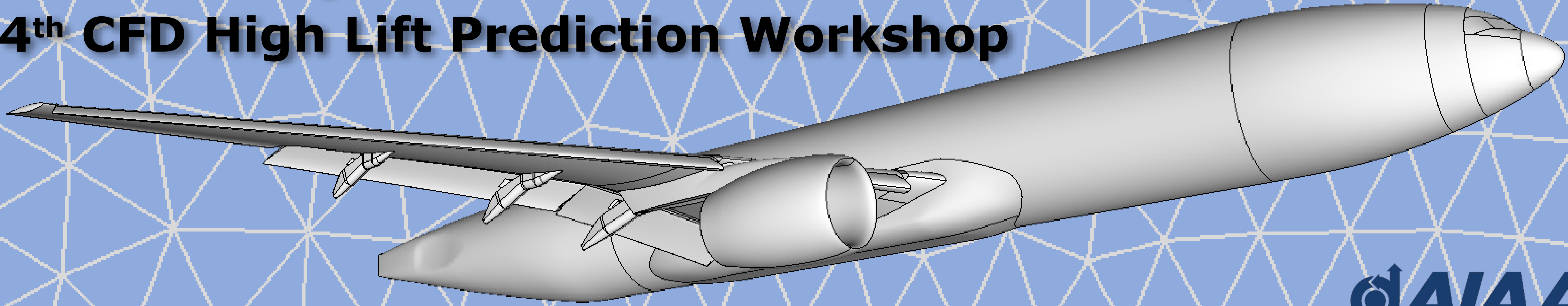
3rd Geometry and Mesh Generation Workshop
4th CFD High Lift Prediction Workshop



SHAPING THE FUTURE OF AEROSPACE

FUN3D Simulations for the 4th AIAA High-Lift Prediction Workshop

Nash'at Ahmad, Li Wang, Kyle Anderson, Ponnampalam Balakumar, Prahladh Iyer, Eric Nielsen

NASA Langley Research Center

APA-37/MVCE-09, AIAA Aviation Forum, June 29th, 2022, Chicago, Illinois

Outline

- Simulation Setup and Results for the 4th AIAA High-Lift Prediction Workshop
    - Case 1a: assessment of CFD methods to accurately predict changes in flap settings
    - Case 1b: grid convergence for nominal landing configuration
    - Case 2a: prediction of maximum lift, $C_{L,max}$
    - Case 3: verification of turbulence models
- Comparison of RANS and WMLES results
- Results are compared with data collected in the QinetiQ wind tunnel for the NASA High-Lift Common Research Model (CRM-HL)
    - Forces and pitching moment
    - Pressure data
    - Oil flow visualization
- Simulation results are also compared with data submitted by the participants of the RANS and WMLESLB Technical Focus Groups

Code Description

- FUN3D (Fully Unstructured Navier-Stokes 3D)
  - Uses unstructured grids
  - Node-centered finite volume scheme
  - Second-order accurate
  - Computation of viscous fluxes on tetrahedral meshes is based on the Green-Gauss theorem and on nontetrahedral grids, an edge-derivative augmentation is employed to avoid odd-even decoupling
  - Time integration toward a steady state is based on a backward-Euler scheme with local time-stepping to accelerate convergence
  - Hierarchal Adaptive Nonlinear Iteration Method (HANIM)
  - https://fun3d.larc.nasa.gov
- Several Turbulence Models
  - SA, SA-QCR2000, SA-RC-QCR2000
  - Wall-Modeled Large Eddy Simulation (WMLES)
  - https://turbmodels.larc.nasa.gov/

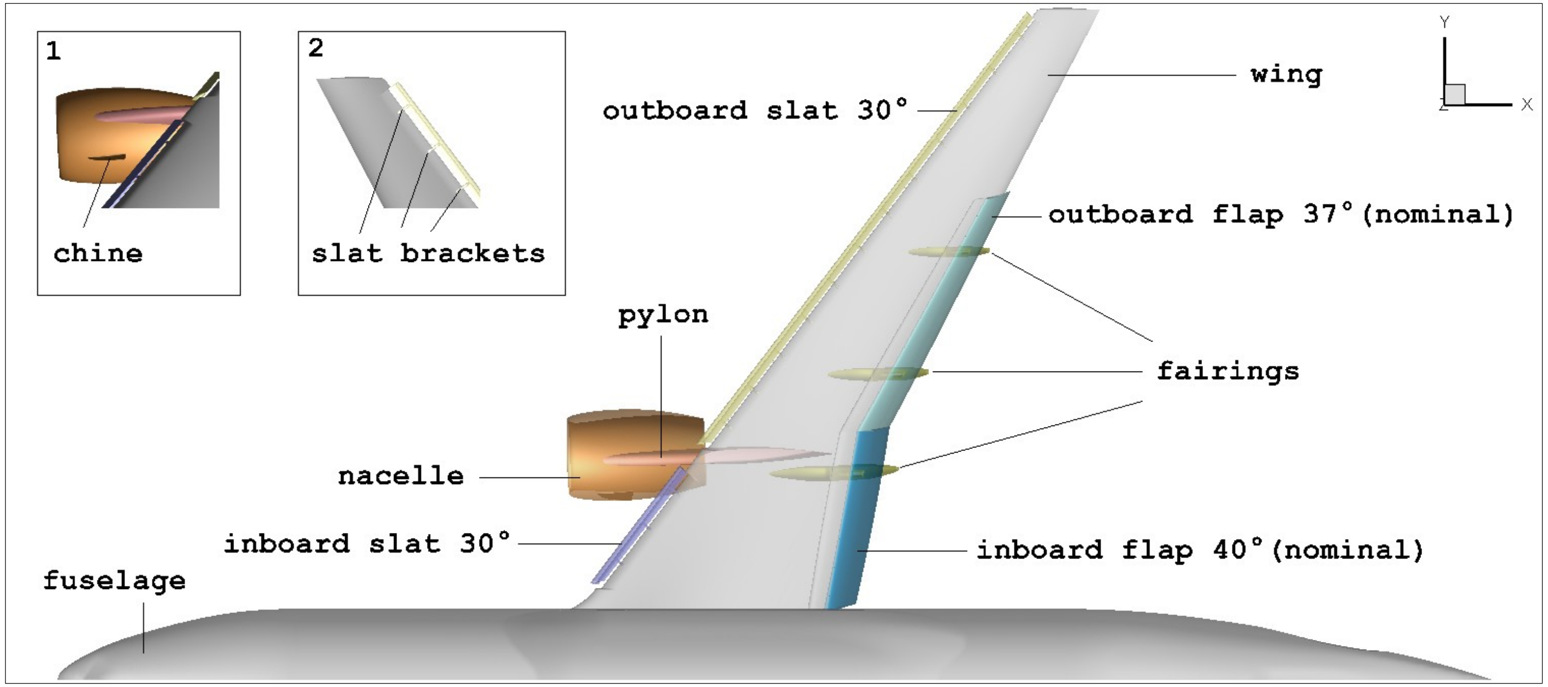
Simulations Setup

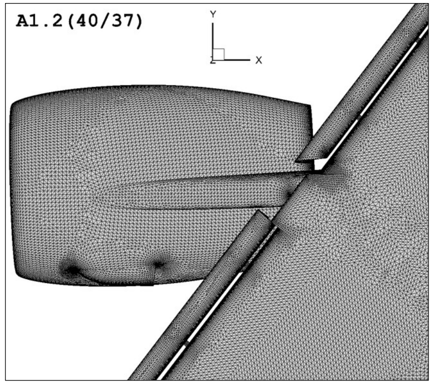
Reference Conditions

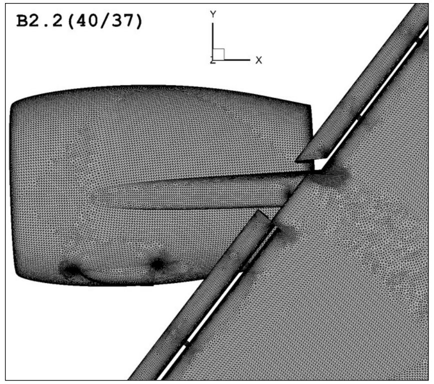
Parameter	**Value**
M	0.2
Re	5.49 million
T_{ref}	521 °R
α_i	2.78°, 7.05°, 11.29°, 14.46°, 17.05°, 19.57°, 20.55°, 21.47° (wall corrected)

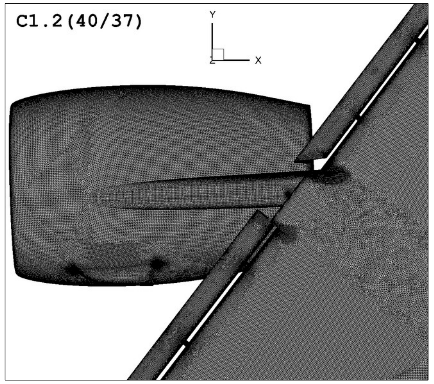
Three different flap settings: 40°/37° (nominal), 37°/34°, and 43°/40°

Geometry/Grids









Committee provided RANS Grids (40/37)

RANS Grid Size

Grid Level	Nodes
A1.2(40/37)	12×10^6
B2.2(40/37)	32×10^6
C1.2(40/37)	91×10^6
D2.2(40/37)	202×10^6

WMLES Grid Size

Grid Level	Nodes
B(40/37)	156×10^6
A(40/37)	418×10^6

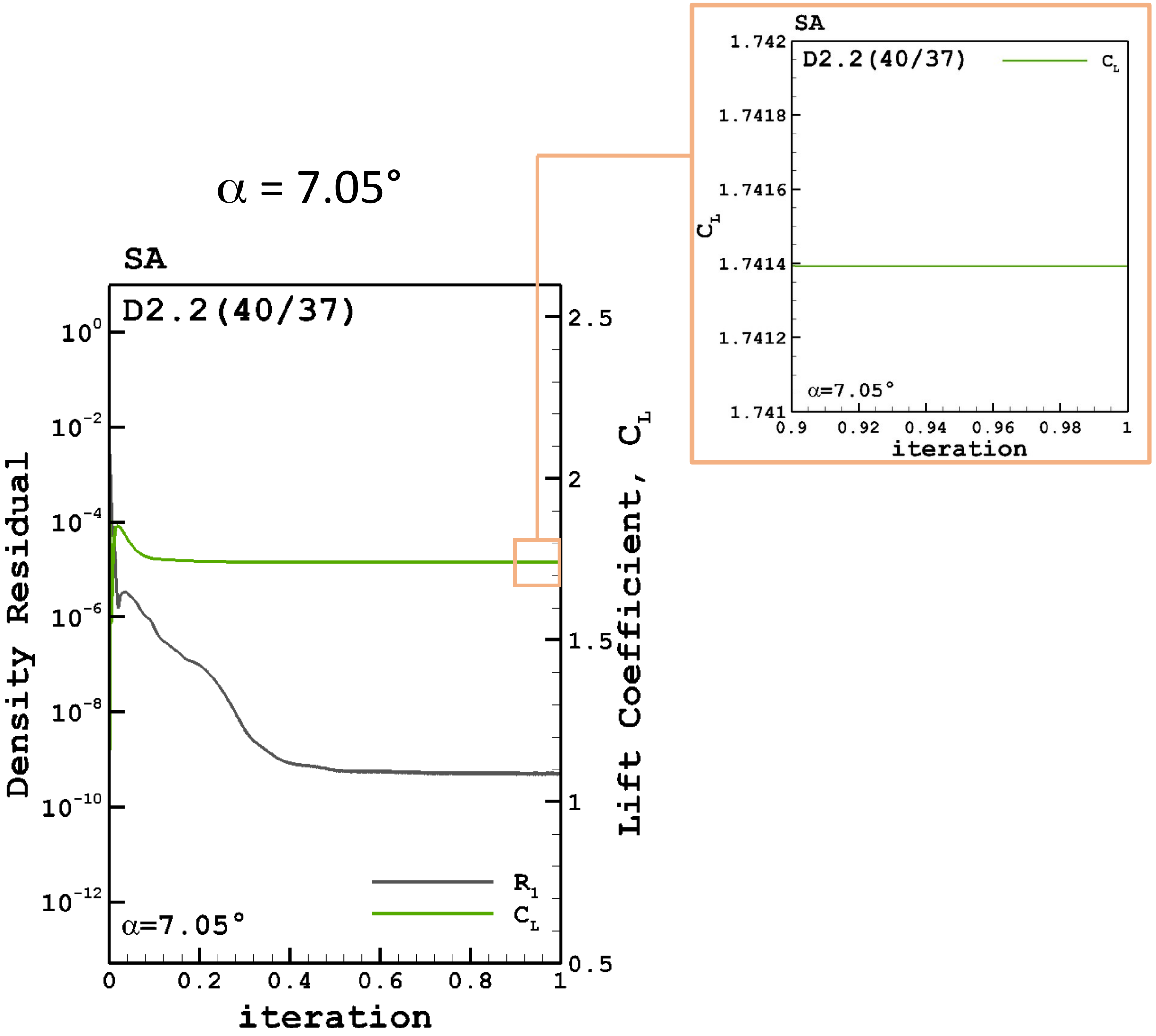
RANS Simulations Setup

- Started from the freestream (except for, α = 20.55° case)
- No initial first-order iterations
- Simulations were "free-air" using a half-model with symmetry boundary conditions in the *x-z* plane
- Riemann-invariants-based boundary conditions were imposed at the farfield.
- All simulations were run fully-turbulent
- SA, SA-QCR2000, SA-RC-QCR2000 turbulence models used
- Roe solver with no flux limiting
- 8–9 orders of magnitude reduction in the mean flow residuals for most cases) to quasisteady-state in case of SA and SA-QCR2000

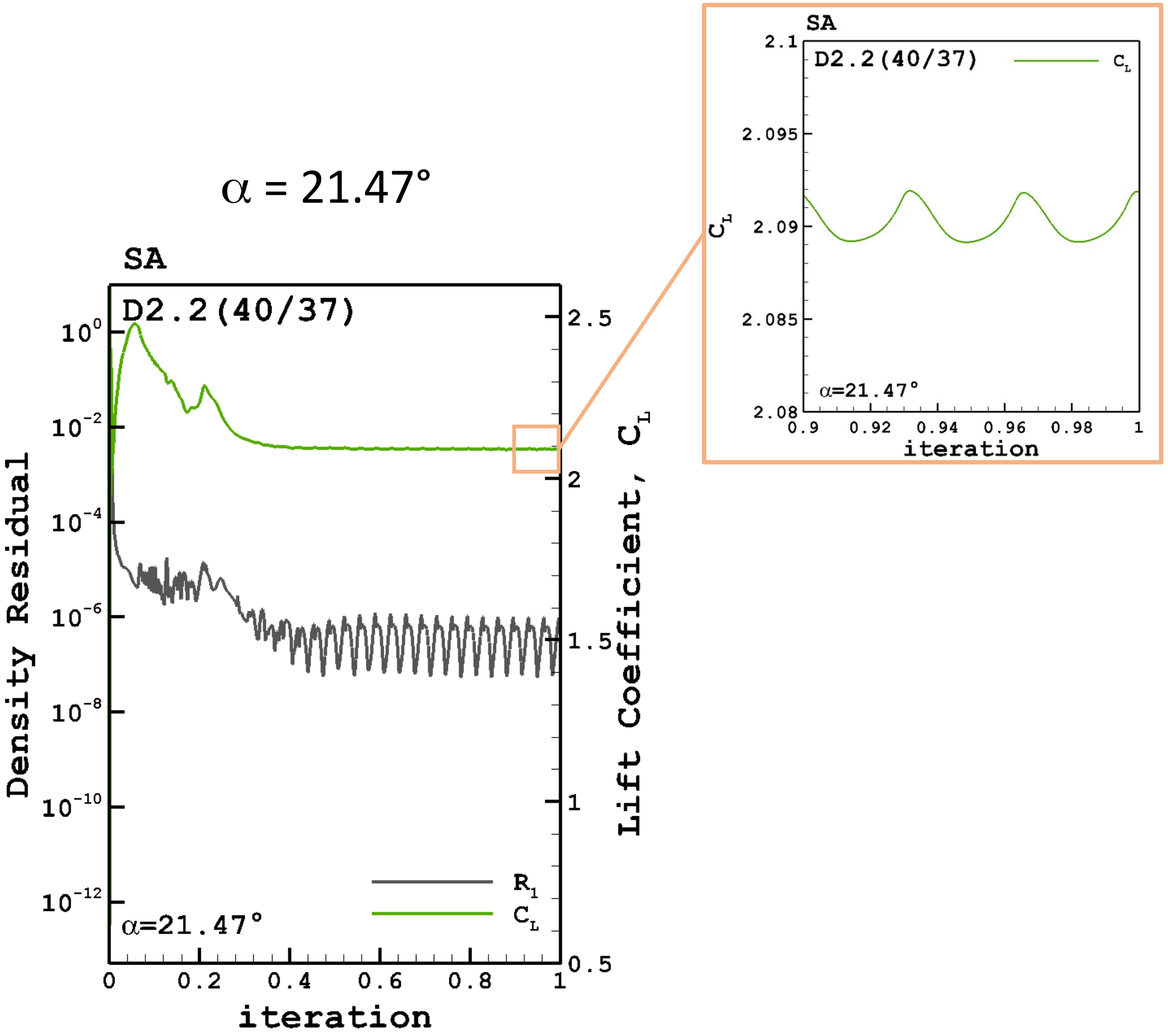
Typical RANS Convergence (flaps:40/37; grid:D2.2; SA)

