Modeling of Roughness Induced Transition Using a Local Correlation Method

Christopher M. Langel, Raymond Chow, C.P. van Dam

University of California, Davis

David Maniaci

Sandia National Labs

Robert S. Erhmann, Edward B. White

Texas A&M University

October 8, 2014
OVERSET Grid Symposium
Atlanta, GA

Motivation

- Despite nearly a century of investigation roughness effects on flow properties are not well understood
  - Limited methods for a priori estimates
  - Scalability of roughness effects with Reynolds number non-trivial
  - Lack of tools to predict roughness effects

- Primary effects on boundary layer flow
  - Premature laminar-turbulent transition
  - Thickening of fully turbulent boundary layer
  - Increase turbulent skin friction

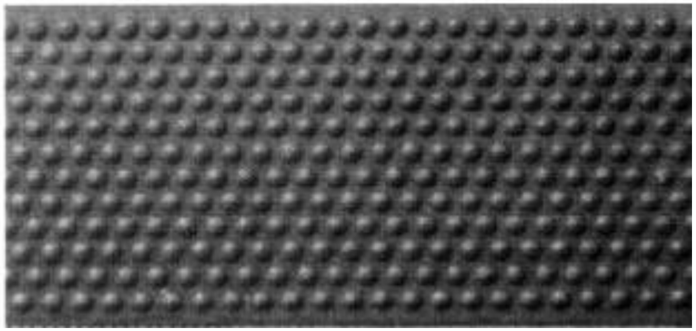
Motivation

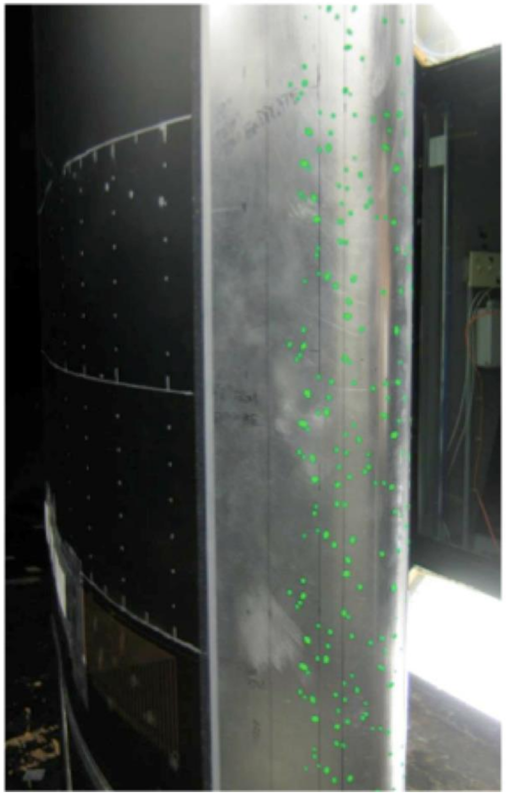
- Examples of leading edge roughness and erosion found in field on utility scale wind turbines

Left: Spruce (2004)
Right: Kanaby (2007)

Roughness Characterization

- Roughness typically classified broadly into three different subsets
  - Two-dimensional roughness
  - Isolated three-dimensional roughness
  - ***Distributed roughness***





Roughness Effects

- Disturbance(s) introduced by distributed roughness depends on a number of parameters
  - Roughness height (k) and local flow velocity (U_k)

$$Re_k = \frac{\rho U_k k}{\mu} \qquad k^+ = \sqrt{\frac{\tau_w}{\rho_w}}\frac{k}{\nu}$$

  - Ratio of roughness height to boundary layer thickness (k/δ)
  - Local streamwise pressure gradient
  - Roughness element distribution density or solidity

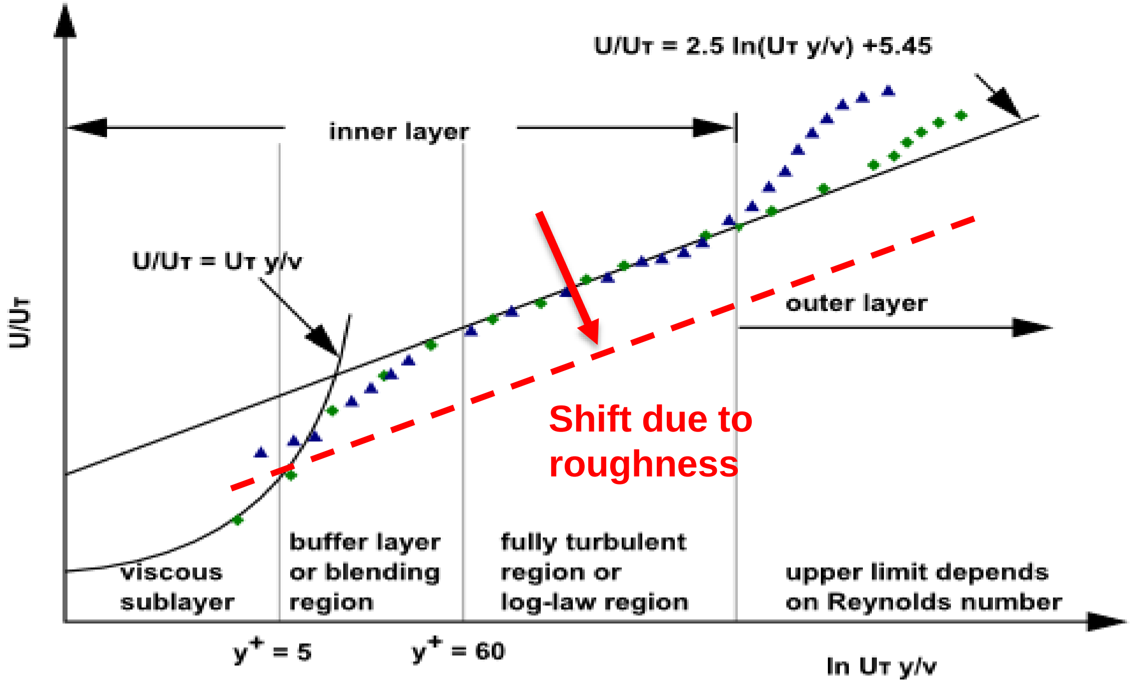
Roughness Effects

- **Critical behavior**
  - Roughness large enough to immediately trigger transition
  - Experiments attempt to identify $Re_{k,crit}$
  - Basic correlations more accurate in critical region

- **Subcritical behavior**
  - Roughness shifts transition location, difficult to predict
  - Incubation distance (Morkovin 1980's)
  - Transient growth of disturbances (Reshotko, Tumin et al. 2000's)
  - Integrated effects and time histories need consideration

Modeling Roughness

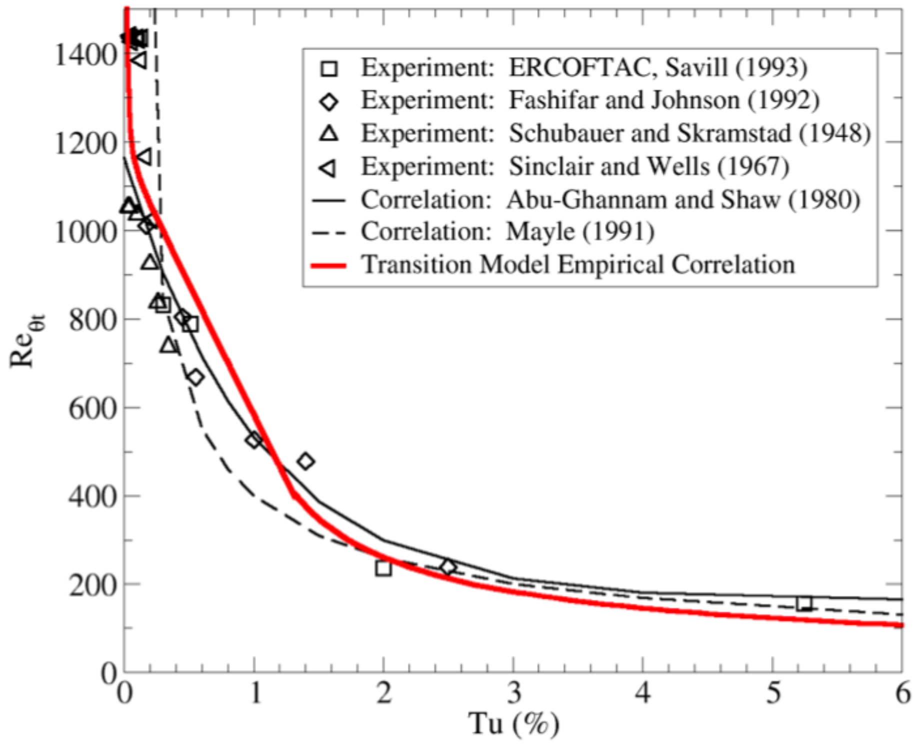
- Typically assumed roughness induces shift in log-layer of turbulent boundary layer
  - Can represent this effect with change in boundary condition of turbulence model (Wilcox, SA modification, etc.)



