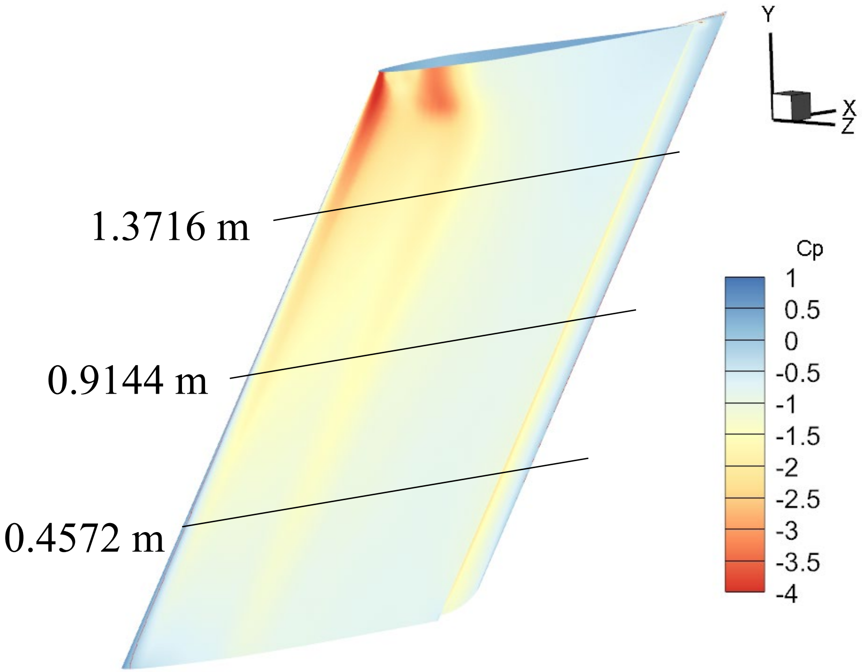
▲Grid configuration of Inboard hybrid wing

Results & Discussion

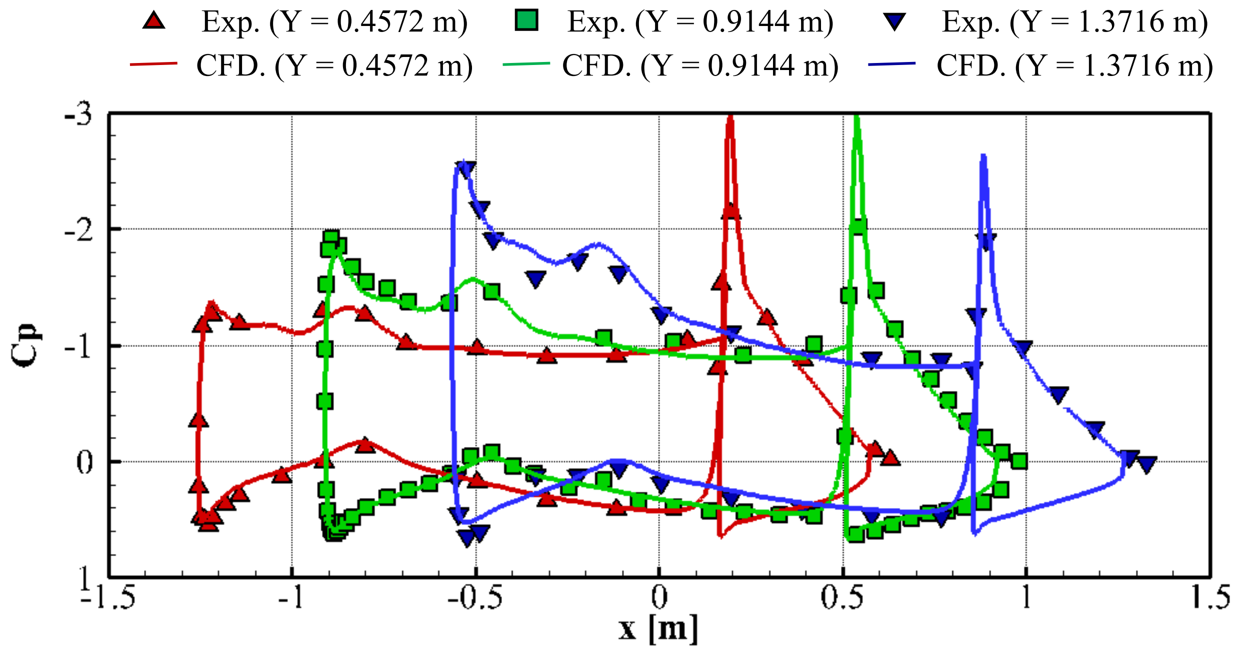
Case 1 & 2 : CRM-65 hybrid (3D)

- **Aerodynamic results of Mid-span case**
  - ✓ Pressure coefficient comparison between experiment and simulation
    - Good agreement with experimental results
      - Especially on the centerline (y = 0.9144m), the main region of interest of the model

Speed (m/s)	T_{static} (°C)	MVD (μm)	LWC (g/m^3)	Time (min.)
66.9	-3.6	25	1.0	29.0



▲ Surface pressure contours



▲ Pressure coefficient comparison between experiment and simulation

Results & Discussion

Case 1 & 2 : CRM-65 hybrid (3D)

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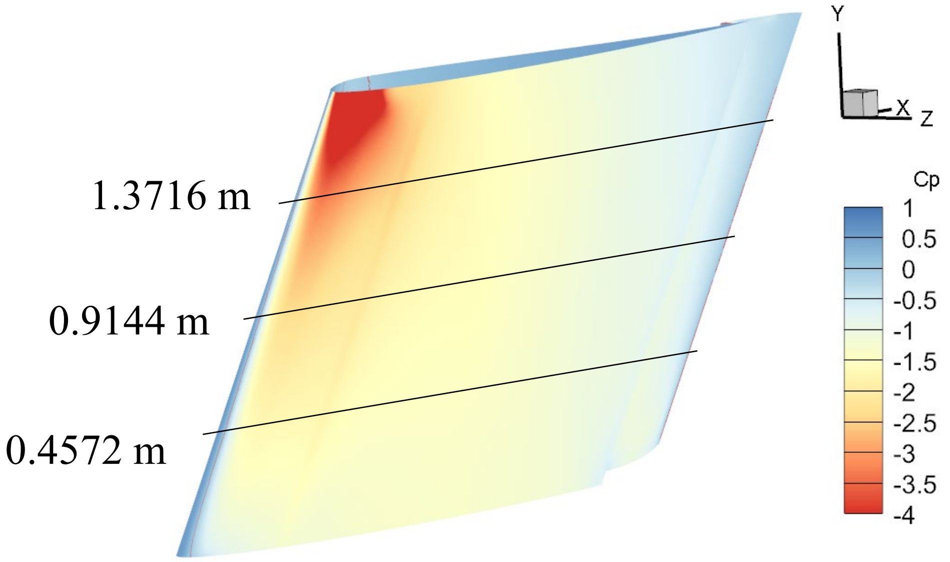

