2ND AIAA ICE PREDICTION WORKSHOP

IPW

ESTABLISHED 2019

SAE INTERNATIONAL

June 20-22, 2023
Vienna, Austria

International Conference on Icing of Aircraft, Engines, and Structures

SIMBA results for the 2nd Ice Prediction Workshop

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CIRA
Centro Italiano Ricerche Aerospaziali

Rationale

Challenge: the numerical prediction of in-flight ice accretion is becoming a valid mean to demonstrate the compliance with certification rules.

Physics: 3D ice-accretion on wings, fuselages, instruments, etc. :

- Performance loss due to 3D accreted walls
- Liquid-film / rivulets run-back
- A time-dependent and highly stochastic phenomena
- Long spray-times imply mixed-ice conditions (e.g. 3D scallops)

Goal: coupling two different methodologies to exploit their respective benefits

- Eulerian approach for water droplet impingement – easy catch efficiency computation
- Immersed Boundary solution – easy geometry handling and mesh generation

SImulation system based on an IMmersed Boundary Approach (SIMBA)

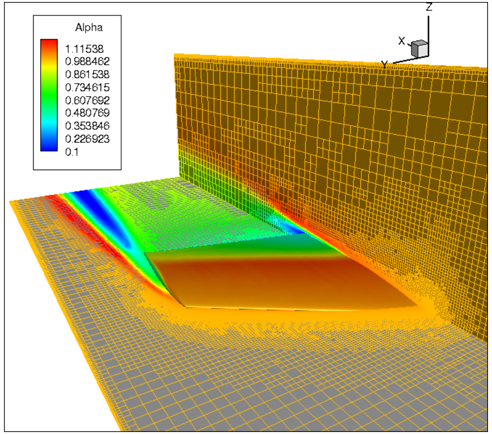
Comput. Domain
Unstructured 2D/3D Cartesian with adaptive mesh refinement (AMR). SIMBA_MESH

Air-phase
RANS/URANS or hybrid RANS-LES, FV IB-method, 2nd order skew-symmetric CDS, wall-modelling, static and dynamic multi-component surfaces.

Water-phase
Eulerian droplet mass momentum and energy balances, FV IB-method, 2nd order CDS. Wright and ONERA SLD modelling available.

Thermodynamics (…on going)
New module fully integrated into the SIMBA system for solving surface balances eqns. (Messinger and SWIM) .

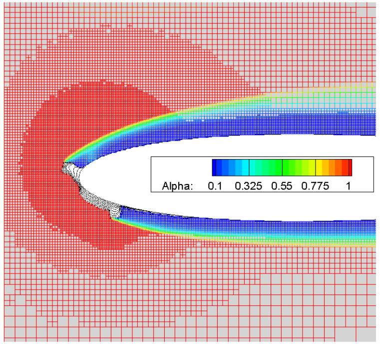
Air-phase by SIMBA_FLOW

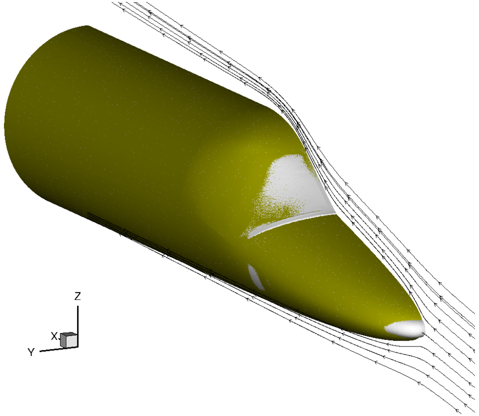


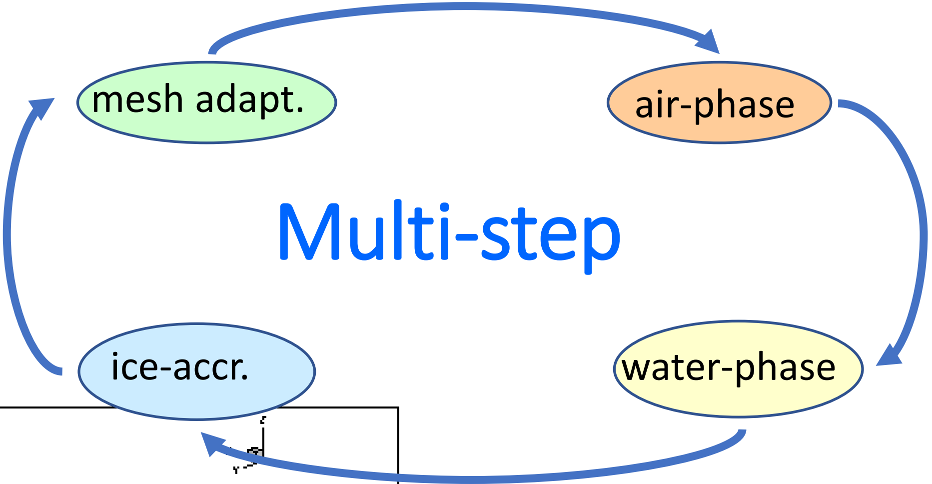
Water-phase by SIMBA_ICE

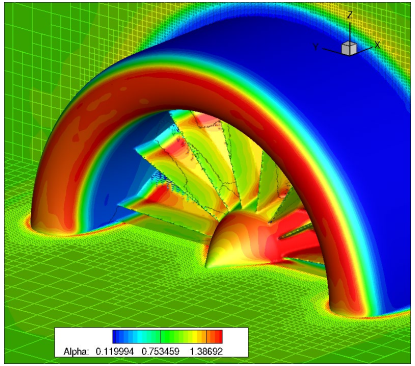
(Capizzano et al., *AIAAJ 2011 and 2016, JFE 2014, IJNME 2017, JCP 2019, C&F 2023*)

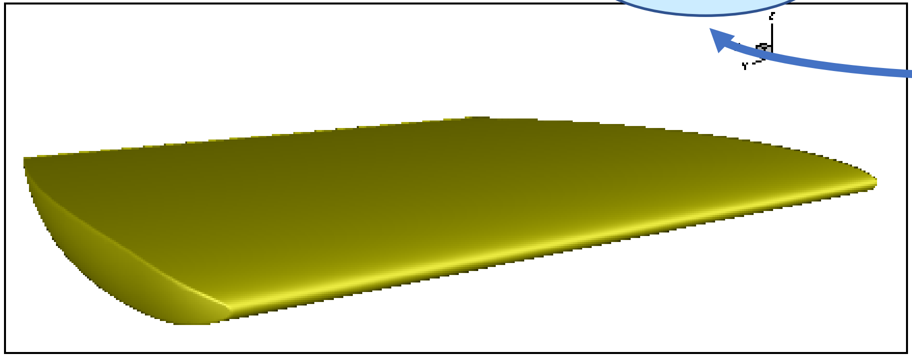
SIMBA ice-accretion chain









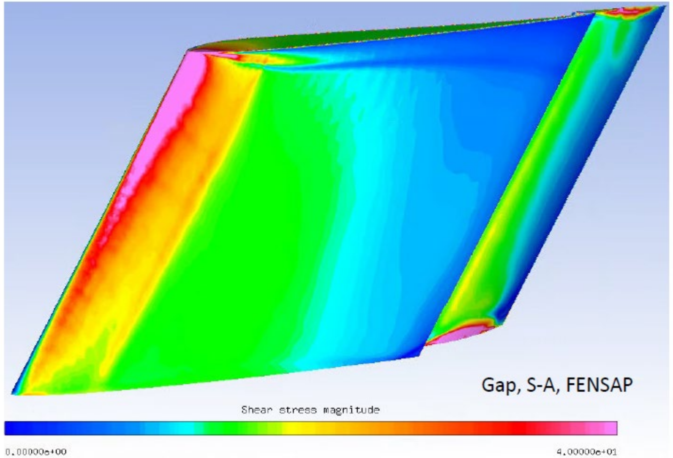


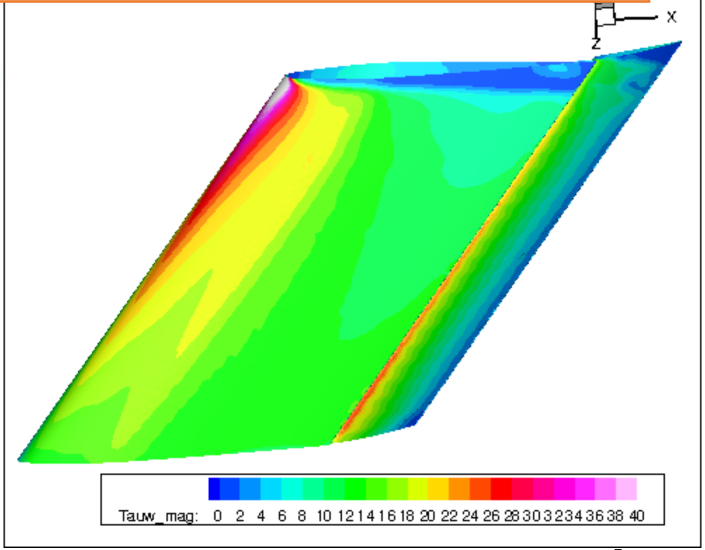
CRM65 Mid-span Hybrid: CASE 1, main and flap distinct components

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

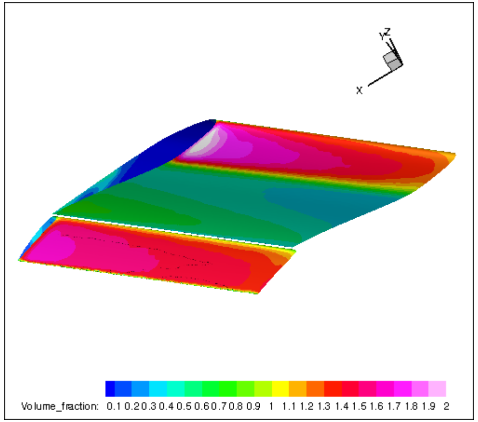
Numerical WT arrangement with GAP

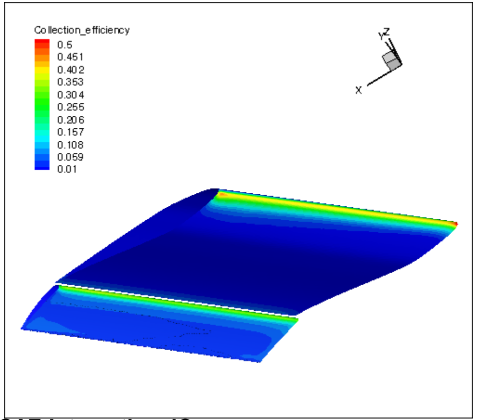
Mesh Ncells = Cartesian AMR mesh (~5.8M cells)
Air-phase = FV, IB-RANS with k-omega TNT turb. model
Water-phase = FV, IB-Eulerian approach (no SLD modelling)
Therm. model = Messinger 3D model
Surf. ice-accr. = Lagrangian one-shot