Langtry-Menter

- Conventional RANS turbulence models do not account for effects of transition
- Modification to turbulence model does not account for transition effects
- Recently developed “local correlation transition model”
- Transition model introduces two additional global parameters
  - $Re_{\theta t}$ - Critical momentum thickness Reynolds number – transition onset criteria
  - γ - Intermittency - scalar quantity that ramps up turbulence model

Local Correlation Principles



Critical momentum thickness ($Re_{\theta t}$) vs. freestream turbulence intensity

Red line indicates Langtry-Menter correlation (Langtry 2006)

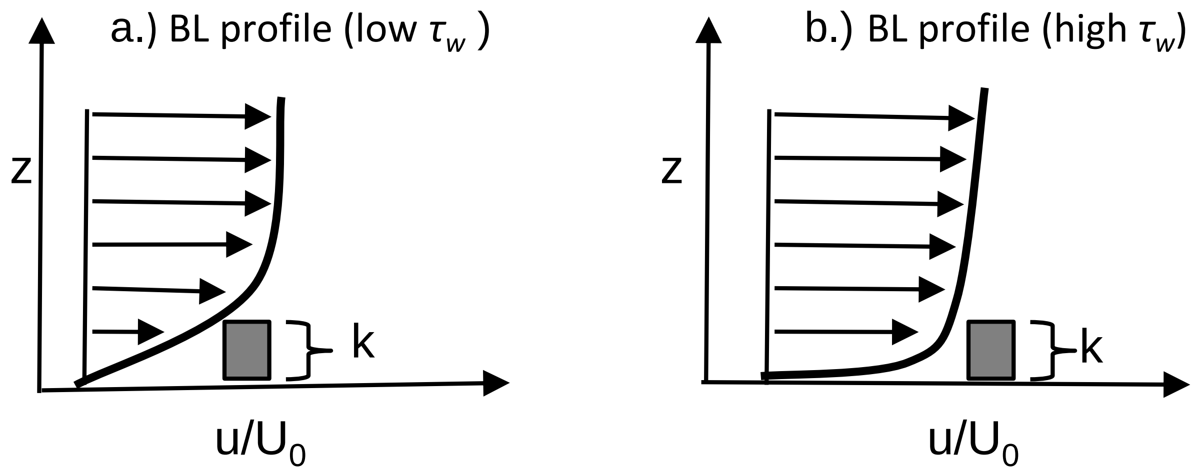
- Momentum thickness Reynolds number, $Re_\theta = \theta U_e/\nu$, correlates with transition location
- Relationship between strain rate magnitude and momentum thickness used to localize calculation (Menter 2002)
- Flow begins transition where local $Re_\theta > Re_{\theta t}$

Roughness Amplification Model

Correlate integrated roughness effects with change in transition onset criteria

- Initially proposed by Dassler, Kozulovic, and Fiala from TU Braunschweig (2010)
- Introduces third term (A_r) to Langtry-Menter transition model that defines a region of "roughness influence"
- Correlation for $Re_{\theta t}$ modified globally by A_r variable to represent new mode of transition

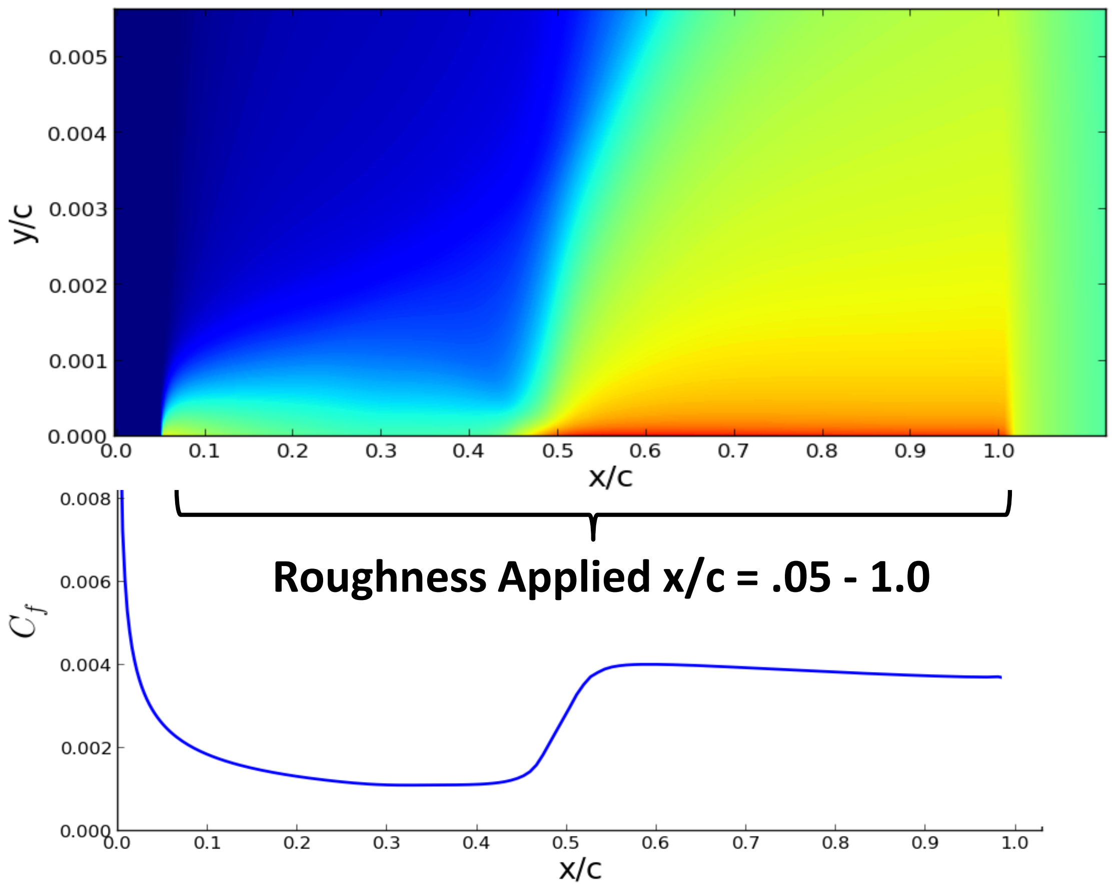
Roughness Amplification Model



- In principle, roughness will alter momentum thickness correlation
- Momentum flux encountered by roughness can be considered a function of the shear stress at the wall (τ_w) and roughness height (k)

$$\Delta Re_\theta = f(k, \tau_w) = f(k^+)$$

A_r Distribution Over a Flat Plate



$$A_R\big|_{\text{Rough Wall Boundary}} = f(k^+)$$

with:

$$k^+ = \sqrt{\frac{\tau_w}{\rho_w}} \cdot \frac{k_s}{\nu}$$

Additionally:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho U_\infty^2}$$

(Top) Distribution of A_r variable above flat plate, $Ma = 0.3$, $Re = 1.34 \times 10^6$
(Bottom) Corresponding skin friction plot

Roughness Amplification Model

Goals:

- Represent subcritical as well as critical transition behavior
- Formulate model as function of k^+
- Account for integrated roughness effects using localized method

Limitations:

- Bounded by turbulence & transition models
  - High Reynolds number limitations
- Cannot account for detailed flow structures produced by individual roughness elements
  - e.g. horseshoe vortex formation

SST/Langtry-Menter/Roughness-Amplification Interaction

General Form of Scalar Transport Equation:

$$\frac{\partial(\rho C)}{\partial t} + \frac{\partial(\rho U_j C)}{\partial x_j} = P_C + \frac{\partial}{\partial x_j}\left[\sigma_C\left(\mu + \mu_t\right)\frac{\partial C}{\partial x_j}\right]$$

Unsteady Term — Convective Flux — Production (Sources/ Sinks) — Diffusive Flux

$$\frac{\partial(\rho A_r)}{\partial t} + \frac{\partial(\rho U_j A_r)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\sigma_{ar}\left(\mu + \mu_t\right)\frac{\partial A_r}{\partial x_j}\right]$$

***A_r* - Roughness Amplification Transport Equation**
Boundary condition a function of dimensionless roughness height (k^+)

$$\frac{\partial(\rho \tilde{R}e_{\theta t})}{\partial t} + \frac{\partial(\rho U_j \tilde{R}e_{\theta t})}{\partial x_j} = P_{\theta t} + \frac{\partial}{\partial x_j}\left[\sigma_{\theta t}\left(\mu + \mu_t\right)\frac{\partial \tilde{R}e_{\theta t}}{\partial x_j}\right]$$

***$Re_{\theta t}$* - Transport Equation**
Production term influenced by ***A_r*** variable

$$\frac{\partial(\rho \gamma)}{\partial t} + \frac{\partial(\rho U_j \gamma)}{\partial x_j} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_f}\right)\frac{\partial \gamma}{\partial x_j}\right]$$