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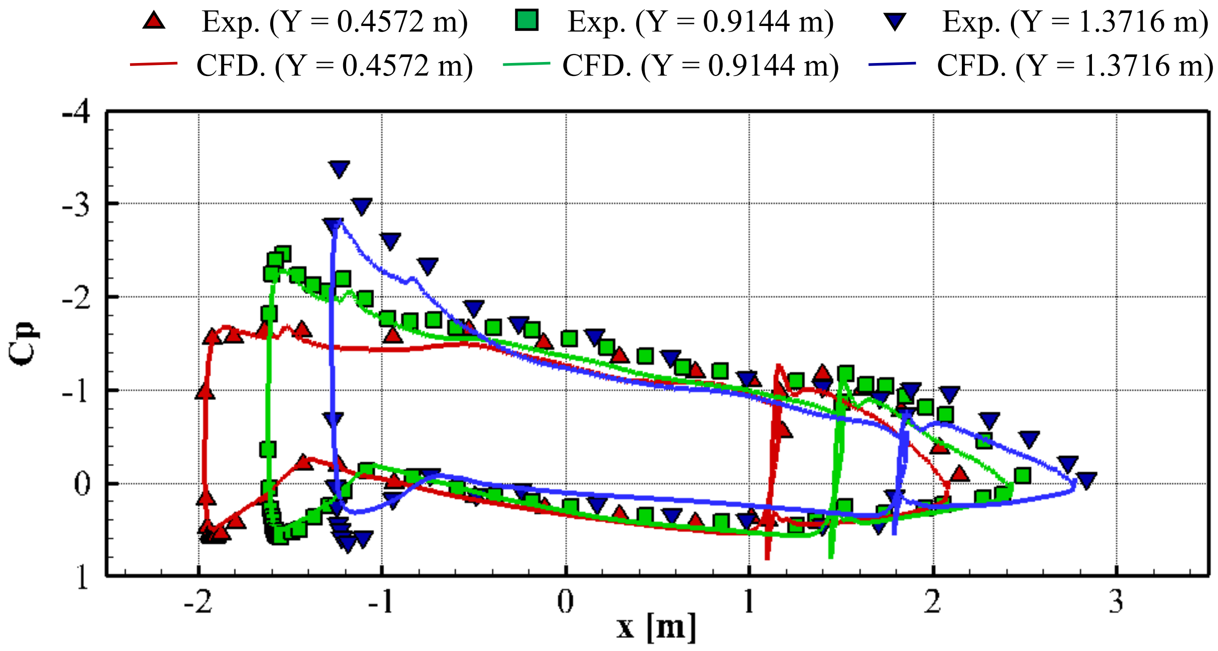


▲ Pressure coefficient comparison between experiment and simulation

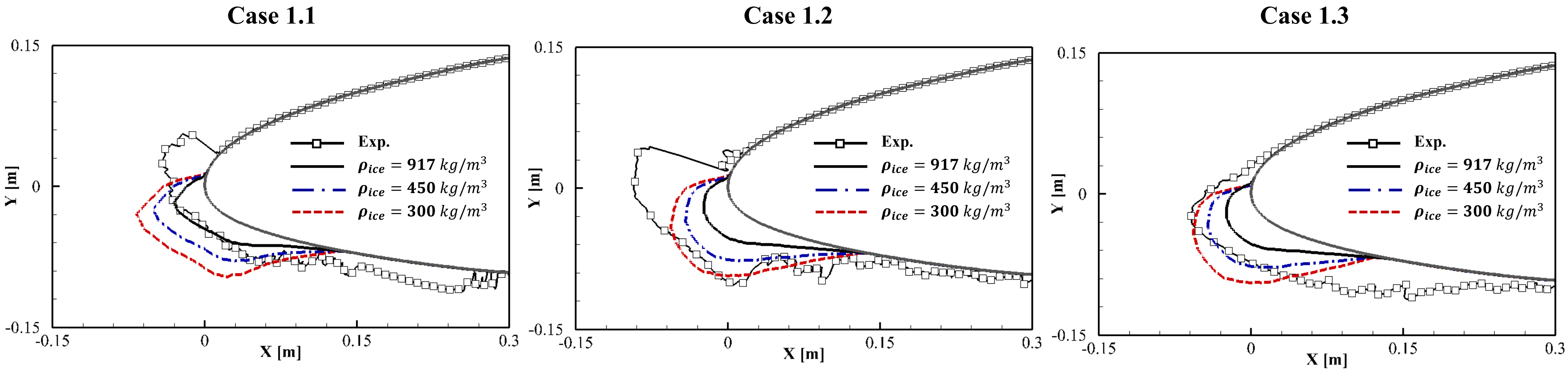
[4] Bidwell, Colin S. "Icing Analysis of a Swept NACA 0012 Wing Using LEWICE3D Version 3.48." 6th AIAA Atmospheric and Space Environments Conference. 2014.

Case 1 & 2 : CRM-65 hybrid (3D)

- **Icing results**
  - ✓ Comparison of **ice density for Mid-span cases**
    - Ordinary ice density
      - 917 kg/m^3
    - Void ice density
      - Constant density was adopted
      - $\rho_{ice} = 300\ and\ 450\ \ kg/m^3$ (Density range is refer to paper [4])

Single MVD / 2D roughness value					
Case No.	Speed (m/s)	T_{static} (°C)	MVD (μm)	LWC (g/m^3)	Time (min.)
1.1	66.9	-3.6	25	1.0	29.0
1.2	66.9	-8.5	25	1.0	29.0
1.3	66.9	-26.0	25	1.0	29.0

➢ **300 kg/m^3 of ice density is set for the largest scallop case**, and 450 kg/m^3 for the rest



▲ Ice shape comparison between experiment and simulation (Mid-span chord length = 1.894 m)

Results & Discussion

[4] Bidwell, Colin S. "Icing Analysis of a Swept NACA 0012 Wing Using LEWICE3D Version 3.48." 6th AIAA Atmospheric and Space Environments Conference. 2014.

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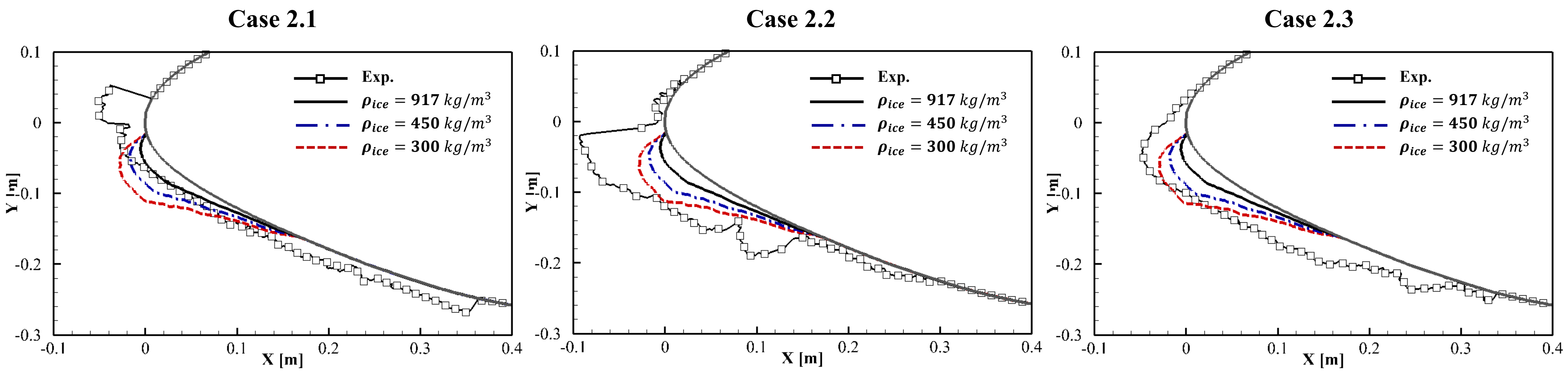


