# Modeling the Effects of a Backward-Facing Step on Boundary-Layer Transition


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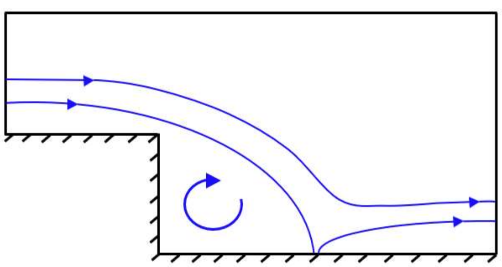


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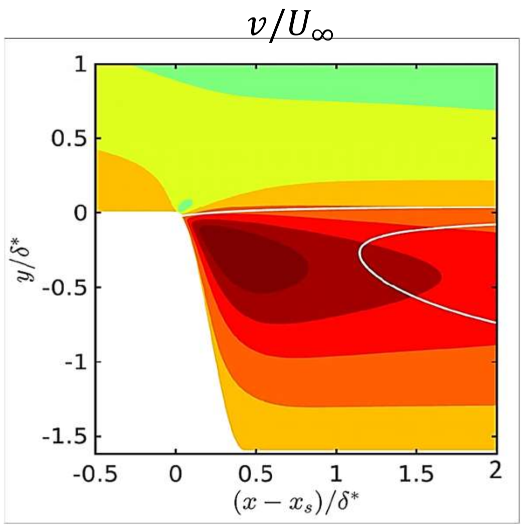

# Approach

- Quantify effects of step excrescences to specify manufacturing tolerances for laminar flow surfaces

- Linear Stability Analysis
  - In-house finite-difference flow solver
  - Laminar basic states with a Backward-Facing Step (BFS)
  - LST, PSE, & HLNSE to model TS waves
  - Compare transition locations to experiments (Wang & Gaster 2005)

- RANS-Based Transition Models
  - FUN3D 13.7 finite–volume code
    - SST2003 turbulence model (Menter, Kuntz, & Langtry 2003)
    - LM2009 transition model (Langtry & Menter 2009)
  - OVERFLOW 2.3d finite-difference code
    - SA turbulence model (Spalart & Allmaras 1994)
    - AFT2019b transition model (Coder 2019)
  - Skin-friction contours

- Conclusions and Future Work

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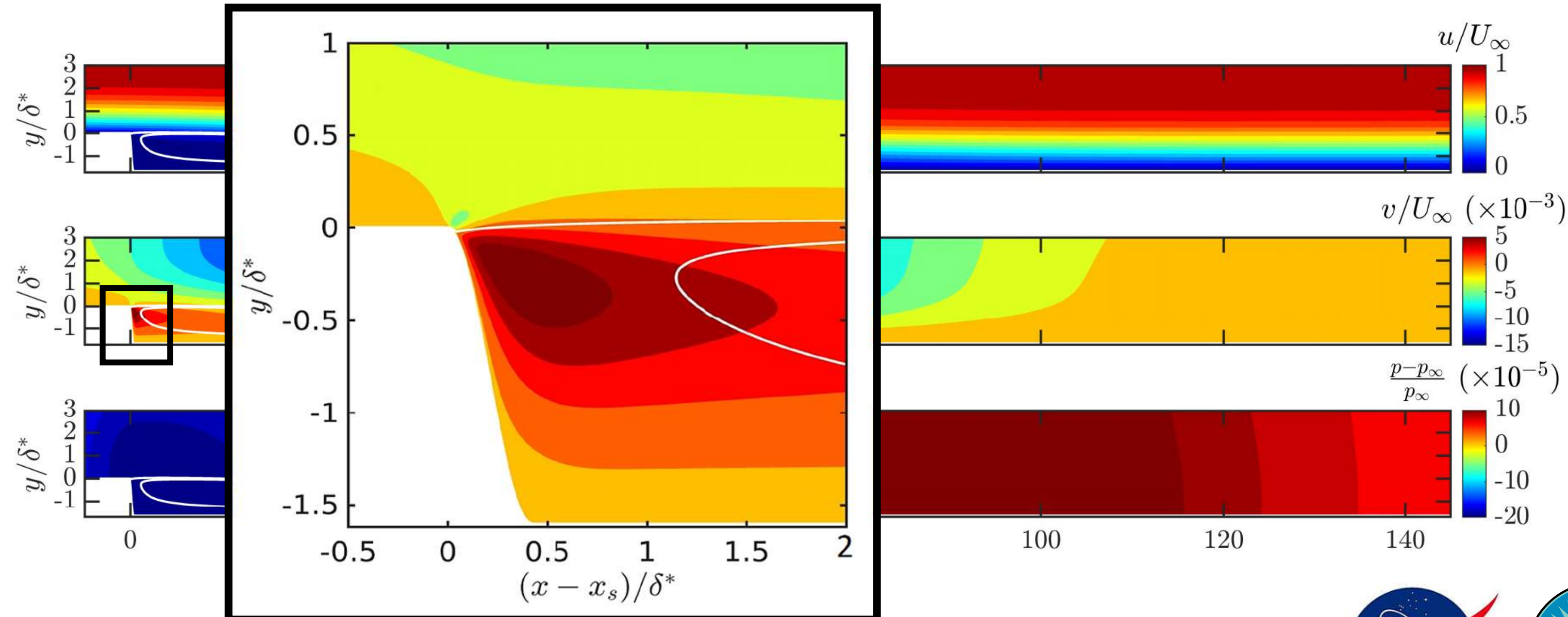
# 2D Laminar Basic States

