Implementation of Two Local Correlation-Based Transition Models in OVERFLOW 2.3e

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Outline

- **Motivation**
- **Details of each transition model**
- **Menter Gamma Equation Transition Model**
  - Test cases
    - T3A, T3A-, Schubauer-Skramstad, NLF-0416
  - Conclusions
- **SA based γ–$\mathrm{Re}_{\theta t}$ (Langtry-Menter) Transition Model**
  - Test cases
    - T3A, T3A-, Schubauer-Skramstad, NLF-0416
  - Conclusions
- **Summary**

Motivation

- Accurate prediction of laminar-to-turbulent boundary layer transition is important for many applications, such as the design of natural laminar flow wings, unmanned aerial vehicles, and crewed reentry vehicles.
  - Crucial given the push for sustainable aviation and greener air transport technology.
- Availability of an increased variety of transition models within NASA's OVERFLOW Overset CFD code will help toward efficient and accurate design of these vehicles.

Goal: Implement two different local correlation-based transition models (LCTMs) into OVERFLOW 2.3e and carry out an initial assessment.

Menter Gamma Equation Transition Model

- In 2015, Florian Menter developed an SST-based, one equation, correlation-based transition model.[1]
- Removed the $Re_{\theta t}$ equation (from LM2009) and modified terms in the *k* and *γ* equations.
    - Modified the F_{onset} terms, F_{length}, and $Re_{\theta c}$
    - In the *k* equation, the Kato-Launder formulation is used in the production term of *k* and an additional source term, that only activates under conditions of low Tu and laminar separation bubble, is included.
- New formulation allows for Galilean Invariance - Important for Rotorcraft applications
- However, the original model implementation does not include crossflow.
    - Current available implementations of crossflow will break Galilean invariance.
- A concurrent implementation in FUN3D is ongoing, allowing for a systematic model verification across the two codes.

1. Menter, F.R., Smirnov, P.E., Liu, T., and Avancha, R., "A One-Equation Local Correlation-Based Transition Model," Flow, Turbulence, and Combustion, 95(4), 583-619, 2015.

SA-Based γ–$Re_{\theta t}$ Transition Model

- Implement an SA-based version of the γ–$Re_{\theta t}$ (Langtry-Menter/LM) transition model.
- Importance of model development:
  - SA-based models tend to converge quicker and easier than SST-based models.
  - One less equation to solve.
  - SA is used in a majority of aerospace applications.
- M. Piotrowski and D. Zingg of the University of Toronto, V. D'Alessandro of Marche Polytechnic University, and S. Medida of the University of Maryland have each developed their own variations of an SA-based γ–$Re_{\theta t}$ transition model.
  - Used these as references to substitute out terms, while trying to remain close to the original form of LM2009.
- Changes:
  - Model uses freestream value of the turbulence intensity, without accounting for decay.
  - Modified F_{wake} , $F_{length,1}$, and removed $F_{sublayer}$, R_{ω}

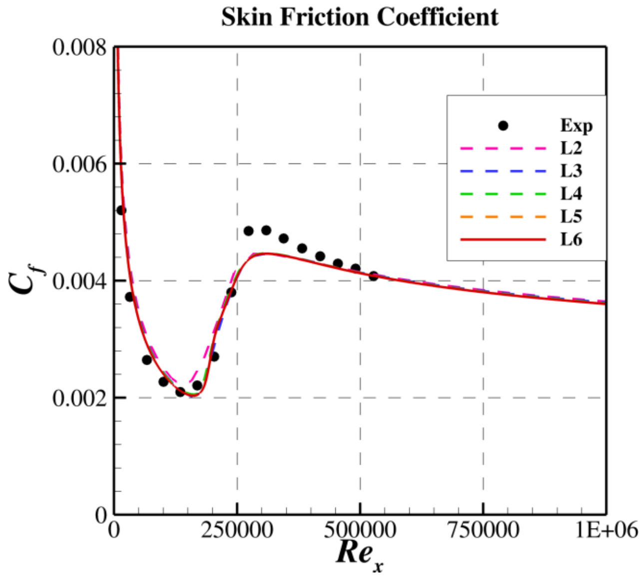
Gamma Model Results

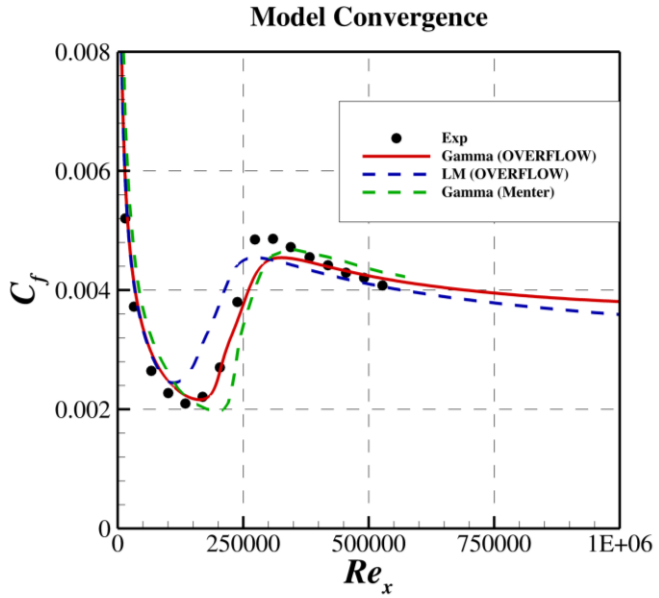
Flat Plate (Bypass transition)

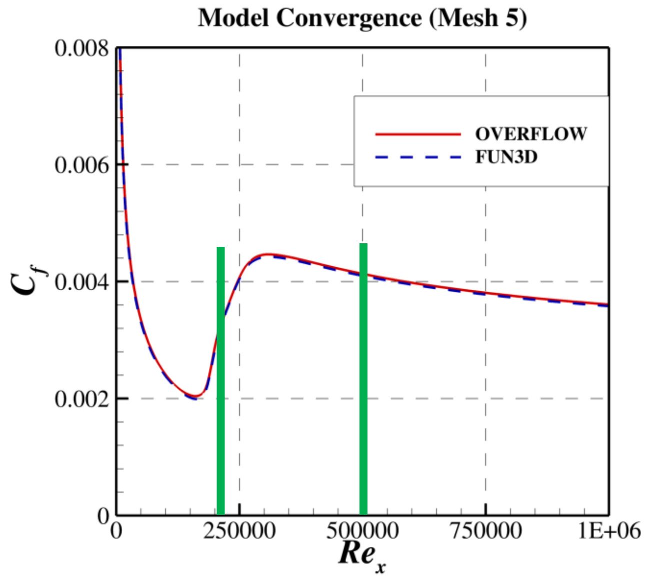
- T3 series flat plate cases: T3A, and T3A-
- T3A and T3A- cases run on a family of six-to-eight different grids, with a doubling of resolution in both the x and y coordinates across each level.
  - T3A : Flow conditions based on the AIAA 1st CFD Transition Modeling Workshop
  - Mesh level 5: y+ = 0.5 (T3A) and 0.25 (T3A-)

Case	T3A	T3A-
Inlet Velocity (m/s)	69.44	19.8
Freestream Temperature (K)	300.0	288.17
Unit Reynolds number (/m)	2.000E5	1.328E6
μ_t/μ at inlet	11.9	9.0
Tu (%) at inlet	5.855	1.0
Tu (%) at leading edge	3.3	0.875
Tu (%) at the leading edge in Experiment	3.3	0.875
Distance from inflow to plate leading edge (m)	0.25	0.15