x-axis is scaled from zero to one

α = 7.05°



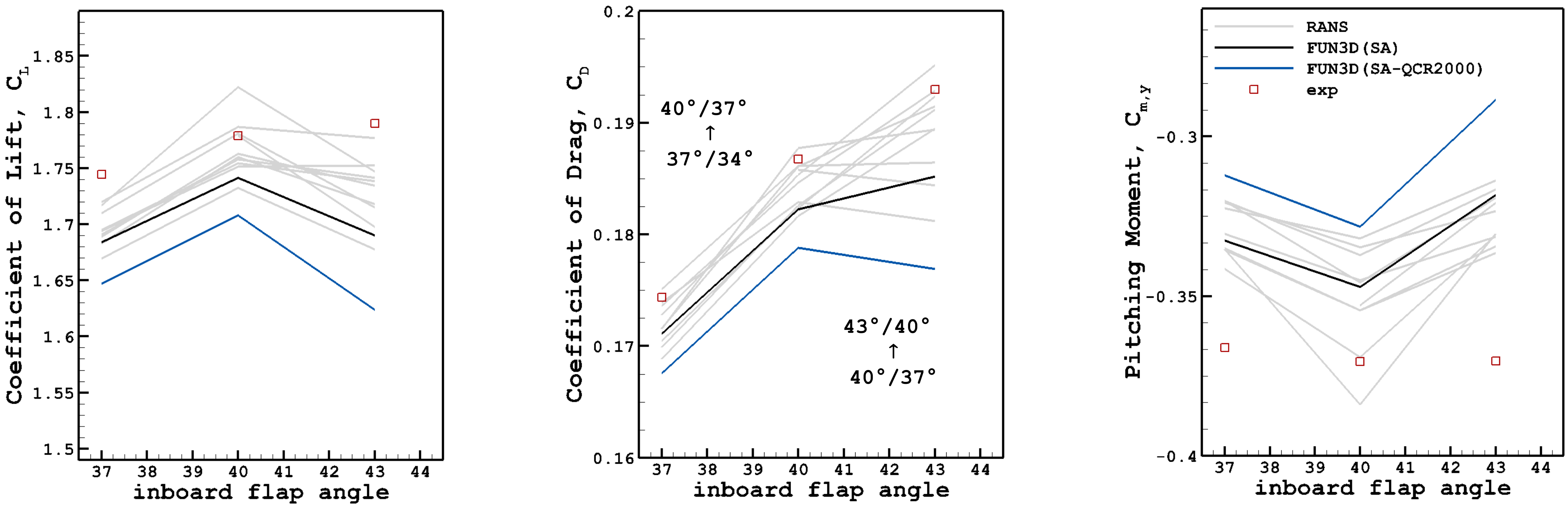
α = 21.47°



WMLES Setup

- Vreman subgrid scale eddy viscosity model
- Initial time step was chosen such that 1,000 time-steps represented a single convective time unit (CTU)
- In the first stage of the simulation, initial transients were eliminated (8–10 CTUs)
- Once the transients were eliminated, the time step was reduced to improve the temporal accuracy (2,000 time steps per CTU)
- The UMUSCL parameter was increased to 0.9 from 0.5 after approximately 8 CTUs in order to reduce spatial dissipation
- Time-averaged quantities were averaged over 5–15 CTUs after the transients in the forces and moments had been sufficiently reduced
- 4–5 orders of magnitude reduction in the residuals was achieved using HANIM

Flap Deflection Study using RANS

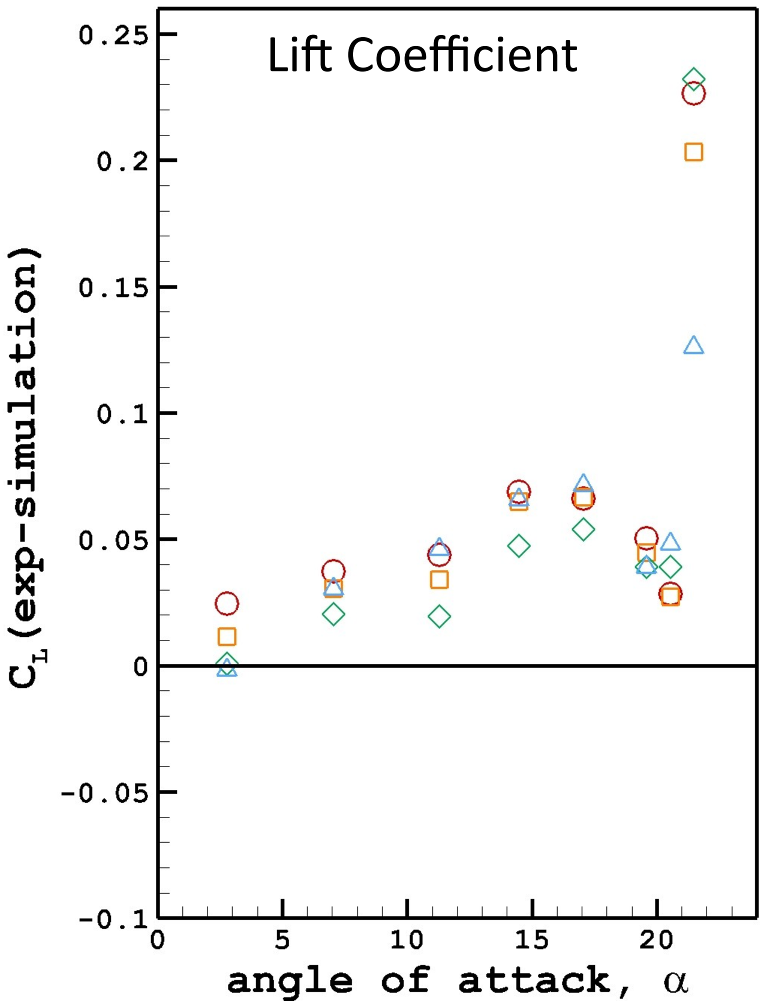


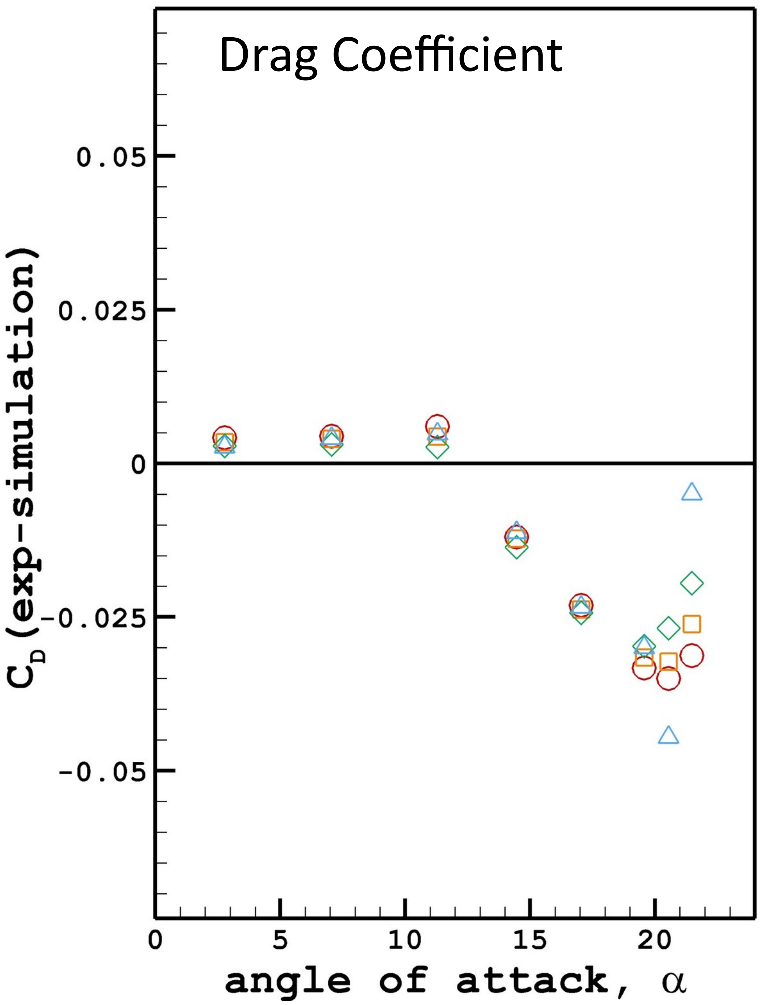
The increase in lift and drag for the first increment seen in the measurements was captured by RANS, while the decrease in pitching moment was overpredicted.

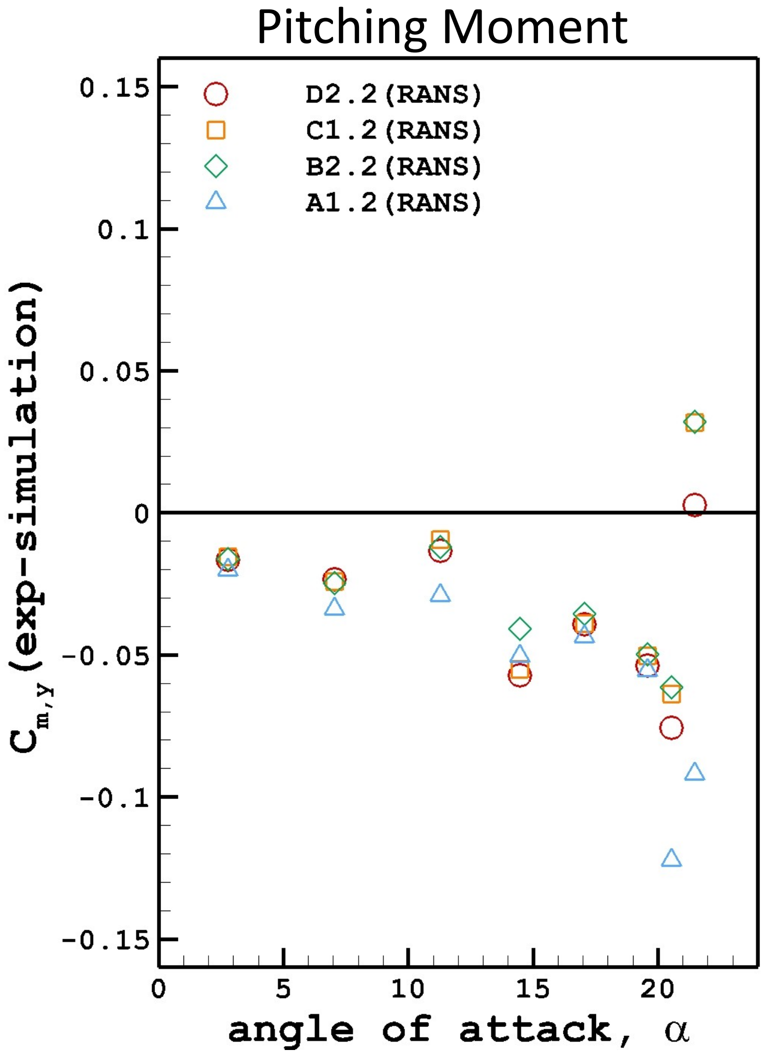
The change in lift and pitching moment seen in the second flap-setting increment was not captured by FUN3D.

The SA-QCR2000 predicts lower values in lift and drag, and higher values of pitching moment than the SA model.

Effect of Mesh Refinement (RANS)

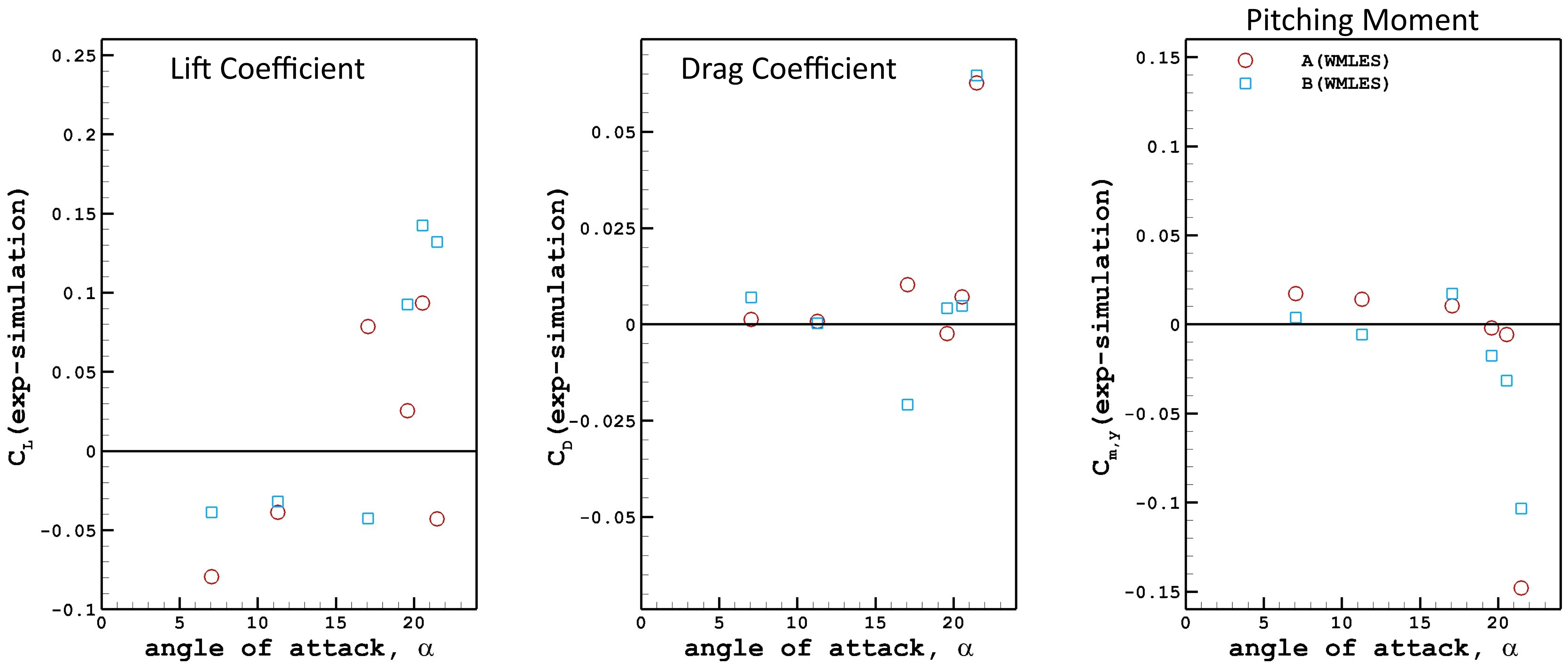






In general, for RANS, no trend toward measurements with increased mesh resolution could be demonstrated through the entire range of angle of attack.