- Flow conditions match experiments (Wang & Gaster 2005)
  - $\rho_\infty = 1.206$ kg/m$^3$ & $T_\infty = 292.7$ K
  - $U_\infty = 20$-34 m/s, $Re_\infty = 1.33$-2.26e6 1/m, & $\delta^* = 8.17$-$6.26e$-4 m

- Smooth BFS with max slope $\theta = 75°$ and heights $h = 0$-1 mm

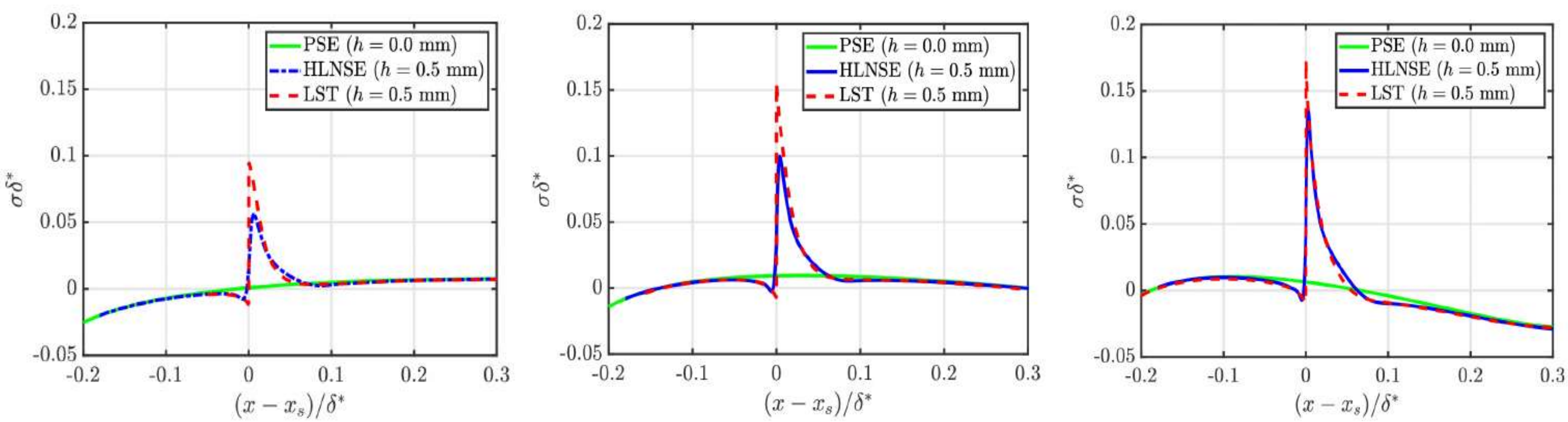
- Nonuniform grid with $5001 \times 351$ points and $y^+ = 0.1$