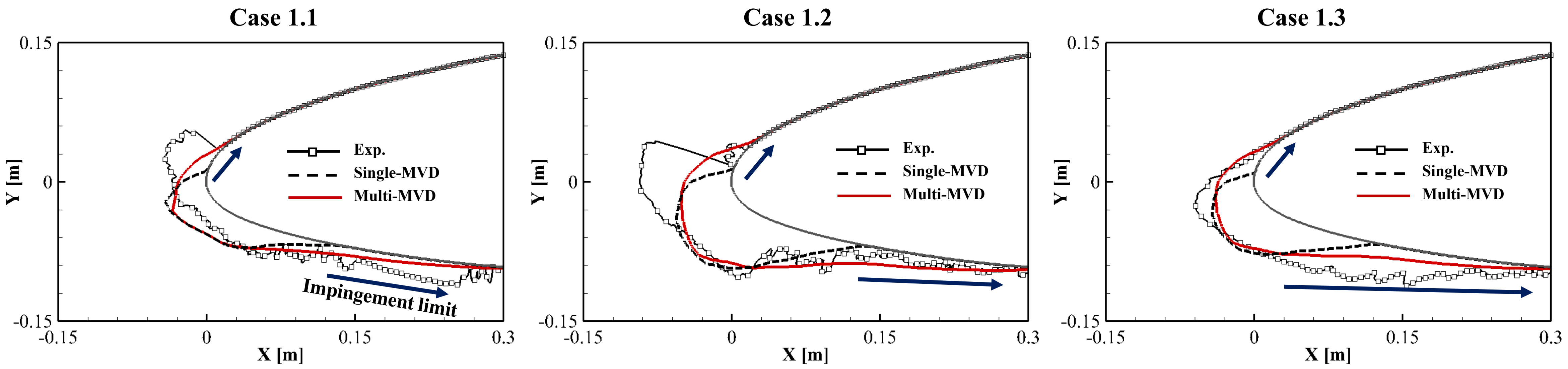
▲ Ice shape comparison between experiment and simulation (Inboard chord length = 4.11 m)

Results & Discussion

Case 1 & 2 : CRM-65 hybrid (3D)

- **Icing results**
  - ✓ Comparison of **MVD approach for Mid-span cases**
    - Single MVD
      - 25 μm
    - Multi-MVD based on IRT droplet distribution
      - 7.3, 9.9, 13.7, 24.9, 44.9, 74.9, and 127.6 μm
  - ➢ **Multi-MVD** has much **better agreement of impingement limit**
    - Multi-MVD approach will be used

Multi MVD / 2D roughness value						
Case No.	Speed (m/s)	T_{static} (°C)	MVD (μm)	LWC (g/m^3)	Time (min.)	Void density (kg/m^3)
1.1	66.9	-3.6	25	1.0	29.0	450
1.2	66.9	-8.5	25	1.0	29.0	300
1.3	66.9	-26.0	25	1.0	29.0	450



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Case 1 & 2 : CRM-65 hybrid (3D)

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      - 7.3, 9.9, 13.7, 24.9, 44.9, 74.9, and 127.6 μm
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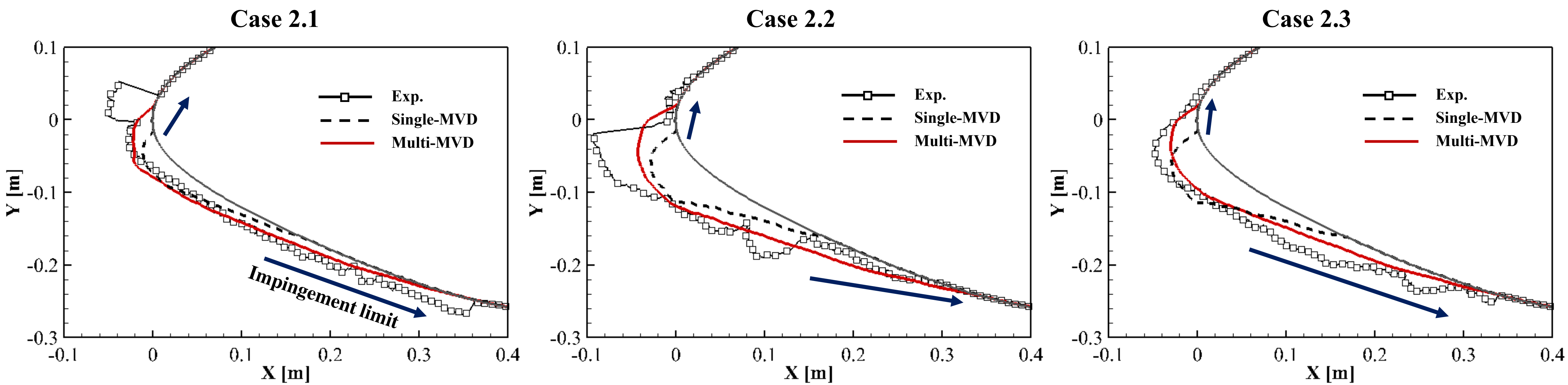


▲ Ice shape comparison between experiment and simulation (Inboard chord length = 4.11 m)

[5] McClain, Stephen T., et al. "Ice Accretion Roughness Variations on a Hybrid CRM65-Midspan Wing Model." AIAA AVIATION 2021 FORUM. 2021..

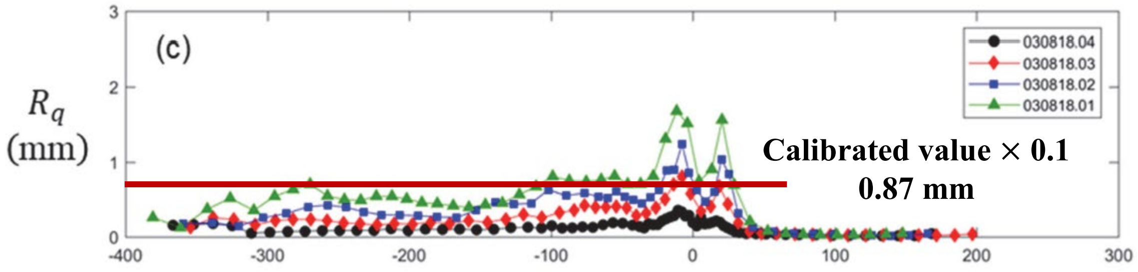
Case 1 & 2 : CRM-65 hybrid (3D)

Icing results

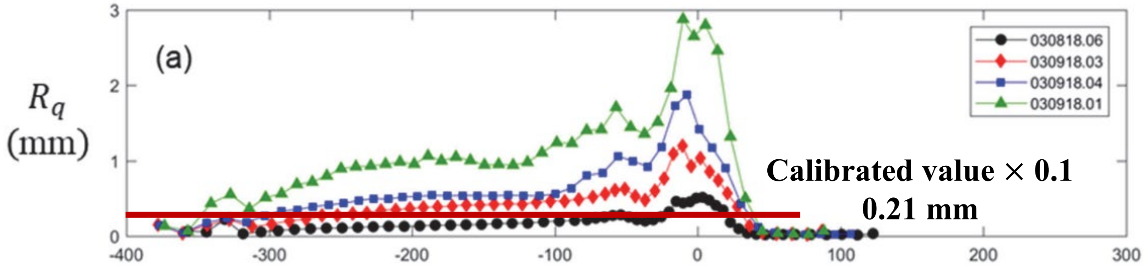
- ✓ Necessity of **different roughness value for scallop cases**
  - **Different physical mechanism** between scallops and water film model
    - **Not describing feather formation and scallop** in simulation → **lower ice horn angle**
  - Larger calibrated roughness values to 2D cases than experimental values [5]

Need to use lower roughness value to describe ice horn angle of the scallop cases

- ✓ Three different roughness values are compared
  - Roughness value calibrated to 2D cases ($\boldsymbol{Calibrated\ k_s\ (2D)}$)
  - $\boldsymbol{Calibrated\ k_s\ (2D)} \times 0.1$ → Usually used for 3D scallop cases in ICEPAC
  - $\boldsymbol{Calibrated\ k_s\ (2D)} \times 0.01$



▲ Calibrated value experimental roughness value of Mid-span case (Case 1) [5]