T3A: Grid Convergence and Comparisons with Reference Data







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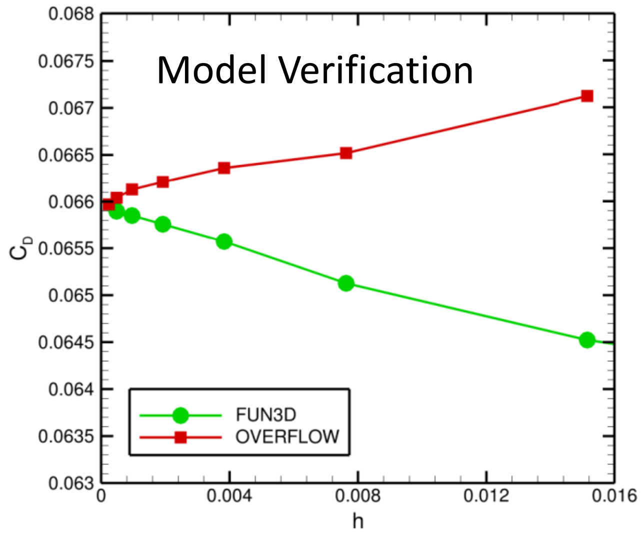
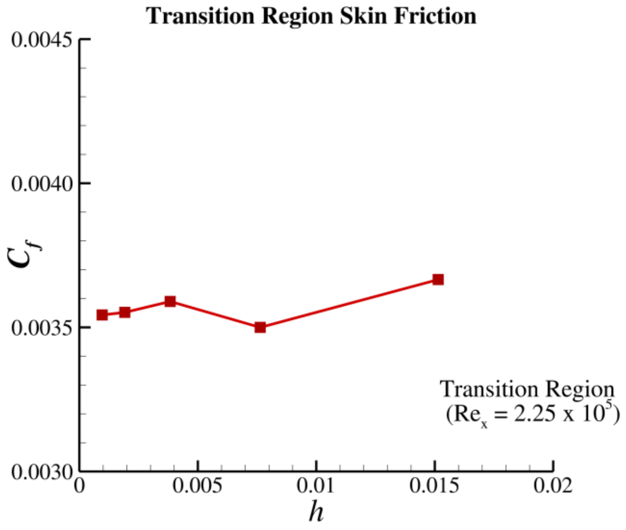
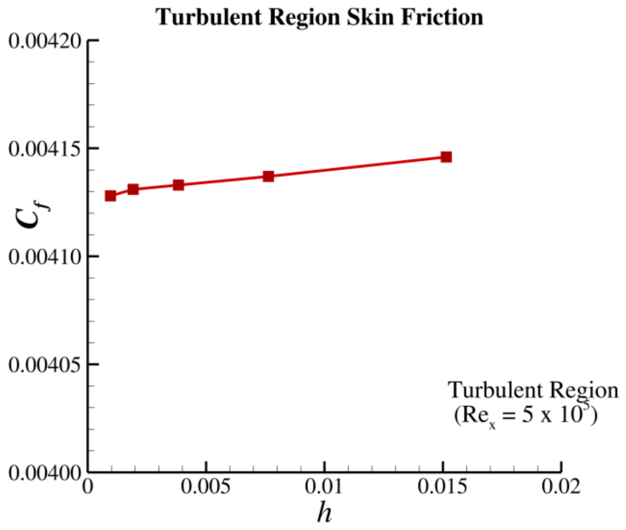
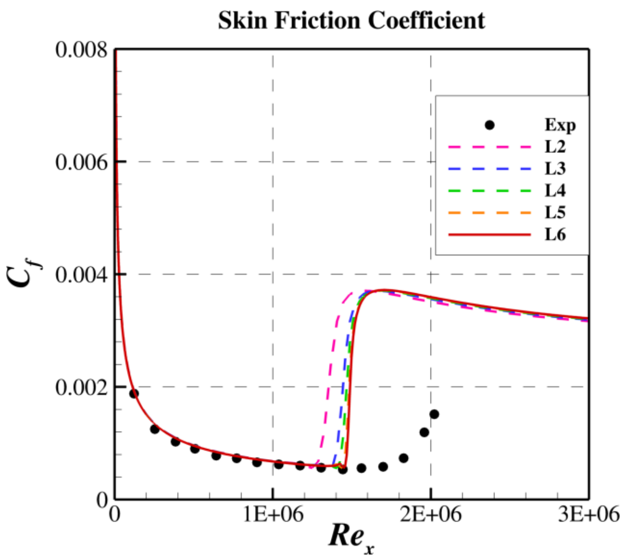
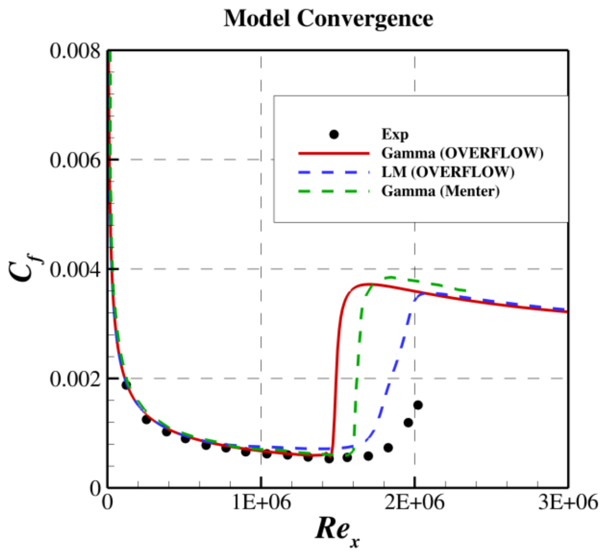


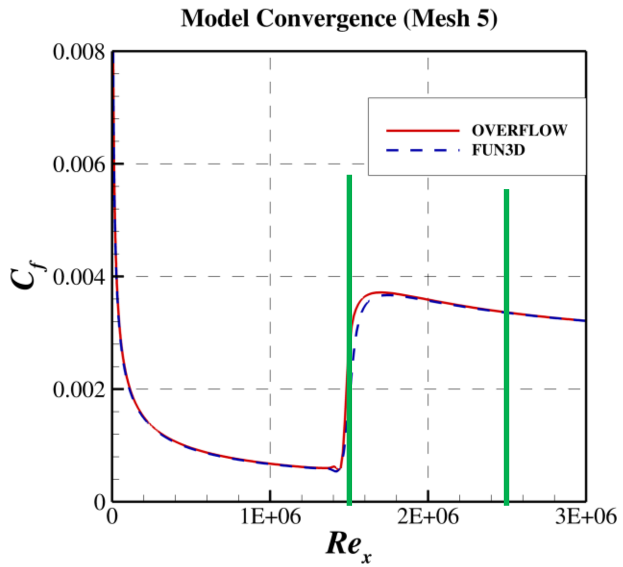


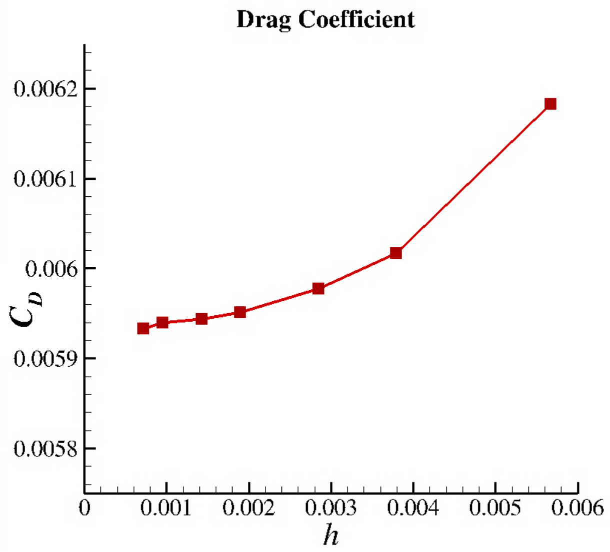


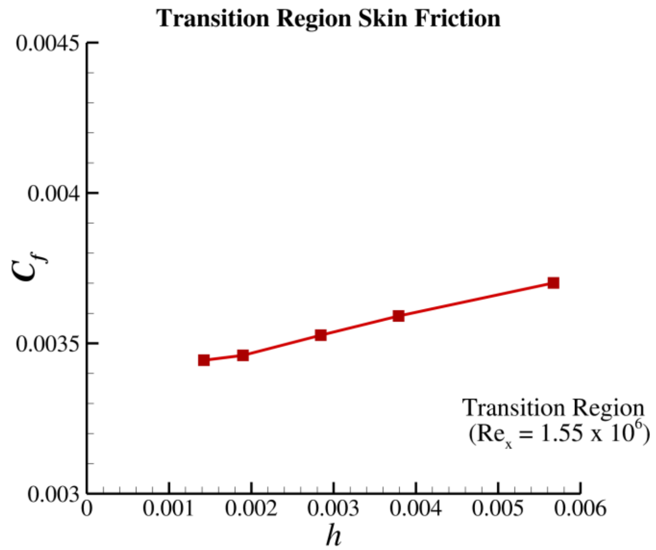
T3A-: Grid Convergence and Comparisons with Reference Data

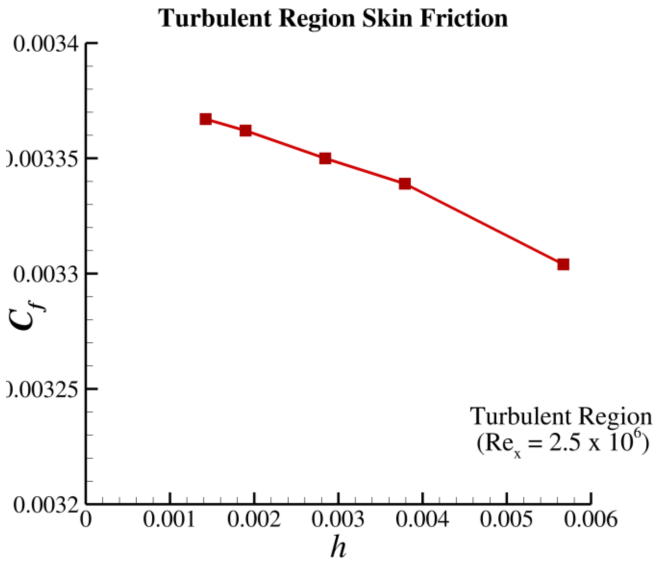












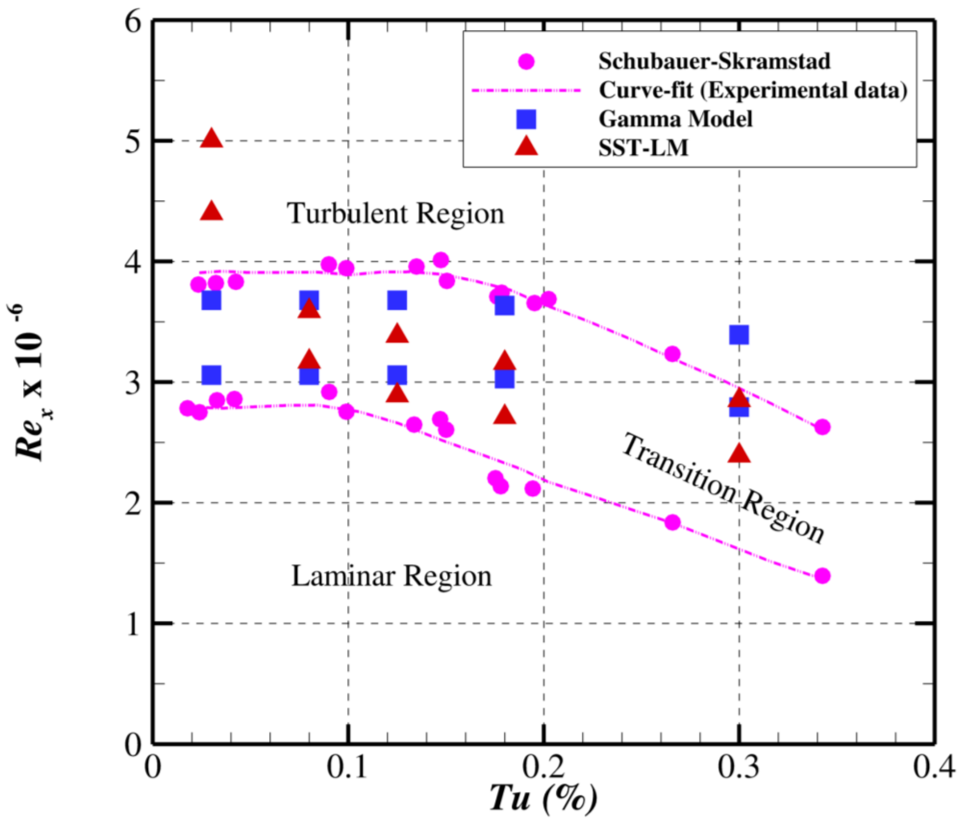
Flat Plate (Natural transition)