# Spatial Growth Rates of TS Instability

- LST & PSE to model flat-plate cases
- LST & HLNSE to model BFS cases
  - Growth rates from BFS cases match flat-plate cases outside of step region
- LST slightly overpredicts the growth rate in BFS region
  - Does not account for nonparallel effects

$f$ = 300 Hz $f$ = 500 Hz $f$ = 700 Hz

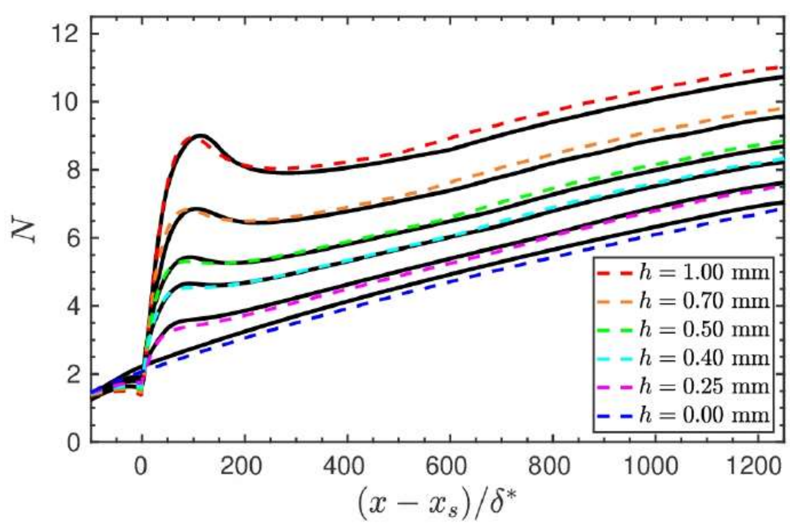


# $N$-factor Envelopes

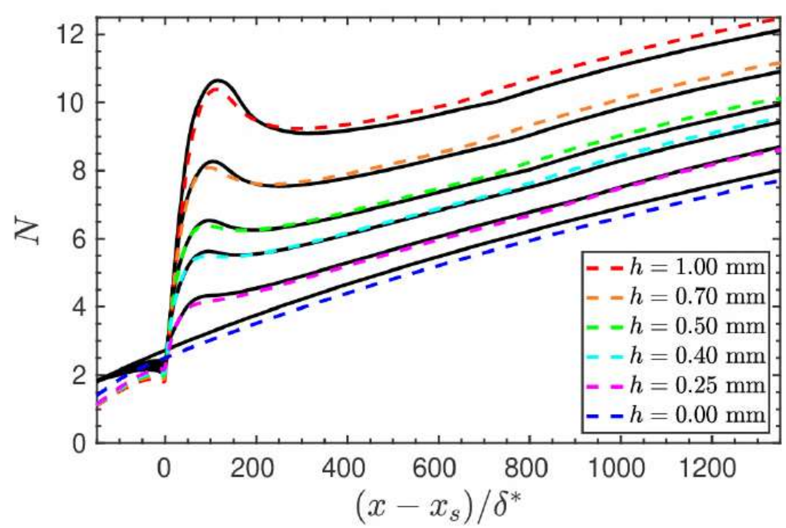
- LST (dashed) & HLNSE (solid) agree well
  - LST has upward shift with increasing step height

- $N_{tr}$ calibrated with exp. transition location of flat-plate case at $U_\infty = 34$ m/s
  - $x_{tr} = 1.016$ m or $(x_{tr} - x_s)/\delta^* = 1215$ from (Wang & Gaster 2005)
  - $N_{tr} = 7.32$ for LST and $N_{tr} = 7.40$ for HLNSE