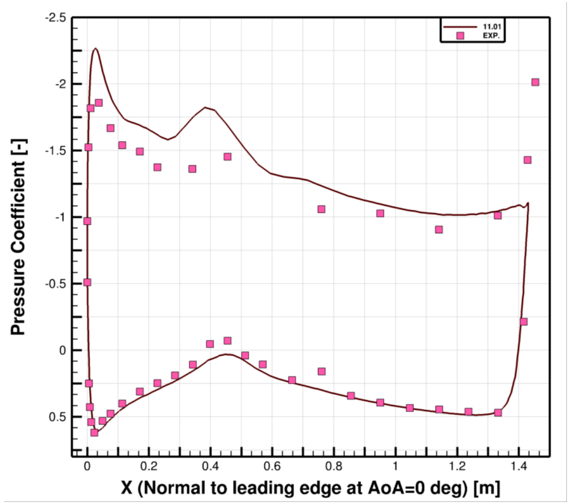


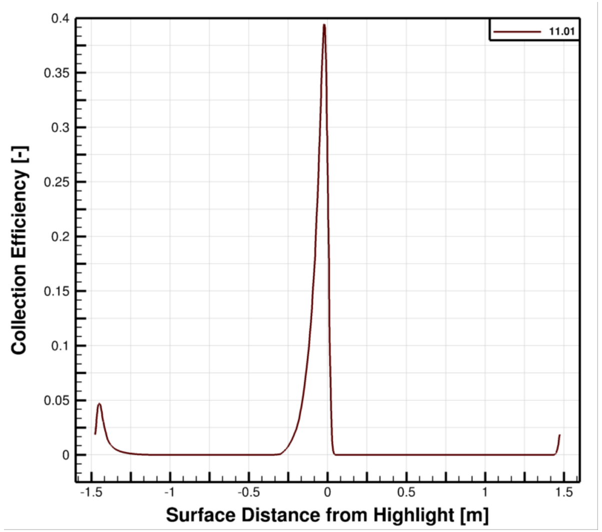
CRM65 Mid-span: CASE 1



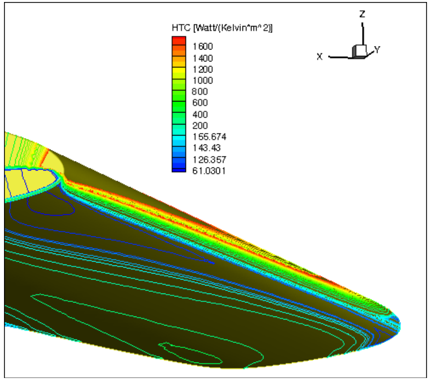


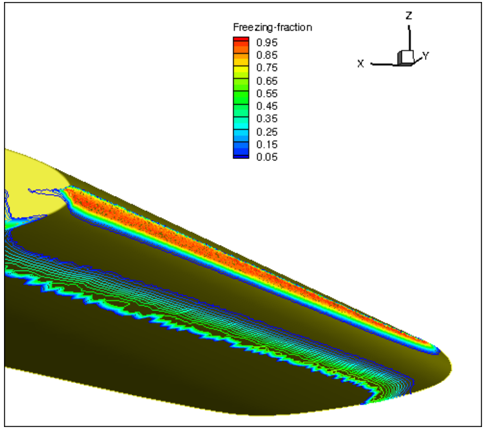
50 PERCENT SPAN





CRM65 Mid-span: CASE 1.1





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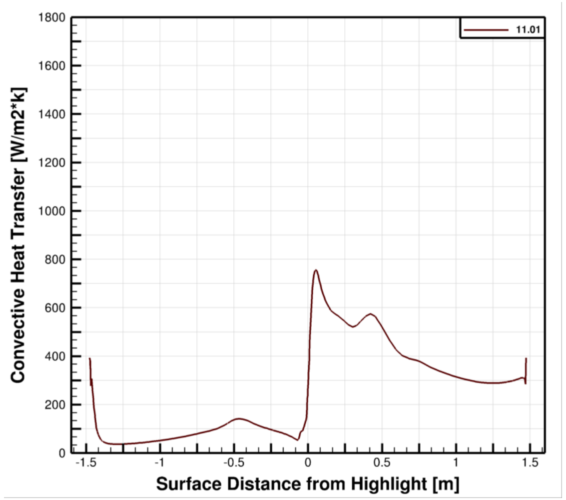
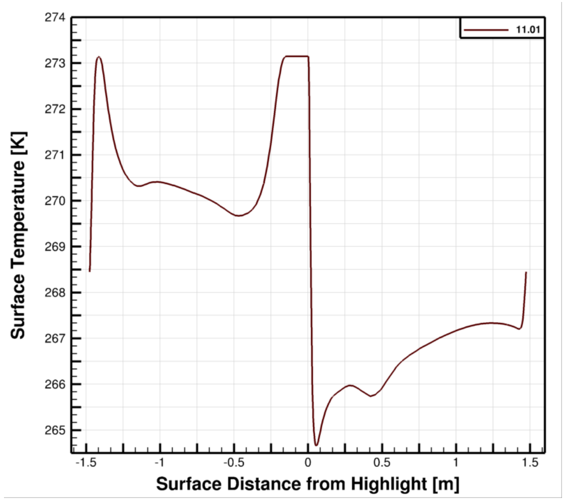
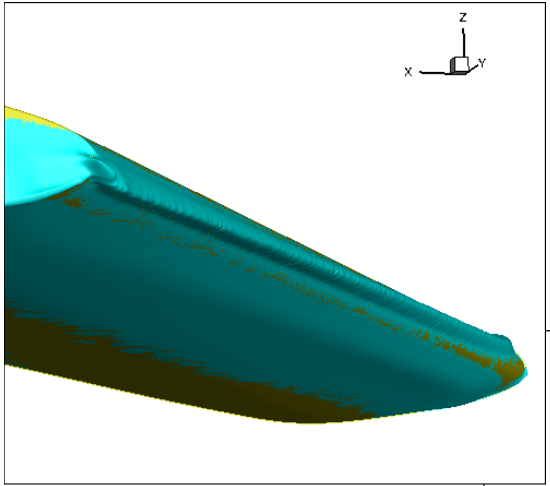
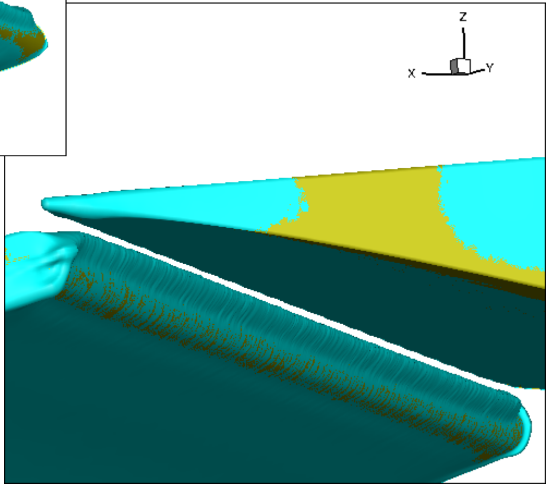
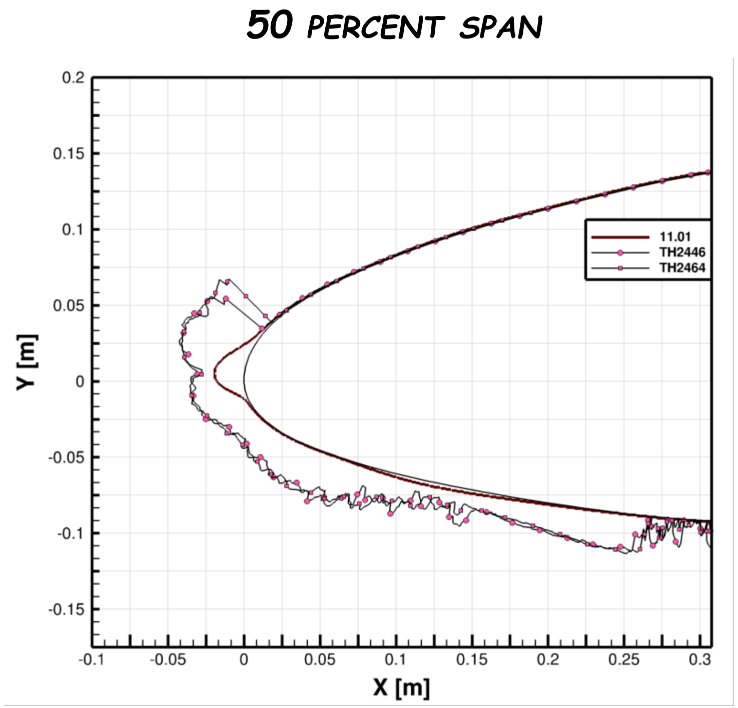