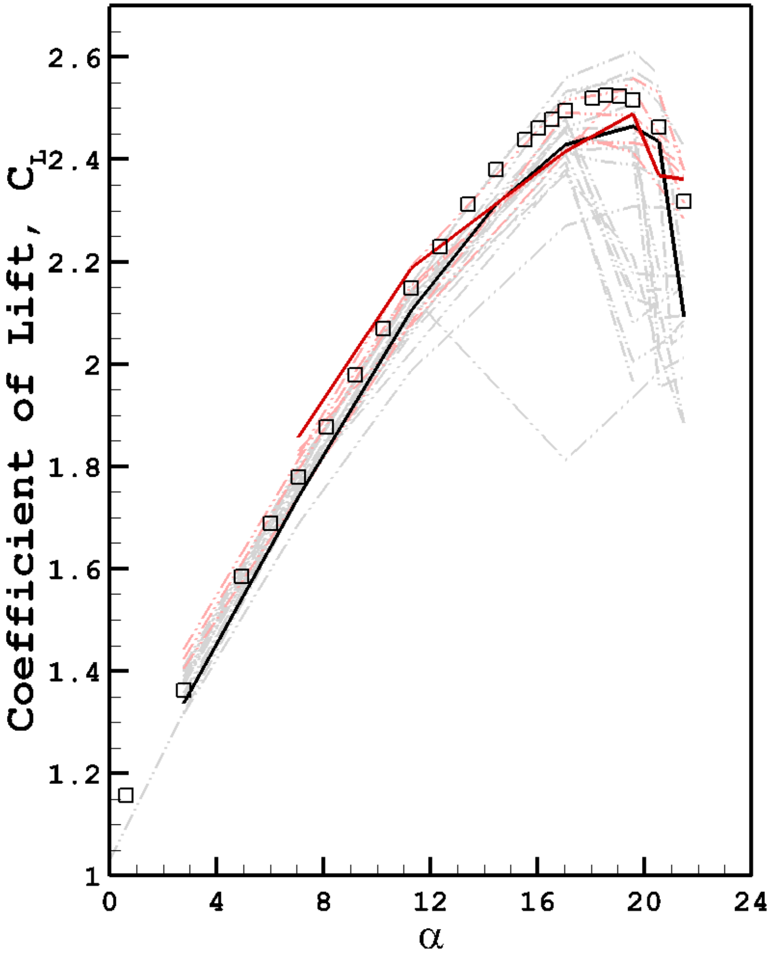
Effect of Mesh Refinement (WMLES)



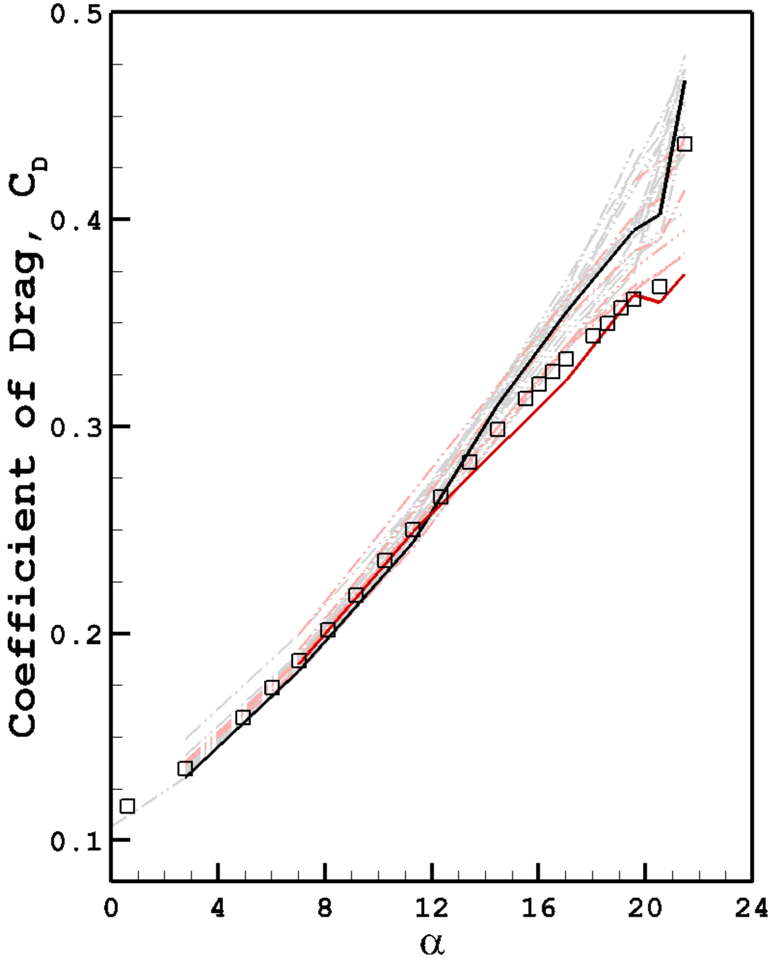
The WMLES accuracy compared with experiment was generally better than RANS near $C_{L,max}$.

Prediction of Maximum Lift

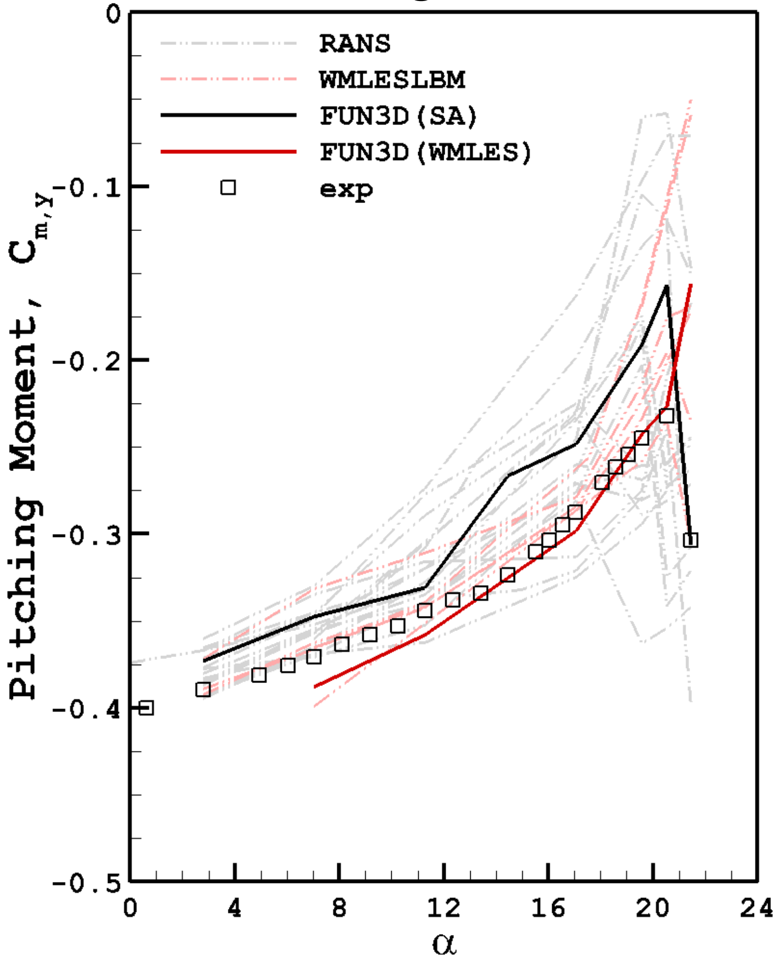
Lift Coefficient



Drag Coefficient



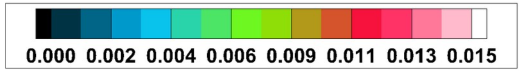
Pitching Moment

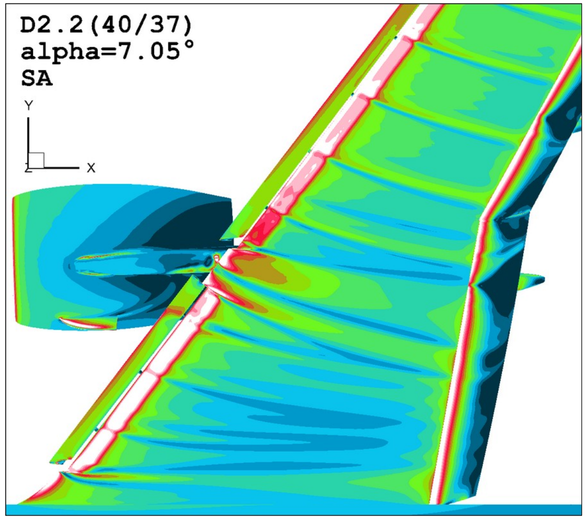


$C_{L,max}$ at α = 18.57°

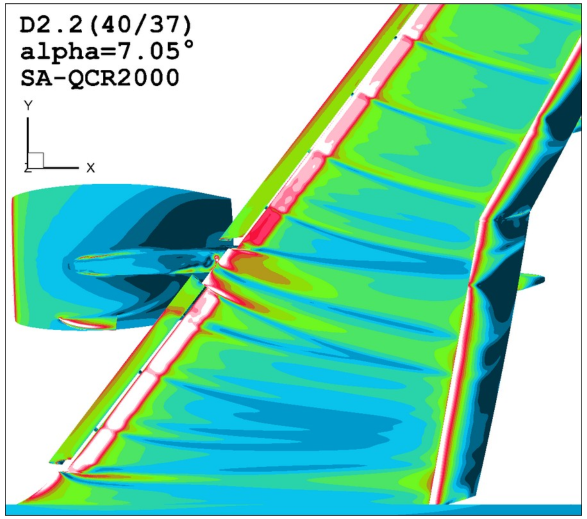
Comparison of RANS and WMLES Results (α=7.05°)

Surface Skin Friction

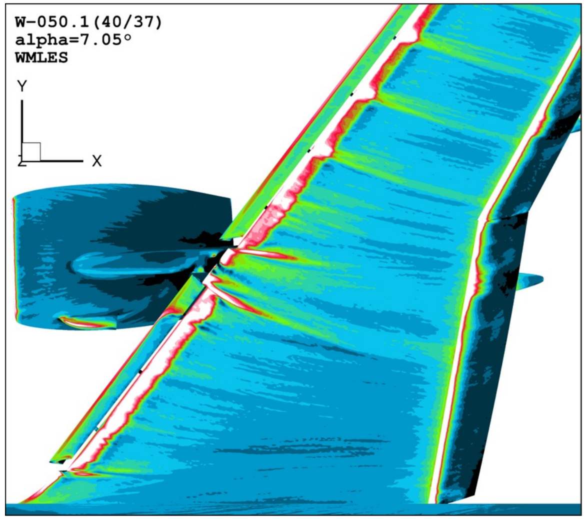




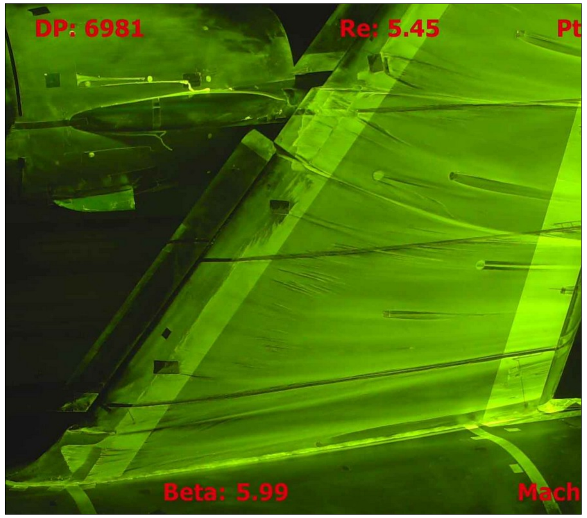
SA



SA-QCR2000



WMLES



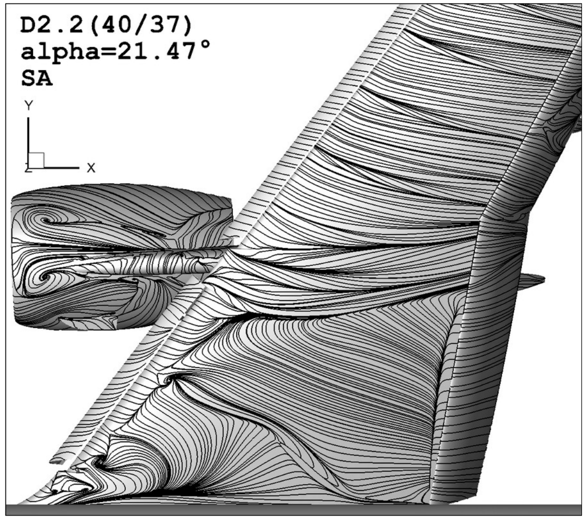
Oil Flow

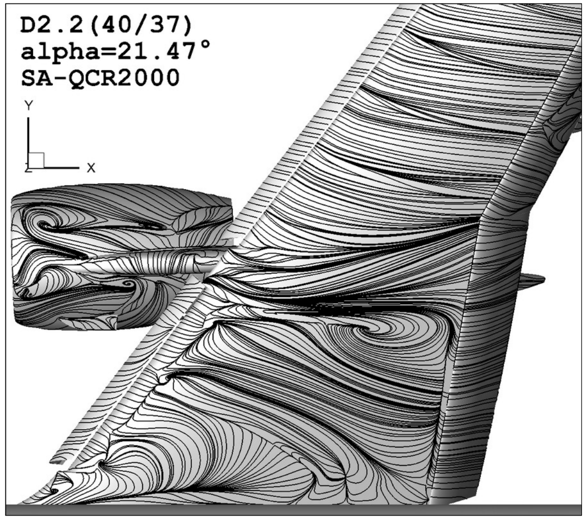
The flow appears more separated on the nacelle/pylon in the simulations compared to what is observed in the oil flow photo.

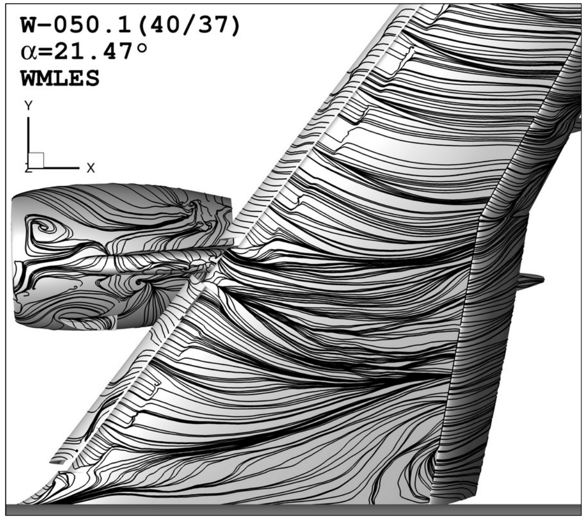
The extent and the level of separation in the WMLES simulations is smaller than what is predicted by RANS.

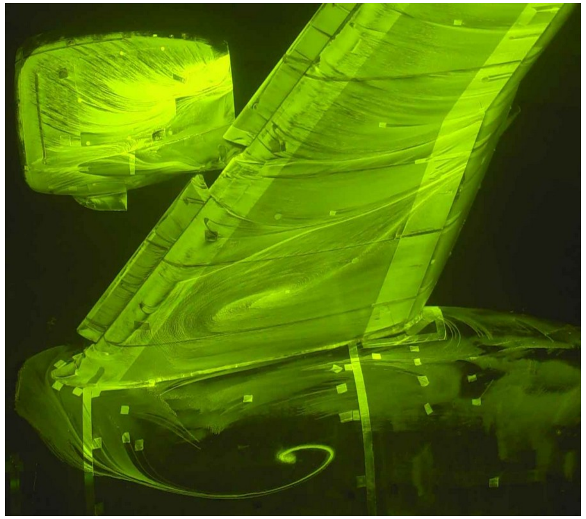
Comparison of RANS and WMLES Results (α=21.47°)

Surface Streamlines









SA

SA-QCR2000

WMLES

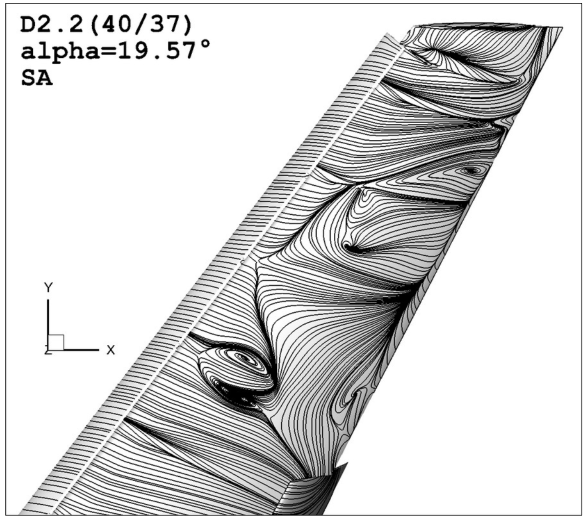
Oil Flow

RANS simulations show massive separation on the inboard wing at this high angle of attack.