***γ* - Transport Equation**
Production term is influenced by ***$Re_{\vartheta t}$***

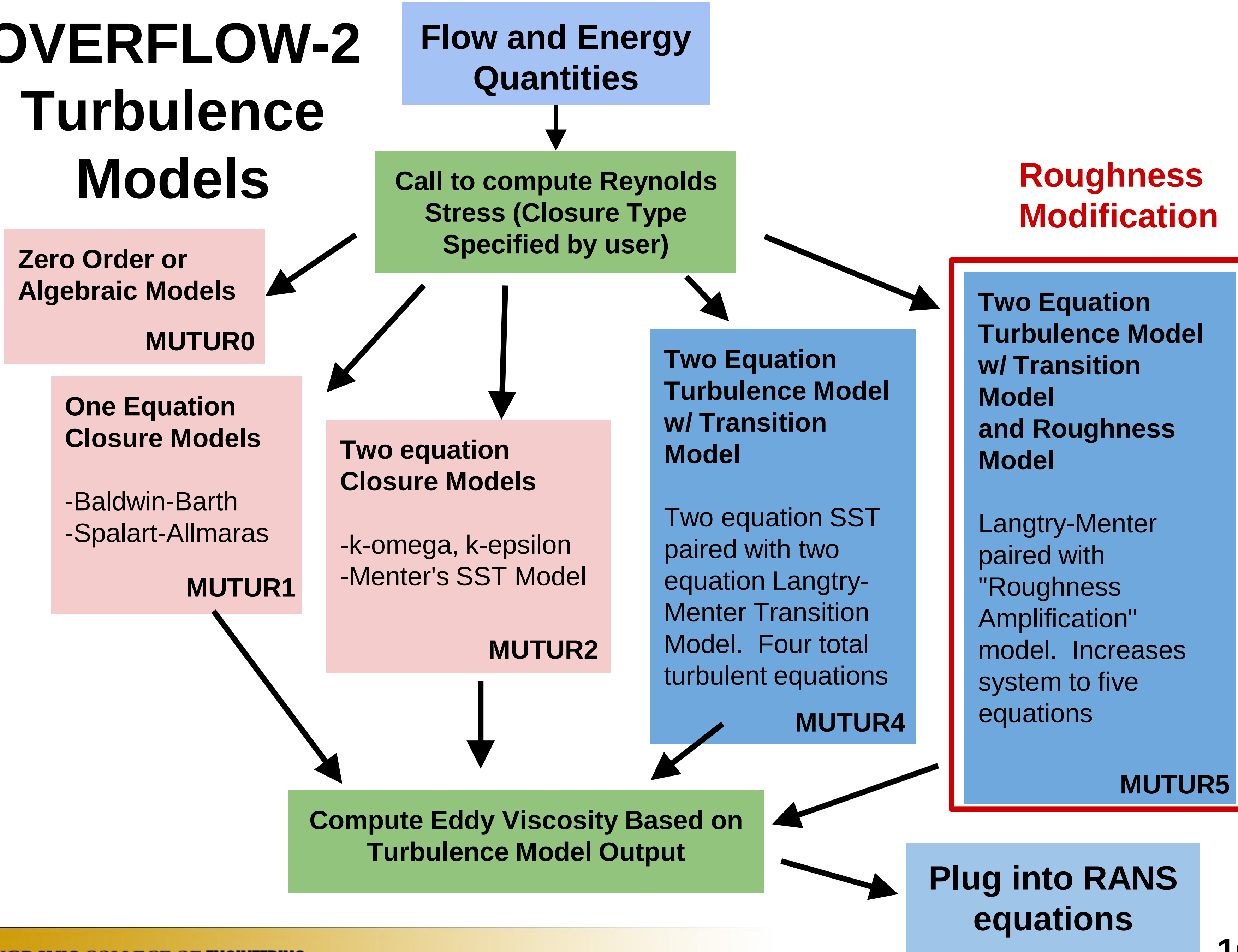
$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_j k)}{\partial x_j} = P_k - D_k + \frac{\partial}{\partial x_j}\left[\left(\sigma_k \mu_t + \mu\right)\frac{\partial k}{\partial x_j}\right]$$

***k* - Transport Equation**
Production term directly multiplied by ***γ***

Implementation in OVERFLOW-2

- Model currently implemented in version 2.2f
- Added as a new turbulence model (NQT) option
- Extends Langtry-Menter routines with addition of new A_r variable
- Convective and diffusive fluxes discretized using 2nd order HLLC upwind scheme
- A_r variable coupled with transition model variables in linear SSOR solver

OVERFLOW-2 Turbulence Models

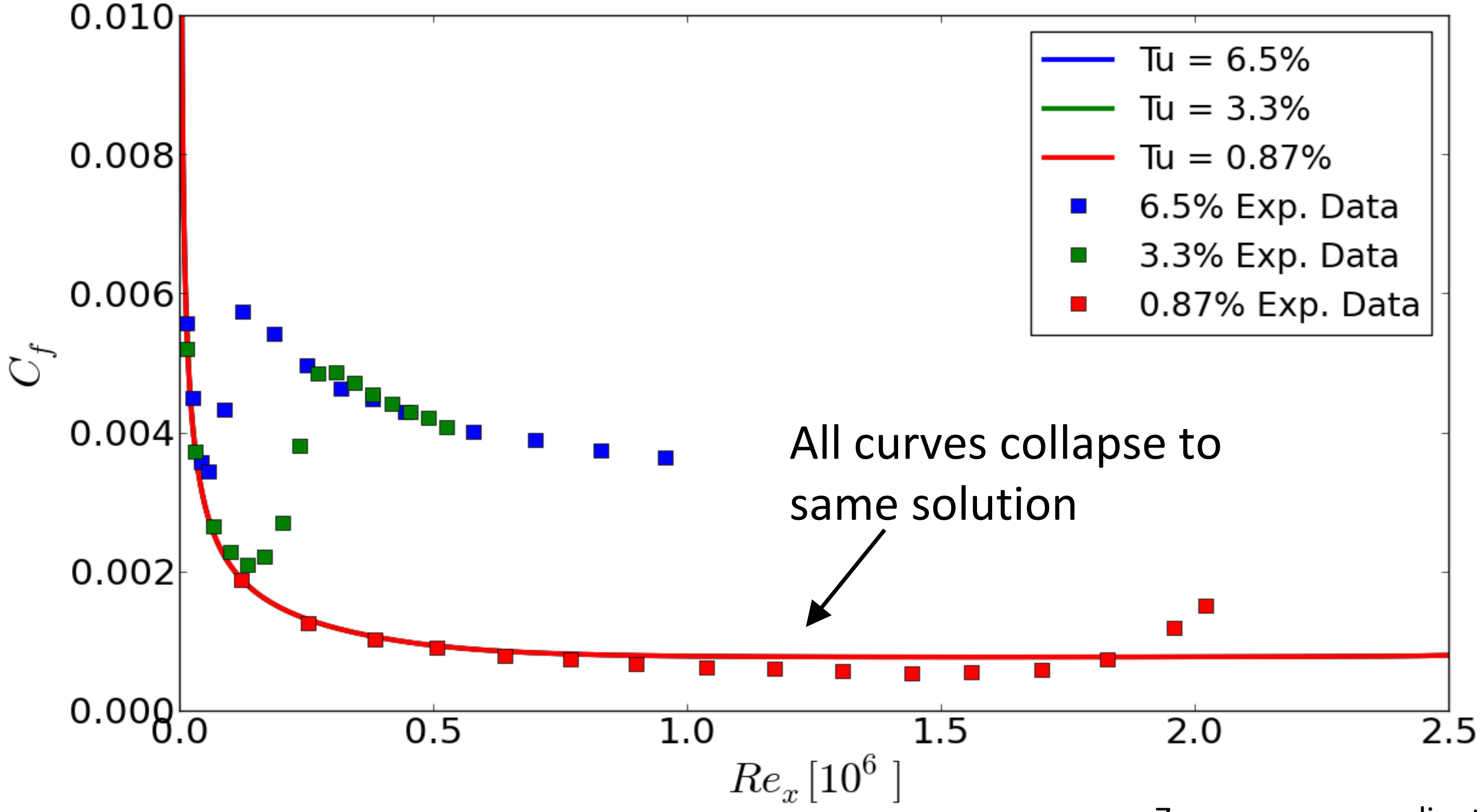


Preliminary Considerations

- Roughness model still relies on Langtry-Menter to predict other transition mechanisms (natural, separation induced, crossflow instability, etc.)
  - Validate behavior of transition model on clean configurations
- Transition model strongly dependent on freestream turbulence intensity (user prescribed parameter)
- Turbulence decay rate exhibits grid dependence

Freestream Turbulence Sensitivity

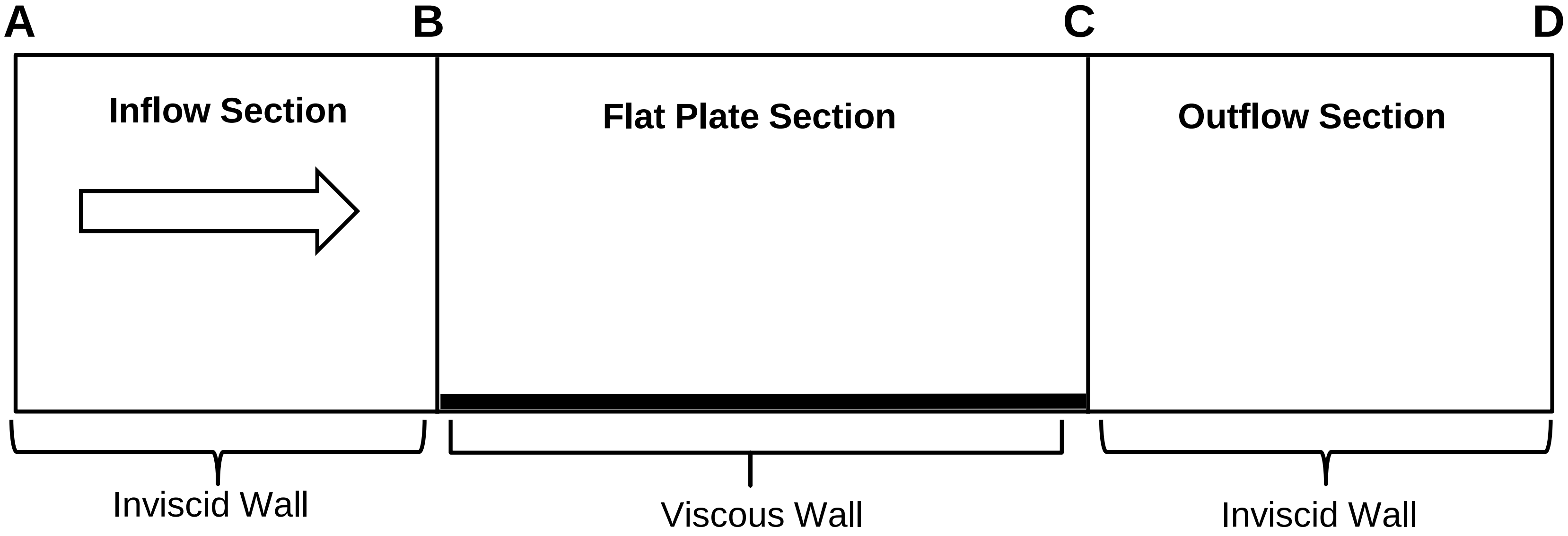
- Transition model sensitive to freestream turbulence conditions