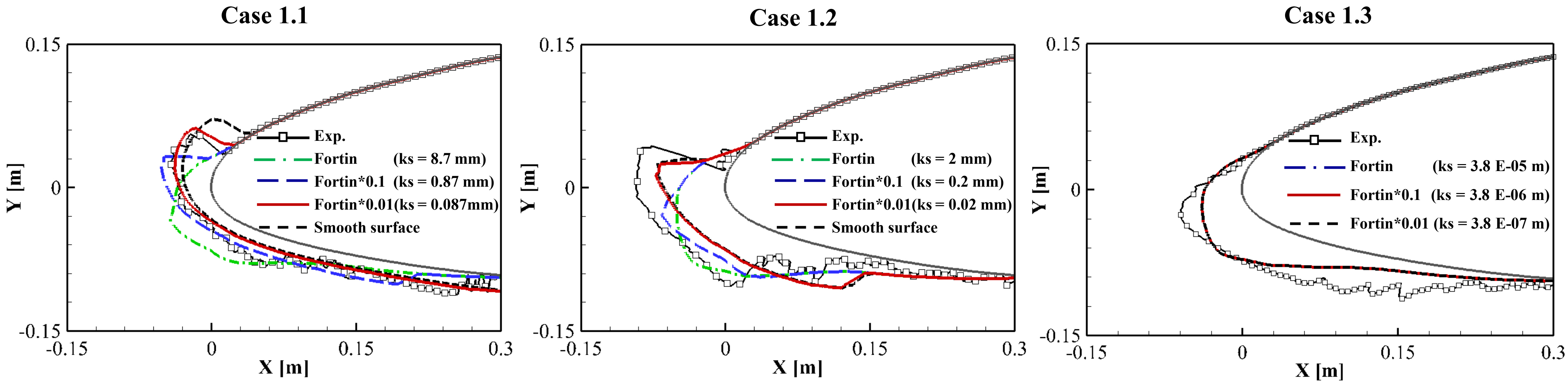
▲ Calibrated value experimental roughness value of Mid-span (Case 2) [5]

Results & Discussion

Case 1 & 2 : CRM-65 hybrid (3D)

- **Icing results**
  - ✓ Comparison of **varied roughness value for Mid-span cases**
    - Roughness value calibrated to 2D cases
      - $\boldsymbol{Calibrated\ k_s\ (2D)}$
    - Roughness value for 3D scallop cases
      - $\boldsymbol{Calibrated\ k_s\ (2D)} \times$ **0.1**
      - $\boldsymbol{Calibrated\ k_s\ (2D)} \times$ **0.01** → Best agreement in hybrid wing case
    - ➢ **Roughness values smaller than calibrated values has better agreement**

Multi MVD / Varied roughness value						
Case No.	Speed (m/s)	T_{static} (°C)	MVD (μm)	LWC (g/m^3)	Time (min.)	Void density (kg/m^3)
1.1	66.9	-3.6	25	1.0	29.0	450
1.2	66.9	-8.5	25	1.0	29.0	300
1.3	66.9	-26.0	25	1.0	29.0	450



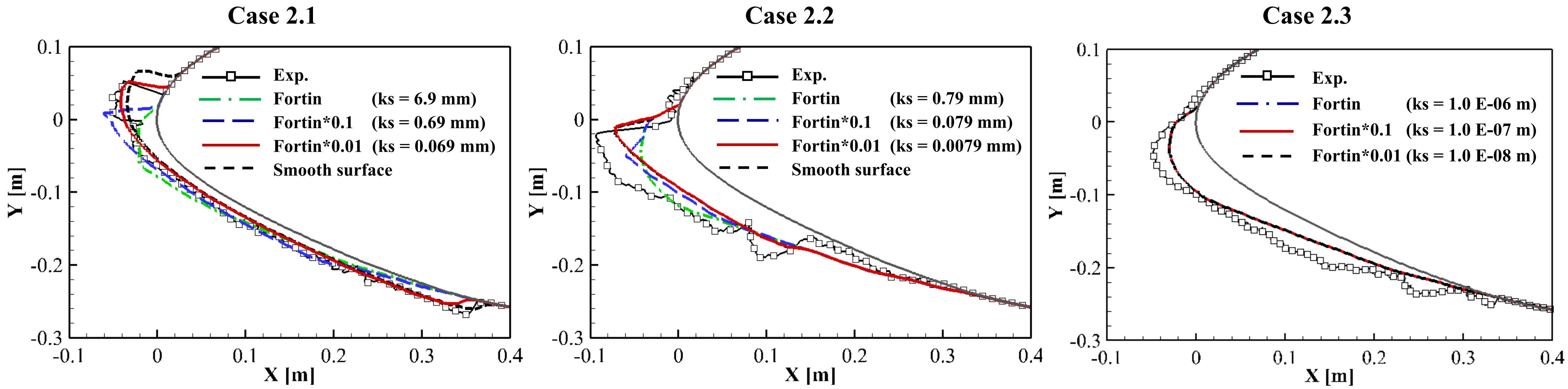
▲ Ice shape comparison between experiment and simulation (Mid-span chord length = 1.894 m)

Results & Discussion

Case 1 & 2 : CRM-65 hybrid (3D)

- **Icing results**
  - ✓ Comparison of **varied roughness value** **for Inboard cases**
    - Roughness value calibrated to 2D cases
      - $Calibrated\ k_s\ (2D)$
    - Roughness value for 3D scallop cases
      - $Calibrated\ k_s\ (2D)$ × **0.1**
      - $Calibrated\ k_s\ (2D)$ × **0.01** → Best agreement in hybrid wing case
  - ➢ **Roughness values smaller than calibrated values has better agreement**

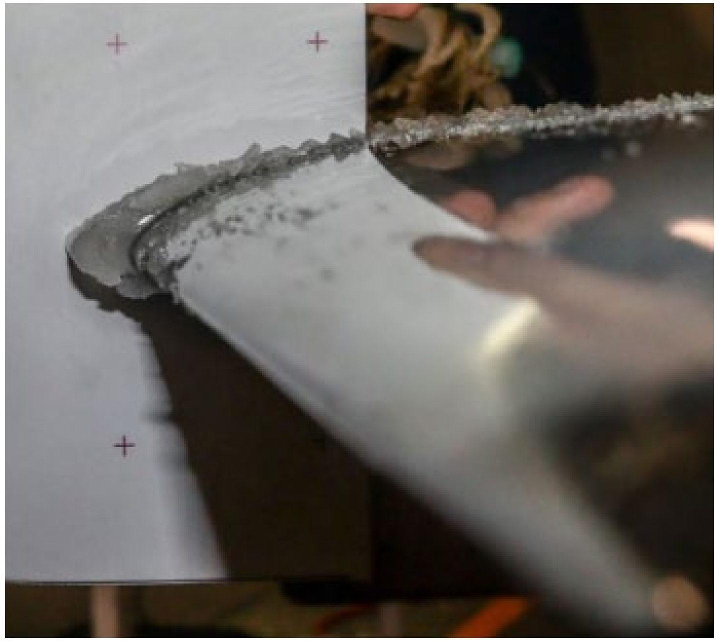
Multi MVD / Varied roughness value						
Case No.	Speed (m/s)	T_{static} (°C)	MVD (μm)	LWC (g/m^3)	Time (min.)	Void density (kg/m^3)
2.1	66.9	-3.6	25	1.0	29.0	450
2.2	66.9	-8.5	25	1.0	29.0	300
2.3	66.9	-26.0	25	1.0	29.0	450

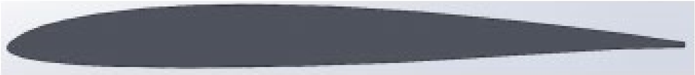


▲ Ice shape comparison between experiment and simulation (Inboard chord length = 4.11 m)