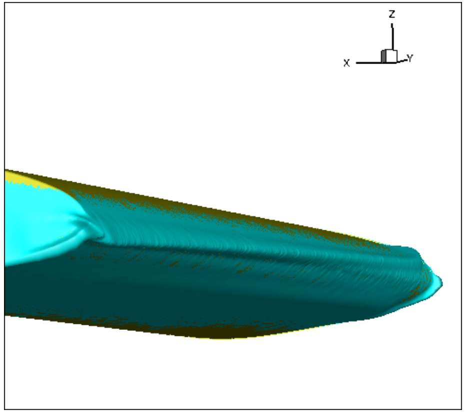
CRM65 Mid-span: CASE 1.1

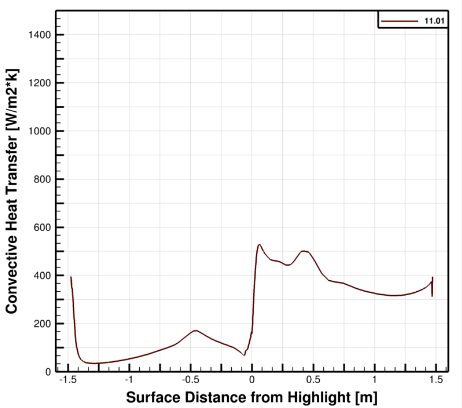






CRM65 Mid-span: CASE 1.2





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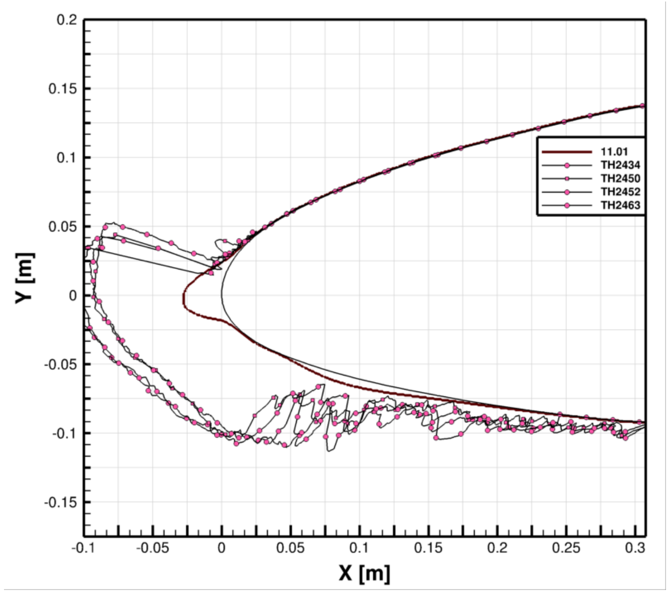
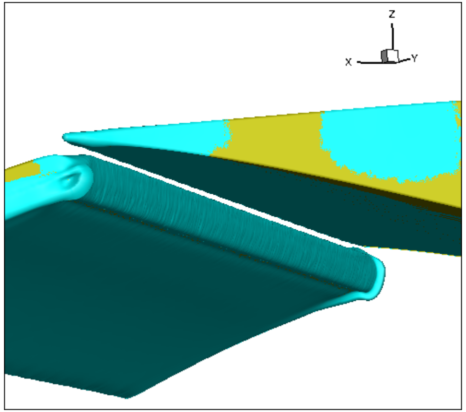
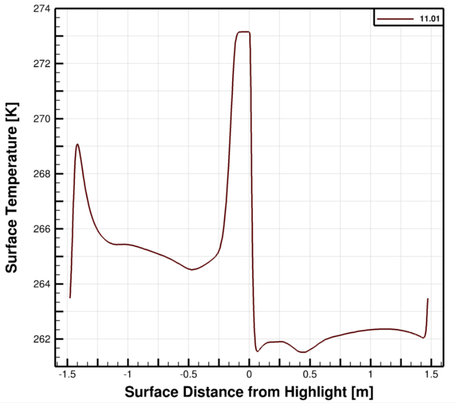
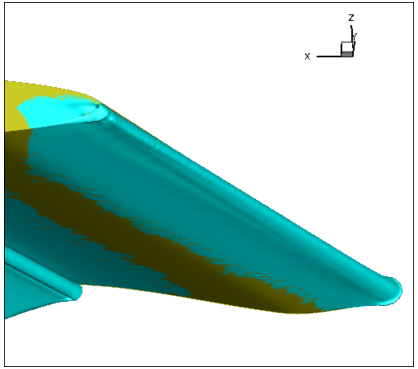
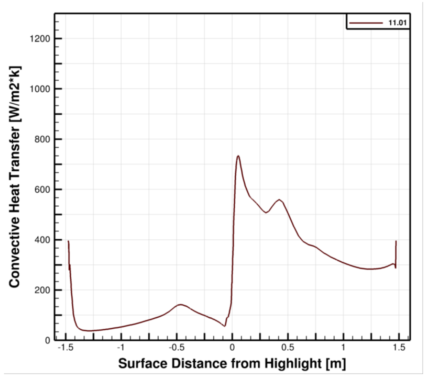


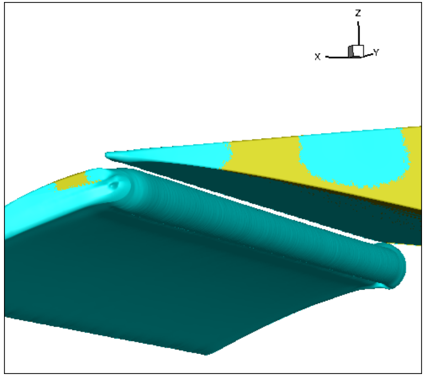


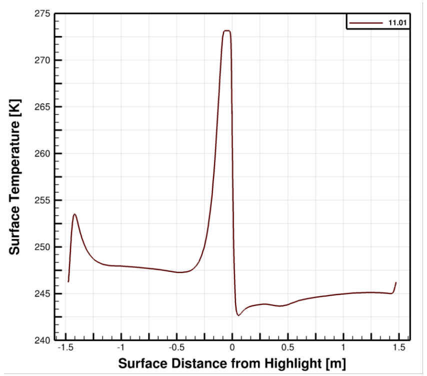


CRM65 Mid-span: CASE 1.3









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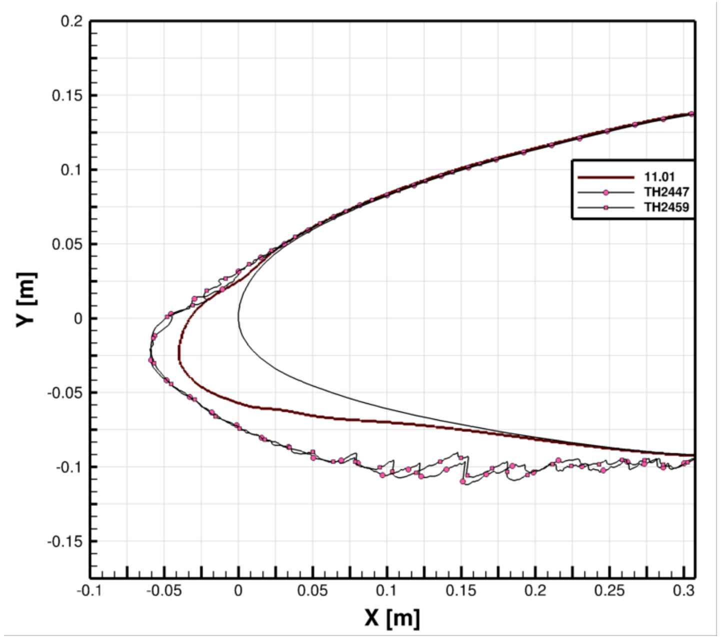


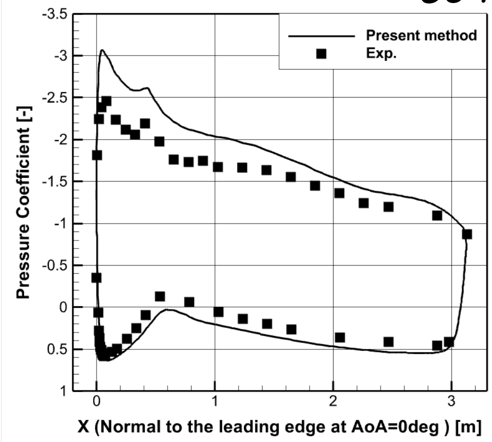
CRM65 Inboard Hybrid: CASE 2

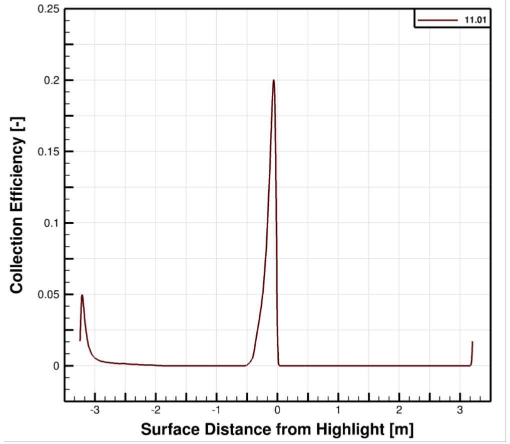
Case 2: CRM-65 Inboard Hybrid (3D)

Numerical WT arrangement with GAP

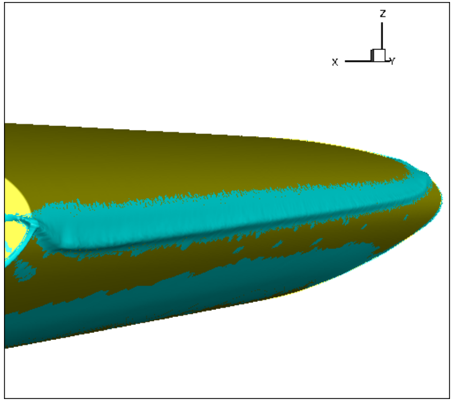
Mesh Ncells	= Cartesian AMR mesh (~9.8M cells)
Air-phase	= FV, IB-RANS with k-omega TNT turb. model
Water-phase	= FV, IB-Eulerian approach (no SLD modelling)
Therm. model	= Messinger 3D model
Surf. ice-accr.	= Lagrangian one-shot

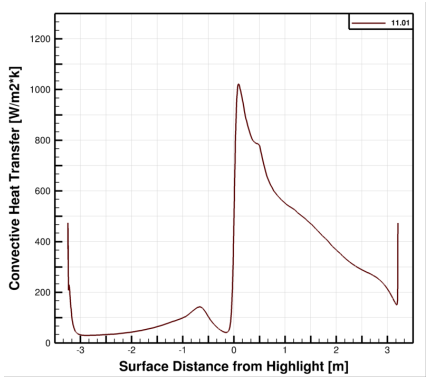
50 PERCENT SPAN





CRM65 Inboard Hybrid: CASE 2.1





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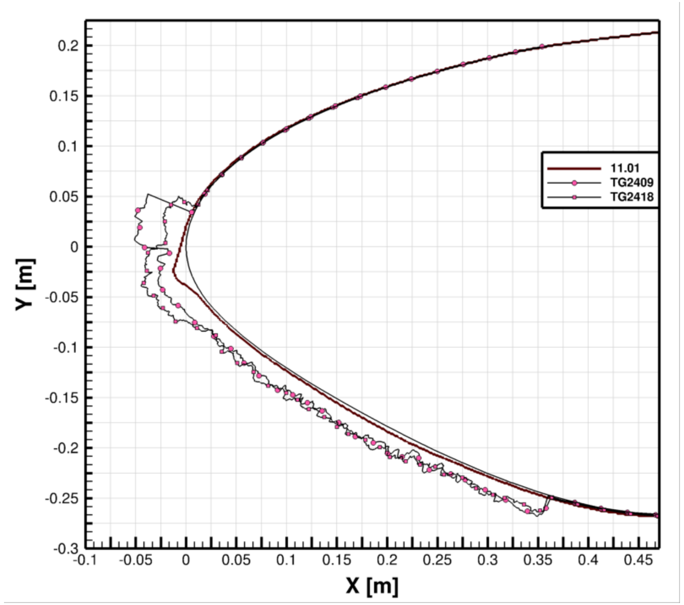
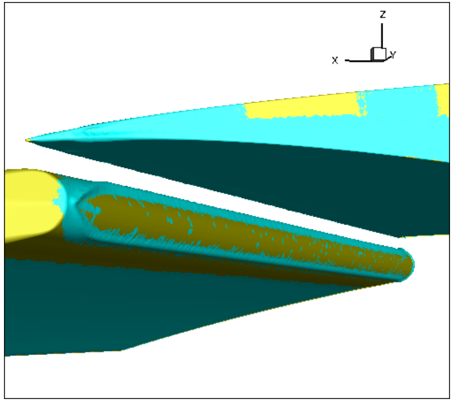
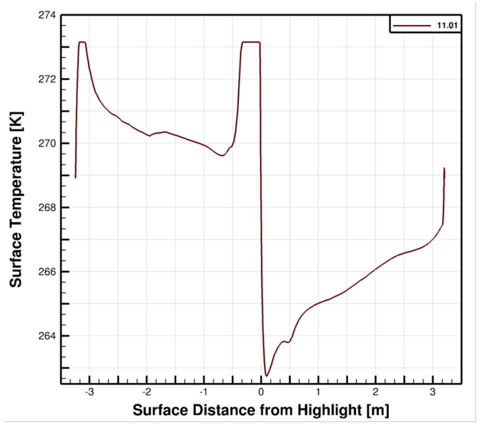
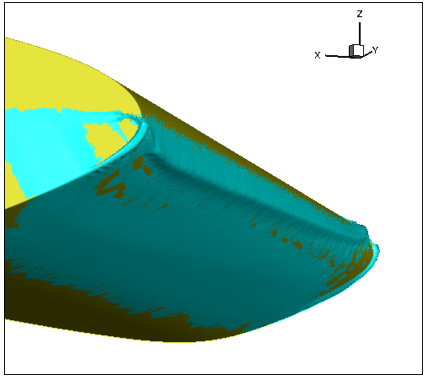
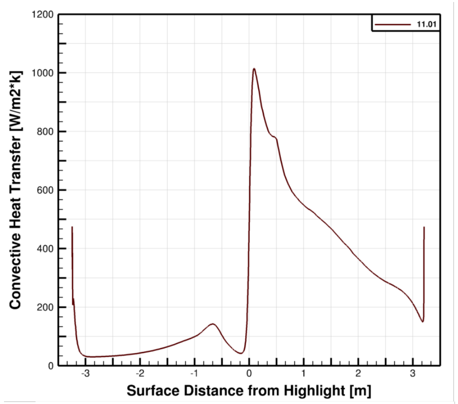