$U_\infty = 28$ m/s



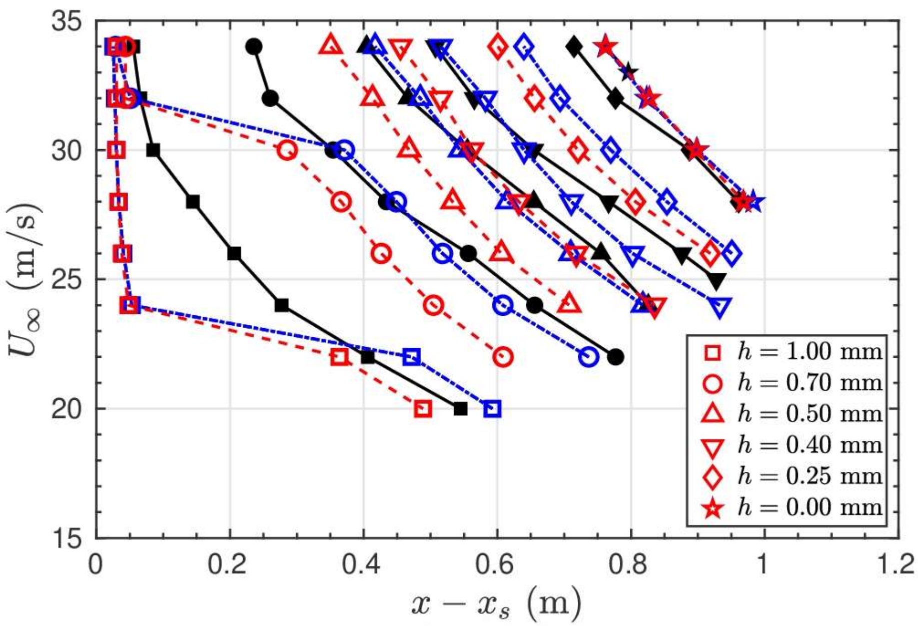

$U_\infty = 34$ m/s



# Transition Locations

- LST (red dashed-dotted lines) & HLNSE (blue dashed lines) have same behavior
  - LST transition locations are further upstream

- HLNSE agrees with experiments* (black solid lines) for moderate step heights
  - Disagreement at large step heights and freestream velocities
  - Discrepancy at $h = 0.25$ mm




*Experimental transition locations from (Wang & Gaster 2005)

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- RANS-Based Transition Models
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# RANS-Based Transition Models

- LST & HLNSE can successfully predict transition for moderate step heights
  - Difficult for large step heights and freestream velocities
- RANS-based models are less computationally expensive and do not require any knowledge of hydrodynamic stability theory
  - Lack of transition physics
- RANS-based models solve additional transport equations
  - SST2003-LM2009 & SA-AFT2019b
- FUN3D 13.7 (Biedron, Carlson, Derlaga et al. 2019)
- OVERFLOW 2.3d (Nichols & Buning 2019)
- Can existing RANS-based models accurately predict transition onset for moderate step heights without modification?
- If not, why?