Zero pressure gradient flat plate, α = 0°

Freestream Turbulence Sensitivity

- Incorrect “laminar” solution predicted due to poorly resolved freestream decay rates along inflow
- Two different solutions explored
  - Modification to ω destruction term in SST turbulence model
  - Shut off turbulent production in specified regions



Freestream Turbulence Decay Limiter

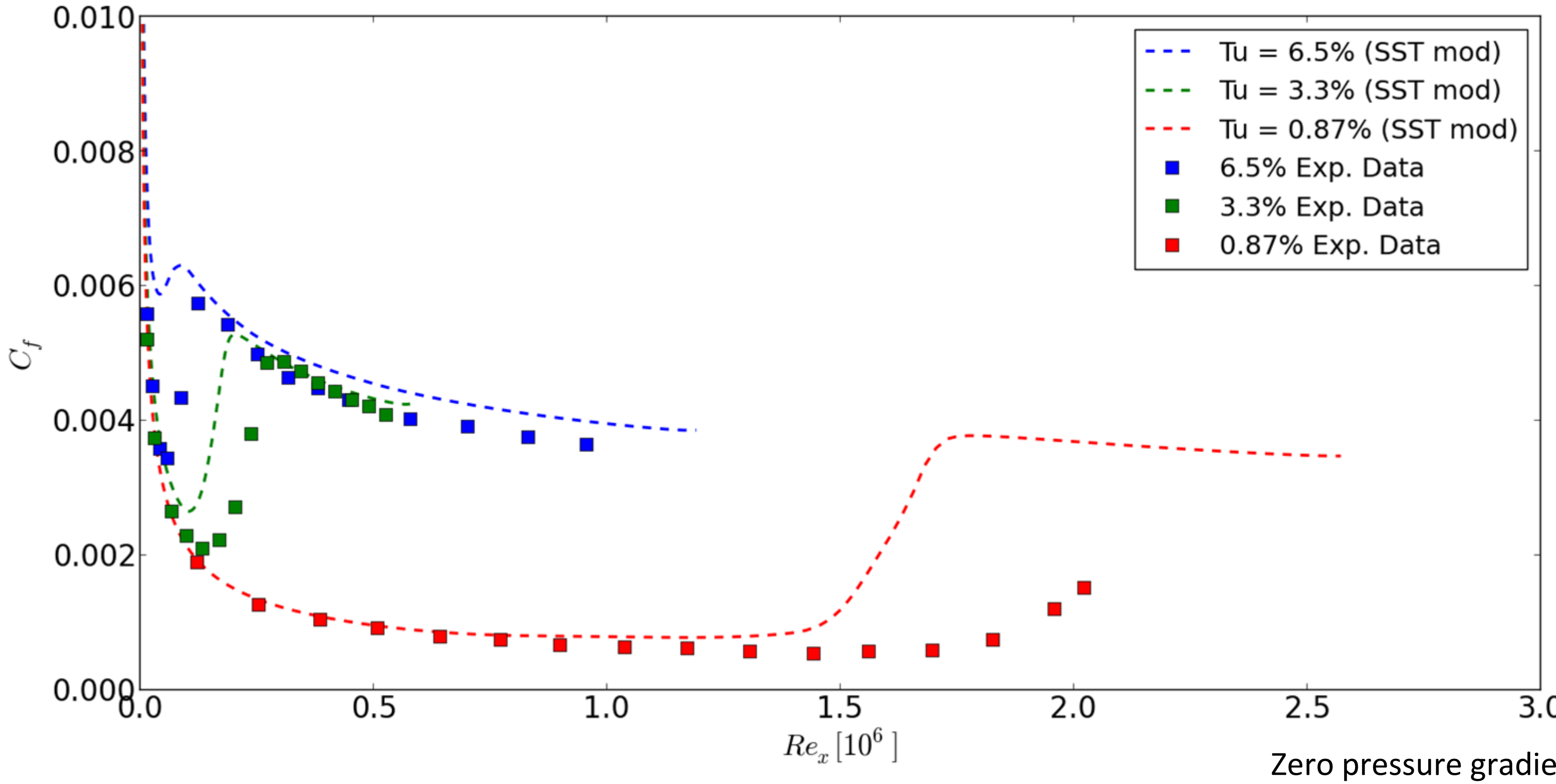
- Modifies destruction term for ω in the SST model
- Impact of modification
  - ω near viscous wall ~O(1)
  - ω near inviscid wall ~O(10^{-5}-10^{-6})
  - Freestream decay rate (C_ω) ~O(10^{-5}-10^{-6})
- Modification to turbulence dissipation transport equation

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho U_j \omega)}{\partial x_j} = \gamma P_\omega - \beta\rho\omega^2 + \text{diffusive terms}$$

$$\beta\rho\omega^2 \rightarrow \beta\rho\omega(\omega - C_\omega) \qquad C_\omega = \text{Freestream decay rate}$$

Flat Plate Results with Decay Limiter

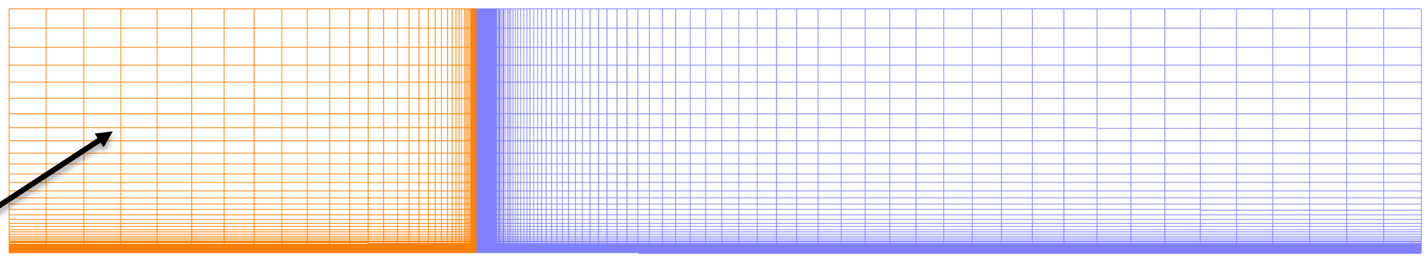
- Decay limiter functions as desired and produces more accurate results



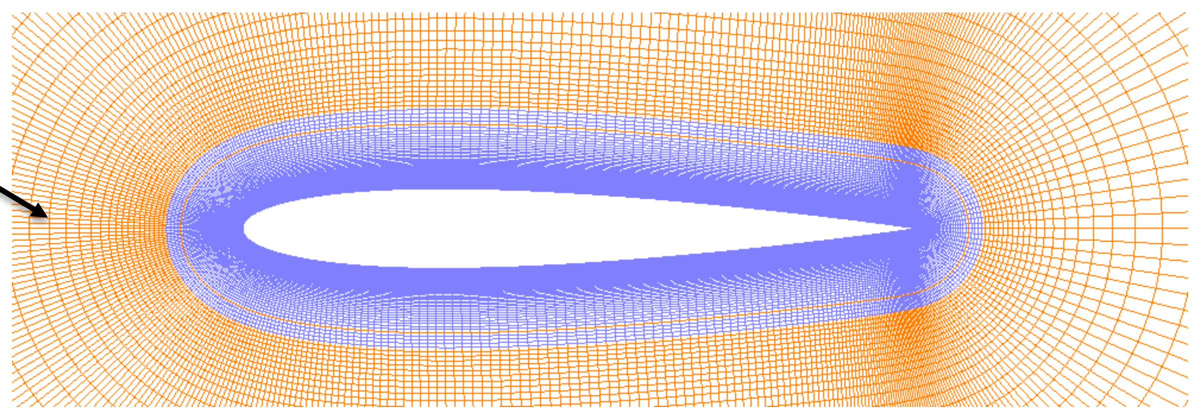
Zero pressure gradient flat plate, α = 0°

Specifying Turbulent Production

- Separate inflow and viscous wall regions, shut off turbulent production terms (**ITTYP=102**) in inflow section
- Shutting off viscous terms (**VISC = .F.**) still results in decay of FSTI