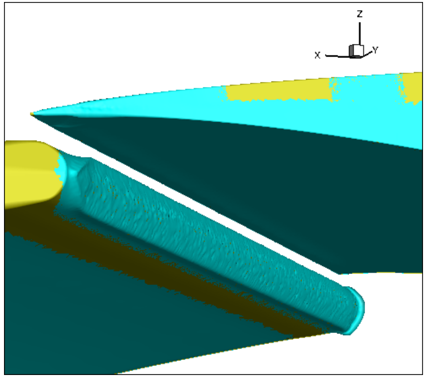


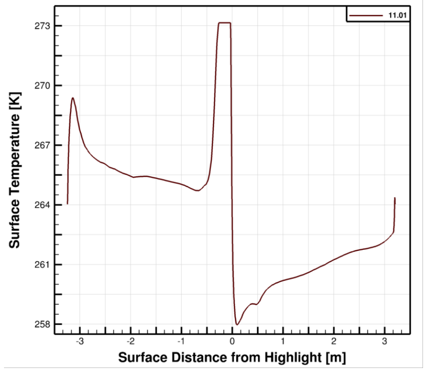


CRM65 Inboard Hybrid: CASE 2.2









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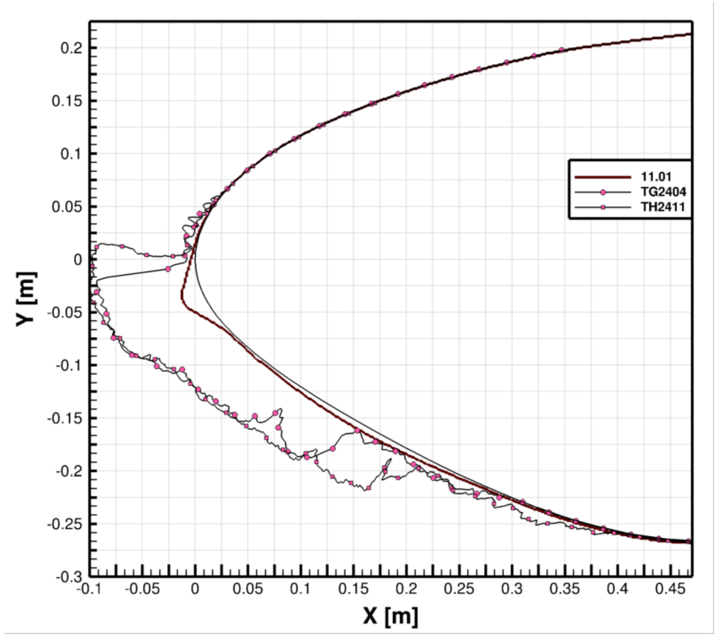
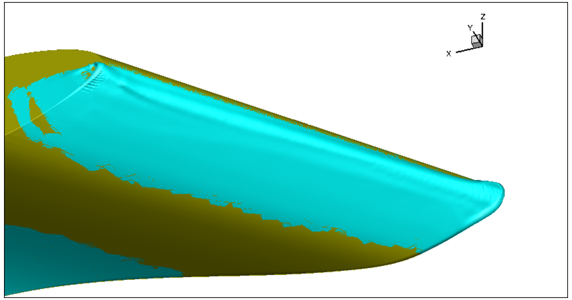
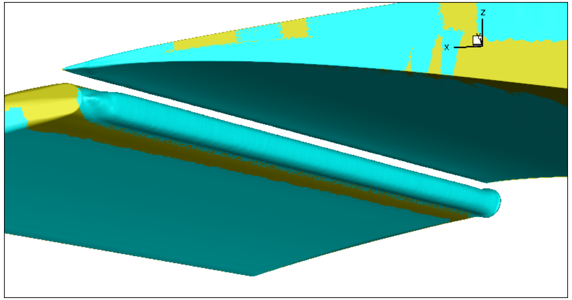
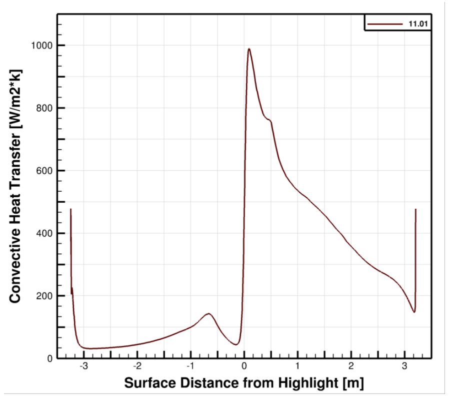
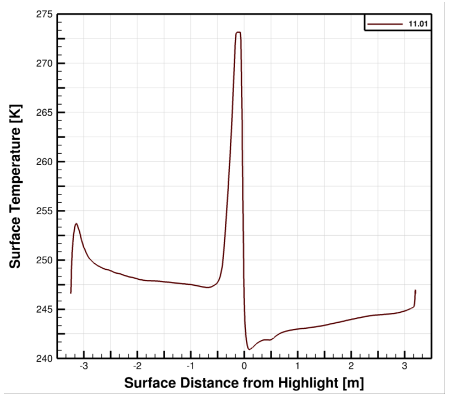


CRM65 Inboard Hybrid: CASE 2.3









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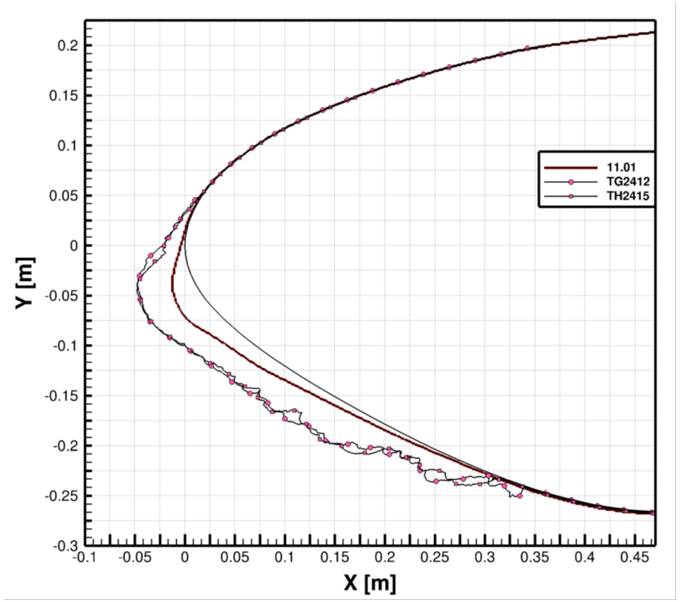
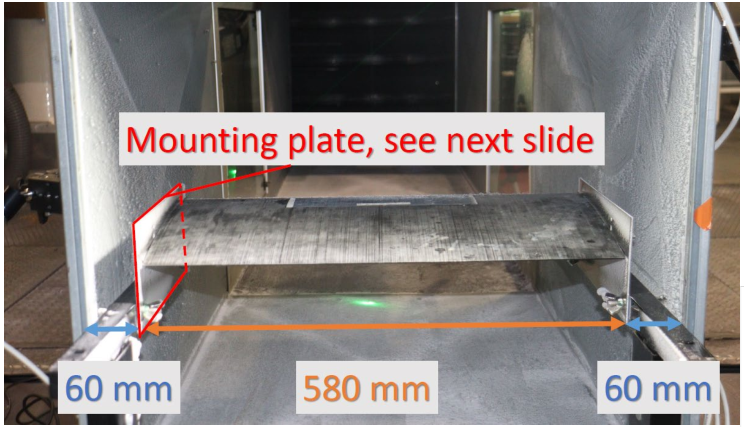
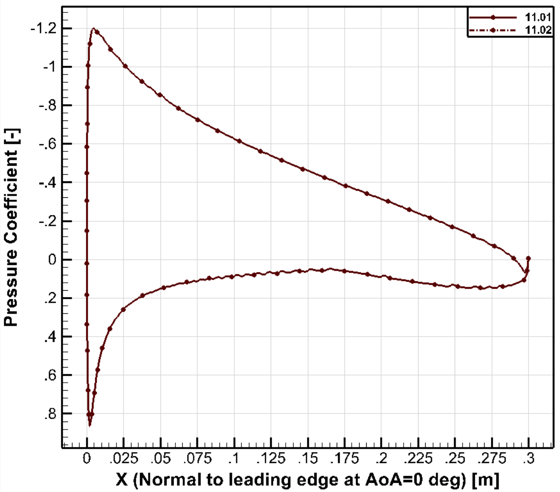


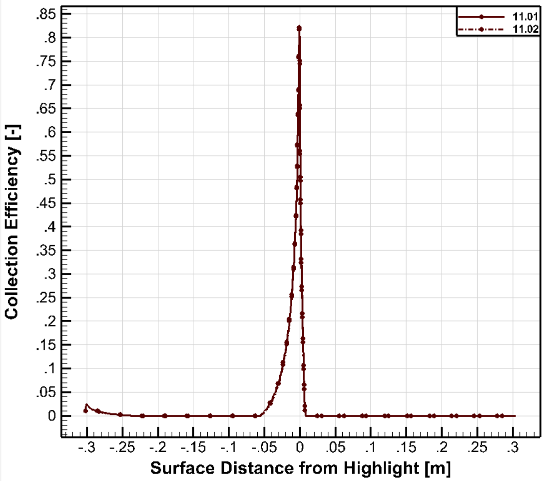
RG-15 small wing: CASE 3



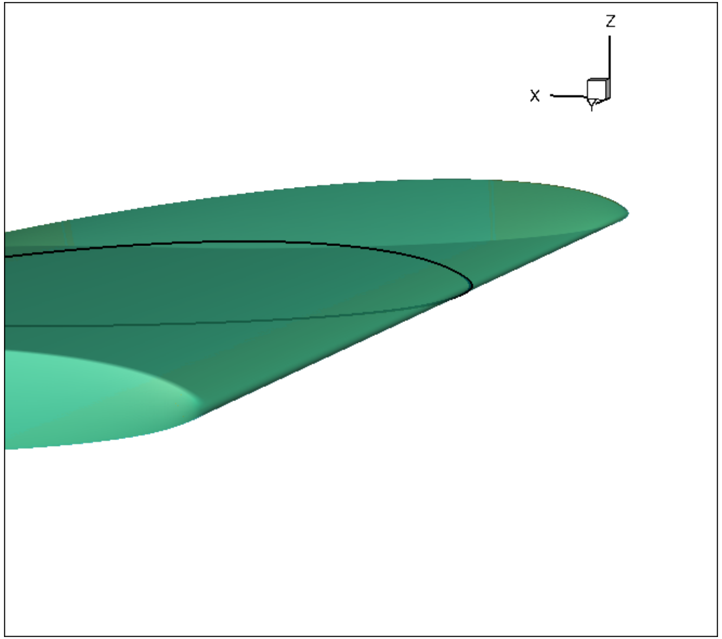
Numerical WT arrangement with periodic BCs