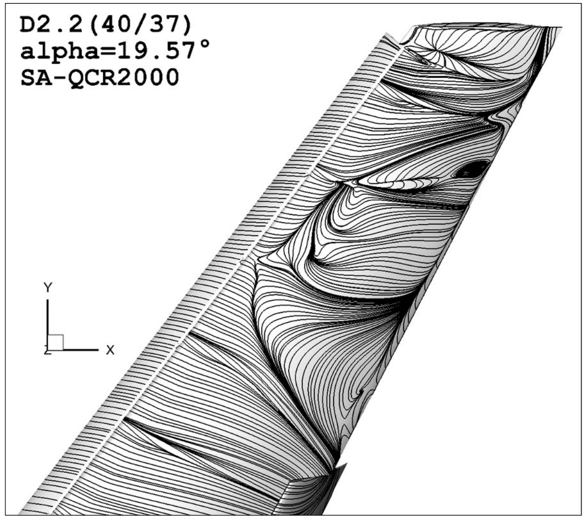
The WMLES simulation show less separation and is qualitatively closer to the oil flow visualization on the inboard wing.

Comparison of RANS and WMLES Results (α=19.57°)

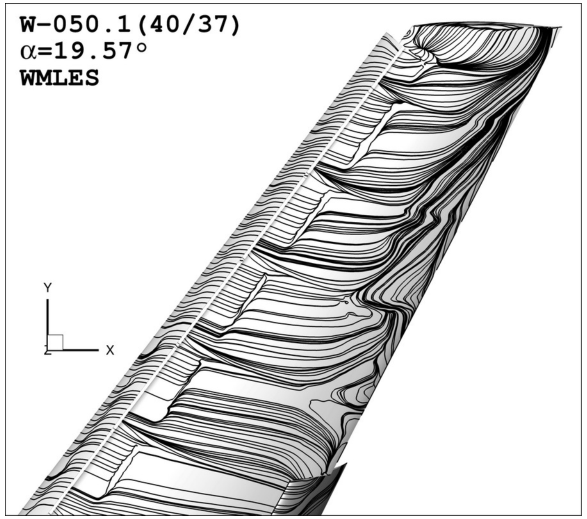
Surface Streamlines



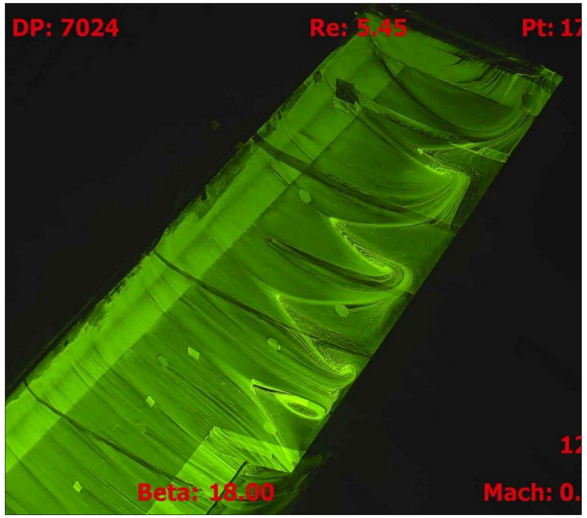
SA



SA-QCR2000



WMLES

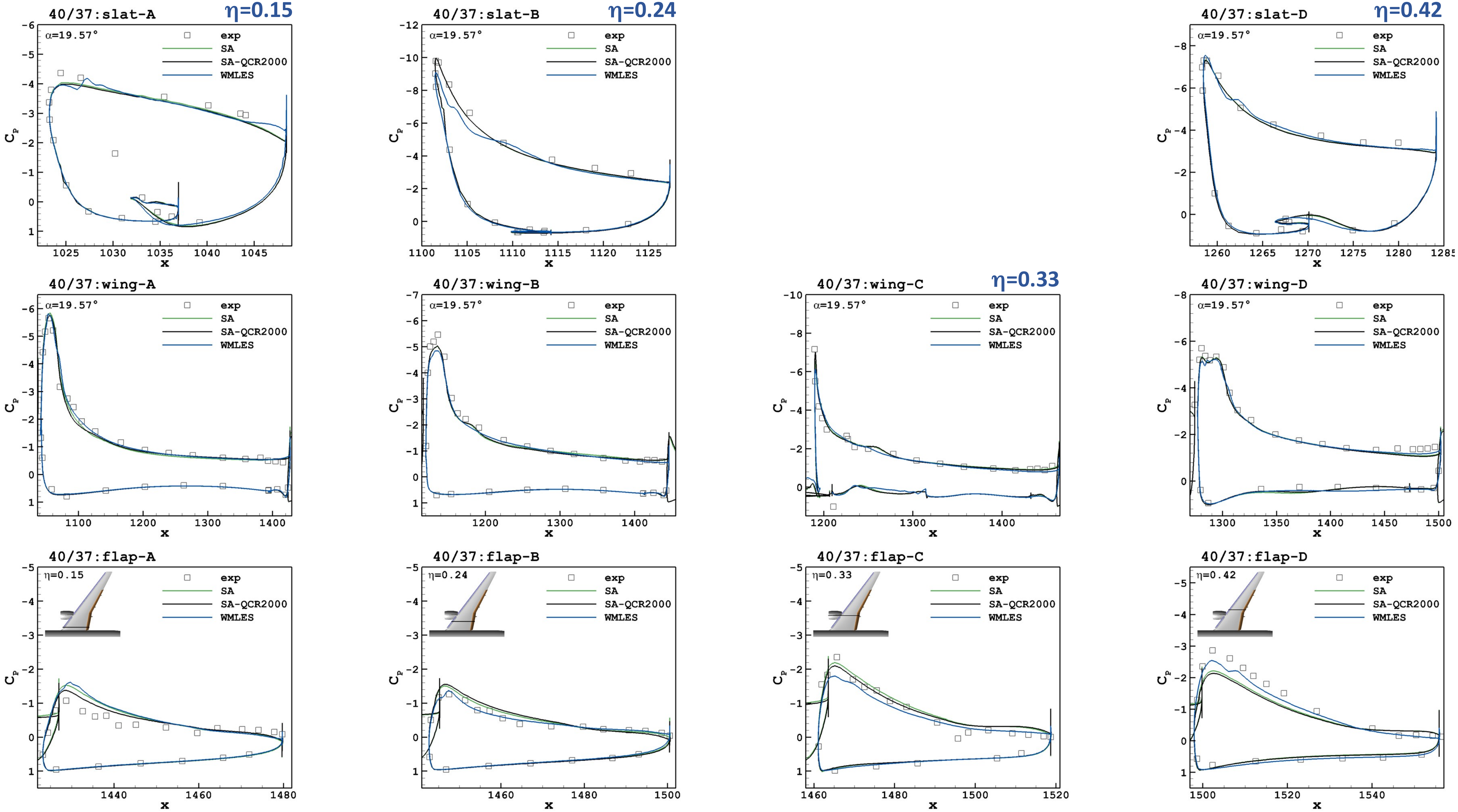


Oil Flow

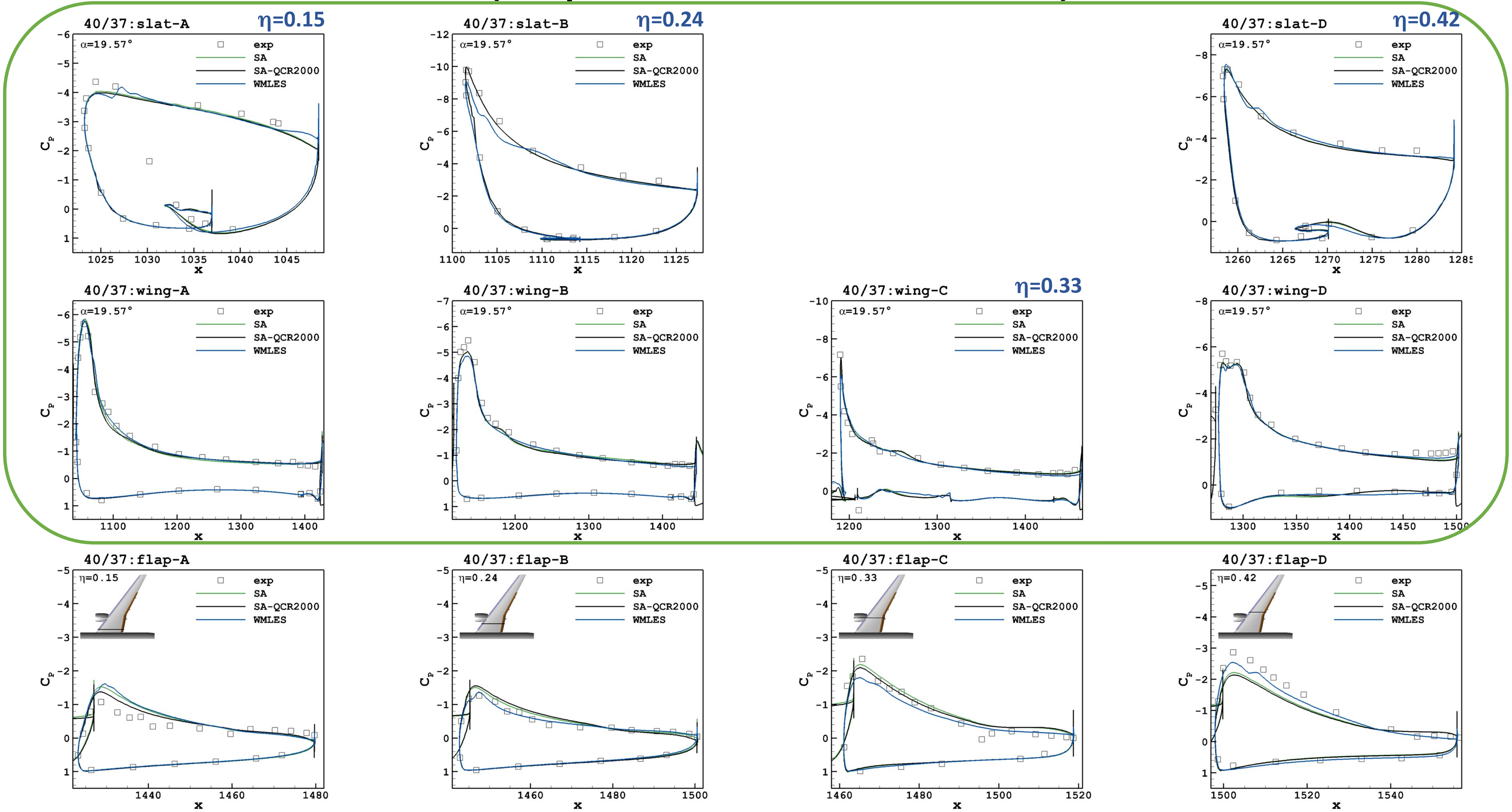
RANS shows a large region of massive separation on the outboard wing.

The level of separation in WMLES is smaller, however, the simulated flow pattern at the wing trailing edge is different than what is observed in the oil flow visualization.

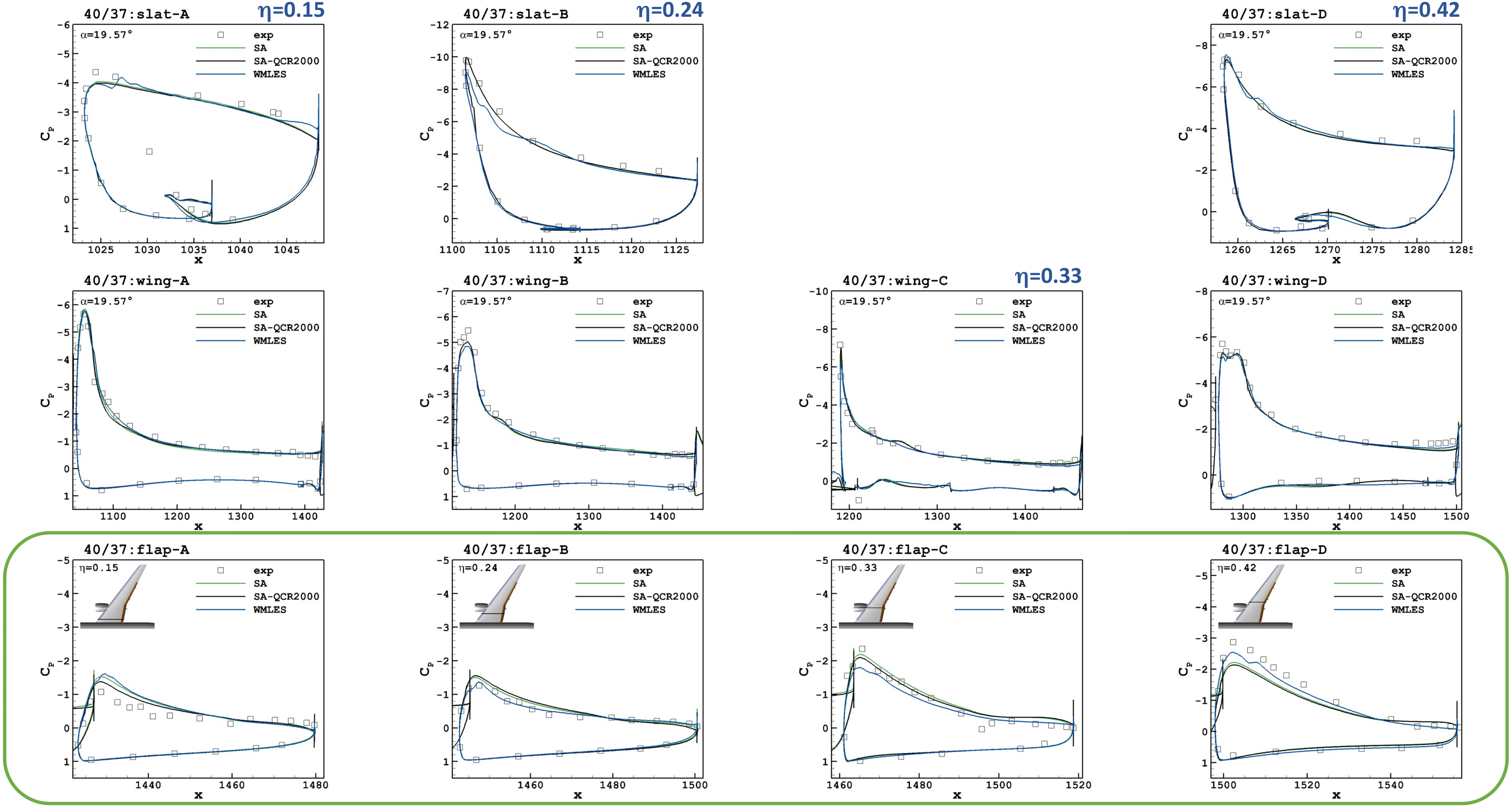
Pressure Coefficient (flaps:40/37; α = 19.57°)



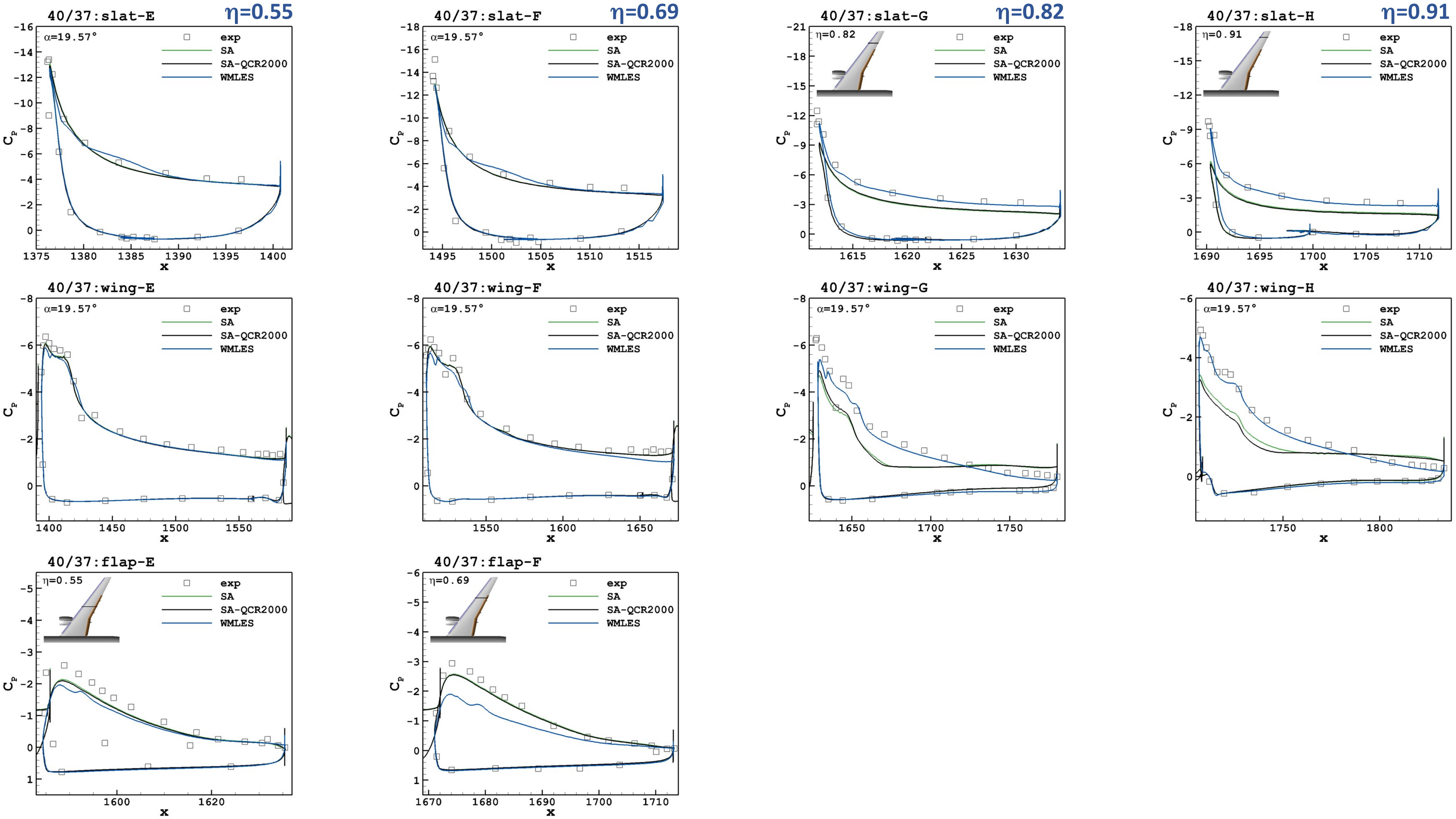
Pressure Coefficient (flaps:40/37; α = 19.57°)