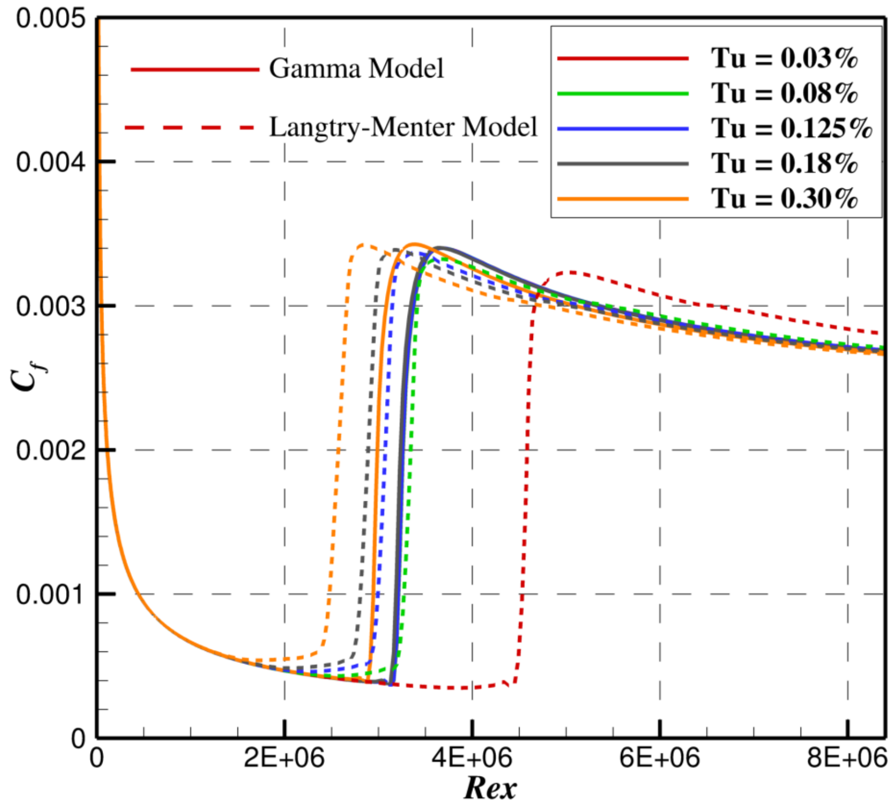
- Flow conditions correspond to the experiment by Schubauer and Skramstad (S&S)
- Mesh level 5 (y+ = 0.25) from T3A- case was used for this condition.
    - Detailed mesh convergence study currently under way
- Five Tu levels studied

Case	S&S
Inlet Velocity (m/s)	50.1
Freestream Temperature (K)	288.17
Unit Reynolds number (/m)	3.36E6
Distance from inflow to plate leading edge (m)	0.15

	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
μ_t/μ at inlet	1.0	1.0	1.0	5.0	5.0
Tu (%) at inlet	0.0302	0.084	0.141	0.189	0.346
Tu (%) at the leading edge	**0.03**	**0.08**	**0.125**	**0.18**	**0.30**

S&S: Influence of Model, Tu, and Comparisons with Reference Data

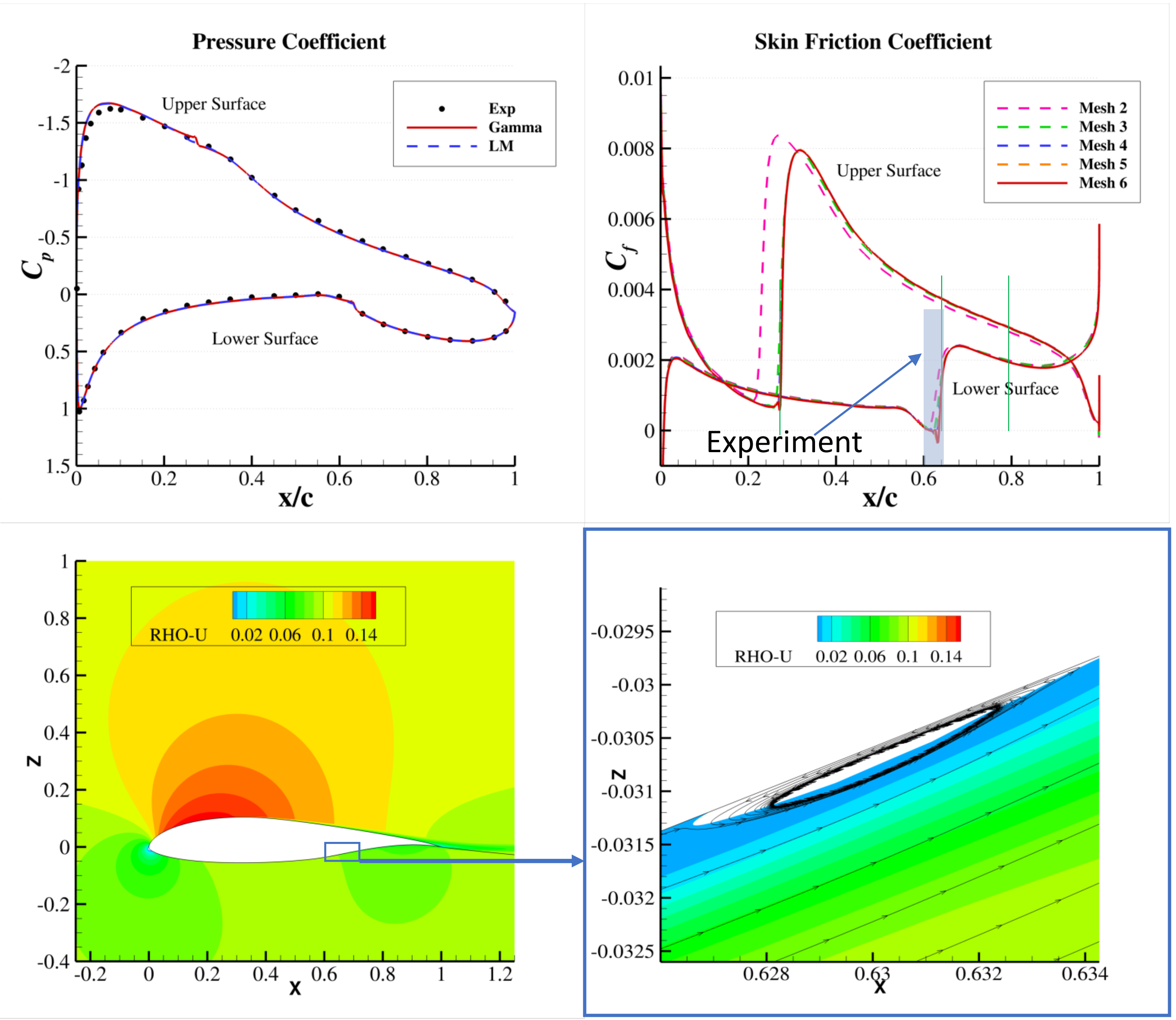




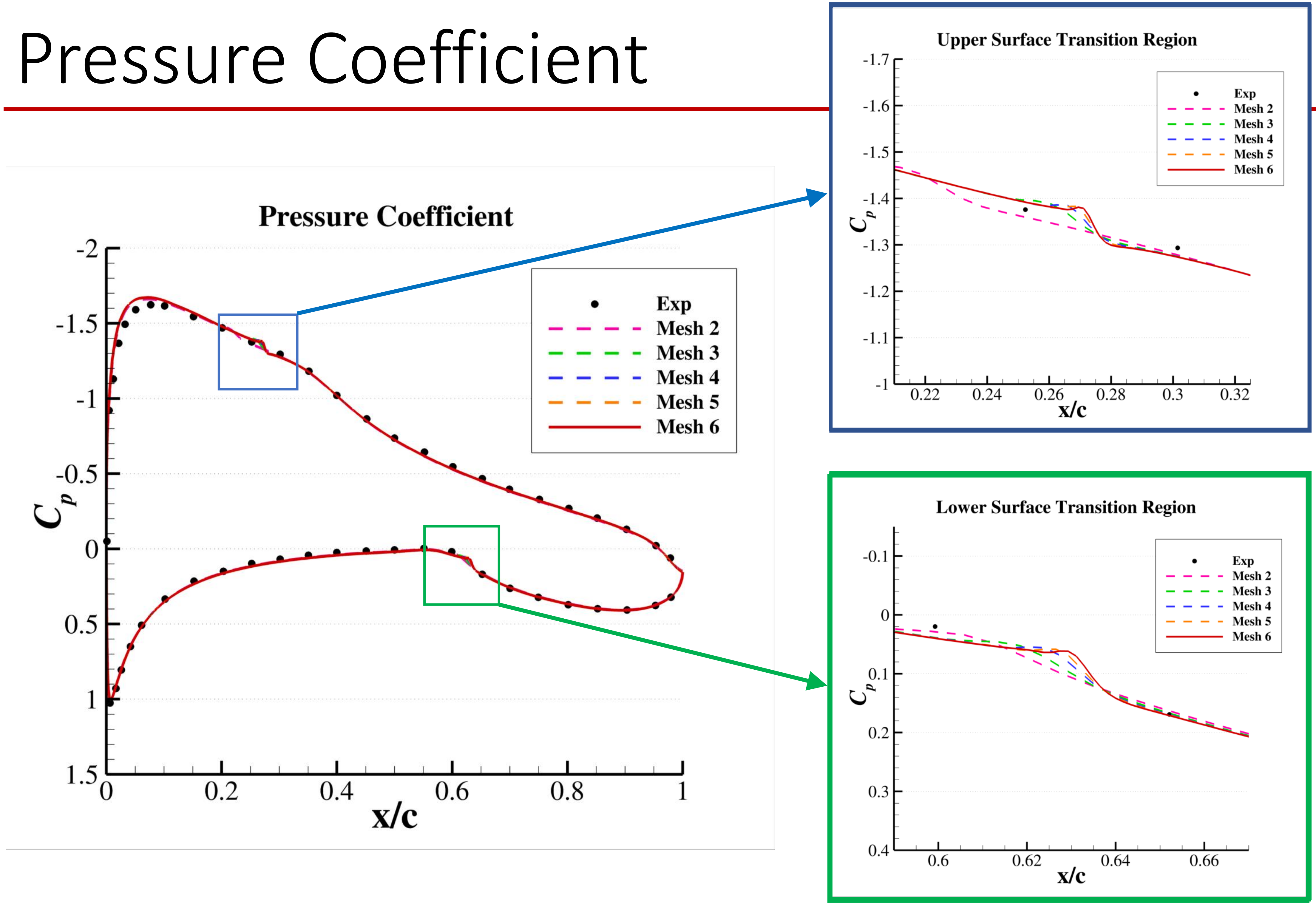
- Gamma model results (solid line) show narrow variation in transition onset with Tu , but closer to measured onset at Tu = 0.03%; no variation in results for Tu = 0.03 to 0.18%
- LM model (dashed line) predicts transition onset significantly downstream of measured location at Tu =0.03% (this was one of the improvements in the Gamma model) and shows larger variation in transition onset with Tu.
- Width of transition zone with both models appear to be much narrower than in the experiment.