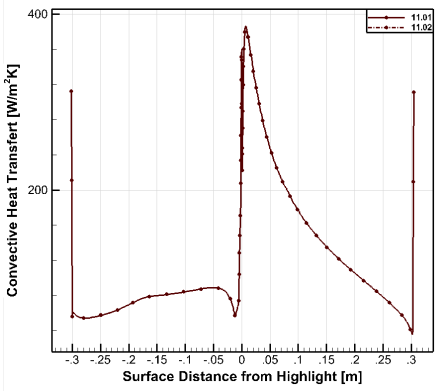
Mesh Ncells	= Cartesian AMR mesh (~4M cells)
Air-phase	= FV, IB-RANS with k-omega TNT turb. model
Water-phase	= FV, IB-Eulerian approach (no SLD modelling)
Therm. model	= Messinger 3D model
Surf. ice-accr.	= Lagrangian one-shot

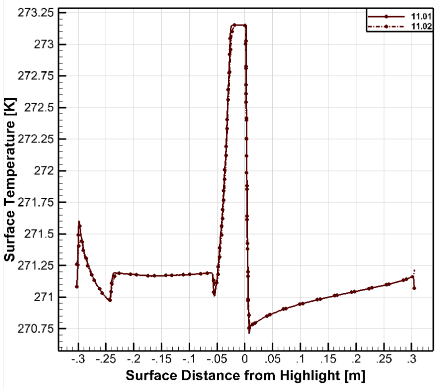




RG-15 small wing: CASE 3.1







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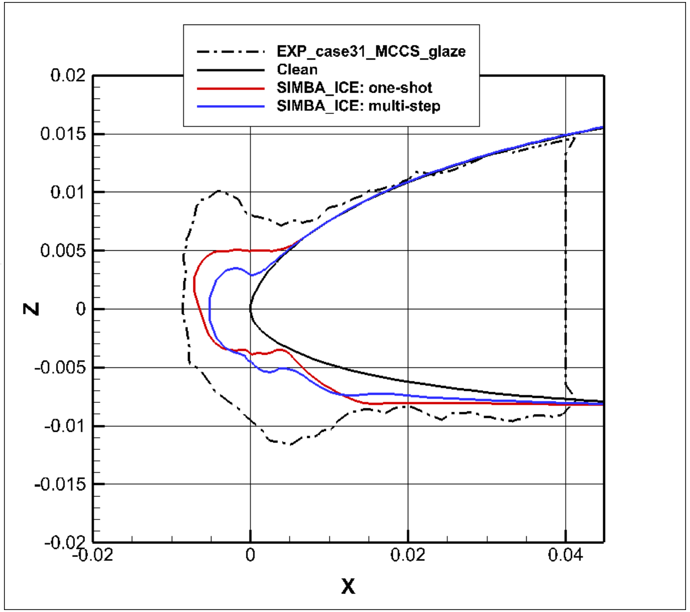

RG-15 small wing: CASE 3.2

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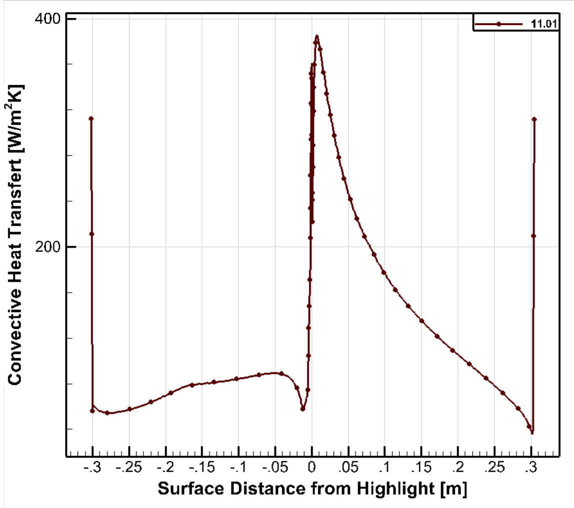

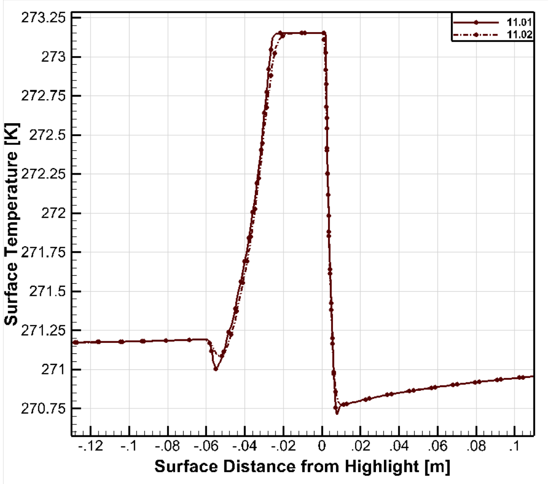

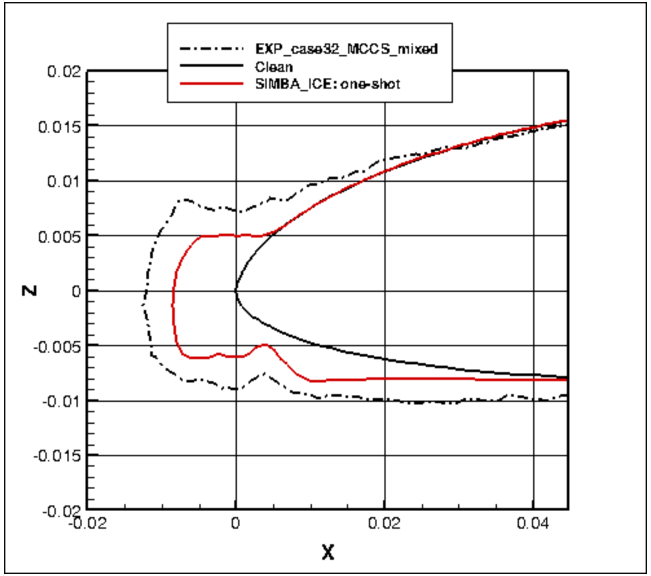

RG-15 small wing: CASE 3.3

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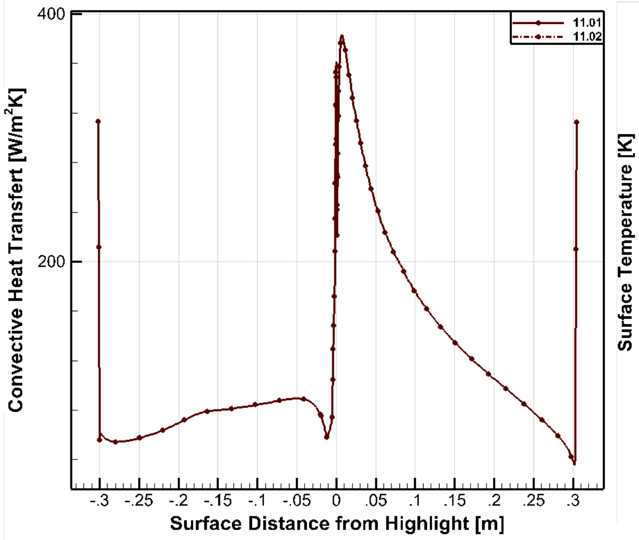
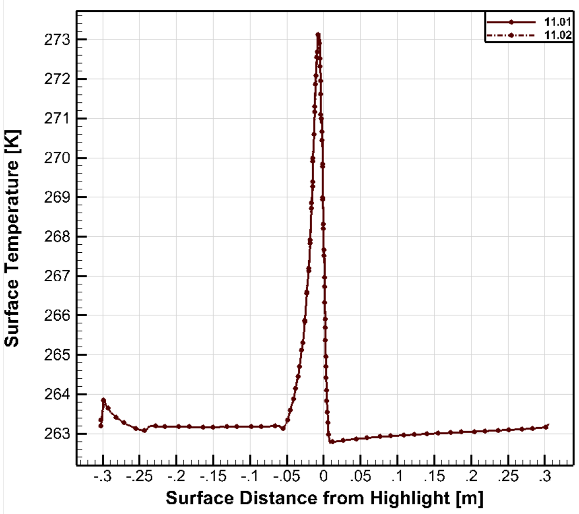
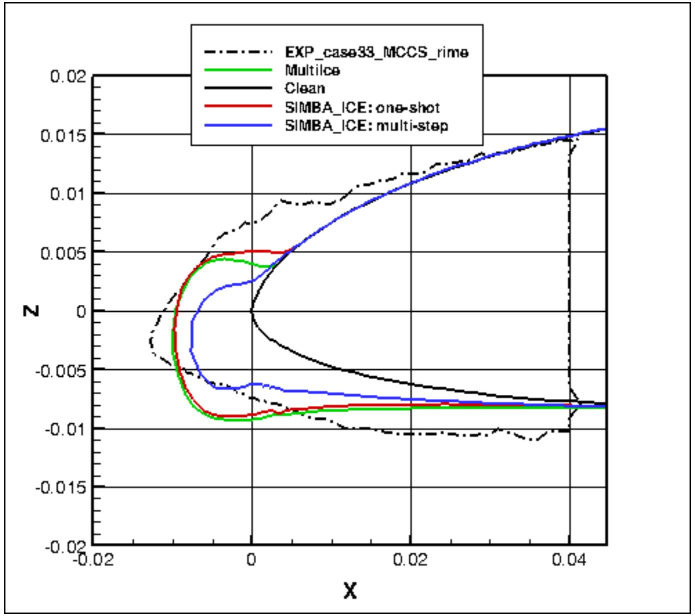






Encountered difficulties

Issues related to the benchamrks themselves

- Major:
  - CRM65 Midspan-model: separation at the top-section
  - Few info on the inlet-outlet pressure jump Δp into the WT test-section (…useful for a proper numerical setting)
  - Some ice-density measures would be appreciated
- Minor:
  - Unified post-processing by PyTecplot is welcome but possible failures due to different versions as well as compiled libraries (…Tecplot macros?).
  - RG-15 cases: ambiguity between WT and FF numerical setting

Issues related to the numerical method itself

- Major:
  - Numerical ice-accretions suffer from a constant density assumption.
  - The Lagrangian accretion is not conservative and prone to geometric failures.
  - Roughness and ice-density models can help.
- Minor:
  - HTC estimate
  - Multi-bin analyses can improve the RG-15 rime accretions
  - Run-back water may need some additional work/check
  - Local surface mesh-refinement by ad-hoc flow-based sensors (e.g. the collection efficiency).