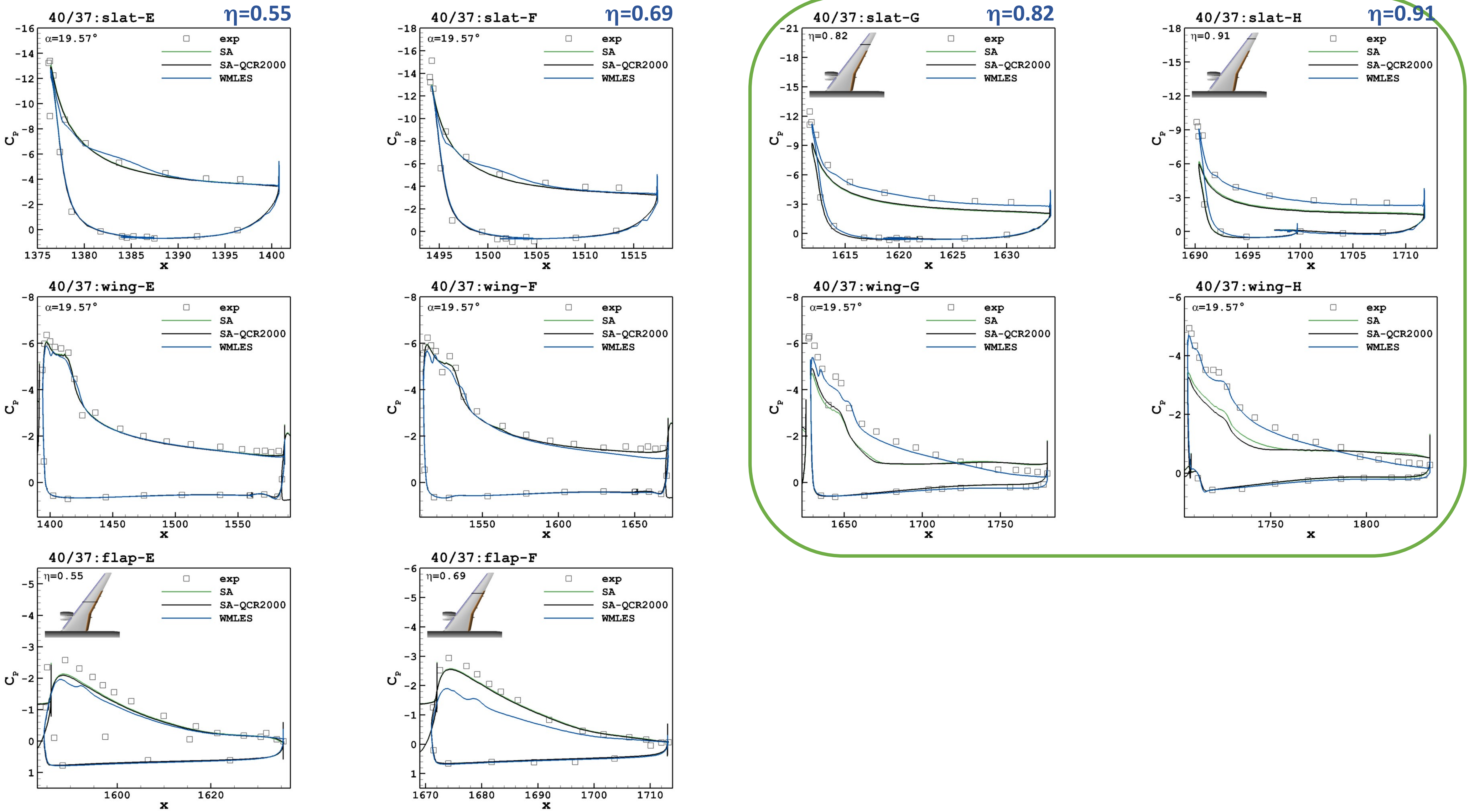
Pressure Coefficient (flaps:40/37; α = 19.57°)



Pressure Coefficient (flaps:40/37; α = 19.57°)



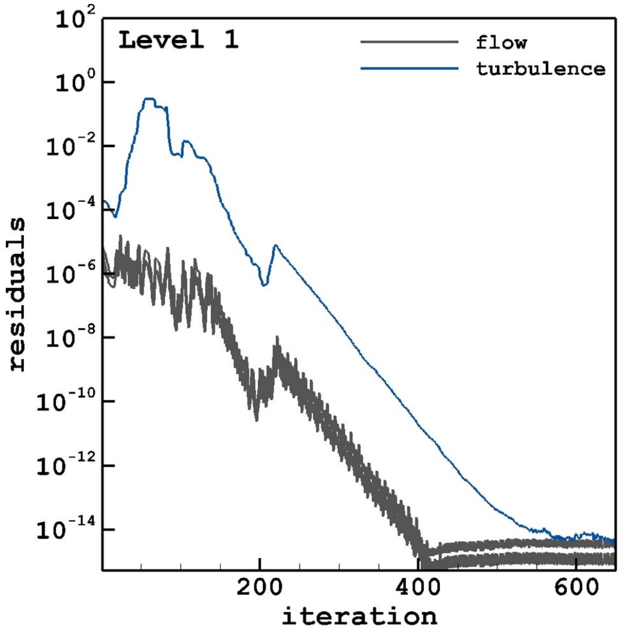
Pressure Coefficient (flaps:40/37; α = 19.57°)

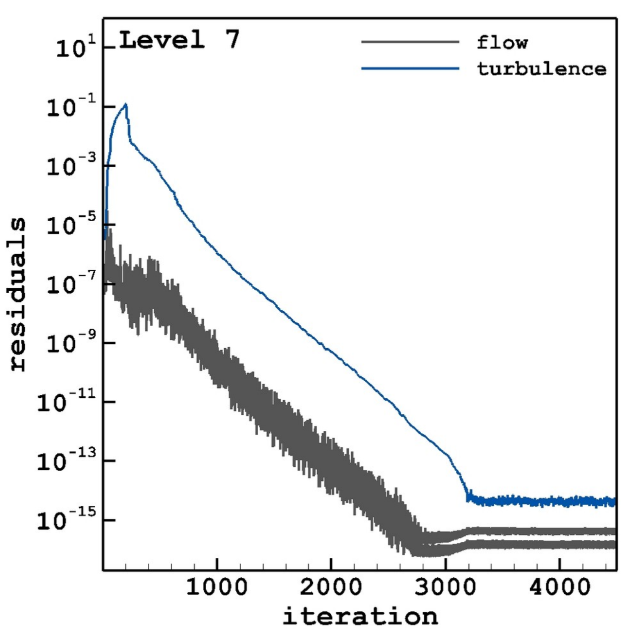


Verification of Turbulence Models

Reference Conditions

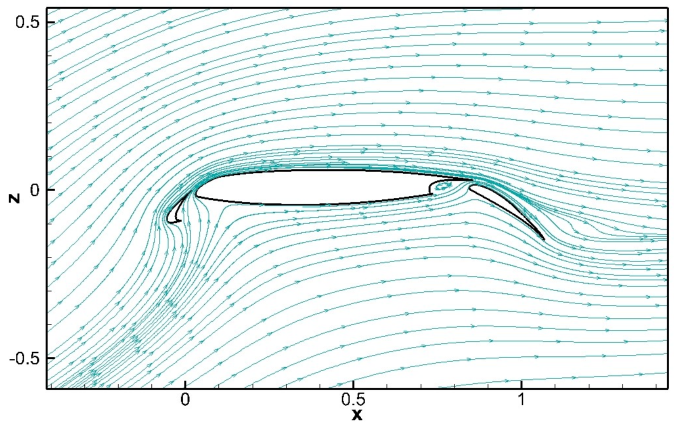
Parameter	Value
M	0.2
Re	5,000,000.0
T_{ref}	272.1 K
α	16°





Grids

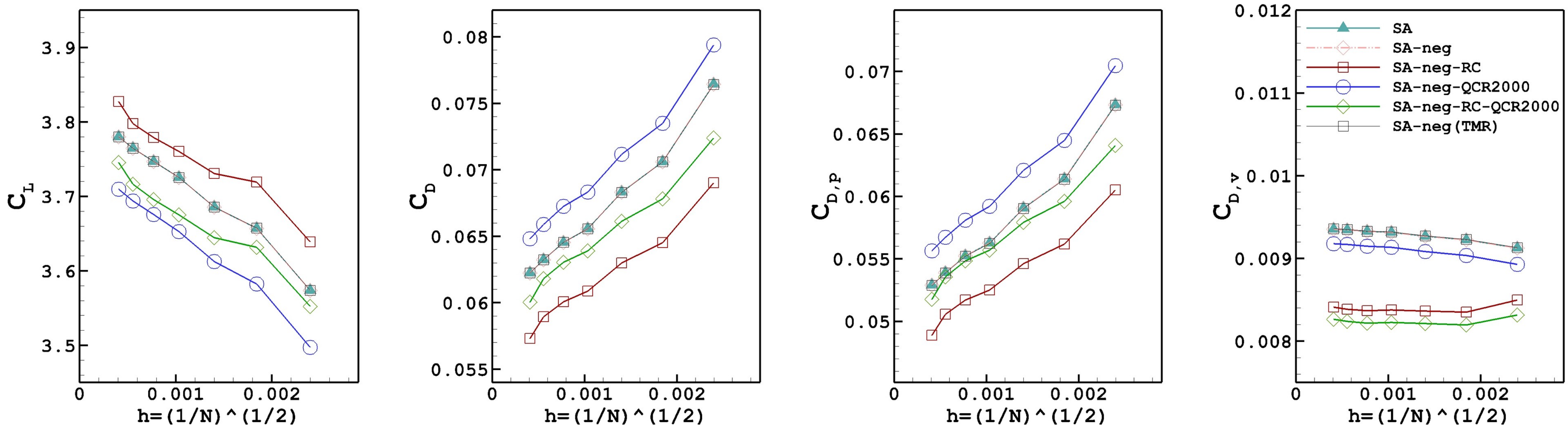
Grid Level	Nodes
1	1.73×10^5
2	2.94×10^5
3	5.08×10^5
4	9.30×10^5
5	1.67×10^6
6	3.22×10^6
7	5.98×10^6



2D multielement airfoil based on CRM-HL

Verification of Turbulence Models

Note: SA, SA-neg, SA-neg (TMR) curves are identical



Verification is only possible when plotting the results in conjunction with other verified benchmark CFD results that use the same model. Although not shown here, FUN3D's SA and SA-neg models were fully consistent (verified) with other SA results.

Conclusions

- RANS results for lift compared relatively well with measurements at lower alphas in the linear range with larger deviations from measurements at higher alphas.
- In general, the WMLES results showed an improvement in the drag and pitching moment predictions compared to RANS.
- The simulated C_p compared relatively well with measurements on the slats and the wing, with differences on the flaps for both RANS and WMLES.
- At higher alphas, the RANS results showed massive separation on the outboard wing, whereas the WMLES C_p predictions agreed reasonably well with the measurements on the outboard wing at high angles of attack.
- In general, for RANS, no trend toward measurements with increased mesh resolution could be demonstrated through the entire range of angle of attack.
- WMLES accuracy compared with experiment was generally better than RANS near $C_{L,max}$.

Acknowledgments

- NASA Transformational Tools and Technologies (TTT) Project of the Transformative Aeronautics Concept Program

- Many thanks to Chris Rumsey, Mike Park, Beth Lee-Rausch, Mohagna Pandya, and Michael Bozeman for very helpful discussions on the topic

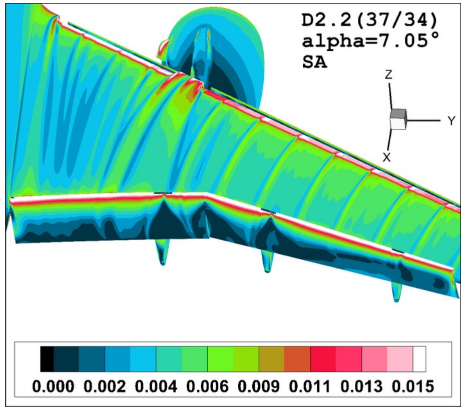
- Participants of the RANS and WMLESLB TFGs

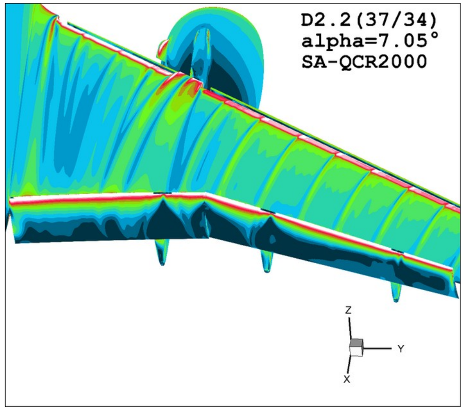
- Mike Wiese, Scott Brynildsen, and Norma Farr for providing the WMLES grids

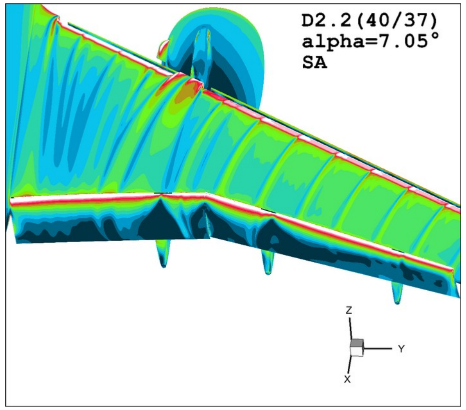
- The simulations were conducted using the NASA Advanced Supercomputing (NAS) resources at NASA Ames research Center and on NASA Langley's K-cluster