RESULTS & DISCUSSION

■ Case 3 : RG-15 low speed Icing

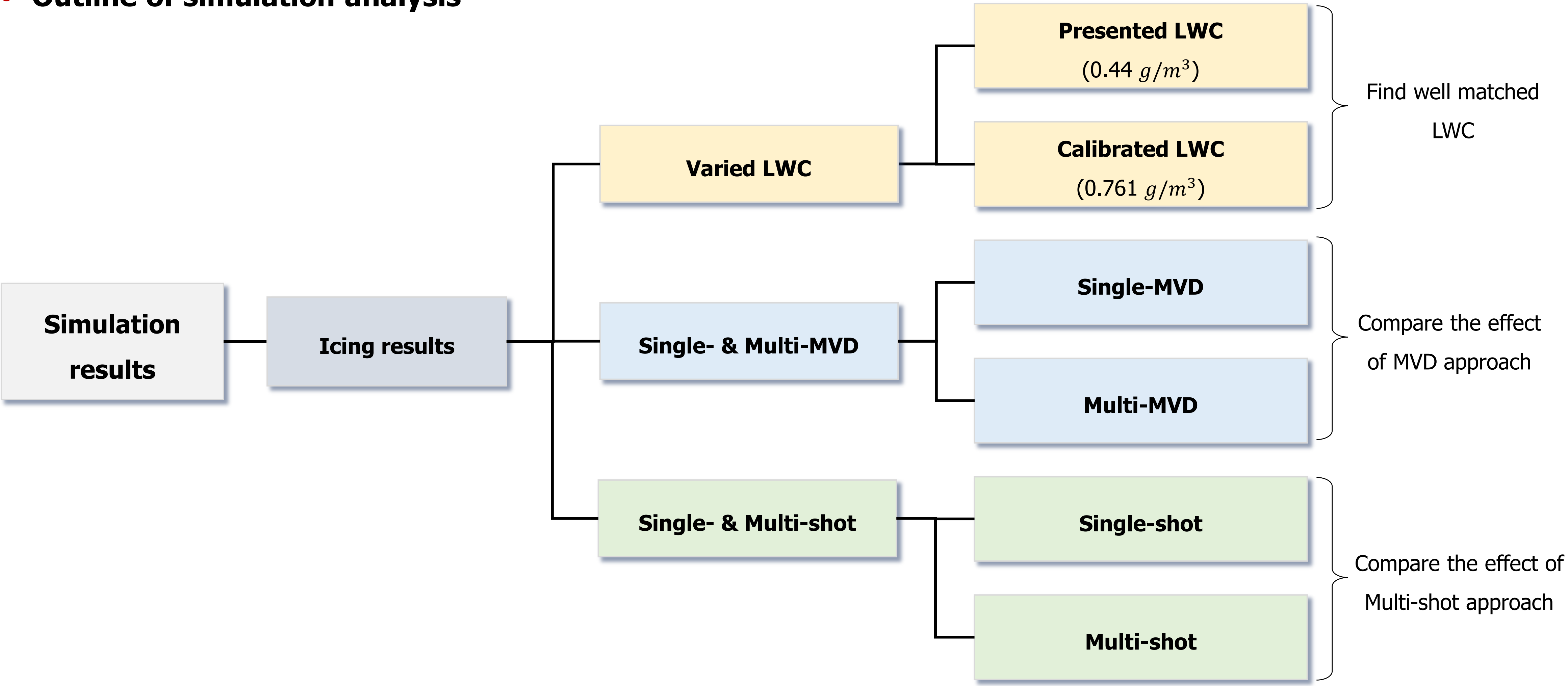




Case 3: RG-15 Low Speed Icing

Case 3 : RG-15 low speed Icing

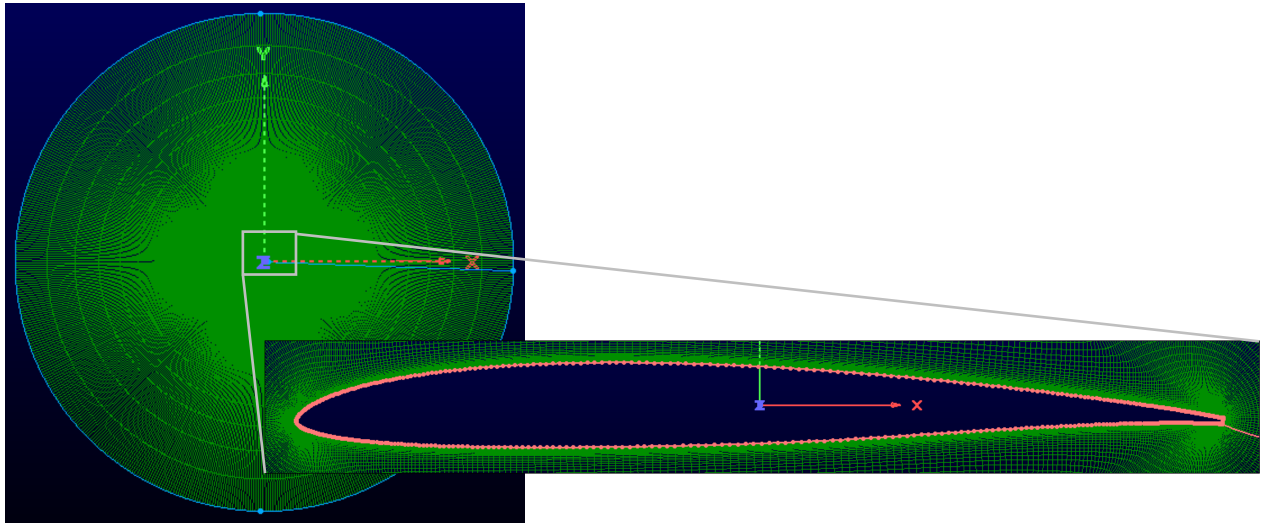
- **Outline of simulation analysis**



▲ Outline of presenting Ice shapes

Case 3 : RG-15 low speed Icing

- **Computational grid and numerical setup**
  - ✓ Computational grid
    - O-type grid
      - **Composed of 53,416 volume cells**
      - y+=1 at wall
  - ✓ Numerical setup
    - Spatial Discretization
      - Upwind 2nd order
    - Temporal Integration
      - PIMPLE algorithm
    - Turbulence model
      - $Re_\theta - \gamma$ turbulence model
    - Roughness model
      - Fortin's ESGR model



▲ **O-type grid of RG-15**

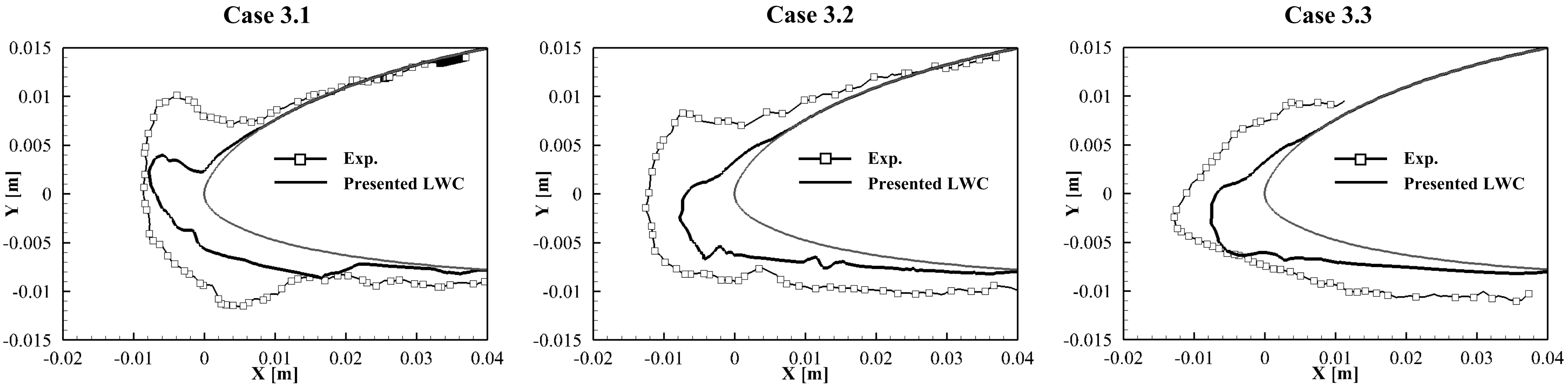
Domain boundary	Aerodynamic boundary condition	Droplet boundary condition
Inlet	Velocity inlet, 25 m/s	Velocity inlet, 25 m/s
Outlet	ZeroGradient	ZeroGradient
Model walls	No-slip wall (Isothermal)	ZeroGradient