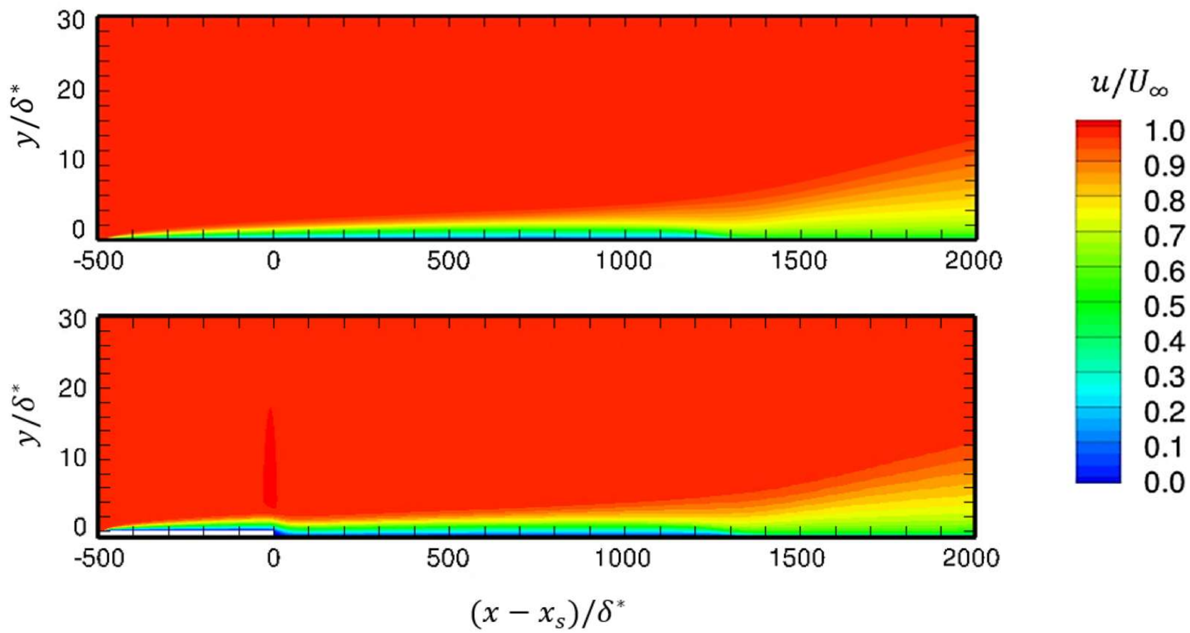
# SST2003-LM2009 Solutions

- $Tu = 0.37\%$ & $\mu_t/\mu = 5$ (match exp. transition locations for flat-plate cases)
- Transition location for $h = 0.5$ mm downstream of flat-plate value
  - Disagrees with experiments and stability analysis

$U_\infty = 34$ m/s

Flat Plate ($h = 0$):

BFS ($h = 0.5$ mm):

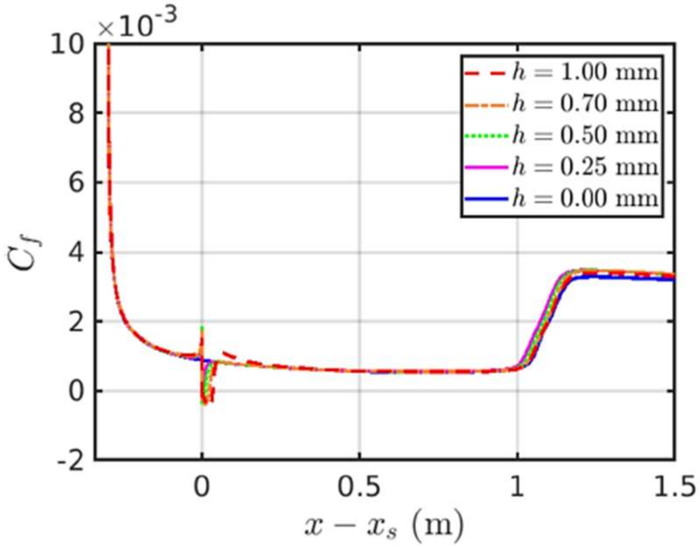


# Skin-Friction Contours for SST2003-LM2009

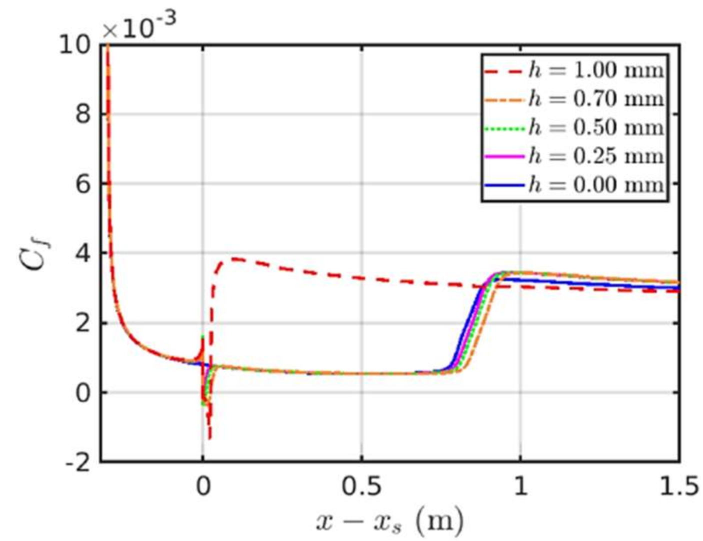
- BFS transition locations close to flat-plate values
  - Except at $U_\infty = 34$ m/s & $h = 1$ mm