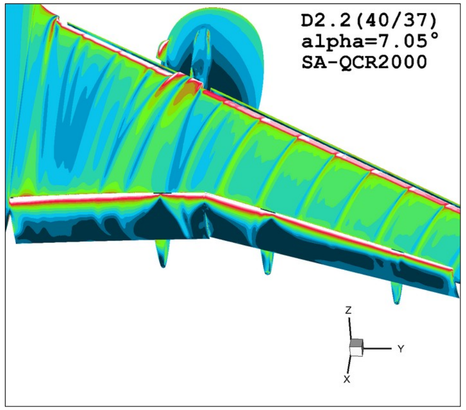
Backup Slides

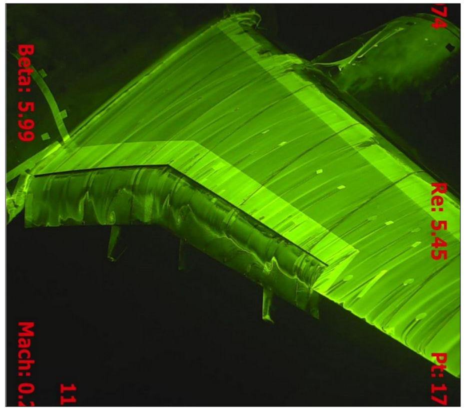
Flap Deflection Study

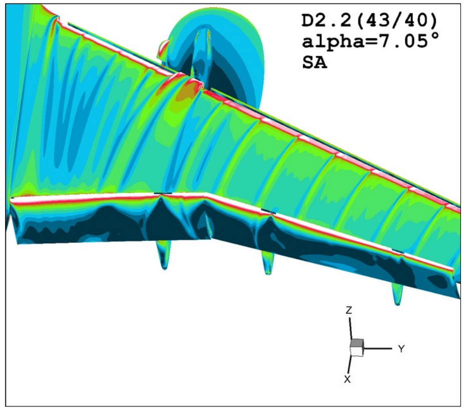


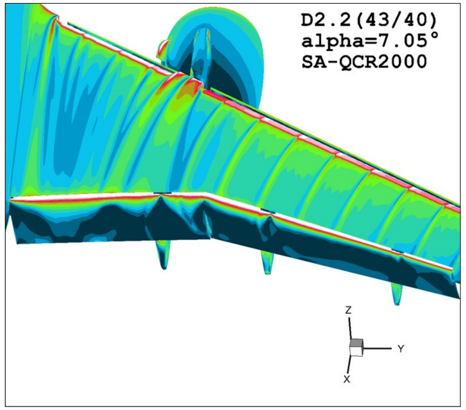




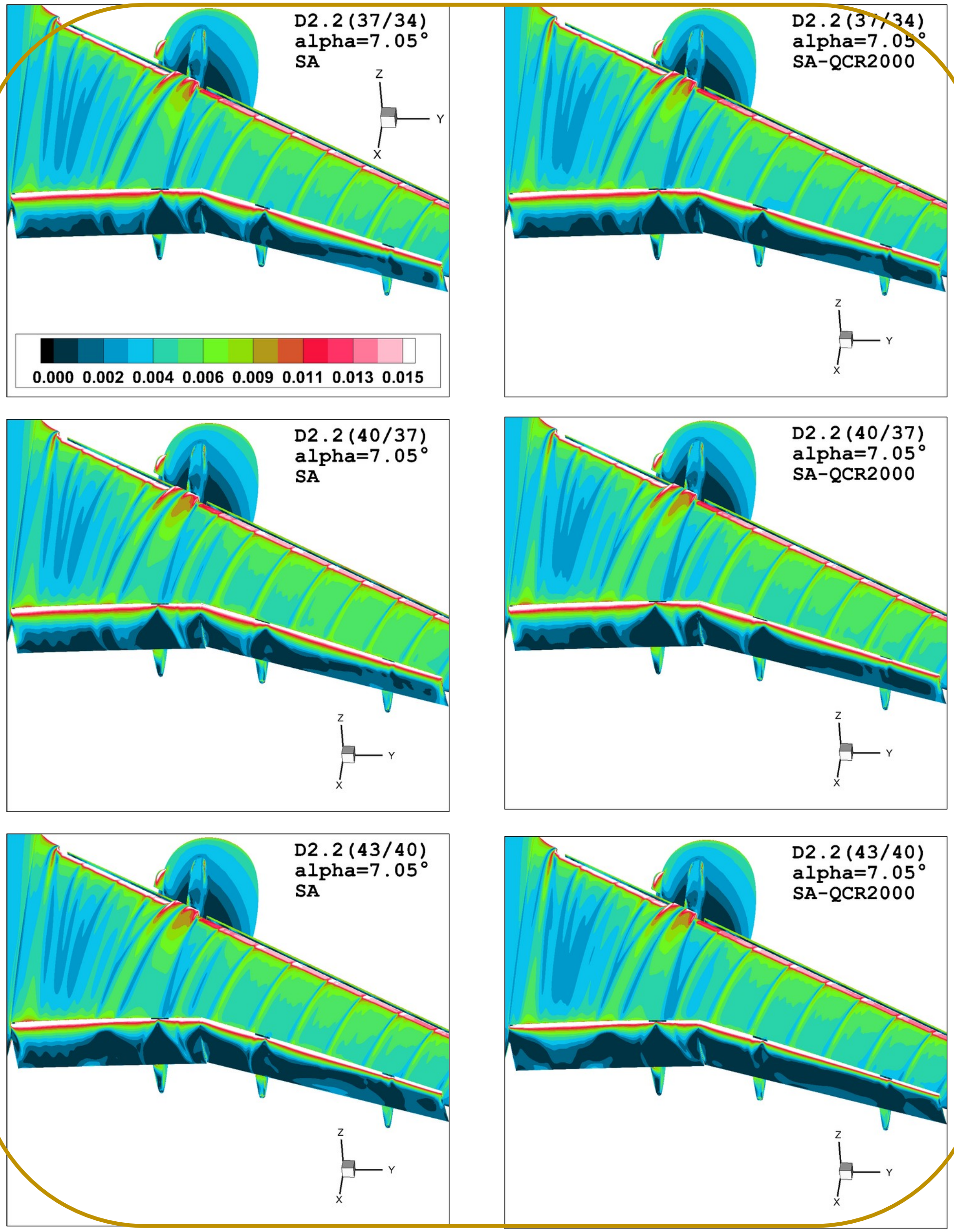




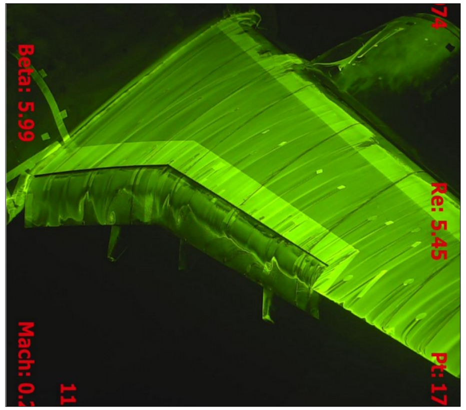




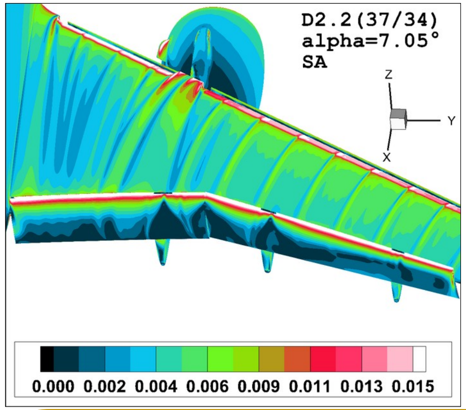
Flap Deflection Study

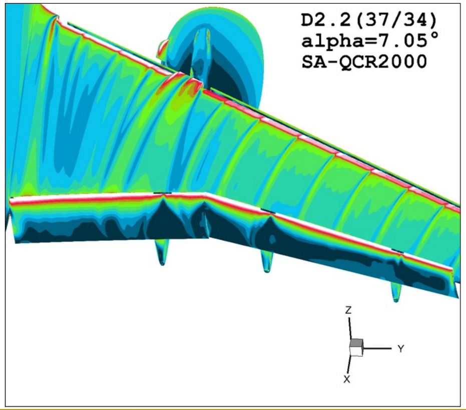


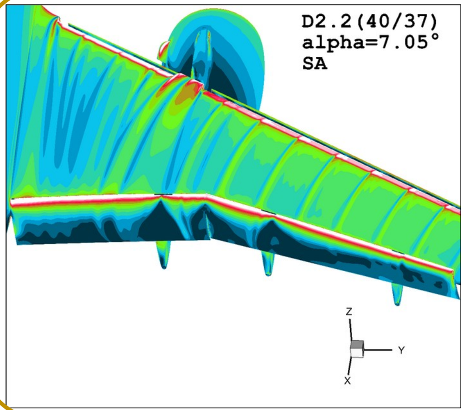
The flow topology for the two turbulence models in general is similar

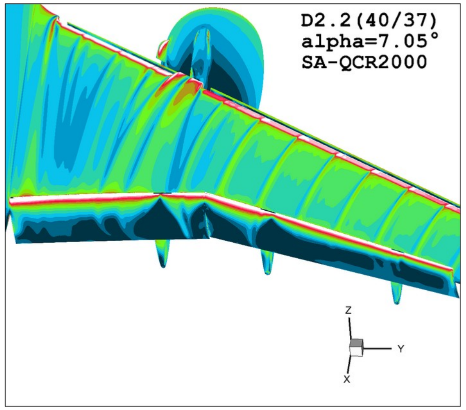


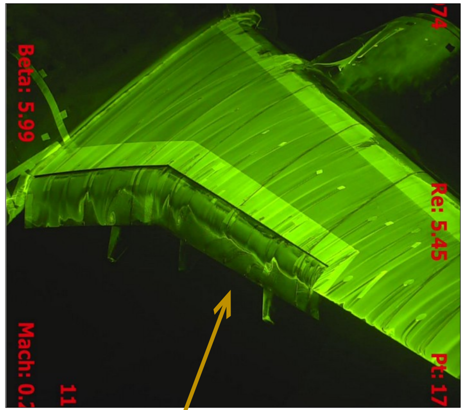
Flap Deflection Study

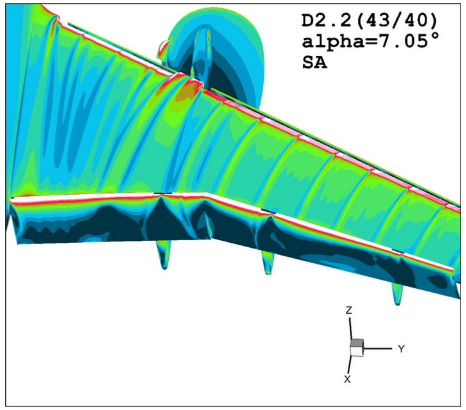


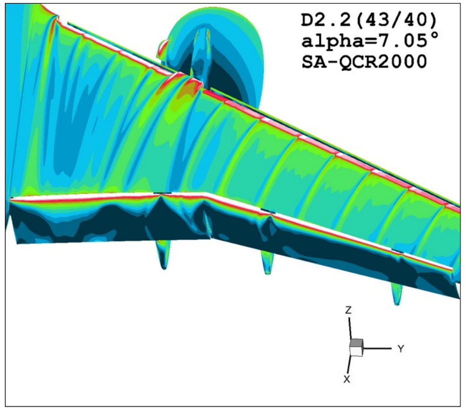






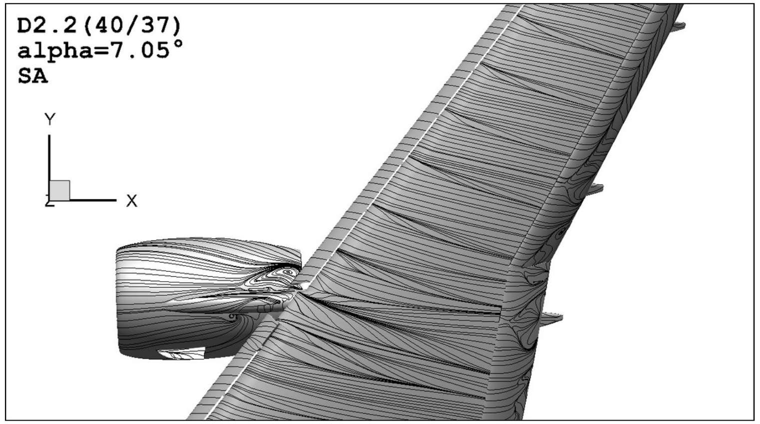


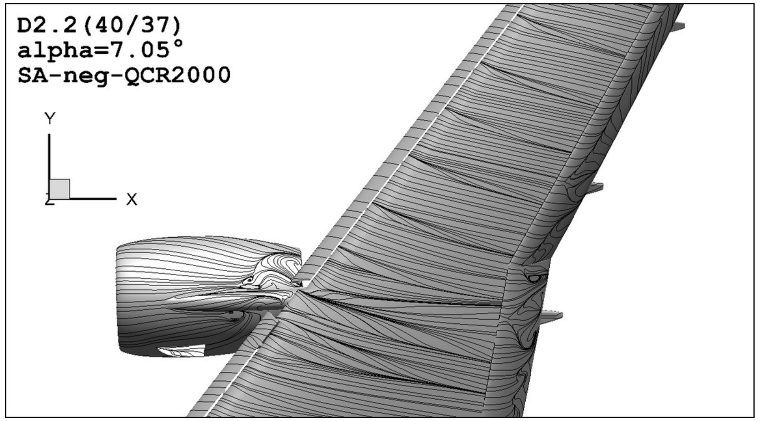


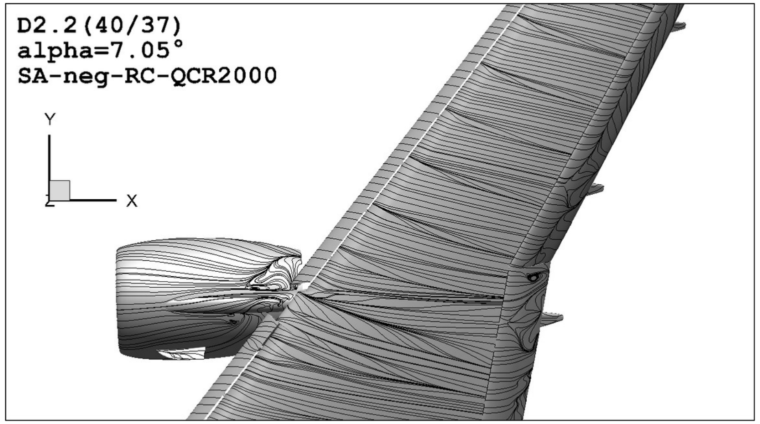


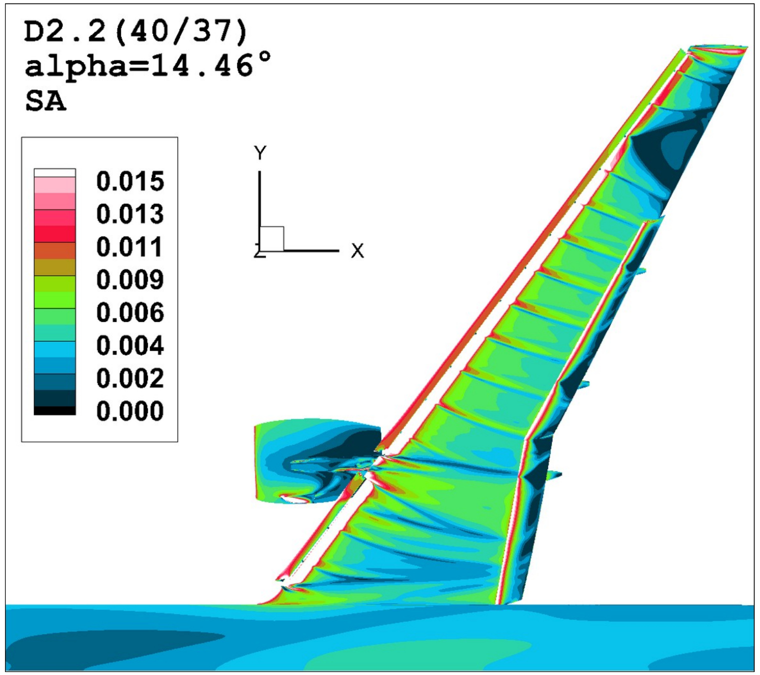
The separation on the outboard flap in the experiment is less extensive than in the FUN3D predictions