Overall considerations

- The IPW-2 is a unique opportunity to exchange new ideas and data on the icing-topic (…and meeting in person many colleagues known in virtual Projects' meetings) .
- The IPW-2 cases themselves result very challenging and I regard the present ones as preliminary results, due to the short time-range between the exp. data release and the IWP-2 meeting.
- Besides, the obtained results need more time to be analysed also w.r.t. experimental data in order to summing-up clear findings.
- Most of the present IPW-2 analyses are carried-out in few weeks and outside office-hours (i.e. in the night!) …For my personal health, next time, please release the benchmarks one year before!

Acknowledgments

- The IPW-2 Committee for organizing this exciting workshop and in particular Maxime Blanchet and Mohamad Karim Zayni for the data collection work and kind support.

- Thank you

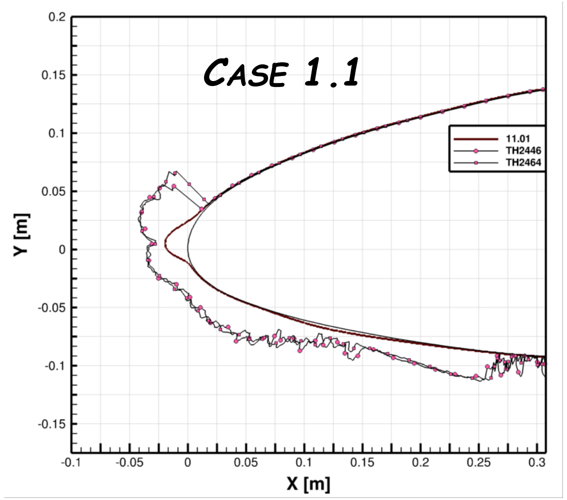
  - Eng. Giovanni Andreutti (CIRA) for CAD support
  - Dr. Donato de Rosa (CIRA) and Eng. Francesco D'Aniello (CIRA) for fruitful discussion on water run-back and HTC estimate.

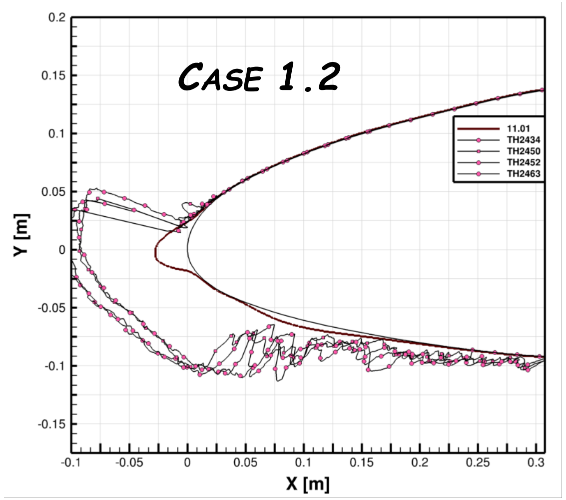
THANK YOU

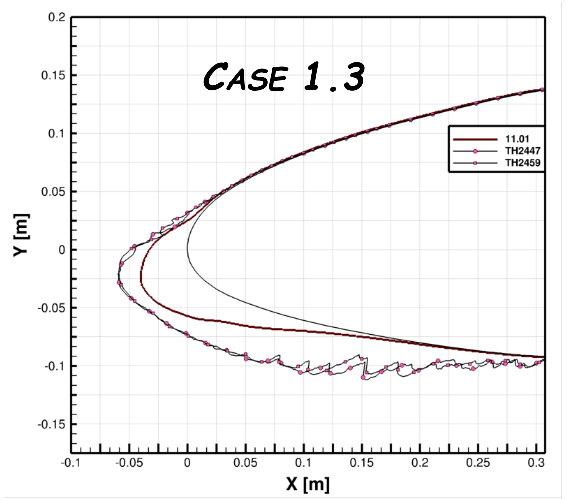

June 20-22, 2023
Vienna, Austria
SAE INTERNATIONAL
International Conference on Icing
of Aircraft, Engines, and Structures
sae.org/icing

CRM65 Mid-span: CASE 1

50 PERCENT SPAN

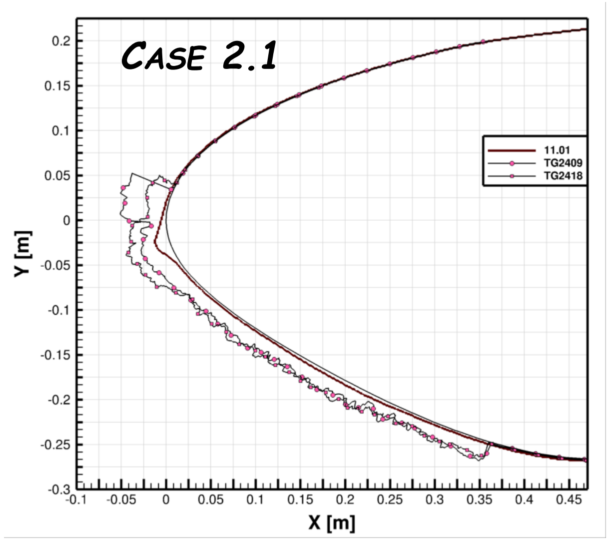


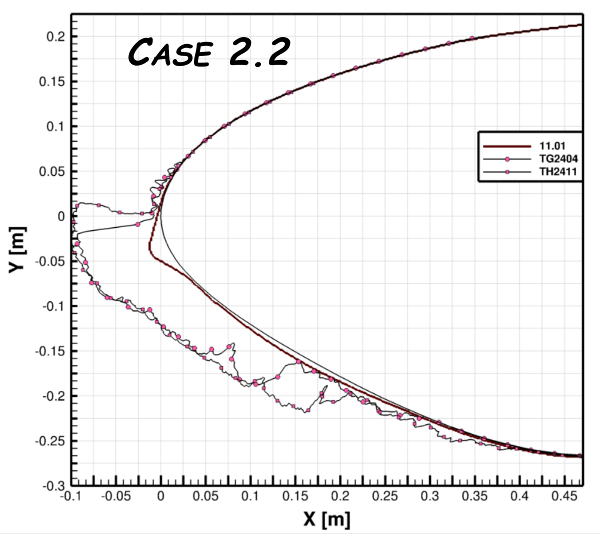


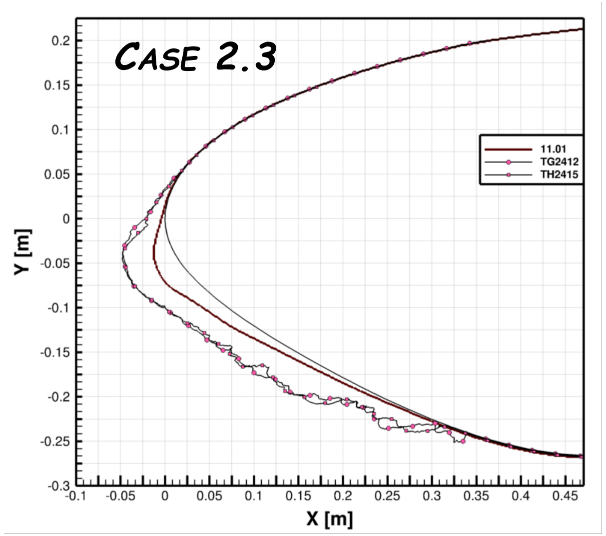


CRM65 Mid-span: CASE 2

50 PERCENT SPAN



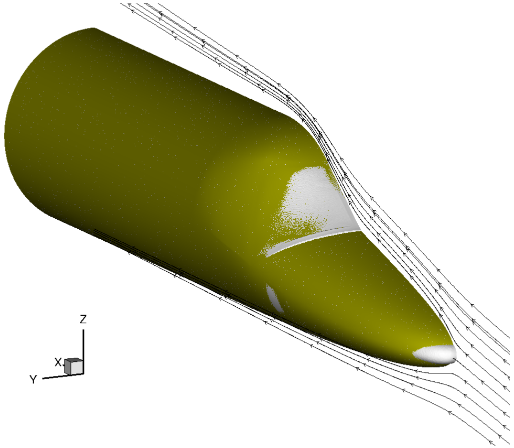


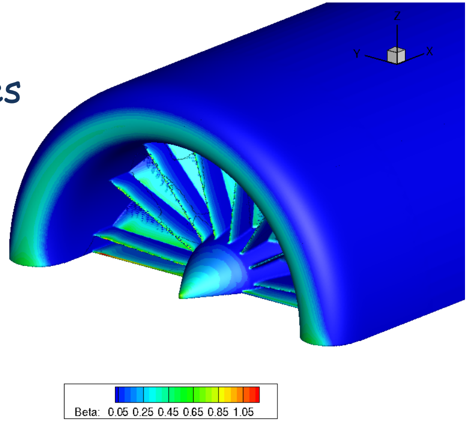


Background

Liquid-film and 3D ice-accretion: models and methods.

- Surface models based on mass, momentum and energy balances
- 3D geometry modification based on Lagrangian, Eulerian and stochastic approaches
- One-shot analyses proven accurate/robust only for simple and mono-component geometries
- Multi-step analyses are more consistent but present many issues related to the modification of multi-connected surfaces as well as surface re-meshing



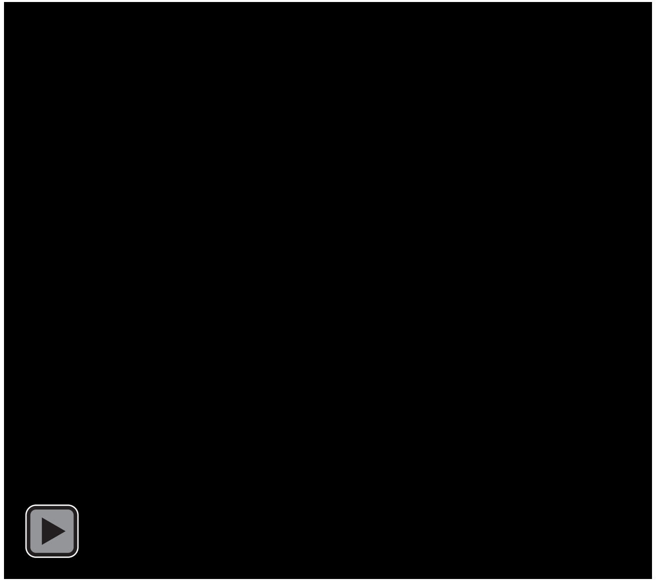


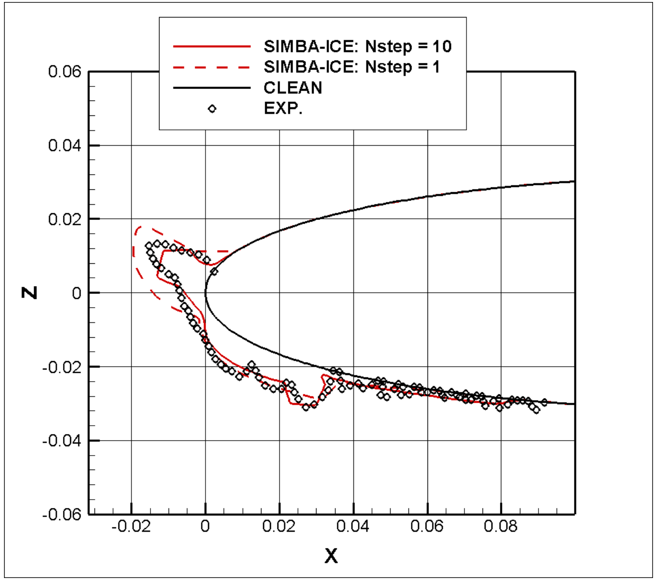
NACA0012 airfoil: NASA-RUN401 (Glaze)

Validation: Messinger, Multi-Step (MS)

2D test-case, App-C.