- Transition locations from SST2003-LM2009 model disagrees with experiments and stability analysis for moderate step heights

$U_\infty = 28$ m/s



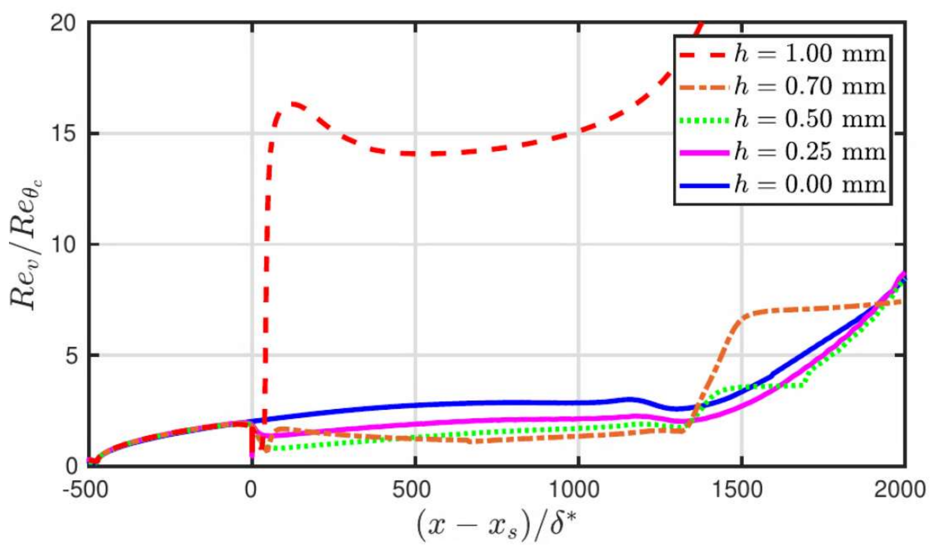

$U_\infty = 34$ m/s



# SST2003-LM2009 Transition Prediction

- SST2003-LM2009 model does not account for any flow history effects
  - $F_{onset1}$ is a function of $Re_{\theta_c}$ & $Re_v$
- $Re_v/Re_{\theta_c}$ for $h = 0.25, 0.4, 0.5,$ and $0.7$ mm below flat-plate value after $x_s$
- Boundary-layer flow returns to unperturbed state after $x_s$ for moderate $h$