RESULTS & DISCUSSION

Case 3 : RG-15 low speed Icing

- **Icing results**
  - ✓ **Ice shapes of presented LWC** (from workshop)
    - **Smaller ice shapes** than ice shape of experiment
    - Large mass difference → No mass conservation

Case	Speed (m/s)	AoA (deg.)	T_{static} (°C)	MVD (μm)	LWC (g/m^3)	Time (min.)
3.1	25	4	-4	23	**0.44**	20
3.2	25	4	-4	23	**0.44**	20
3.3	25	4	-10	23	**0.44**	20



▲ Ice shape comparison between experiment and simulation

[6] Tuomas Jokela., "Validation of droplet size in the VTT icing wind tunnel test section", PPT

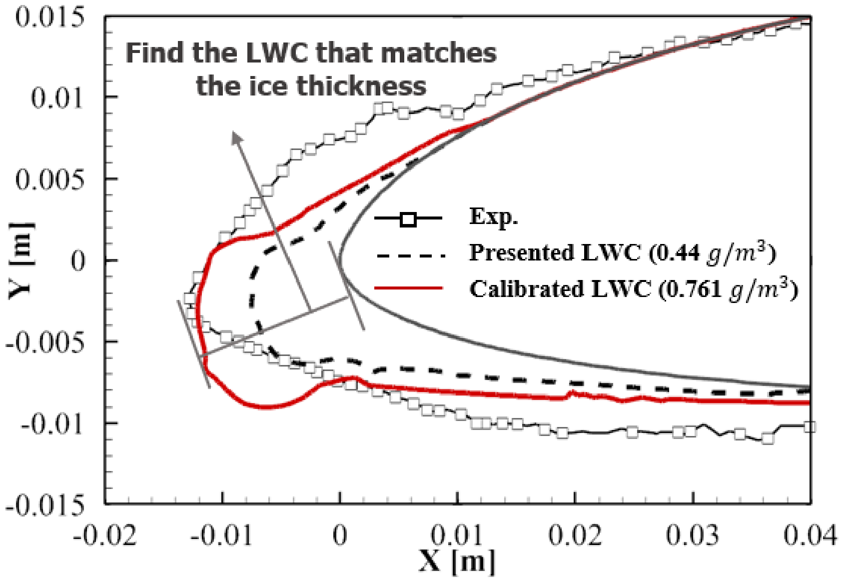
Case 3 : RG-15 low speed Icing

- **Icing results**
  - ✓ Considering **uncertainty of LWC**
    - **The measured LWC by instruments differ** by almost a factor of two
      - ICEMET : 0.42 ~0.48 / CDP (DTU & FMI) : 0.74 ~ 0.84
    - **New LWC are estimated** considering **the uncertainty in LWC**
      - Using the LWC calibrated to rime ice thickness
      - **0.761 g/m^3 will be used for LWC**

▲ VTT icing wind tunnel validation material [6]

	Case 1.	Case 2.	Case 3.	Case 4.	Case 5.
VTT IWT $LWC_{Theoretical}$ [g/m3]	0,25	0,44	0,44	0,25	0,44
ICEMET					
MVD [µm]	25,5±0,7	24,3±0,4	25,7±0,5	16,1±0,3	16,6±0,2
LWC [g/m^3]	0,27±0,03	0,42±0,03	0,48±0,02	0,22±0,03	0,46±0,05
CDP FMI					
MVD [µm]	18,5±1,7	17,8±1,4	-	13,5±0,4	14,1±1,0
LWC [g/m^3]	0,45±0,06	0,81±0,12	-	0,56±0,14	0,84±0,33
CDP DTU					
MVD [µm]	18,5±1,6	18,8±1,7	-	13,8±0,8	-
LWC [g/m^3]	0,34±0,05	0,74±0,13	-	0,52±0,10	-

▲ Results of validation measurement [6]

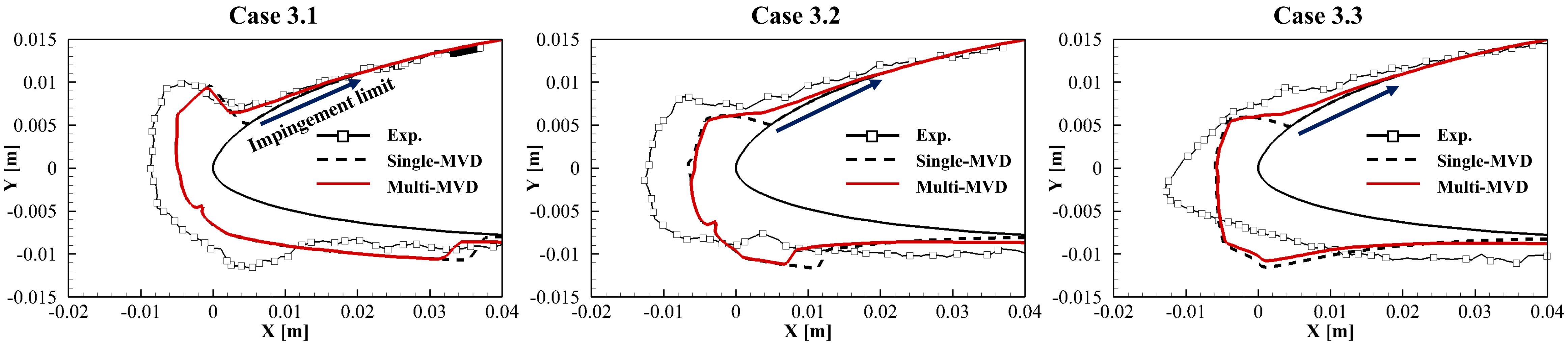


▲ Calibrated LWC to match the ice thickness

Case 3 : RG-15 low speed Icing

- **Icing results**
  - ✓ Comparison of **MVD approach**
    - Single MVD
      - 23 μm
    - Multi-MVD based on IRT droplet distribution
      - 6.5, 11.2, 15.7, 22.7, 32.9, 59.5, and 96.7 μm
    - ➢ **Multi-MVD** has much **better agreement of impingement limit**
      - Multi-MVD approach will be used

Multi MVD / Single shot / 2D roughness value					
Case No.	Speed (m/s)	T_{static} (°C)	MVD (μm)	LWC (g/m^3)	Time (min.)
3.1	25	-2	23	0.761	20
3.2	25	-4	23	0.761	20
3.3	25	-10	23	0.761	20