NLF-0416: Grid Convergence and Comparisons with Reference Data

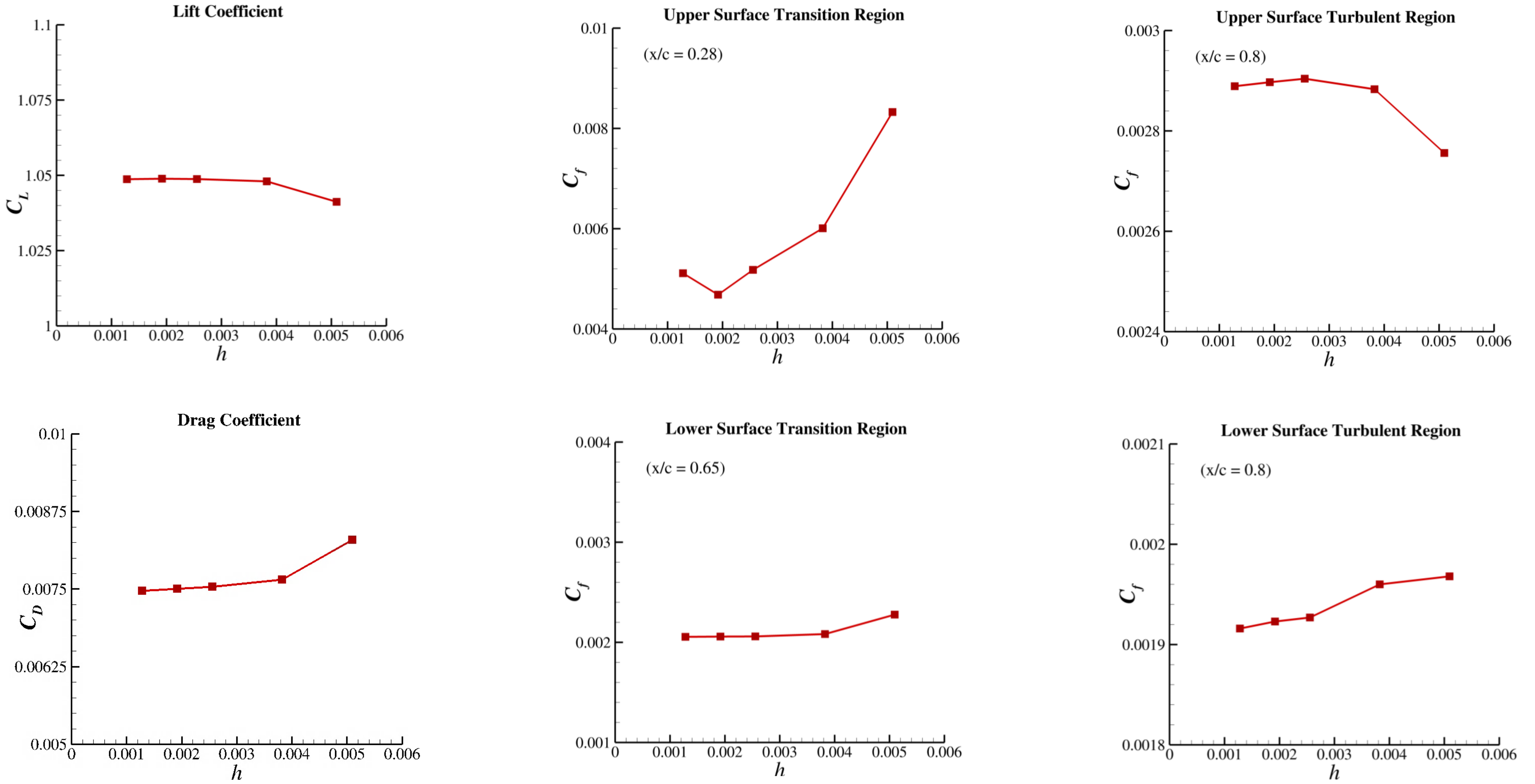
- Flow conditions from AIAA Transition Modeling Workshop:
  - Mach = 0.1
  - $Re_c = 4 \times 10^6$
  - $\alpha = 5°$
  - $T_\infty = 300$ K
- Tested on six different grid levels; Mesh level 5: y+ = 0.2
- Separation bubble induced transition on lower surface (data from expt. shown as gray colored bar).
- TS induced transition on upper surface.



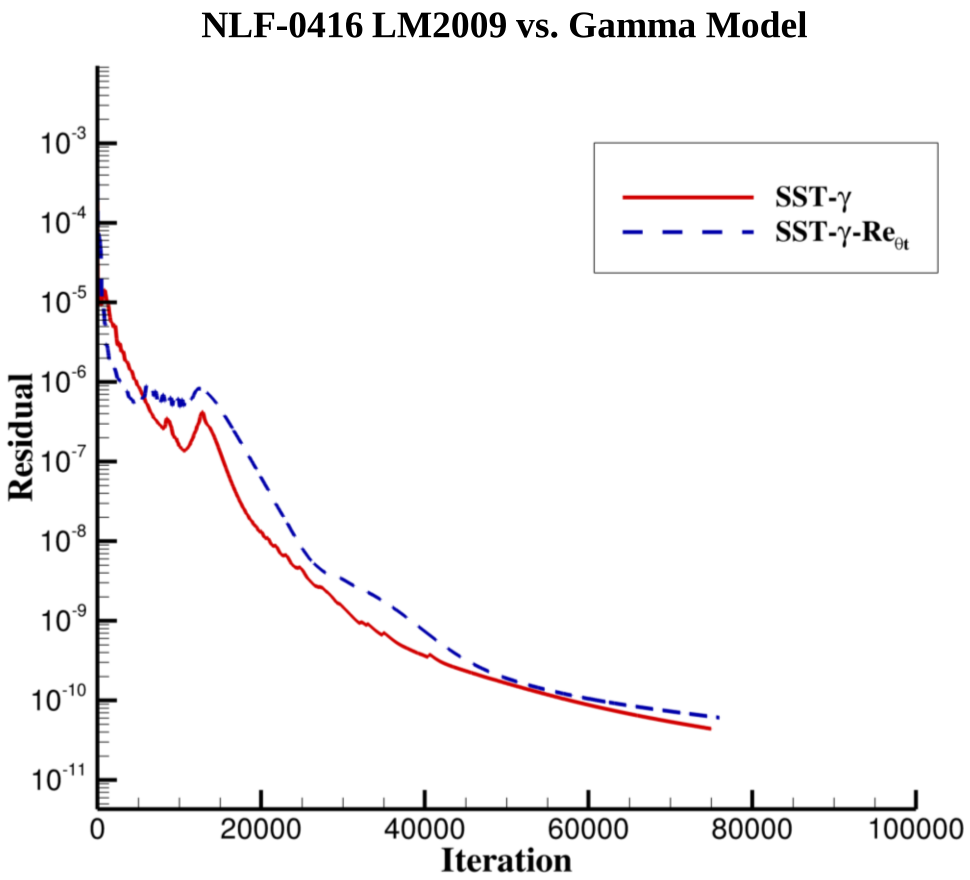
Pressure Coefficient



NLF-0416 (Grid Convergence Plots – Selected Metrics)