- NACA0012
- NASA – RUN401 (glaze)

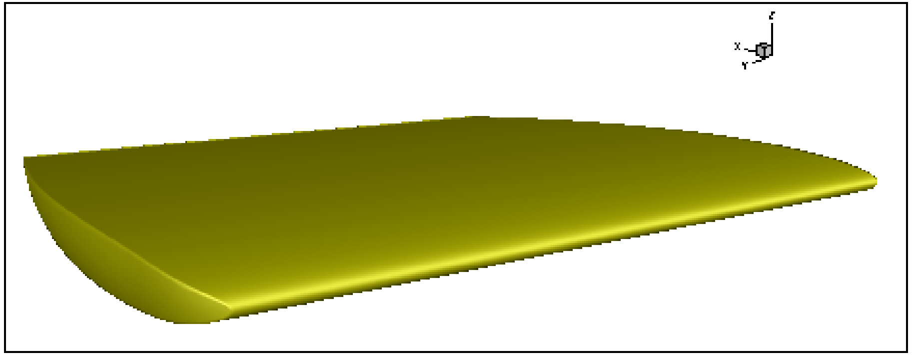




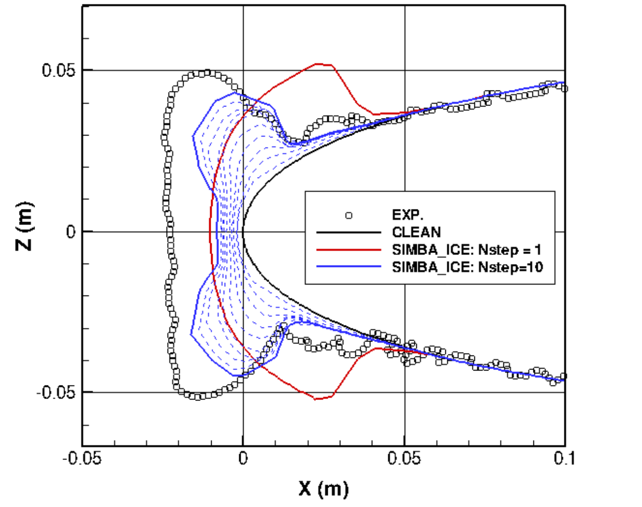
Swept-wing: IPW-1 case-362

3D benchmark, App-C. (optional)

- 30° swept NACA0012
- Cartesian-IB
- Case 362
- Glaze-ice



MULTISTEP, NSTEPS = 10

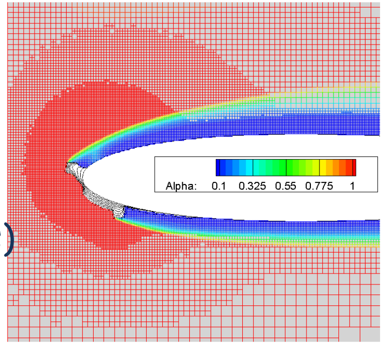


ONE-SHOT VS. MULTISTEP

..cont'd

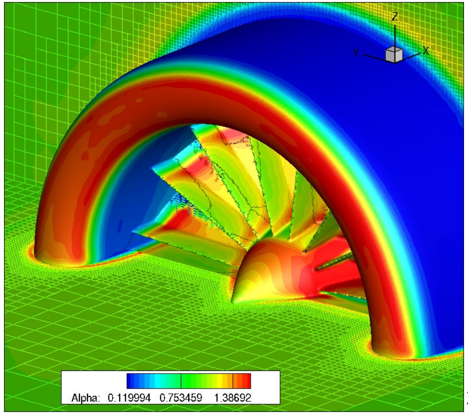
3D ice-accretion status

- Volume mesh displacement → grid quality issues
- Iced-surface deform. → mesh entanglement & ice-front collision
- Lack of volume conservation → not guaranteed for Lagrangian displacements
- Ice-density → significant variation in 3D accr. (e.g. swept wings)



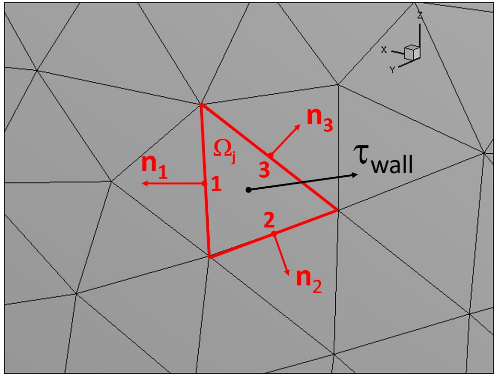
Potential remedies

- Global or local volume remeshing → to improve mesh quality
- Remeshing of iced surface → not trivial due to non-smooth surfaces
- Ice-density models → to improve volume conservation
- Lagran. PC and MS approaches → ice-volume error reduces with N steps
- Eulerian ice-accretion methods → to reduce ice-volume error



Iterative Messinger 3D model on unstructure meshes

- Iterative Messinger model distributes runback-out based on the surface local shear-stress
- HTC accepted as input or computed internally by Reynolds analogy
- Lagrangian ice-accretion



Mass balance $$\dot{m}_{imp} + \dot{m}_{rbi} = \dot{m}_{rbo} + \dot{m}_{es} + \dot{m}_{ice}$$

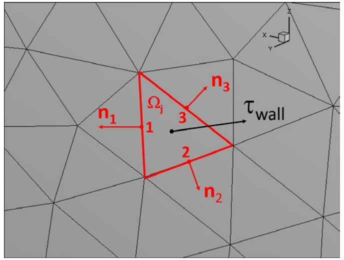
Energy balance $$\dot{Q}_{ice} + \dot{Q}_{rbi} = \dot{Q}_{imp} + \dot{Q}_{rbo} + \dot{Q}_{es} + \dot{Q}_{c}$$

Compatib. conds.

- *running-wet* : $\dot{m}_{ice} = 0$ and $T_{eq} > T_m$.
- *rime-ice* : $\dot{m}_{rbo} = 0$ and $T_{eq} < T_m$.
- *glaze-ice* : $\dot{m}_{rbo} > 0$ and $T_{eq} = T_m$.

Iterative Messinger 3D model on unstructure meshes

- Iterative Messinger model distributes runback-out based on the surface local shear-stress
- HTC accepted as input or computed internally by Reynolds analogy
- Lagrangian ice-accretion



Mass balance

$$\dot{m}_{imp} = \beta \; LWC \; U_\infty$$

$$\dot{m}_{rbo} = -\sum_{i=1}^{3} \dot{m}_{rbo,i}, \quad \dot{m}_{rbo,i} = \dot{m}_{out} \frac{l_i \left(\tau_{wall} \cdot \mathbf{n}_i\right)}{F_{rbo}} \quad if \quad \left(\tau_{wall} \cdot \mathbf{n}_i\right) > 0$$

$$F_{rbo} = \sum_{i=1}^{3} \left(l_i \tau_{wall} \cdot \mathbf{n}_i\right), \quad if \quad \left(\tau_{wall} \cdot \mathbf{n}_i\right) > 0$$

$$\dot{m}_{rbi} = \sum_{i=1}^{3} \dot{m}_{rbi,i}, \quad \dot{m}_{rbi,i} = \dot{m}_{rbo,i} \frac{A^i}{A}$$

$$\dot{m}_{es} = -0.696 \, \frac{h_c}{C_{p,a}} \, \frac{\left(p_{vs}\right)_{wall} - \left(p_{vs}\right)_\infty}{.5 \left(p_{wall} + p_\infty\right)}$$

$$\dot{m}_{ice} = f \left(\dot{m}_{imp} + \dot{m}_{rbi} - \dot{m}_{es}\right)$$

Energy balance

$$\dot{Q}_{imp} = \dot{m}_{imp} \left[c_{p,w} \left(T_d - T_m\right) + \frac{U_d^2}{2}\right]$$

$$\dot{Q}_{rbi} = \dot{m}_{rbi} \left[C_{p,w} \left(T_{rbi} - T_m\right)\right]$$

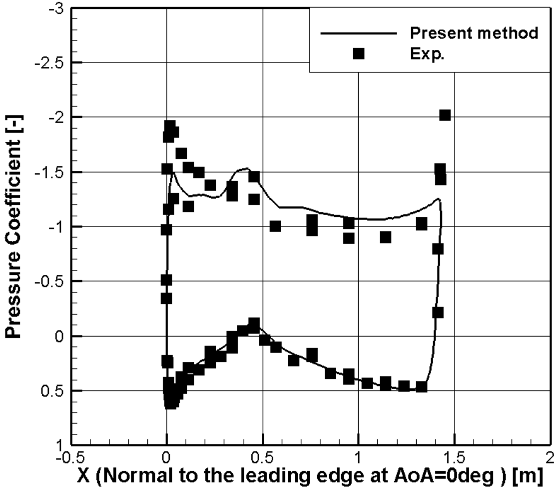
$$\dot{Q}_{rbo} = \left(\dot{m}_{rbo} + \dot{m}_{es}\right) \left[C_{p,w} \left(T_m - T_{eq}\right)\right]$$

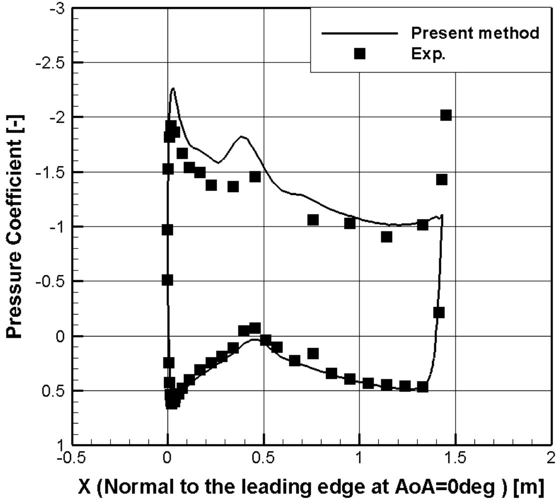
$$\dot{Q}_{es} = \dot{m}_{es} \left[\left(1 - f\right) L_{ev} + f L_s\right]$$