$U_\infty = 34$ m/s

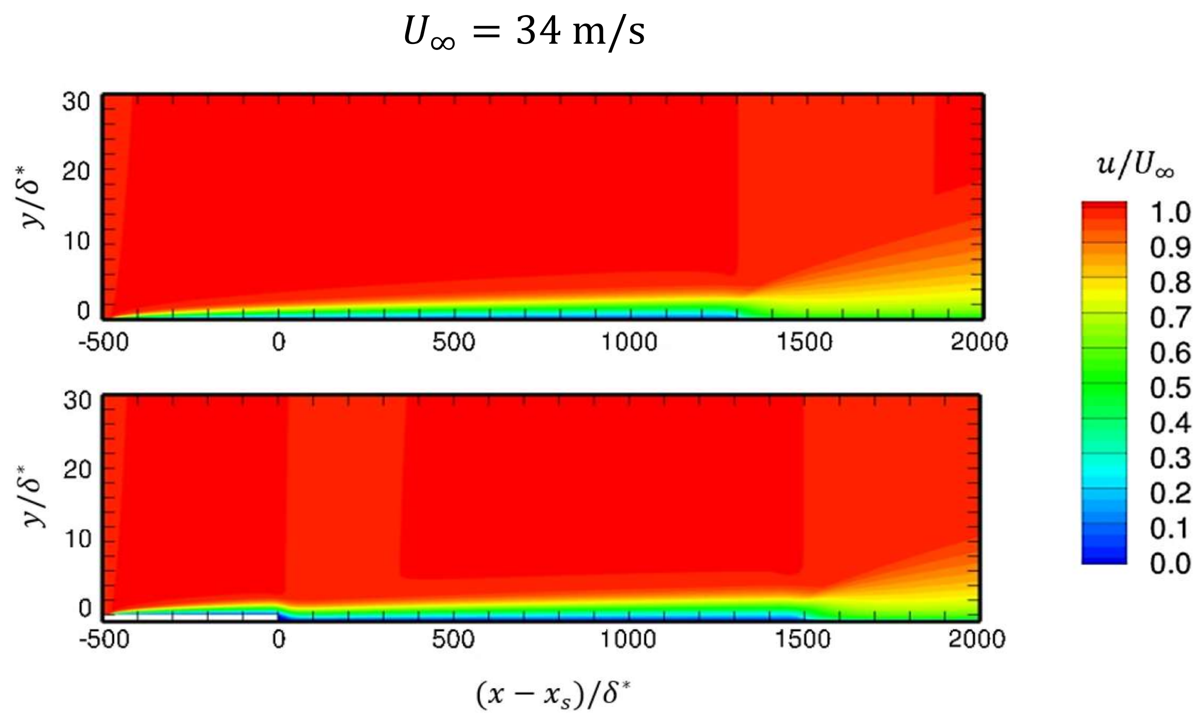


# SA-AFT2019b Solutions

- $Tu = 0.17\%$ & $\mu_t/\mu = 0.01$ (match exp. transition locations for flat-plate cases)
- Transition location for $h = 0.5$ mm downstream of flat-plate value
  - Disagrees with experiments and stability analysis

Flat Plate ($h = 0$):

BFS ($h = 0.5$ mm):