Meanflow Residual Convergence



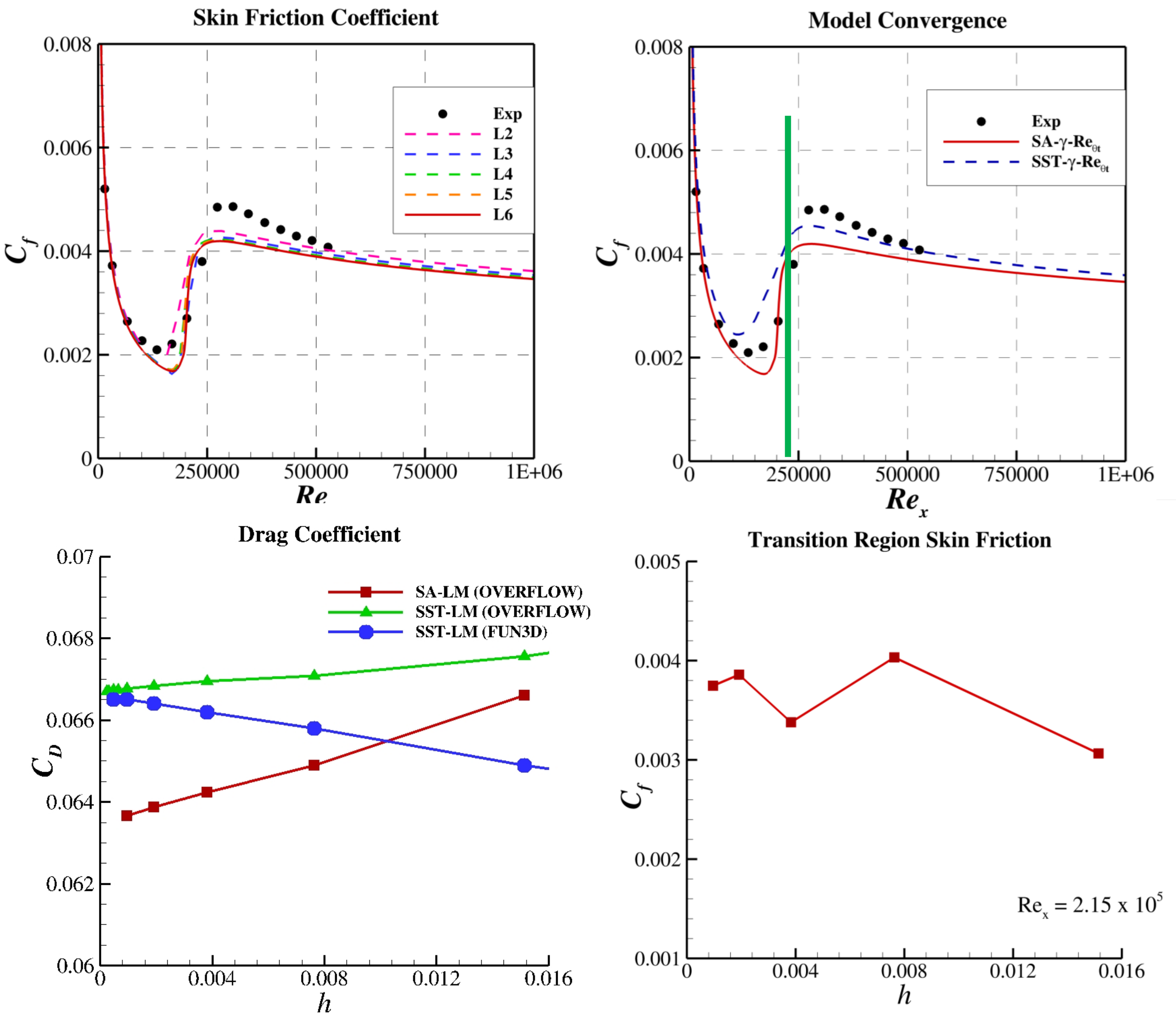
Conclusions

- Successfully implemented the SST-based Gamma transition model from Menter et al. (2015) in OVERFLOW.
  - Laid foundation for systematic model verification with FUN3D.
- Test cases:
  - Transition was well predicted for the T3A flat plate case (LM was upstream).
  - In case of T3A-, transition was predicted much earlier than experimental data. LM was closer to the experimental data.
  - For S&S, prediction of transition onset was closer to measured data at Tu=0.03% than LM; downstream of LM at other conditions
  - For the NLF-0416, pressure coefficient distribution within the transition region was sensitive to grid resolution (need to explore additional grids).
- Benefit of model: Galilean invariance allows model to be well-suited for rotorcraft applications.
- Future work: Accounting for stationary crossflow effects without violating Galilean invariance; additional test cases.

SA-based γ–$Re_{\theta t}$ (LM) Results

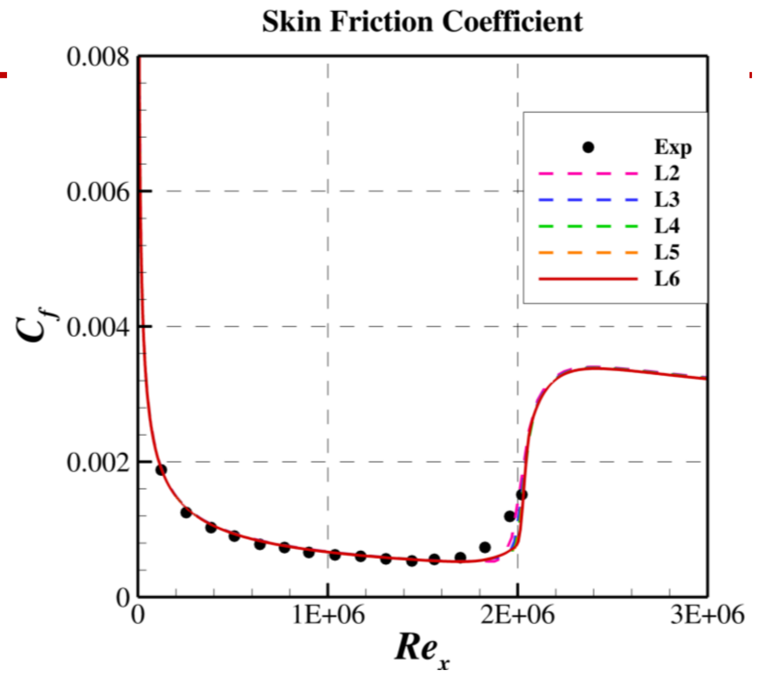
T3A

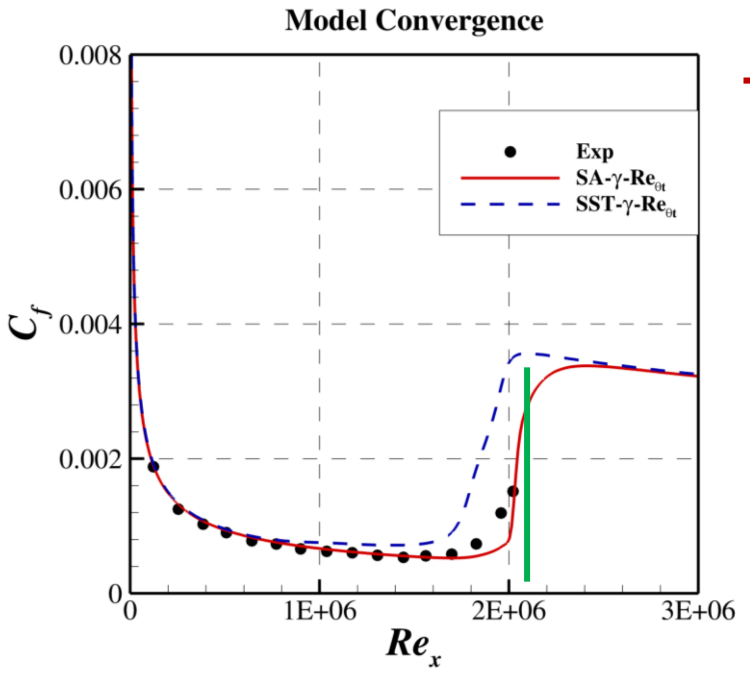
- Same run conditions as before, except:
  - **Tu$_\infty$ = 2.0%**, based on the condition at the transition location in the experiment.
  - **$(\mu_t/\mu_l)_\infty$ = 1 x 10^{-5}**
- Transition onset from SA-based LM closer to measured onset.
  - Lower C_D than SST-based LM results.
- Unable to predict measured C_f peak near end of transition.

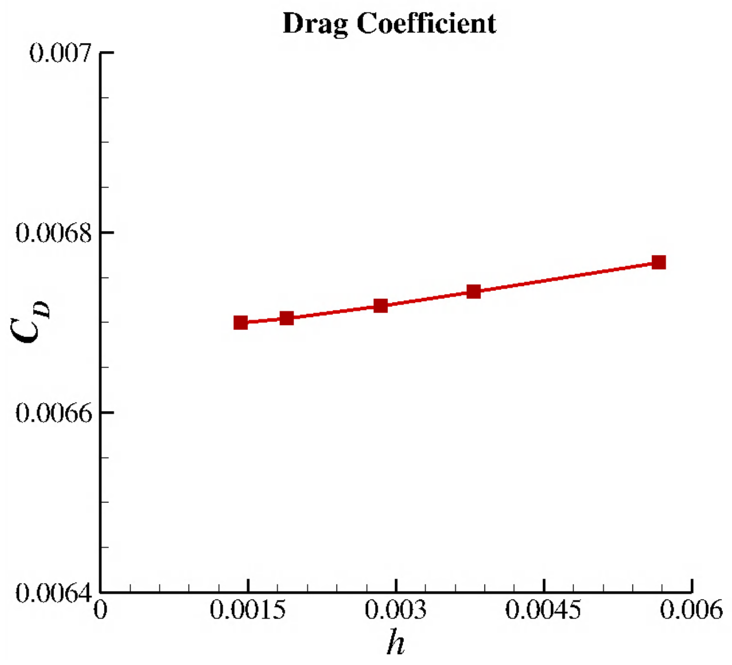


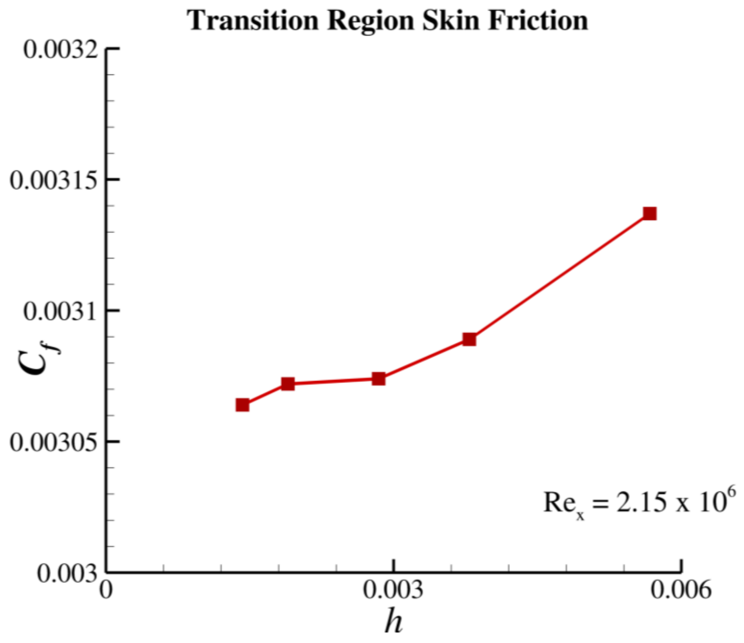
T3A-

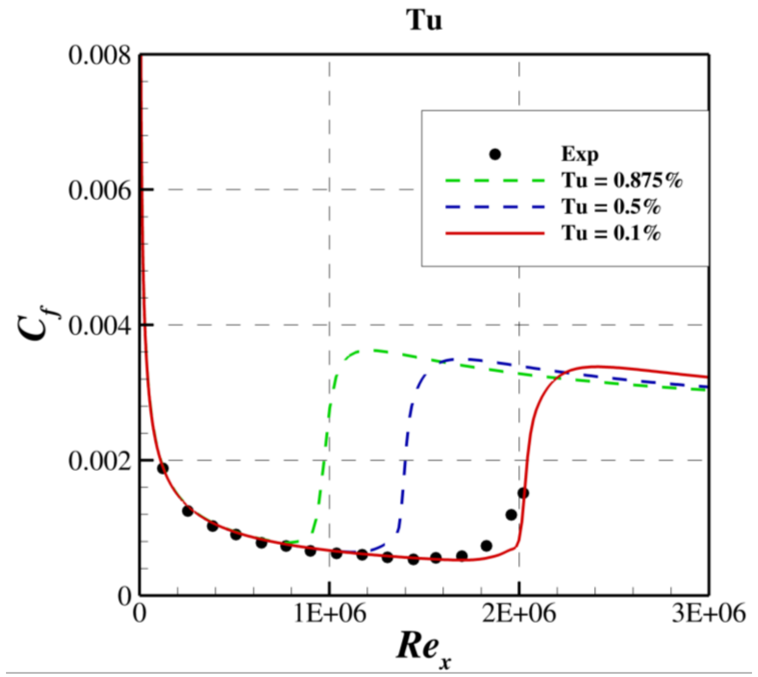
- Same run conditions as before, except:
  - **Tu_∞ = 0.1%**
  - **$(\mu_t/\mu_l)_\infty = 1 \times 10^{-5}$**
- Also ran cases with **Tu_∞ = 0.5%** (Tu at transition location in experiment)and **Tu_∞ = 0.875%** (Tu at LE in experiment) for Mesh 5