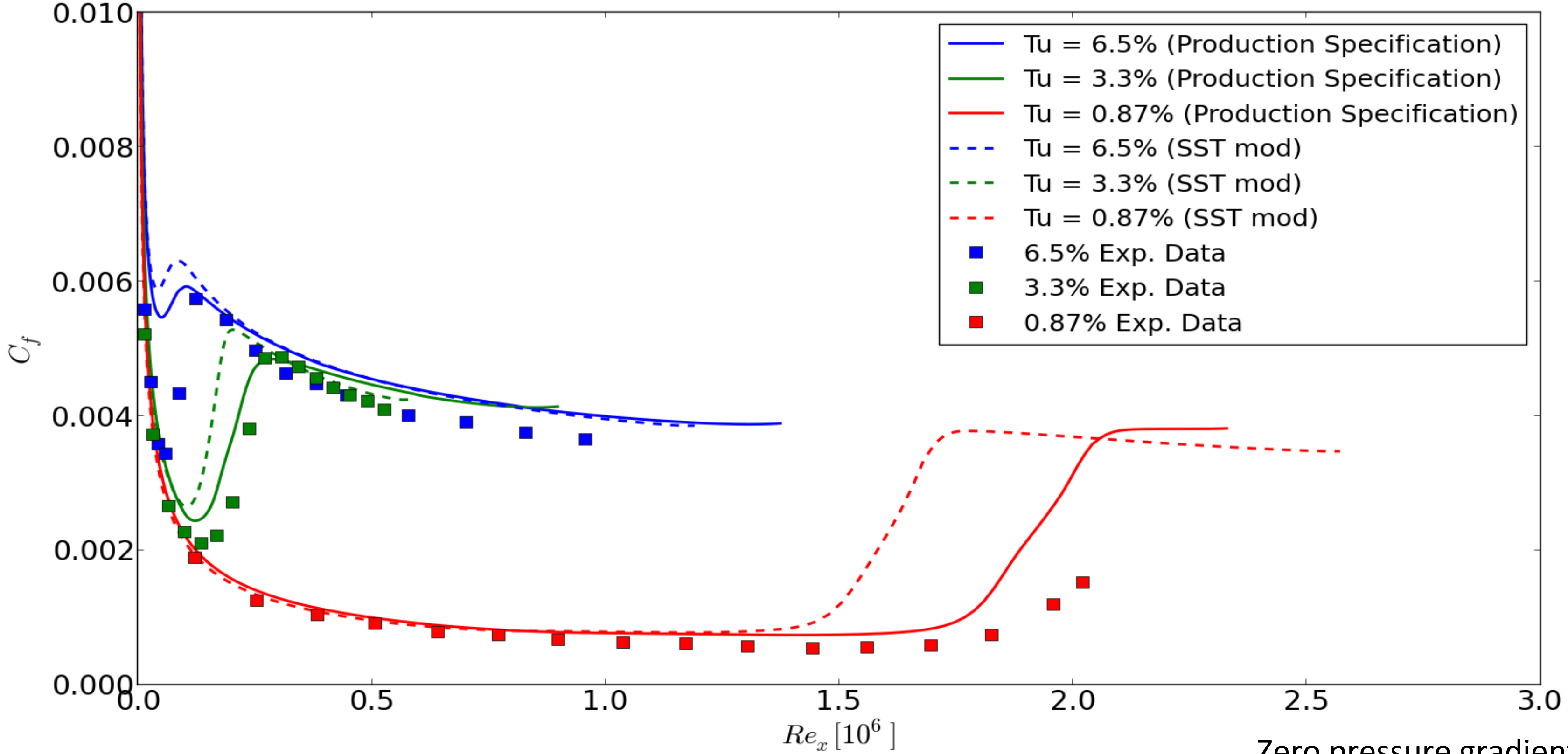


No production/ destruction in inflow region



Flat Plate with Decay Limiting Methods

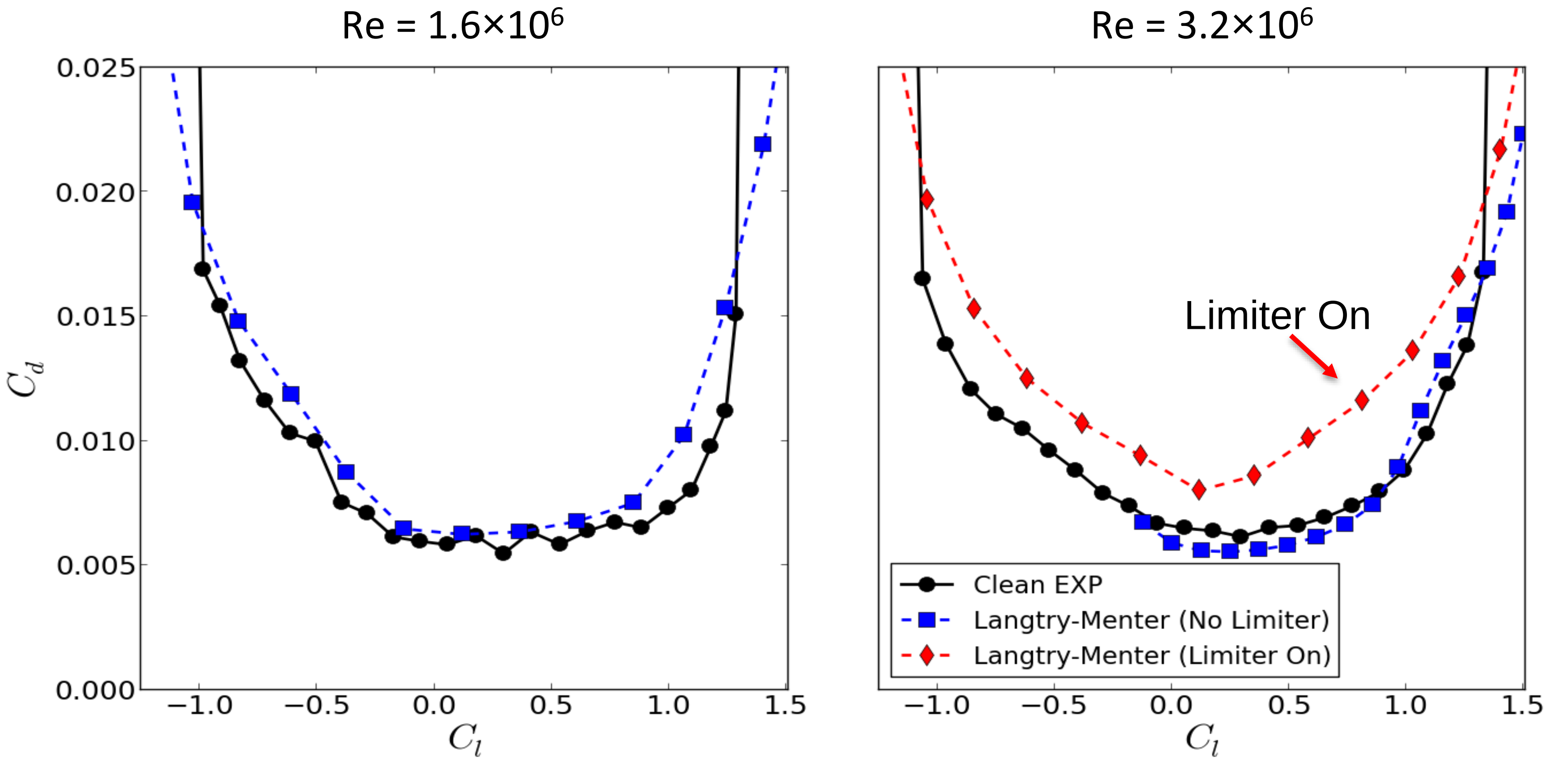
- Production specification produced the best results of remedies tested



Zero pressure gradient flat plate, α = 0°

Results with Decay Limiting Methods - NACA 63_3- 418

- While necessary for flat plate, discrepancies arise when limiter is applied to low FSTI airfoil cases



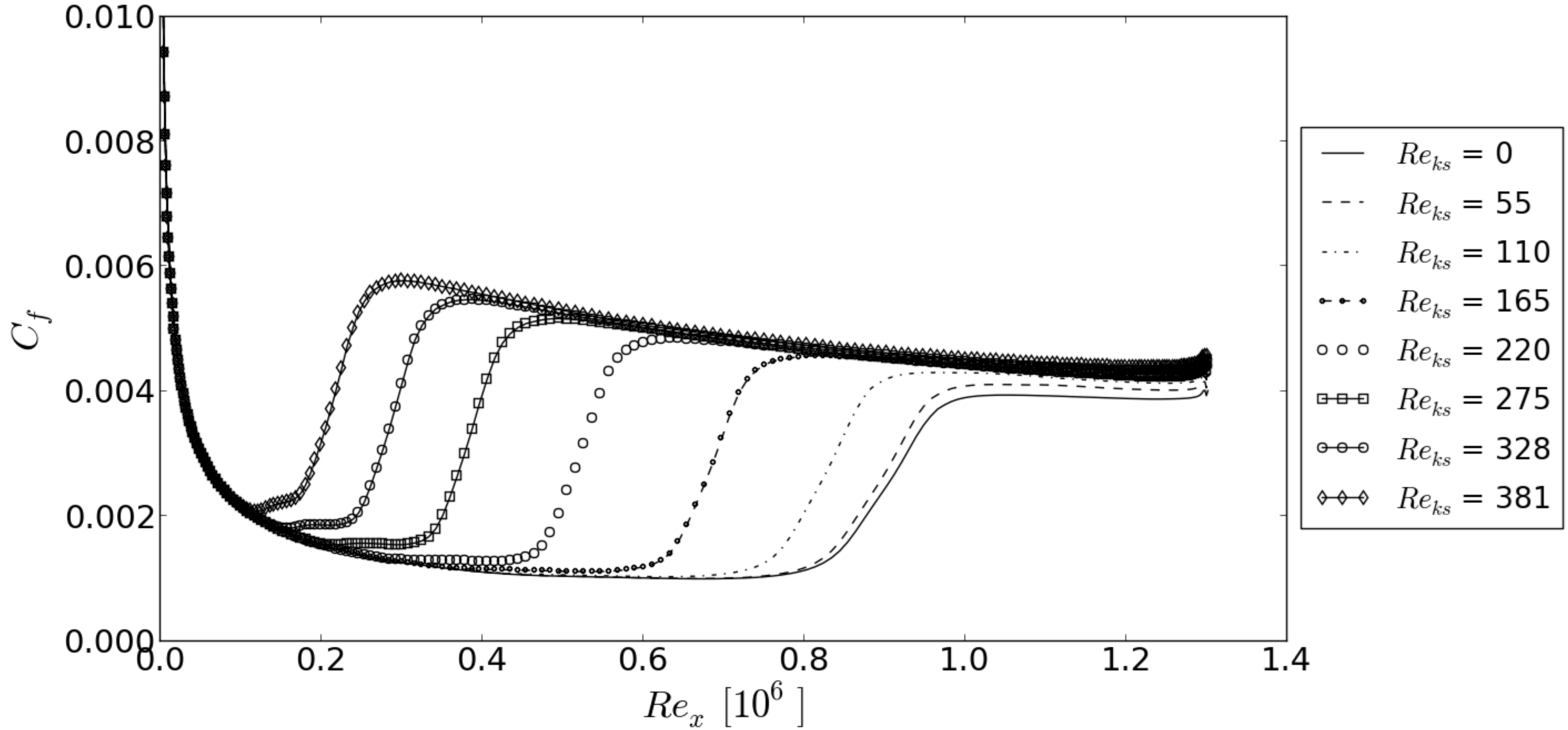
Decay Limiting Conclusions

- Inconsistencies observed regarding when turbulence decay limiter should be applied
- Model development yields insight
  - Flat plate and other high freestream turbulence cases calibrated without large inflow region (no FSTI decay accounted for in model)
  - Low turbulence intensity airfoil cases calibrated with large inflow regions (FSTI decay effectively included in model formulation)
- Subsequent tests run accordingly
  - Flat plate cases use turbulence decay limiter
  - Airfoil tests run without decay limiting