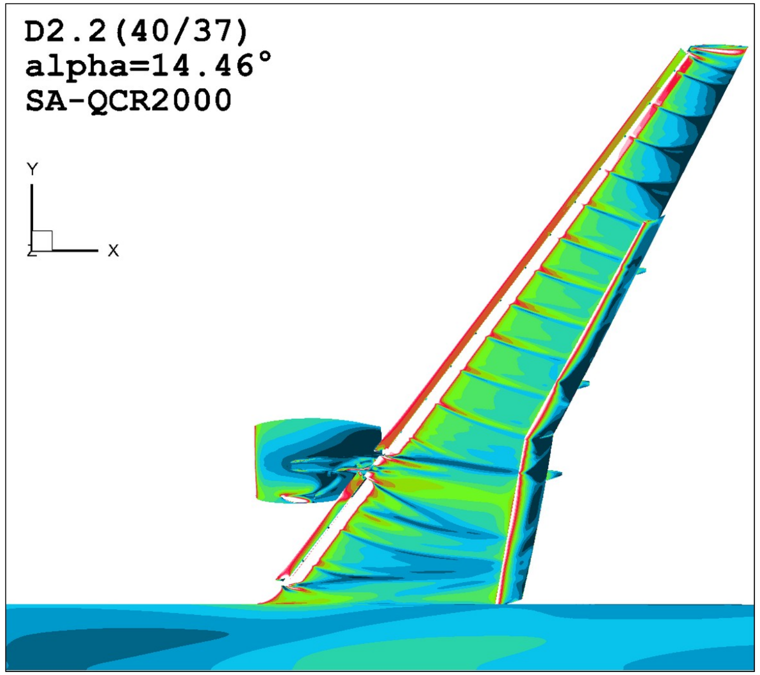
Turbulence Methods

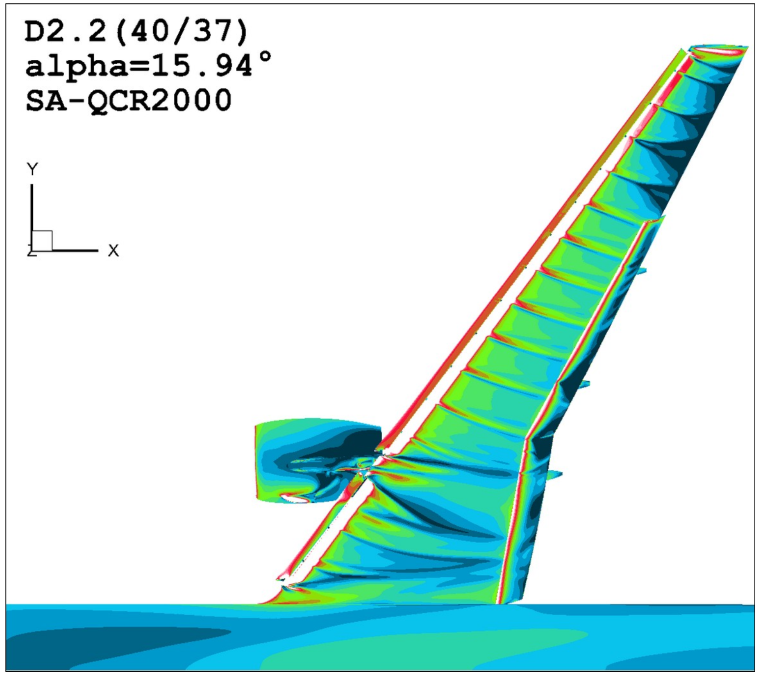




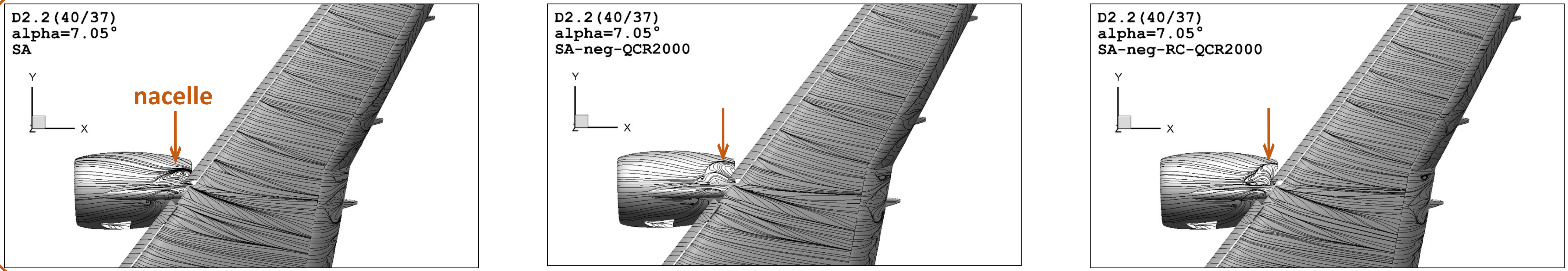


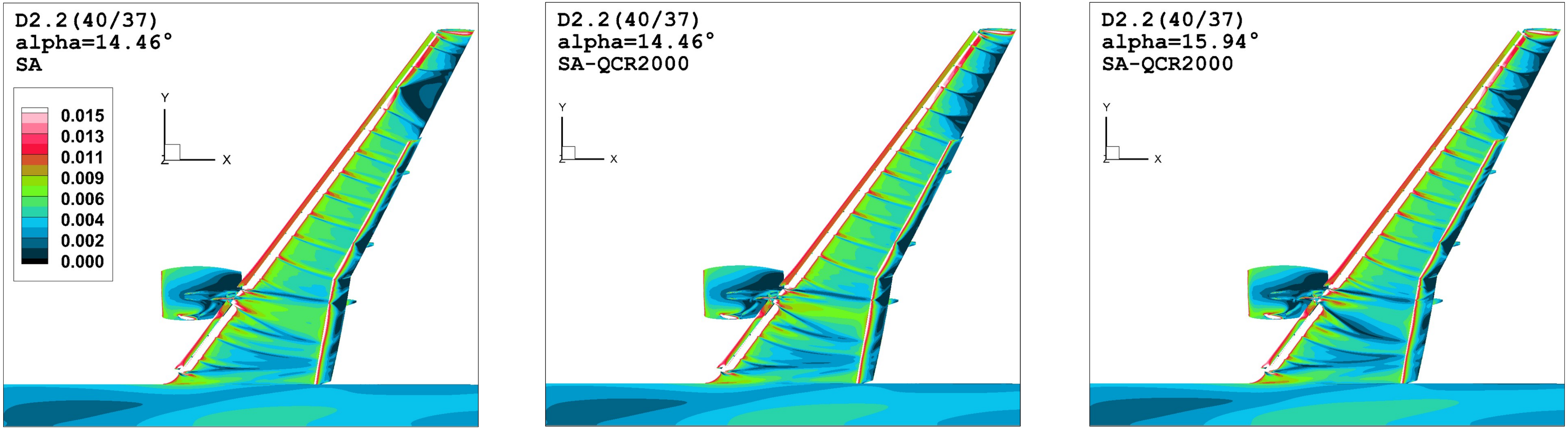




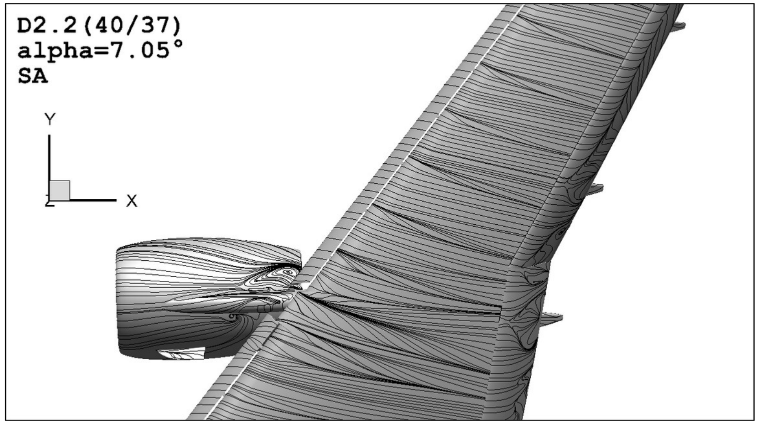


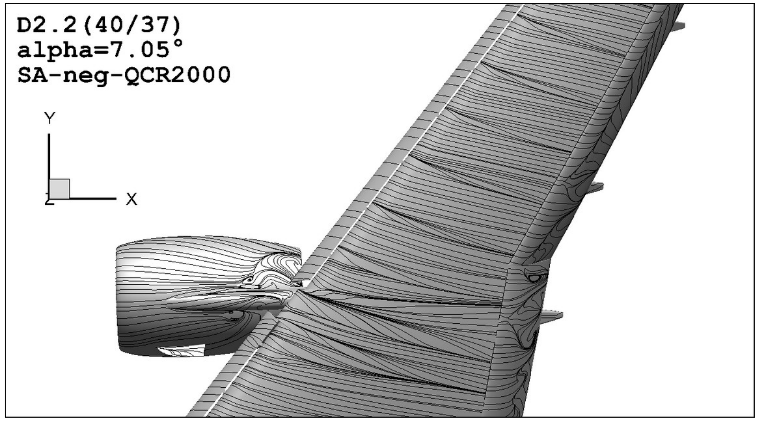
Turbulence Methods

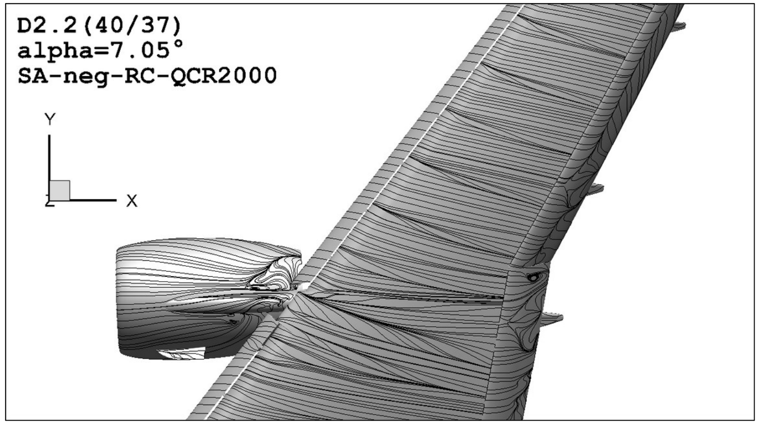


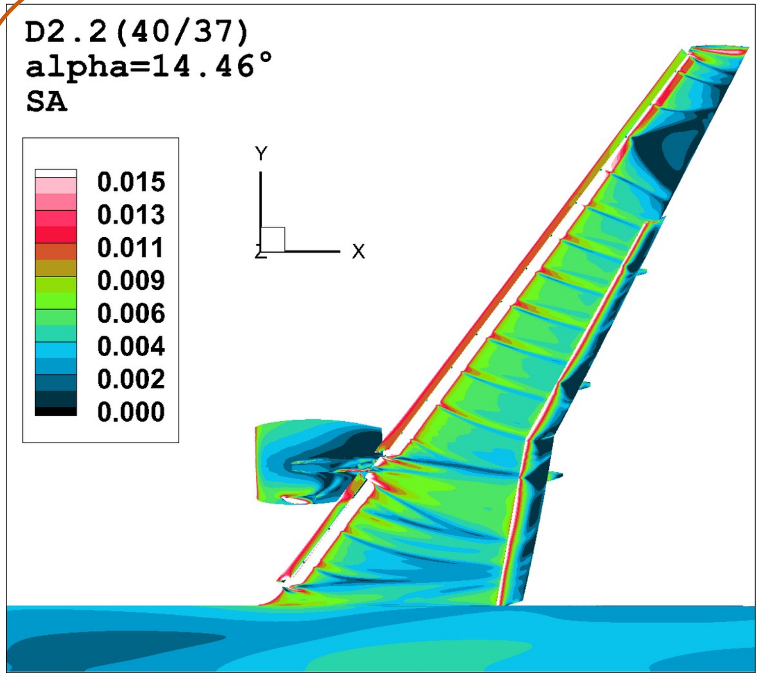


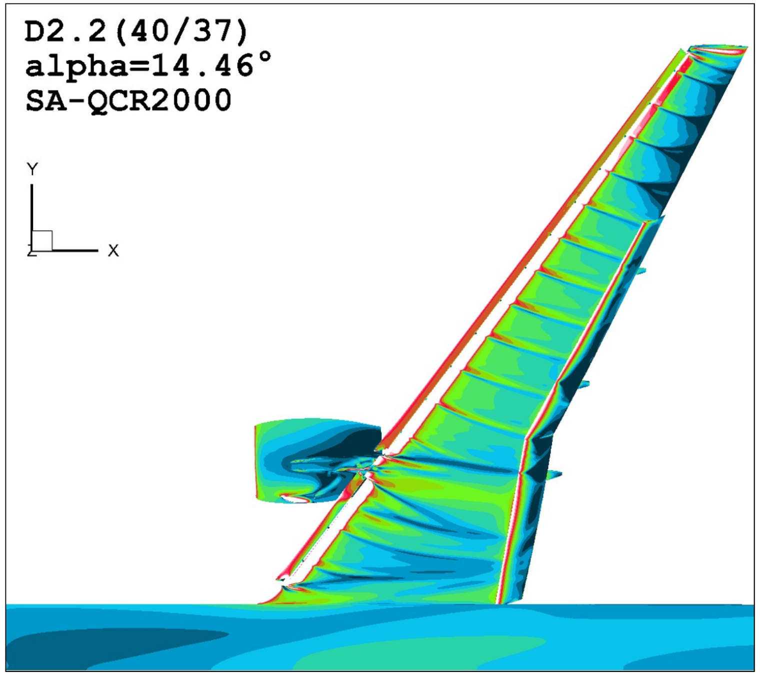
Turbulence Methods

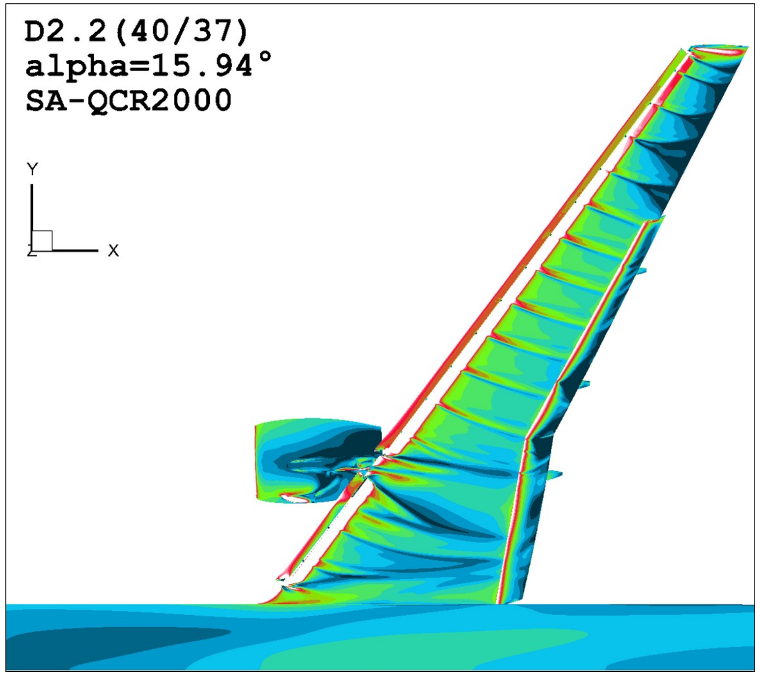




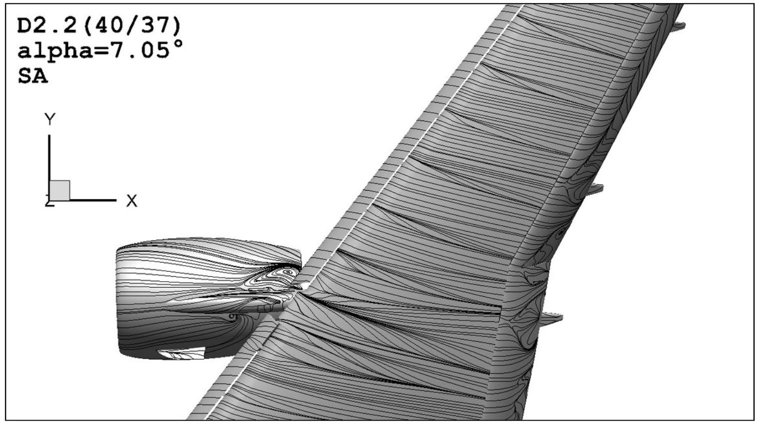


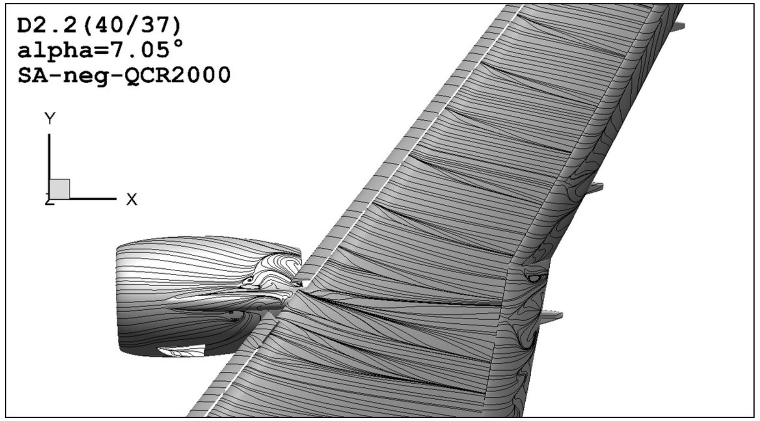


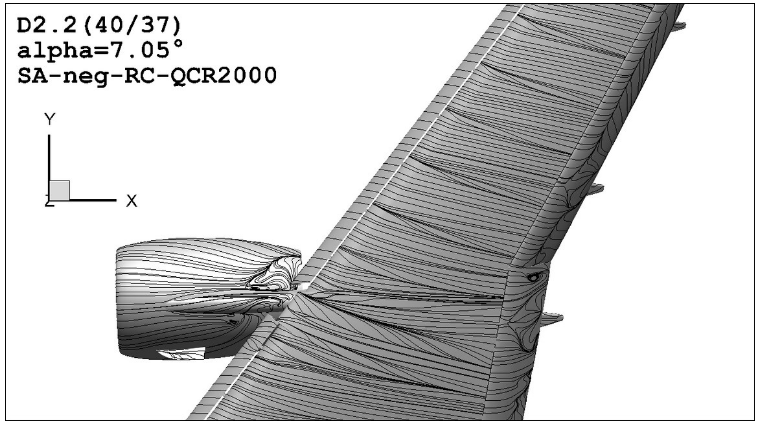


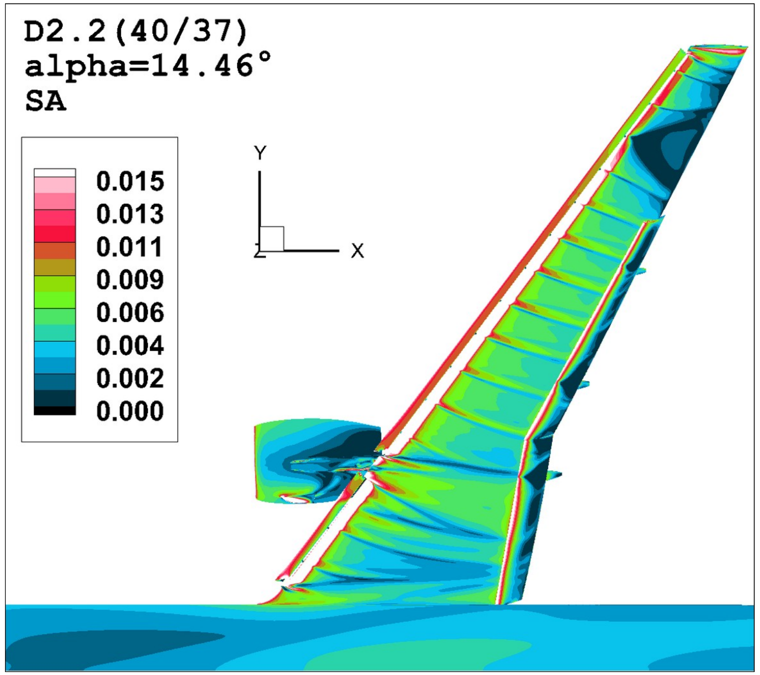


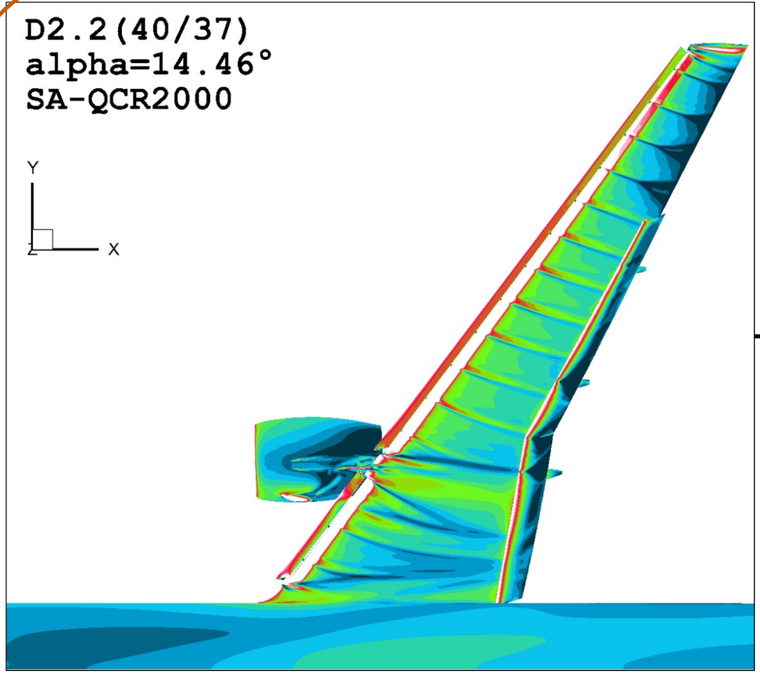
Turbulence Methods

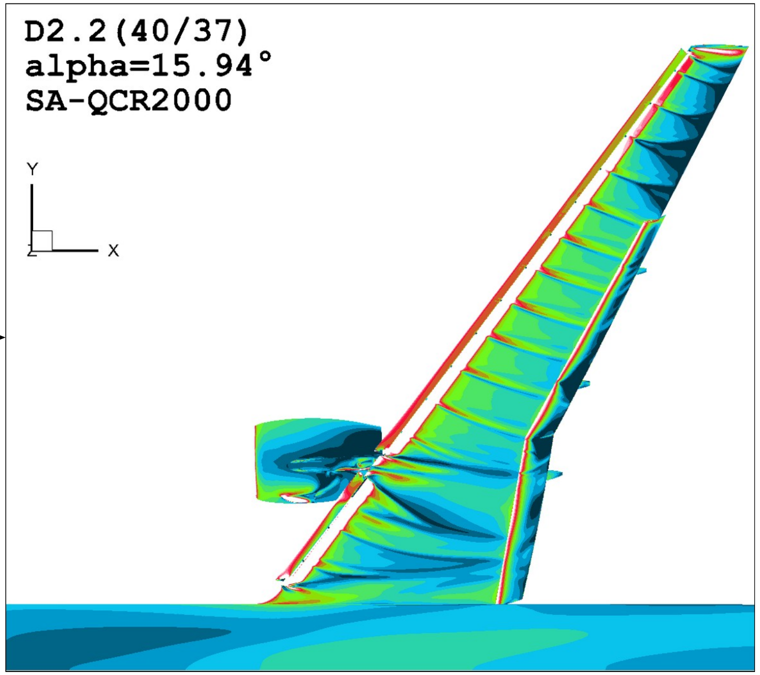




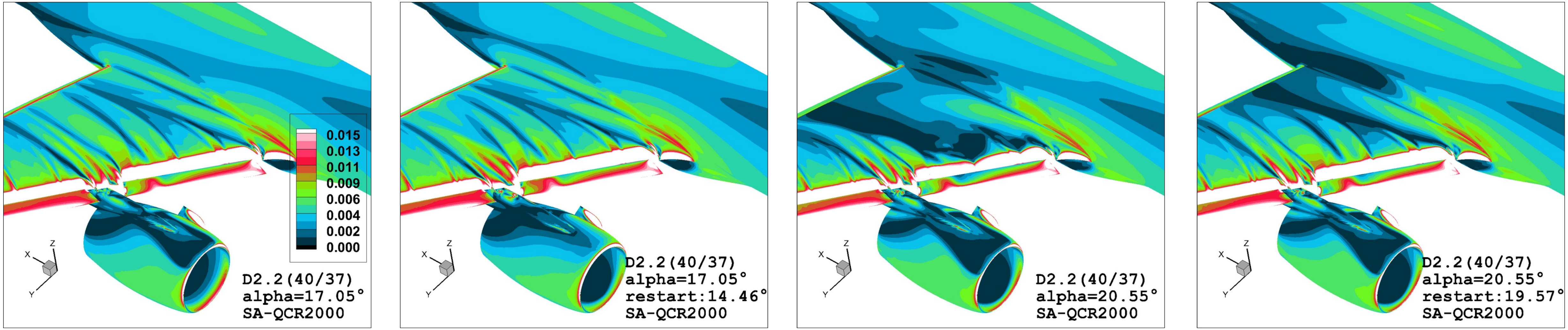






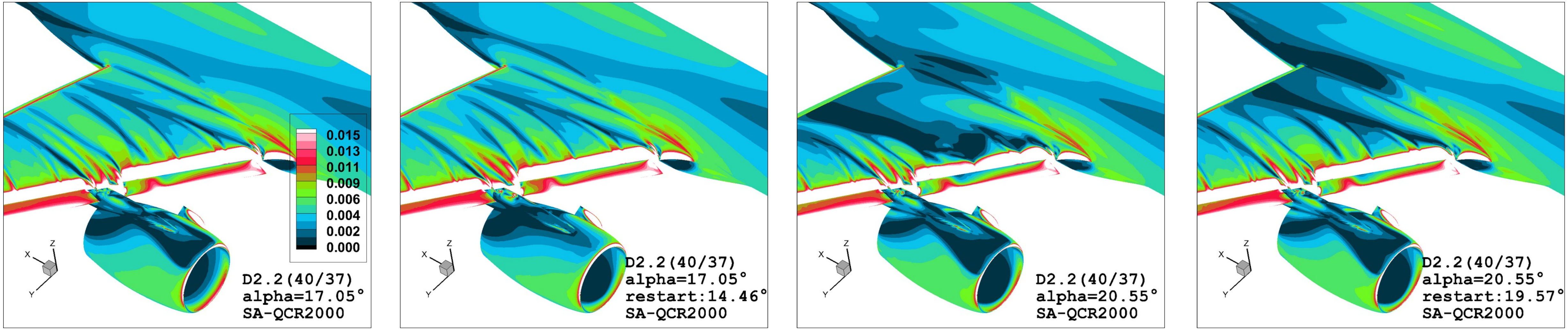


Cold vs. Warm Start