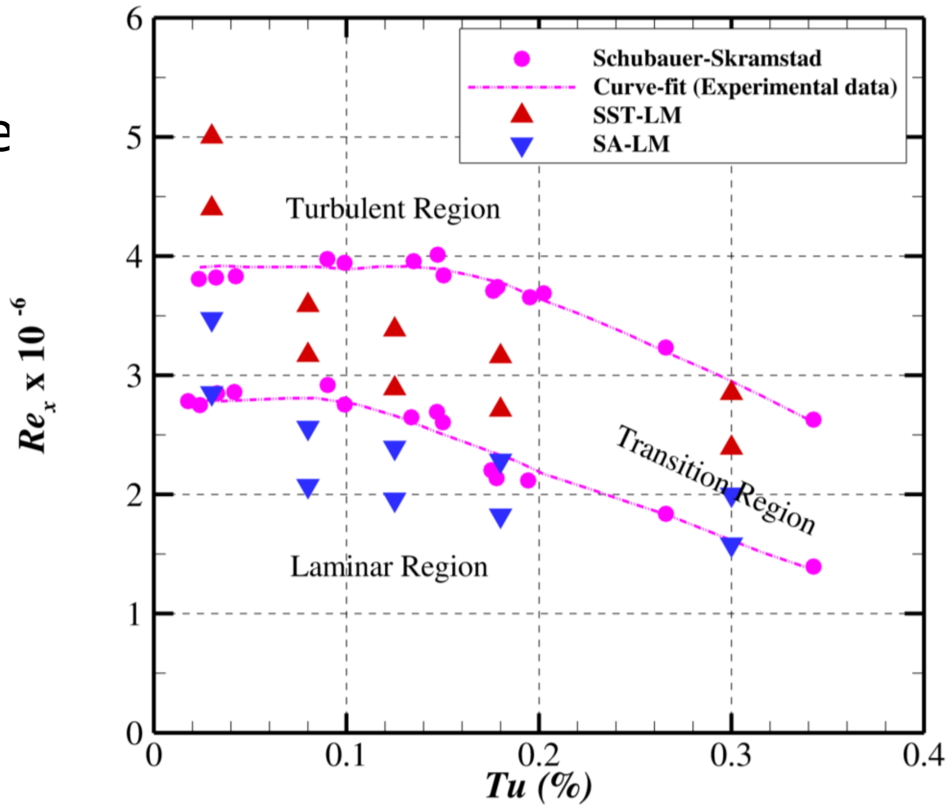


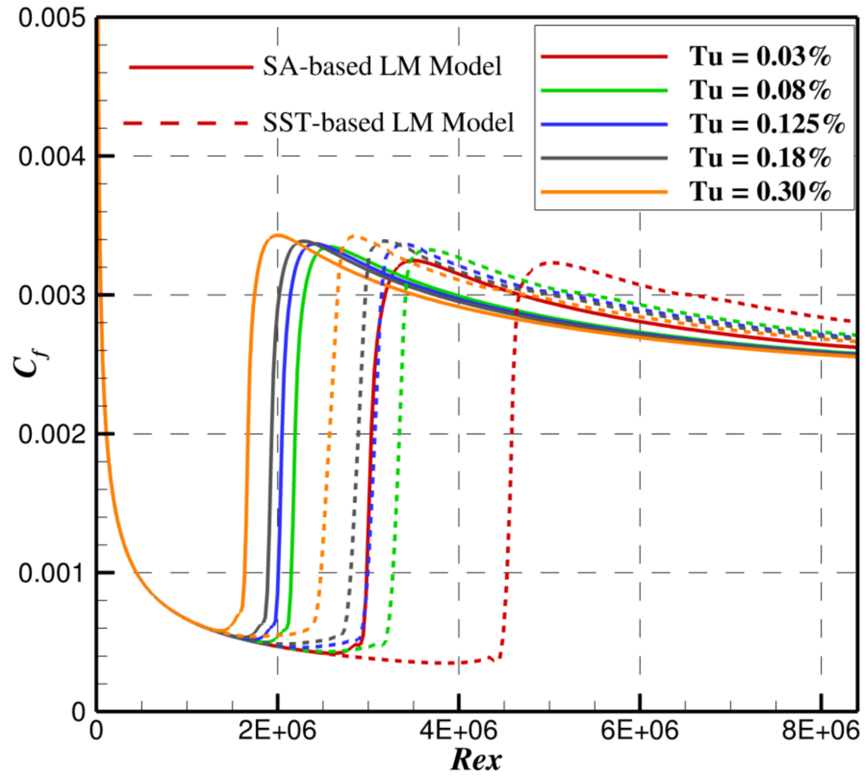




S&S: Influence of Model, Tu, and Comparisons with Reference Data

Same run conditions as before, except for change of model to SA-LM, where $\mathbf{Tu_\infty = Tu}$ **(leading edge)** and $(\mu_t/\mu_l)_\infty = 1 \times 10^{-5}$

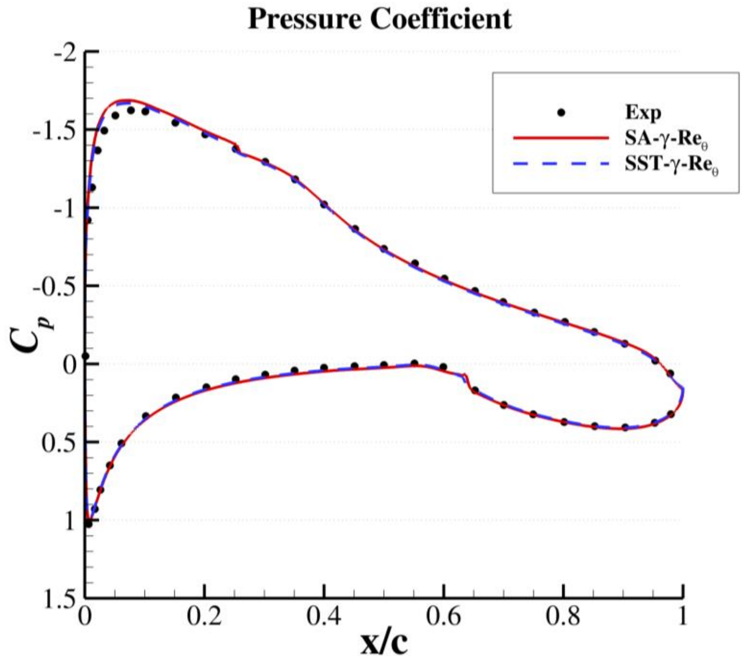


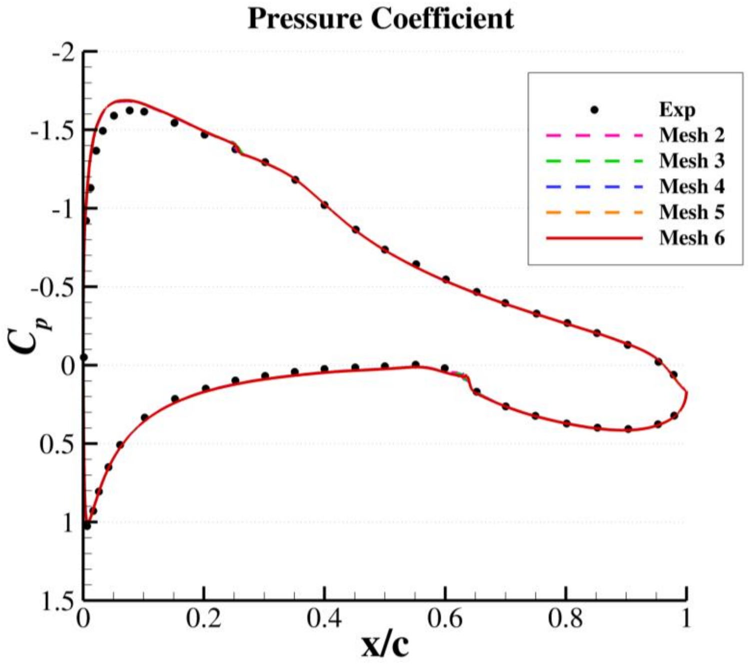


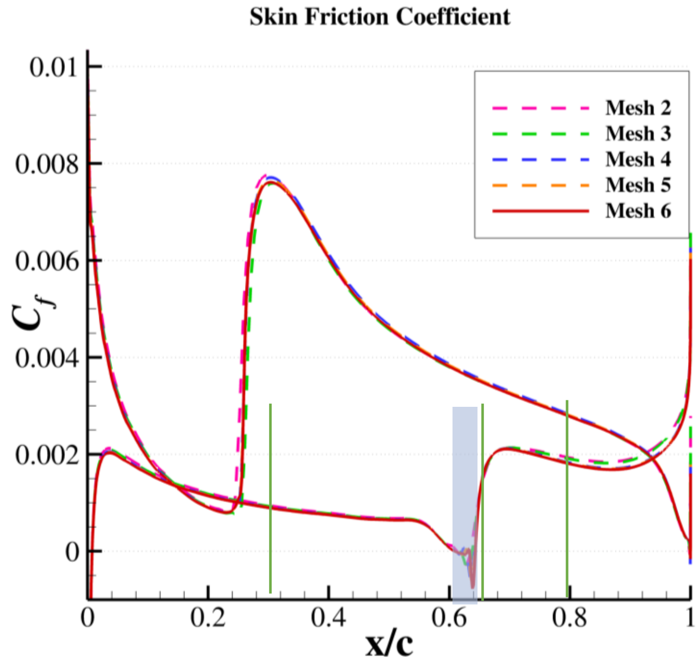
- SA-based LM model results (solid line) indicate earlier transition onset as opposed to SST-based LM and appear to be closer to measured onset at Tu =0.03% and 0.3%;
- Width of transition zone with both models appear to be much narrower when compared to that from the experiment.