Initial Roughness Model Calibration

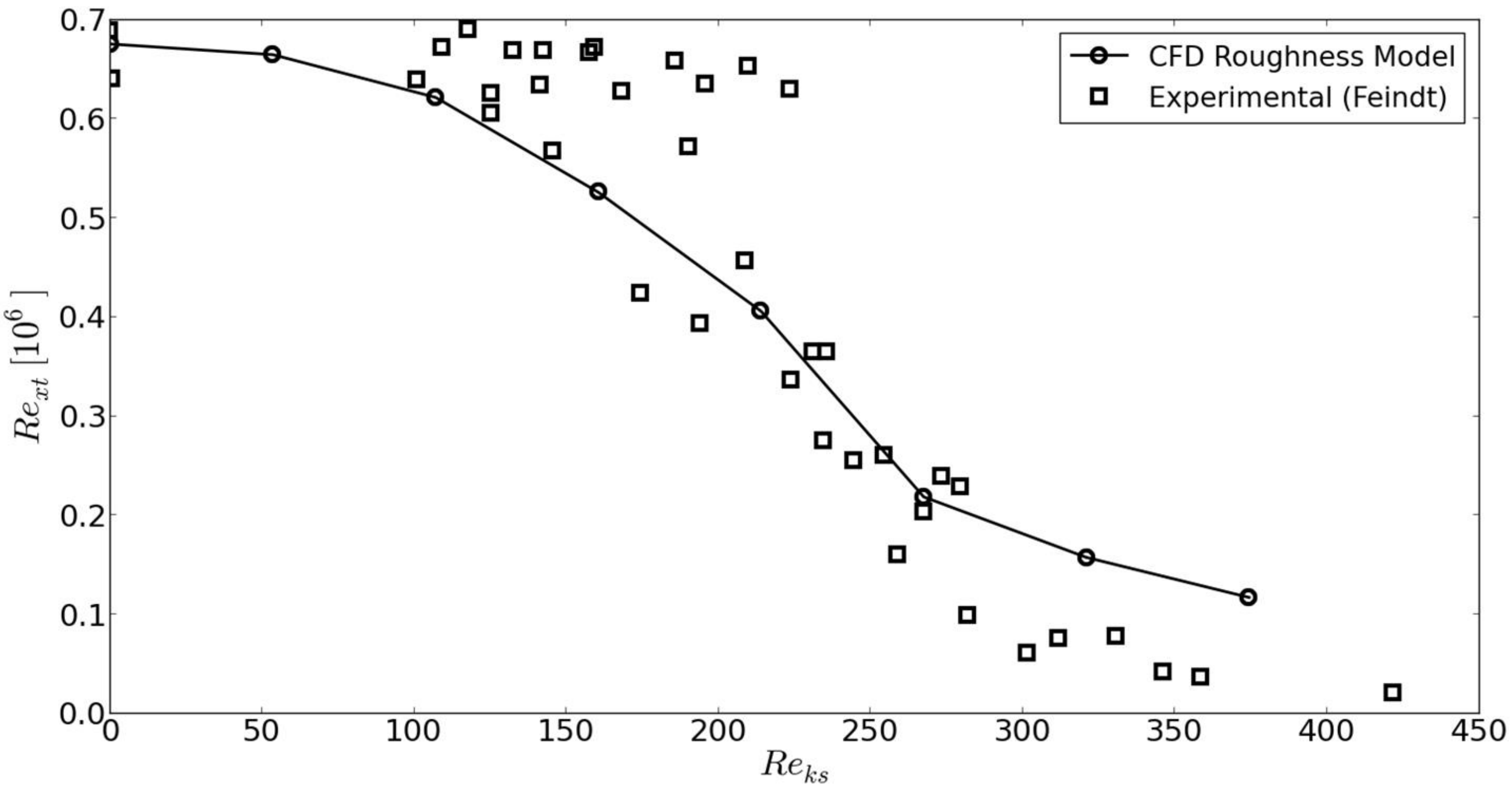
- **Flat plate**
  - Experimental results of Feindt (1956)
  - Varying sand grain roughness heights
    - (40, 80, 120, 160, 200, 240, 280 k/c)
  - Zero and adverse pressure gradient tested
  - Transition location vs. roughness Reynolds number (Re_k) and effects of roughness height on skin friction