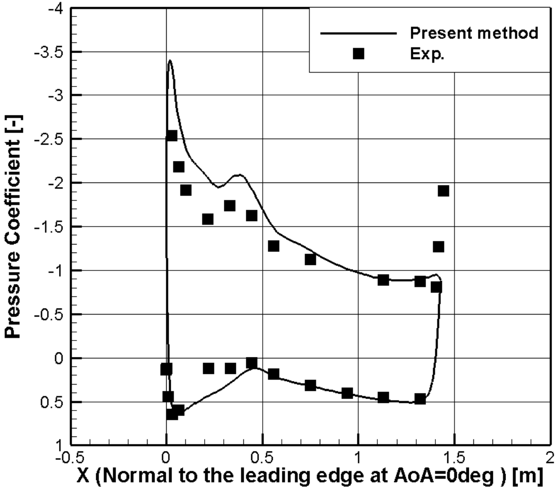
$$\dot{Q}_{ice} = \dot{m}_{ice} L_f + \left(\dot{m}_{ice} + \dot{m}_{es}\right) C_{p,w}$$

$$\dot{Q}_c = h_c \left(T_{ad} - T_{eq}\right)$$

CRM65 Mid-span: CASE 1

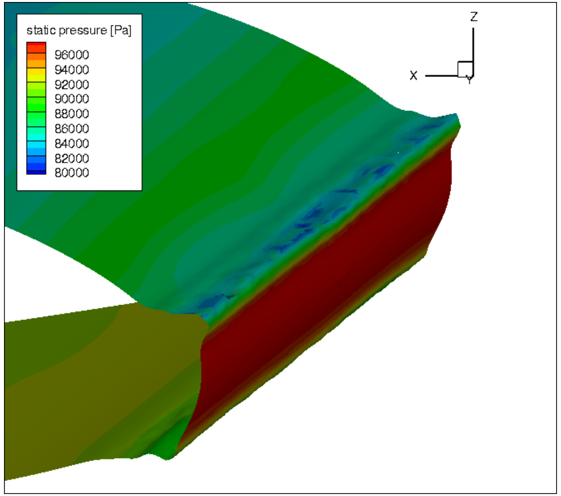






Encountered difficulties and issues for 3D MS

- As expected, slight deviations of mass and energy surf. balances from two-dimensionality generate an irregular 3D iced-surface.
- No particular process-issues encountered for MS 3D analyses on case252 (SLD+glaze) and case361 (rime)
- Strict automation obtained for MS on case362 (glaze) at the cost of local surface smoothing (especially at the wing-tip).
- In general, need of expert/skilled users for monitoring the correctness of the multi-step process due to potential failures (skewed facets, spikes, concavities, restarts, codes' alignment, etc.).



Lessons learned and suggestions

- Ice density modelling is crucial: indeed, the impinging mass is converted into ice-volume via ice-density.
- Re-meshing/refining the iced-surface is definitely a very challenging task. Not prone to automation due to complex shapes (potential meshing errors).
- The more the grid is refined, the smaller the ice structures: this is an issue for meshes and CFD in general.
- The physics of 3D ice-accretion results in non-negligible numerical difficulties
- Models (e.g. density, htc, run-back) are still not satisfactory

2ND AIAA ICE PREDICTION WORKSHOP
IPW
ESTABLISHED 2019

SIMBA results post-IPW2

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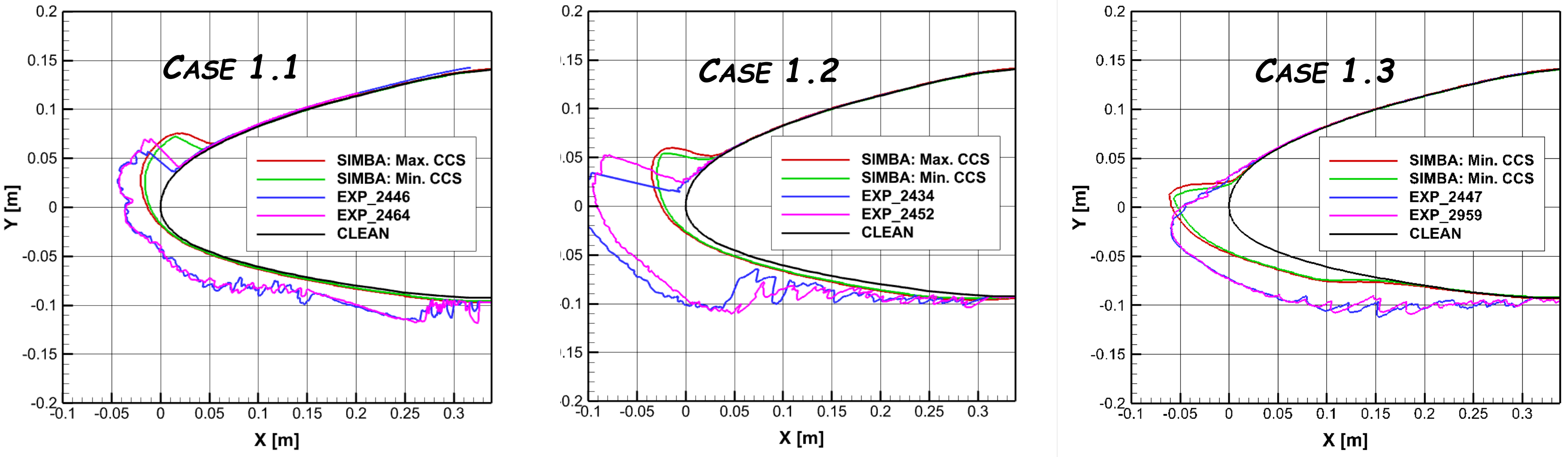
CIRA
Centro Italiano Ricerche Aerospaziali

Improvements occurred post-IPW2

- New water-film solver fully integrated into the SIMBA framework.
- Some implementation bugs have been found and fixed.
- We have re-run all the IPW benchmarks and substantial differences were observed with respect to the preliminary results shown during the IPW2 workshop.
- Remark on the case3: we have re-run the cases by considering an LWC=0.55g/m^3 as pointed out during the IPW2 meeting day.

CRM65 Mid-span: CASE 1

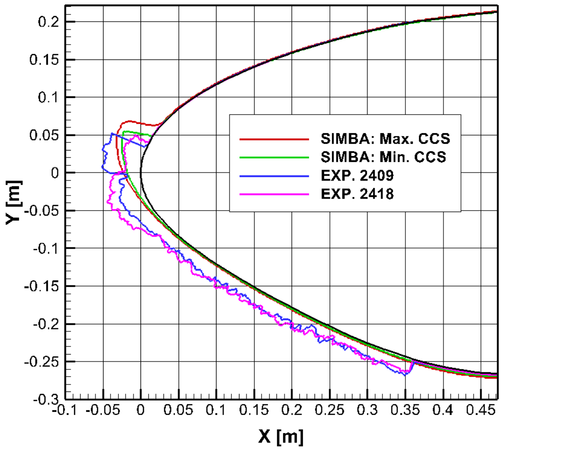
50 PERCENT SPAN



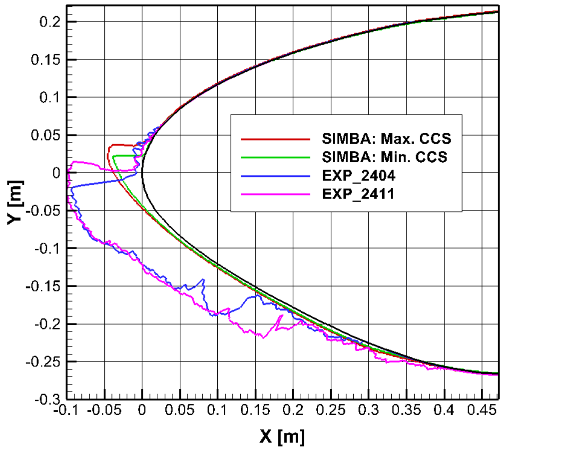
CRM65 Inboard Hybrid: CASE 2

50 PERCENT SPAN

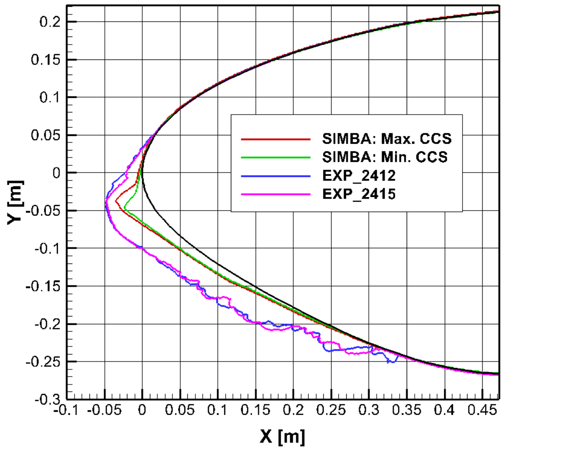
CASE 2.1



CASE 2.2



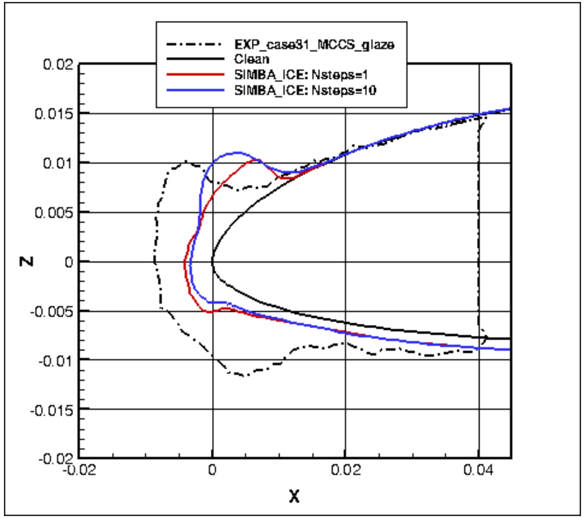
CASE 2.3



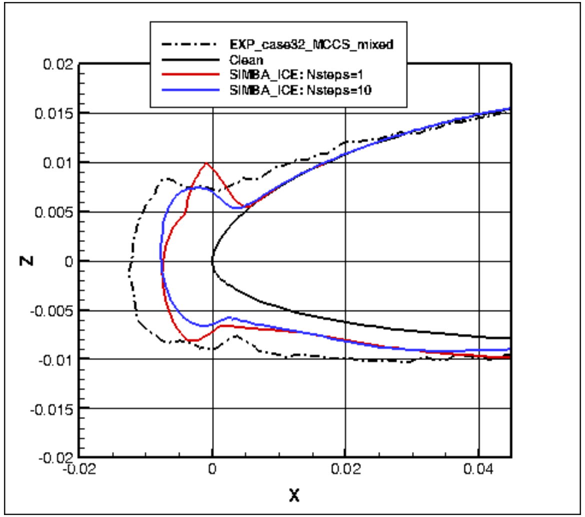
RG-15 small wing: CASE 3

50 PERCENT SPAN

CASE 3.1



CASE 3.2



CASE 3.3