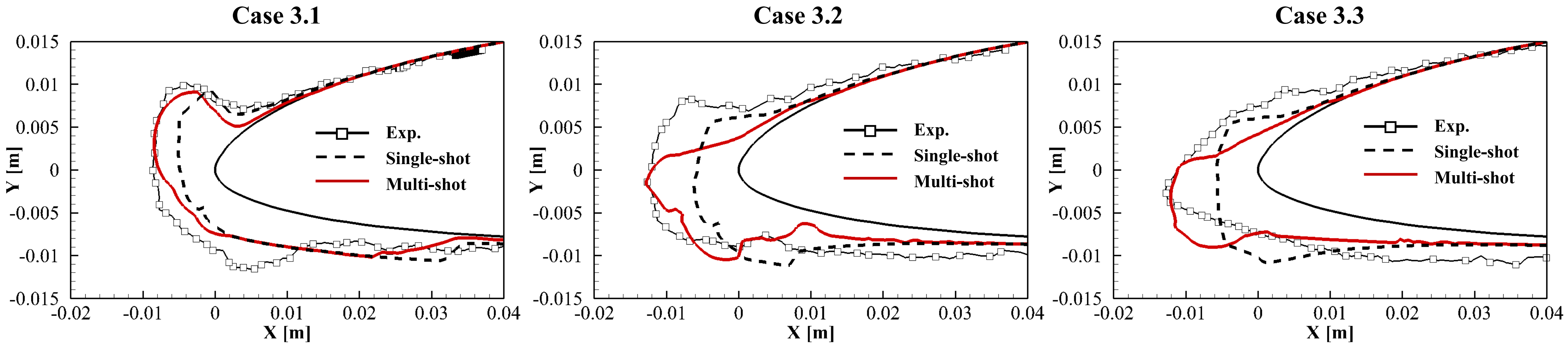
▲ Ice shape comparison between experiment and simulation

Results & Discussion

Case 3 : RG-15 low speed Icing

- **Icing results**
  - ✓ Comparison of **Single & Multi-shot approach**
    - Single-shot approach
    - Multi-shot approach
      - **4 step** was applied
  - ➢ **Multi-shot** has much **better agreement of ice thickness**

Multi MVD / Multi shot / 2D roughness value					
Case No.	Speed (m/s)	T_{static} (°C)	MVD (μm)	LWC (g/m^3)	Time (min.)
3.1	25	-2	23	0.761	20
3.2	25	-4	23	0.761	20
3.3	25	-10	23	0.761	20



▲ Ice shape comparison between experiment and simulation

CONCLUSIONS

CONCLUSION

- **Case 1 & 2 : CRM-65 hybrid (3D)**
  - Multi-MVD has much better agreement of impingement limit
  - Roughness values smaller than calibrated values to 2D cases show better ice horn angle
    - ✓ Especially, roughness value calibrated to 2D multiplied by 0.01 shows best agreement
    - ✓ However, it is necessary to calibrate the roughness value to numerous data for scallop cases

- **Case 3 : RG-15 low speed Icing**
  - Calibrated LWC are used considering the possibility of uncertainty in LWC
    - ✓ LWC value was set to match the rime ice thickness
    - ✓ Simulation results show good agreement with ice thickness in all case
    - ✓ Especially in case 3.1, ice horn angle are accurately predicted

THANK YOU FOR YOUR ATTENTION

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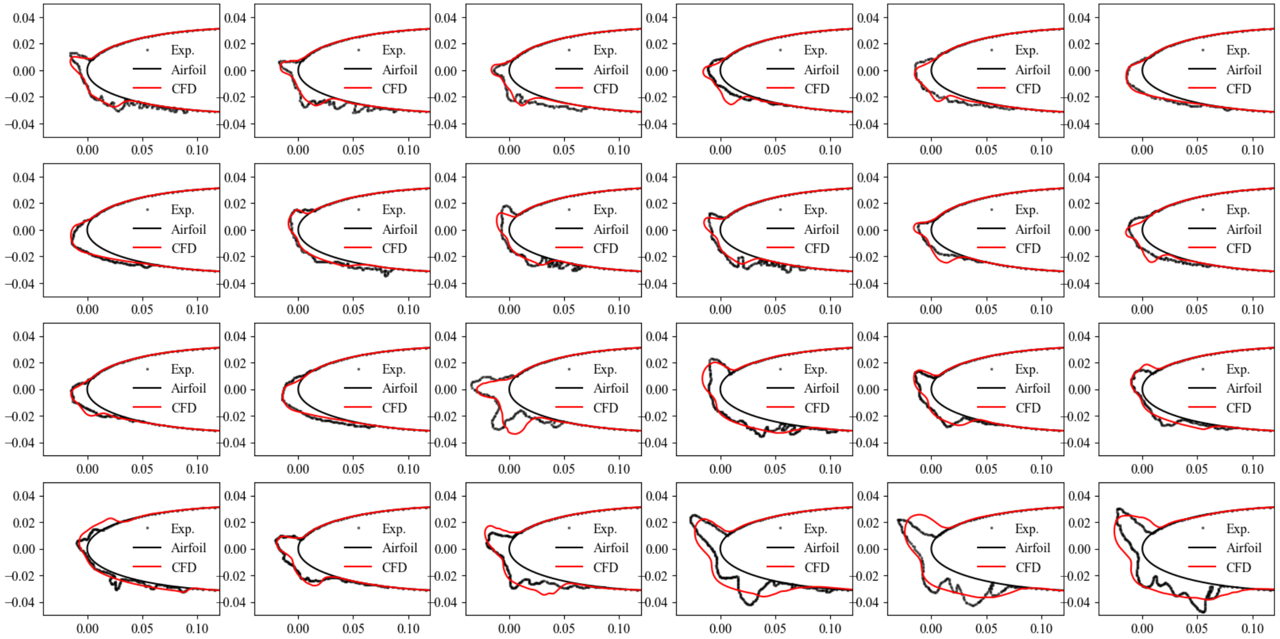
Roughness model

- Fortin's ESGR model calibrated for ICEPAC
  - ✓ Generalizable roughness model based on icing scaling parameters
    - $\left(\frac{\kappa_s}{c}\right)^n \propto \beta \frac{LWC}{\rho_{air}} \frac{L_f}{c_{p,air}(T_f - T_{rec})}$ ➔ $\left(\frac{\kappa_s}{c}\right)^{0.3} = \boldsymbol{a} \ln\left[\beta \frac{LWC}{\rho_{air}} \frac{L_f}{c_{p,air}(T_f - T_{rec})}\right] + \boldsymbol{b}$
  - ✓ Wide range of icing conditions were included for calibration (NASA validation cases)

Case	LWC	MVD	T	V	AoA	τ	Case	LWC	MVD	T	V	AoA	τ
1	0.55	20	265.37	102.8	4	420	13	1	20	253.4	67.1	4	360
2	0.55	20	263.71	102.8	4	420	14	1	20	244.51	67.1	4	360
3	0.55	20	262.04	102.8	4	420	15	0.55	20	262.04	102.8	4	840
4	0.55	20	259.82	102.8	4	420	16	1.6	30	265.07	67.1	4	360
5	0.55	20	256.49	102.8	4	420	17	1.3	20	266.19	58.1	4	480
6	0.55	20	250.37	102.8	4	420	18	1.3	20	269.19	58.1	4	480
7	0.55	20	241.49	102.8	4	420	19	1.3	20	270.19	58.1	4	480
8	1	20	268.4	67.1	4	360	20	1.3	20	263.19	58.1	4	480
9	1	20	266.74	67.1	4	360	21	1	30	262.04	102.8	4	360
10	1	20	265.07	67.1	4	360	22	1.3	30	262.04	102.8	4	360
11	1	20	262.85	67.1	4	360	23	1.6	30	262.04	102.8	4	360
12	1	20	259.51	67.1	4	360	24	1.8	30	262.04	102.8	4	360

▲ Validation cases used for roughness calibration



▲ Roughness calibration result ($a = 0.068, b = 0.4$)