Effect of Roughness Height on Skin Friction



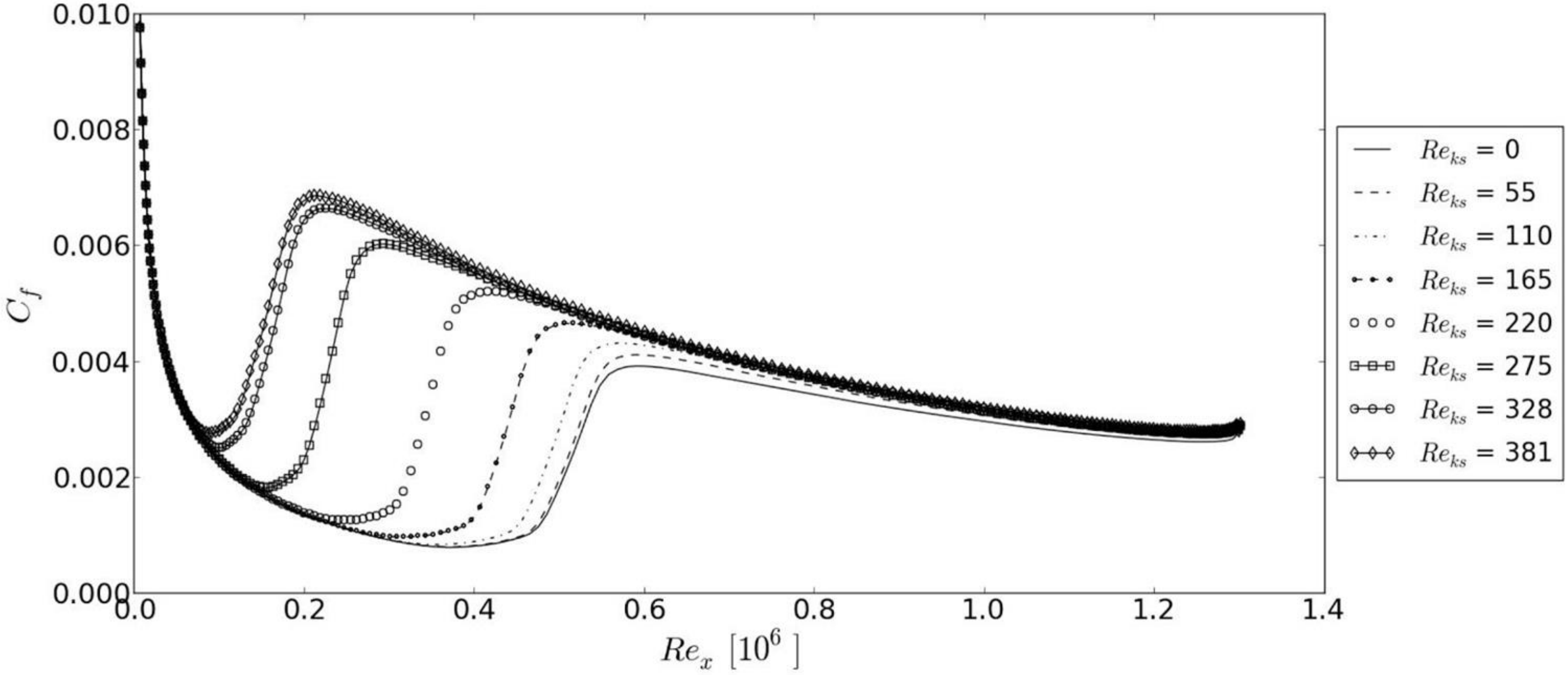
Zero pressure gradient at 0°

Effect of Roughness Height on Transition



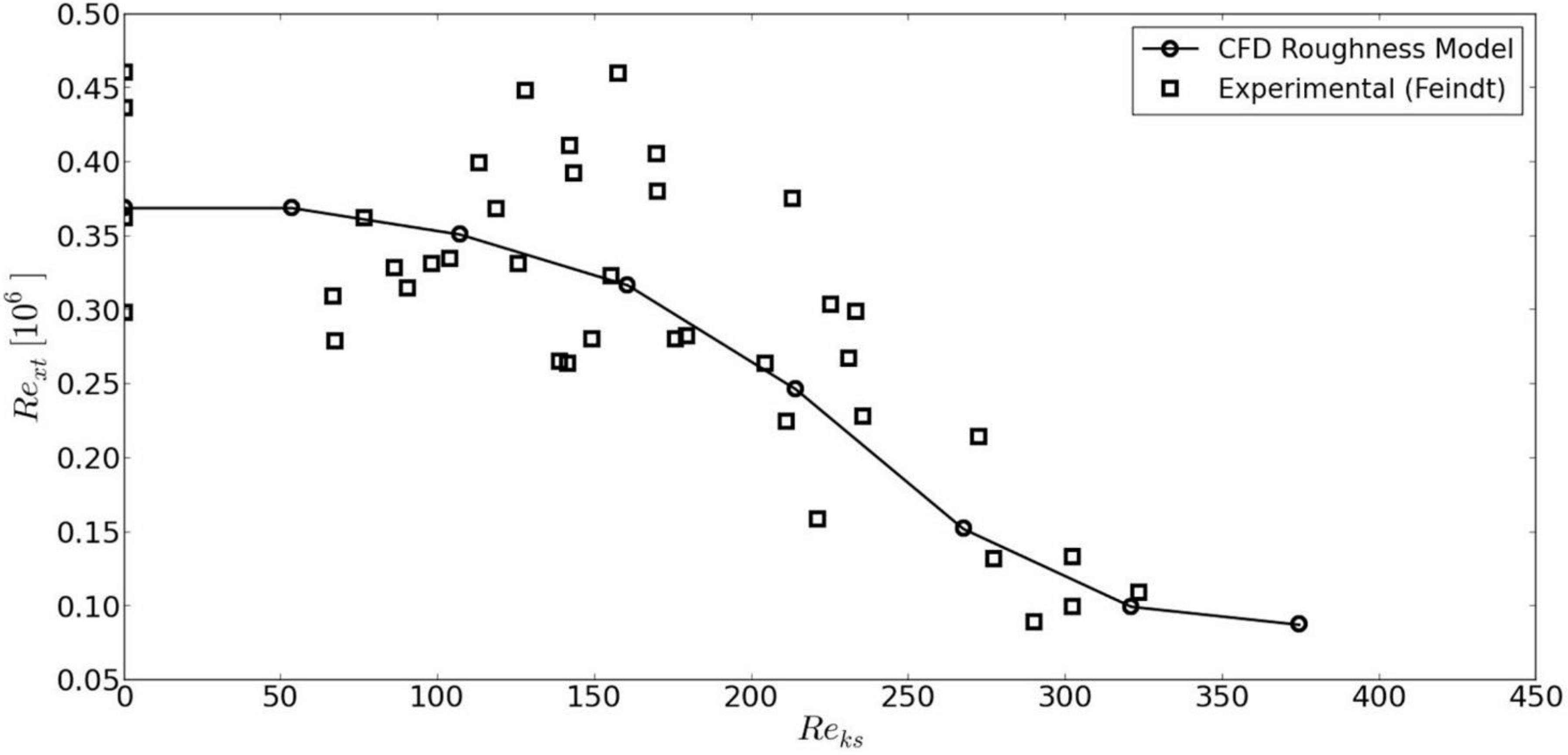
Zero pressure gradient at 0°

Effect of Roughness Height on Skin Friction



Adverse pressure gradient at 0°

Effect of Roughness Height on Transition



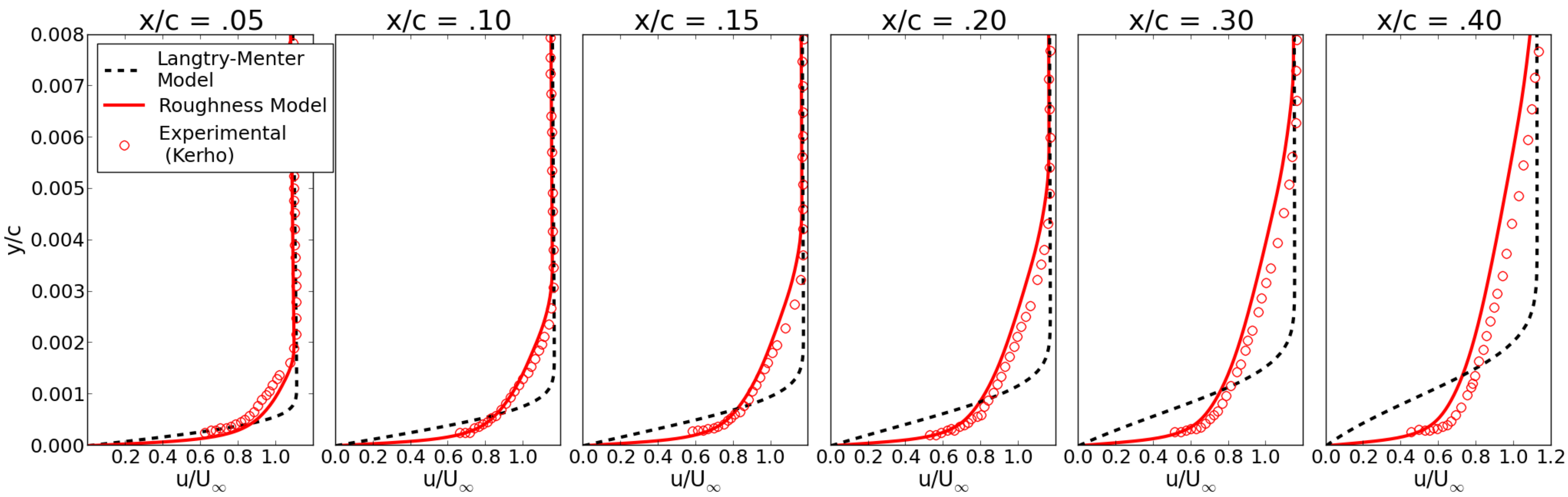
Adverse pressure gradient at 0°

Initial Roughness Model Calibration

- Model predicts shift in transition location well
- Change in skin friction also represented

- **NACA 0012 airfoil**
  - Determine post critical ($Re_k > Re_{k,crit}$) model behavior
  - Comparison with boundary layer profiles
  - Slight discrepancy in the rate of turbulent boundary layer development