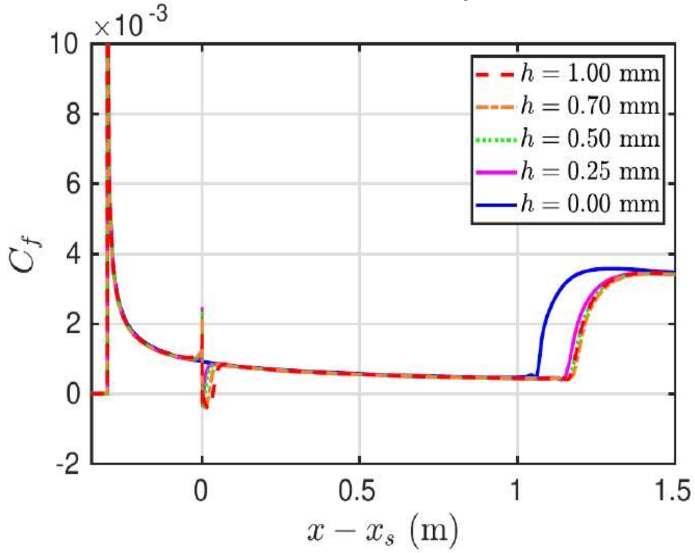


# Skin-Friction Contours for SA-AFT2019b

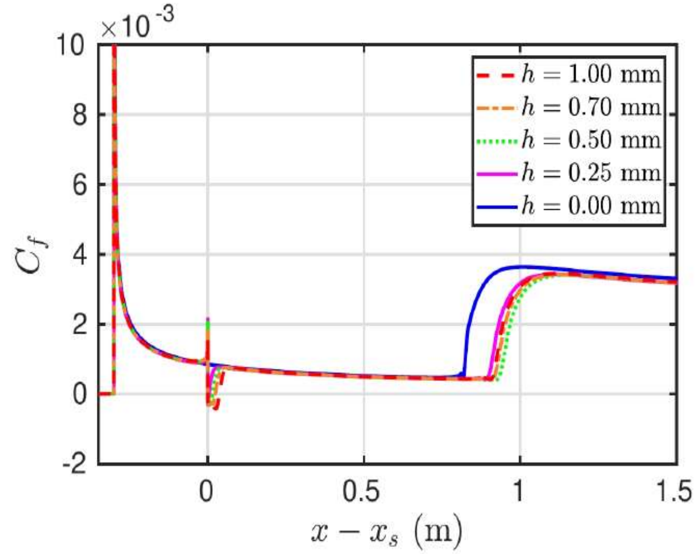
- BFS transition locations close to flat-plate values
    - Further downstream than SST2003-LM2009 model

- Transition locations from SA-AFT2019b model disagrees with experiments and stability analysis for moderate step heights

$U_\infty = 28\ \mathrm{m/s}$




$U_\infty = 34\ \mathrm{m/s}$

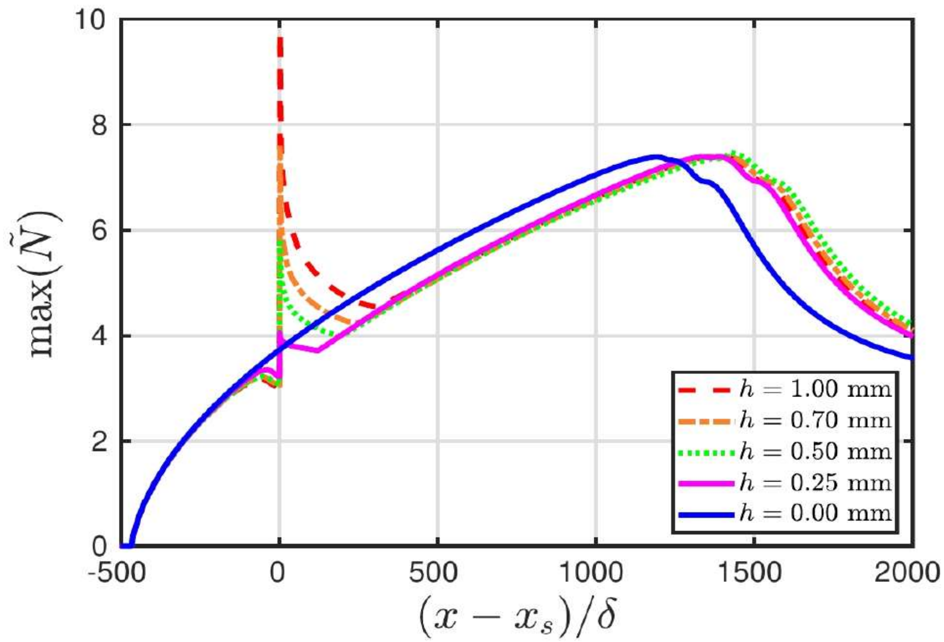


# SA-AFT2019b Transition Prediction

- SA-AFT2019b model does account for some flow history effects
  - Transport of amplification factor

- Net decrease in the *N*-factor envelope across step region compared to flat plate

$U_\infty = 34$ m/s



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# Conclusions and Future Work

- LST & HLNSE can successfully predict transition for moderate BFS heights
  - Difficult for large step heights and freestream velocities
- SST2003-LM2009 and SA-AFT2019b models produce transition locations that disagree with experiments/stability analysis for moderate BFS heights
- SST2003-LM2009 model does not account for any flow history effects
- SA-AFT2019b model results in a net decrease of the *N*-factor envelope compared to a flat plate
- Further analyze why the RANS-based transition models cannot predict accurate transition locations for moderate BFS heights
- Improve the RANS-based transition models
- Model the effects of a forward-facing step on boundary-layer transition

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