Case 3 : RG-15 low speed Icing

- **Icing results**
  - ✓ Effect of **heat convection** according to **transition**
    - Change of the heat convection with different roughness value
      - Calibrated roughness value
      - Calibrated roughness value multiplied by **0.5**
      - Calibrated roughness value multiplied by **0.1** -> **Flow transition** exists

Multi MVD / Multi shot / Varied roughness value					
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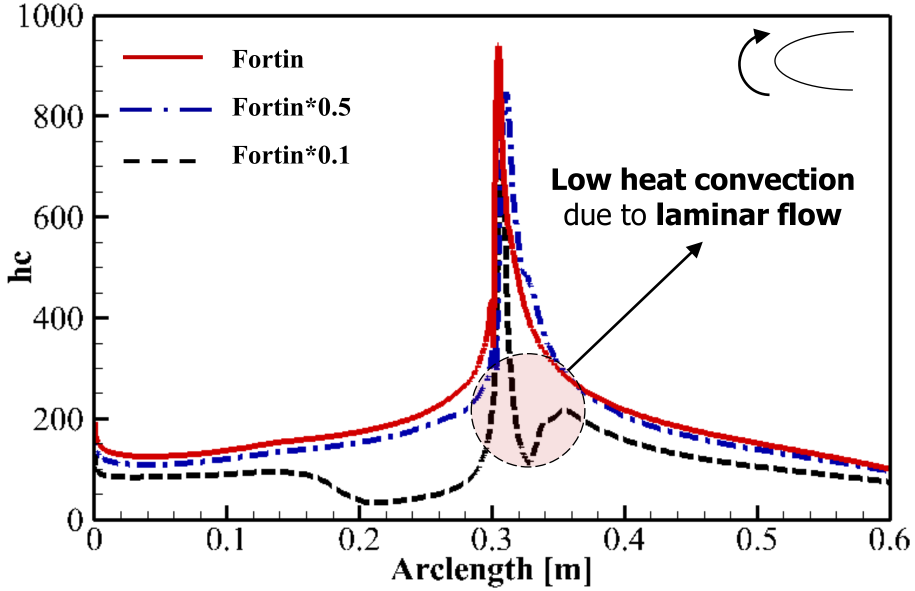

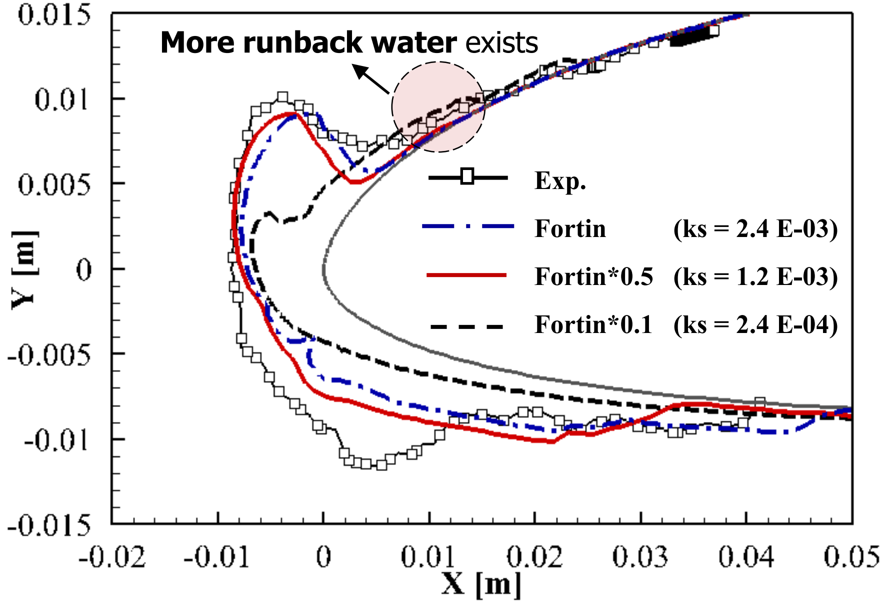

▲ Comparison of heat convection and ice shape in Case 3.1

Case 3 : RG-15 low speed Icing

- **Icing results**
  - ✓ Effect of **heat convection** according to **transition**
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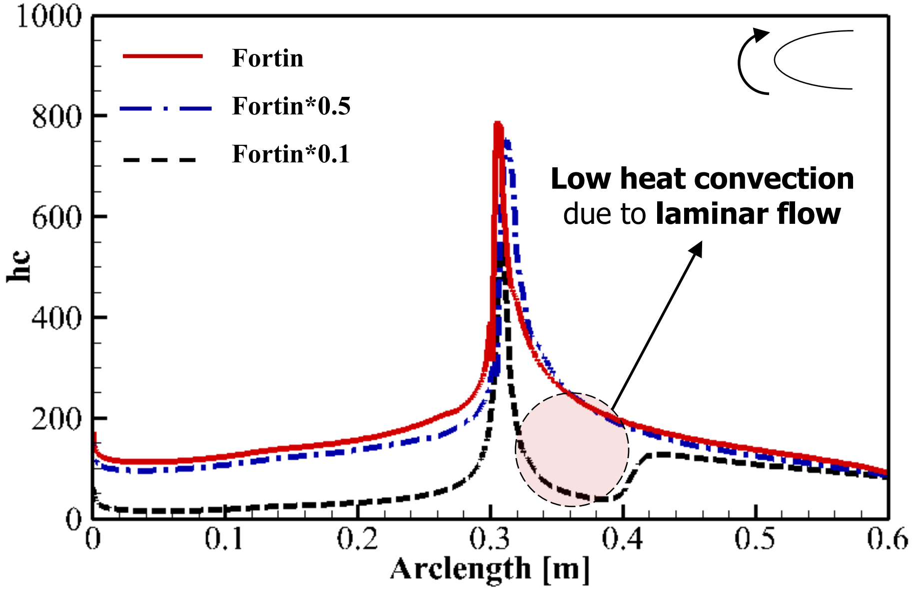

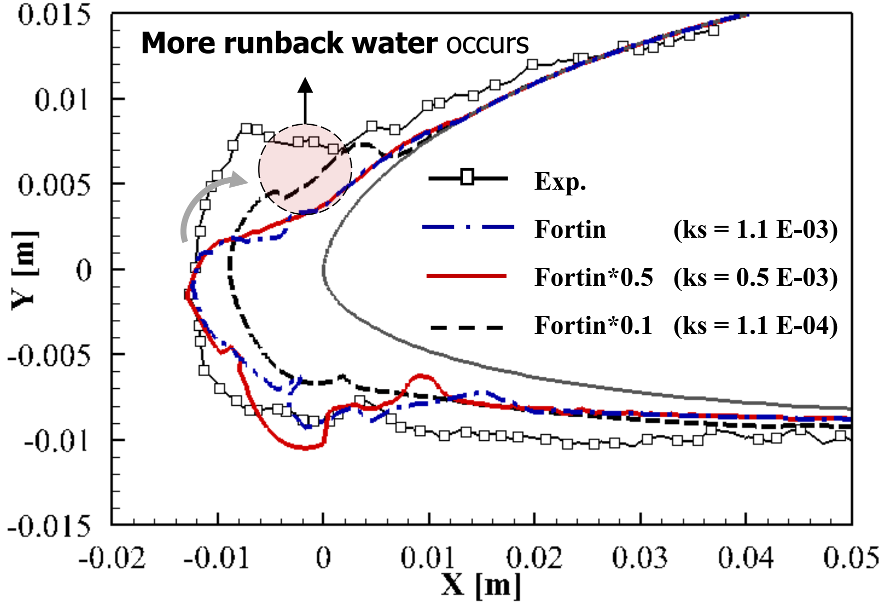

▲ Comparison of heat convection and ice shape in Case 3.1