NLF-0416

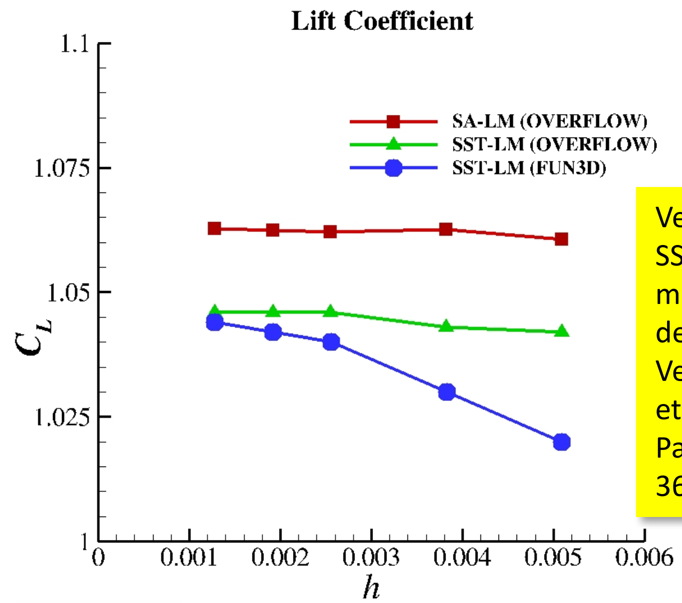
- Same flow conditions as before: $\mathbf{Tu_\infty = 0.15\%; (\mu_t/\mu_l)_\infty = 1 \times 10^{-5}}$
- Converged transition location on the lower surface compares well with those from the experiment (shown as gray colored bar). Transition location on the upper surface is unavailable from the experiment.



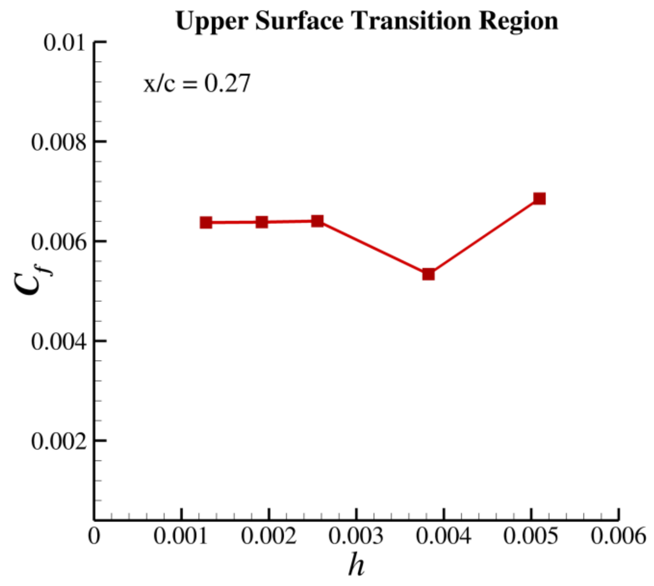


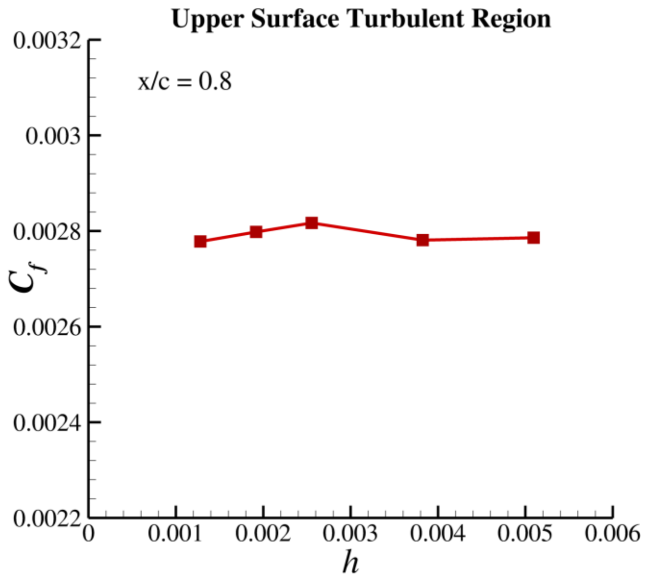


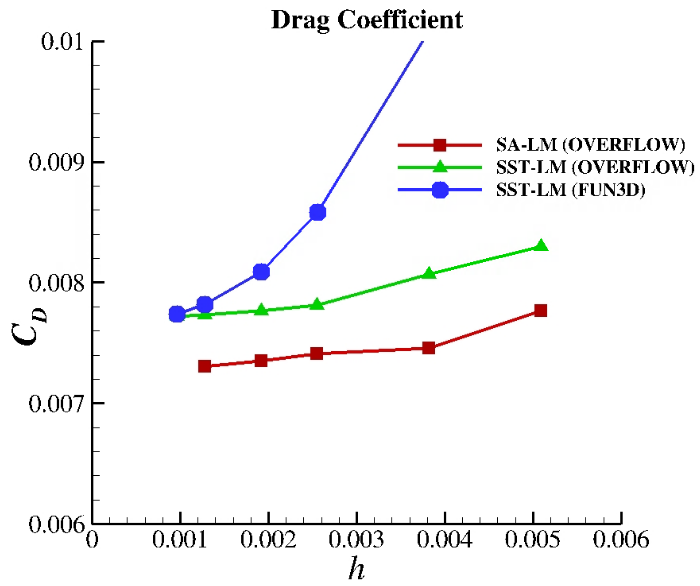
NLF-0416 (Grid Convergence Plots – Selected Metrics)

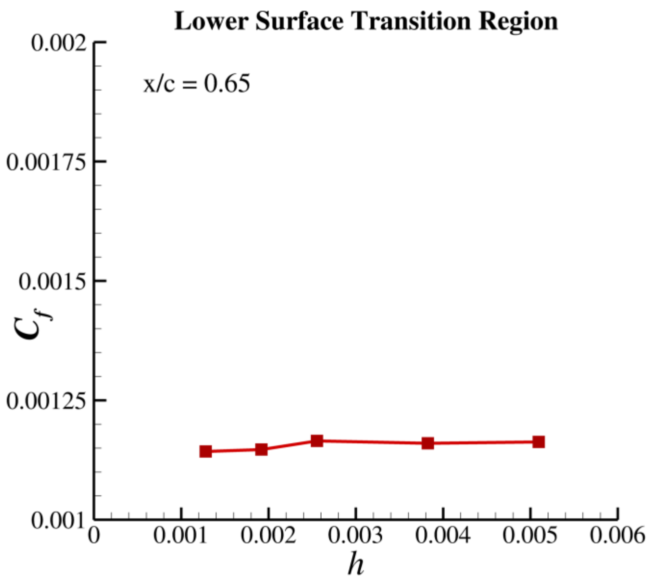


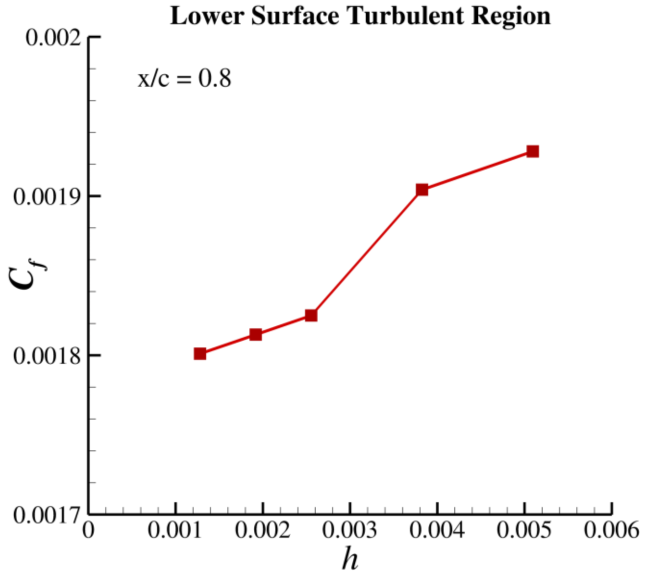
Verification of SST-LM model detailed in Venkatachari et al. AIAA Paper 2022-3679