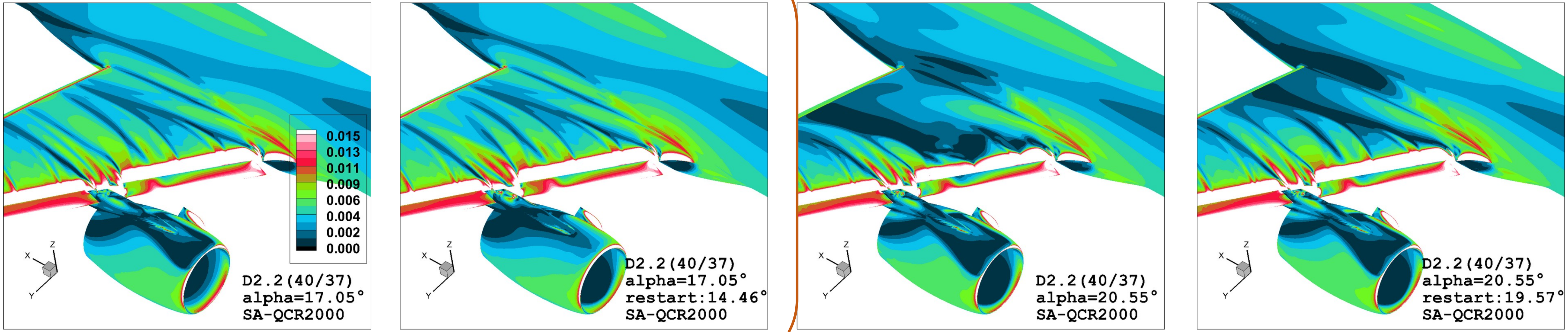
α	**Run**	$C_{L,computed}$	$C_{L,measured}$
17.05°	Cold Start	2.4171	2.4954
	Restarted from 14.46°	2.4491	
19.57°	Cold Start	2.4453	2.5149
	Restarted from 17.05°→14.46°	2.4521	
20.55°	Cold Start	2.3043	2.4632
	Restarted from 19.57°	2.3959	

Cold vs. Warm Start



α	**Run**	$C_{L,computed}$	$C_{L,measured}$
17.05°	Cold Start	2.4171	2.4954
	Restarted from 14.46°	2.4491	
19.57°	Cold Start	2.4453	2.5149
	Restarted from 17.05°→14.46°	2.4521	
20.55°	Cold Start	2.3043	2.4632
	Restarted from 19.57°	2.3959	

Cold vs. Warm Start

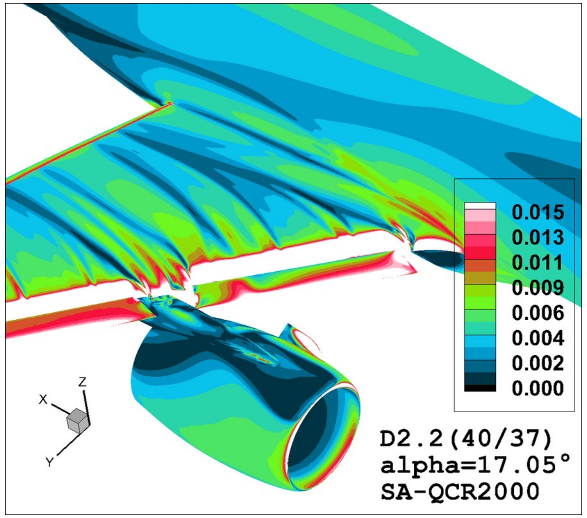


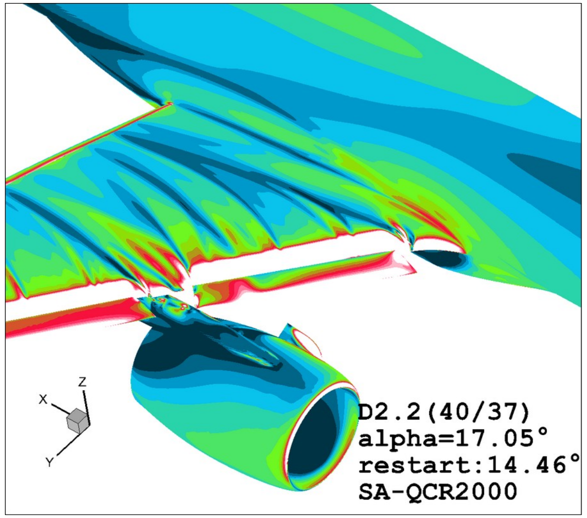
Cold vs. Warm Start

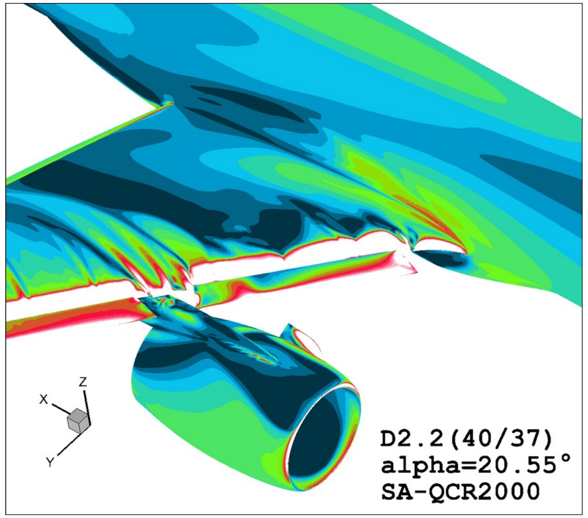
α = 17.05°

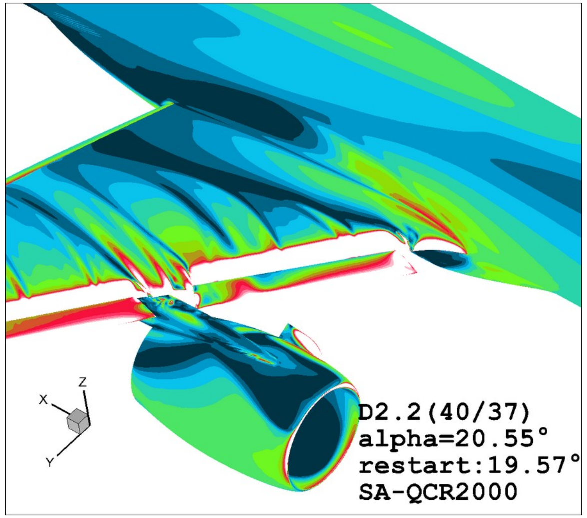
Differences on nacelle/pylon

Cold vs. Warm Start









Cold vs. Warm Start

α = 20.55°

Differences on the inboard wing