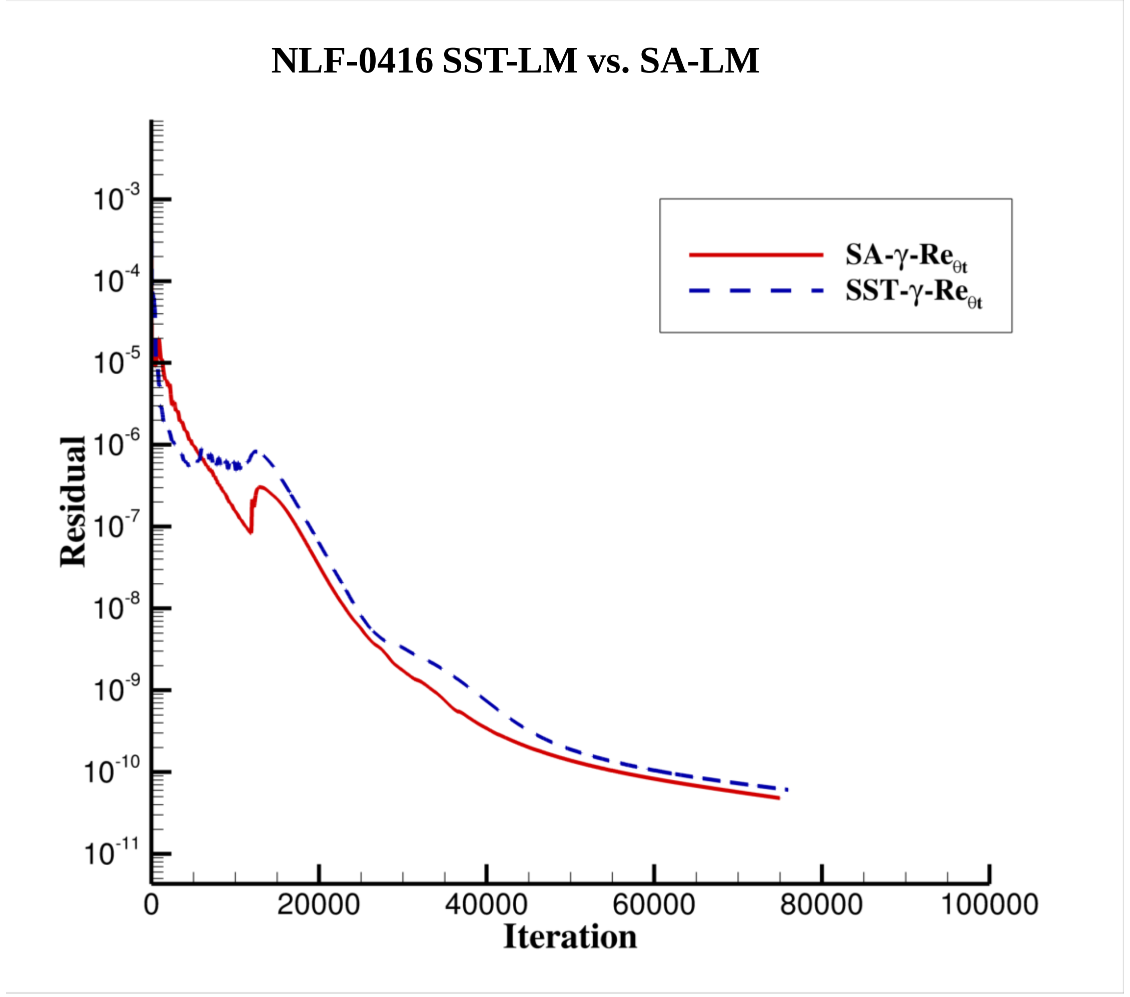








Meanflow Residual Convergence



Conclusions

- Implemented an SA-based version of the Langtry-Menter γ–$Re_{\theta t}$ transition model.
- Test cases:
  - Variations in freestream turbulence intensity (Tu) have a major effect on solution, especially for bypass cases.
    - Inability to account for Tu decay represents possible limitation to model.
- Benefit of model:
  - SA is generally more robust for external aerodynamic applications.
  - Model has one less equation to solve for.
- Future work:
  - Implementing crossflow.
  - Recalibrating the model to account for natural/bypass transition cases.

Summary

- Implemented two local correlation-based transition models in the NASA OVERFLOW Overset Grid CFD solver.
  - Learned how to understand flow of established CFD codes, add new capabilities, and good programming practices.
- Tested each model with T3A, T3A-, S&S, and NLF-0416 cases.
- Need to implement crossflow into both models.
- Need to test against more cases and grids to better understand outstanding issues.
- Detailed code-to-code verification of various models (including SA-based AFT) using OVERFLOW and FUN3D to be reported at AIAA Aviation 2023.

Acknowledgments

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- Samuel Gosin thanks the NASA Office of STEM Engagement and the Tennessee Space Grant Consortium for providing the funding for this research.
- Balaji Venkatachari and Meelan Choudhari acknowledge funding by NASA TTT Project under TACP.

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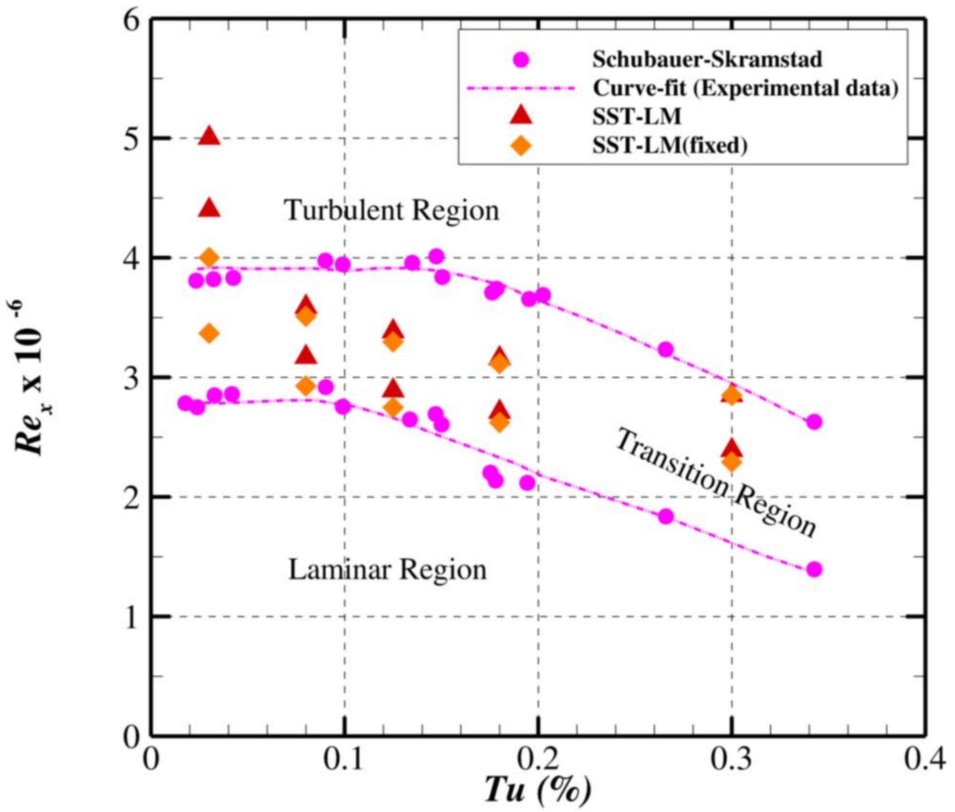
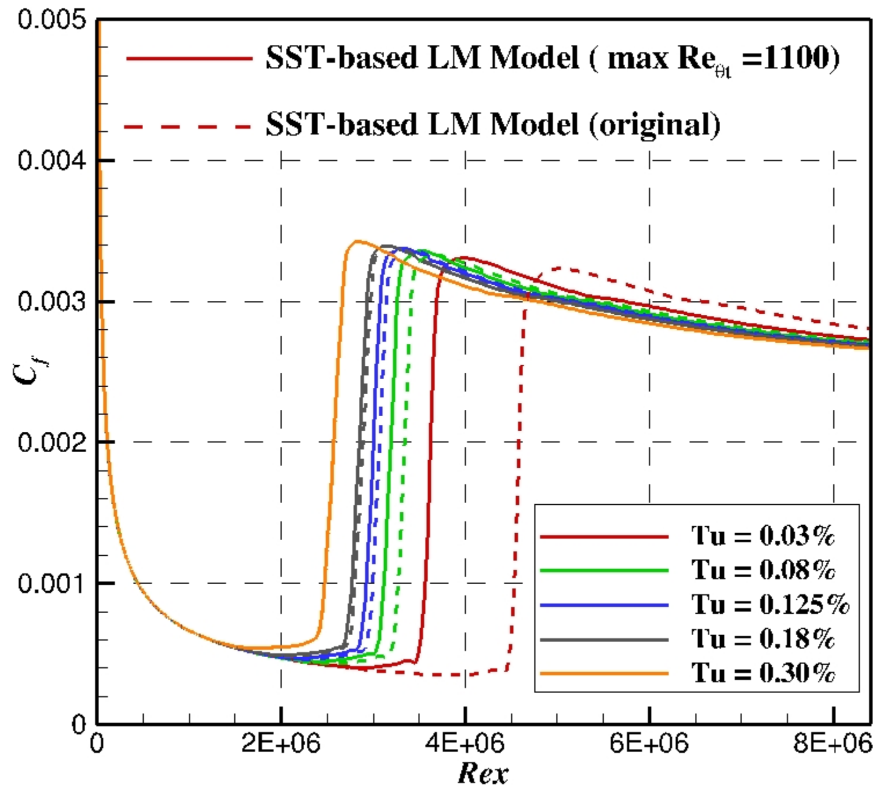
- Piotrowski, M. G., and Zingg, D.W., “Smooth Local Correlation-Based Transition Model for the Spalart-Allmaras Turbulence Model,” AIAA Journal, 59(2), 474-492, 2021.
- NASA Langley Turbulence Model Resource

Questions?

Backup

S&S: Influence of fix to LM, and Comparisons with Reference Data





- Limiting max($Re_{\theta t}$) to 1100.0 for zero pressure gradient boundary layers, in the original LM correlations, similar to that in the gamma model, appears to help at Tu= 0.03%
  - Suggested by Dr. Menter in private communication
  - Unlike in the gamma model, the new source term in the *k* transport equation for the low Tu cases, has not been added.

Mesh Dimensions

T3A

Mesh Level	No. of points in streamwise direction	No. of points in wall-normal direction	Points upstream of leading edge
Mesh 1	45	25	13
Mesh 2	89	49	25
Mesh 3	177	97	49
Mesh 4	353	193	97
Mesh 5	705	385	193
Mesh 6	1409	769	385
Mesh 7	2817	1537	769
Mesh 8	5633	3073	1537

NLF(1)-0416

Mesh Level	No. of points in chordwise direction	No. of points in wall-normal direction	No. of points in wake-cut
Mesh 1	353	49	49
Mesh 2	529	73	73
Mesh 3	705	97	97
Mesh 4	1057	145	145
Mesh 5	1409	193	193
Mesh 6	2113	289	289
Mesh 7	2817	385	385
Mesh 8	4225	577	577