NACA 0012 - BL Profiles - With Roughness

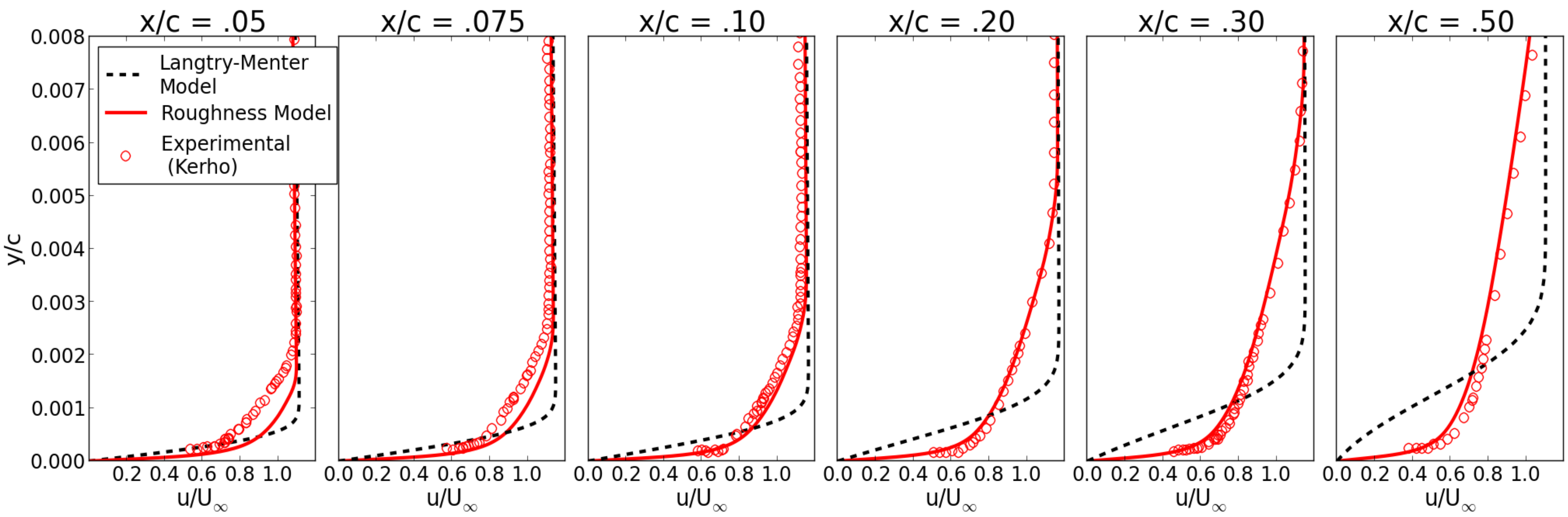


1/2“ rough strip applied at x/c = **.0064 - .0258**

Re = 1.25×10^{6}, $\alpha = 0°$

Kerho & Bragg, 1997

NACA 0012 - BL Profiles - With Roughness

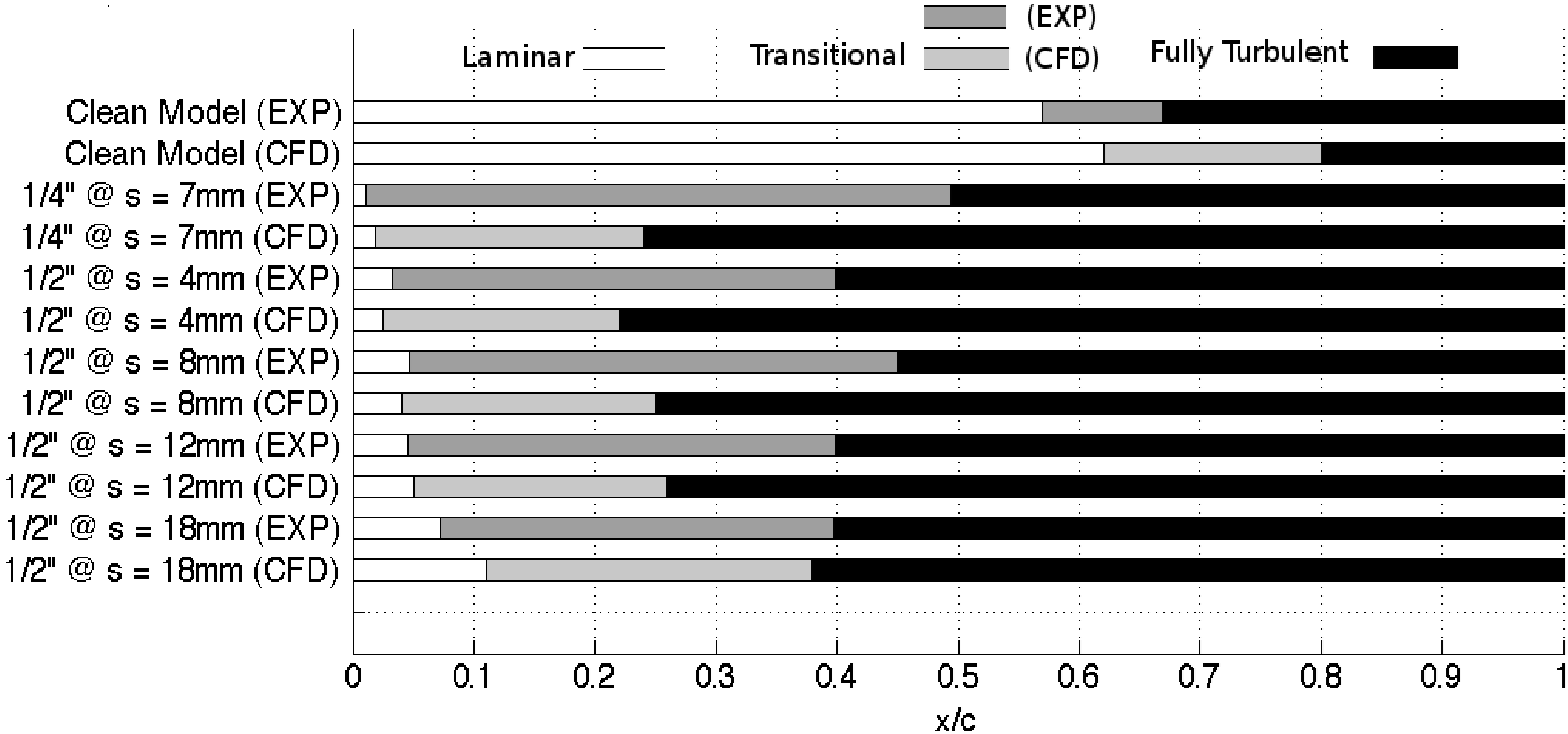


1/2“ rough strip applied at x/c = **.0018 - .0191**

Re = 1.25×10^6, α = 0°

Kerho & Bragg, 1997

Comparison of Boundary Layer States



$Re = 1.25\times10^6$, $\alpha = 0°$

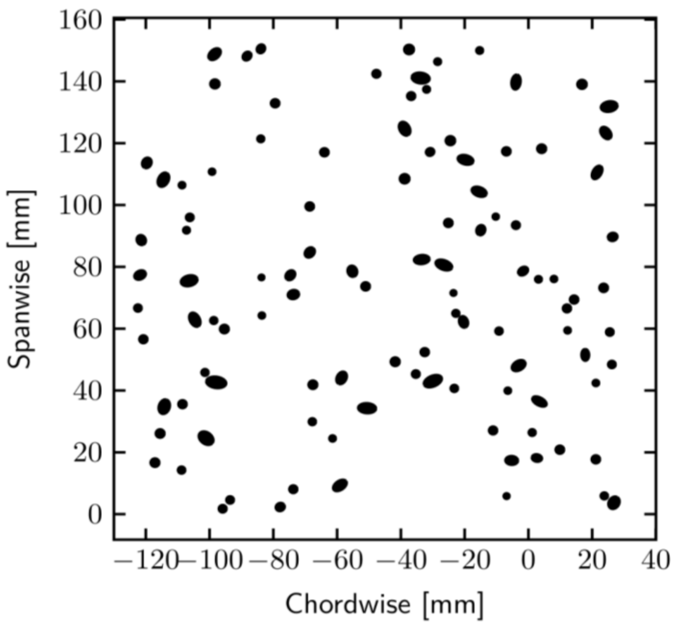
Kerho & Bragg, 1997

Texas A&M Experiment

- Concurrent to development of computational roughness model, tests conducted on NACA $63_3 - 418$
- Roughness height, distribution density, shape, and chordwise extent varied
- Configurations designed to facilitate calibration of the model
  - Flow information from RANS simulations used to help with roughness sizing and placement
- Wide range of Reynolds numbers ($0.8 - 4.8 \times 10^6$) and angles of attack ($-12 < \alpha < 20°$) tested for each roughness pattern

Texas A&M Experiment

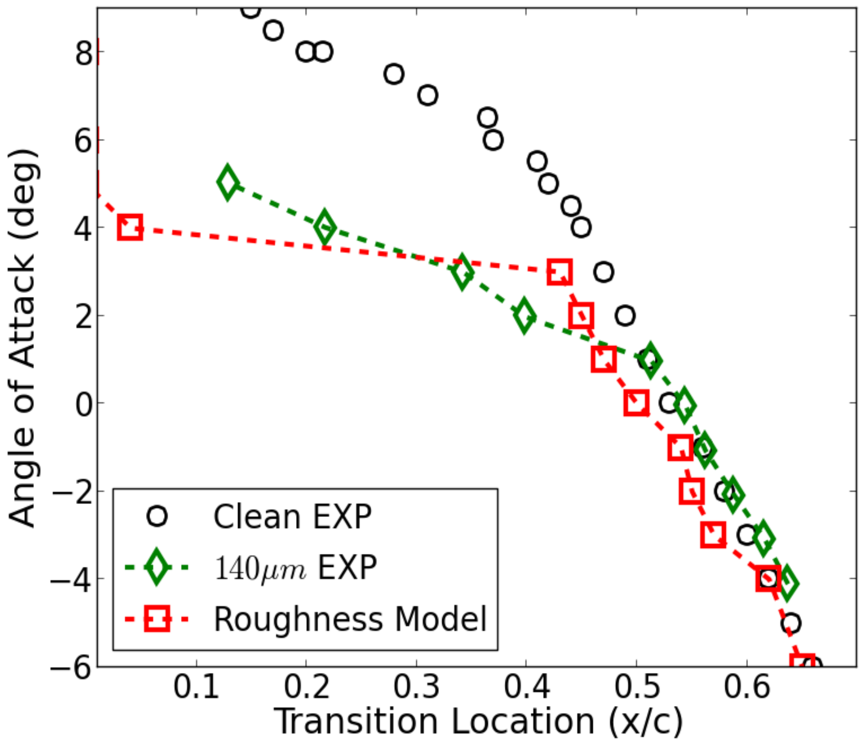
- Oran W. Nicks Low Speed Wind Tunnel
- Roughness heights:
  - 123, 172, 246 $\times 10^{-6}$ k/c (100, 140, 200 μm)
- Distribution densities:
  - 3, 6, 9, 12, 15%



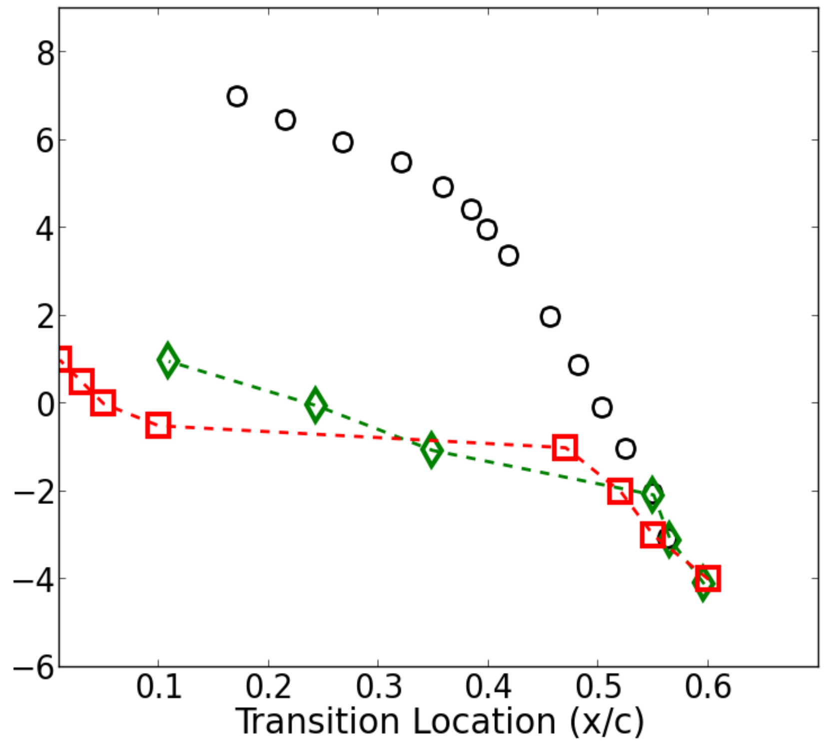
NACA 63_3- 418 Transition Location with Roughness

- Prediction of transition location with roughness model

$Re_c = 1.6 \times 10^6$

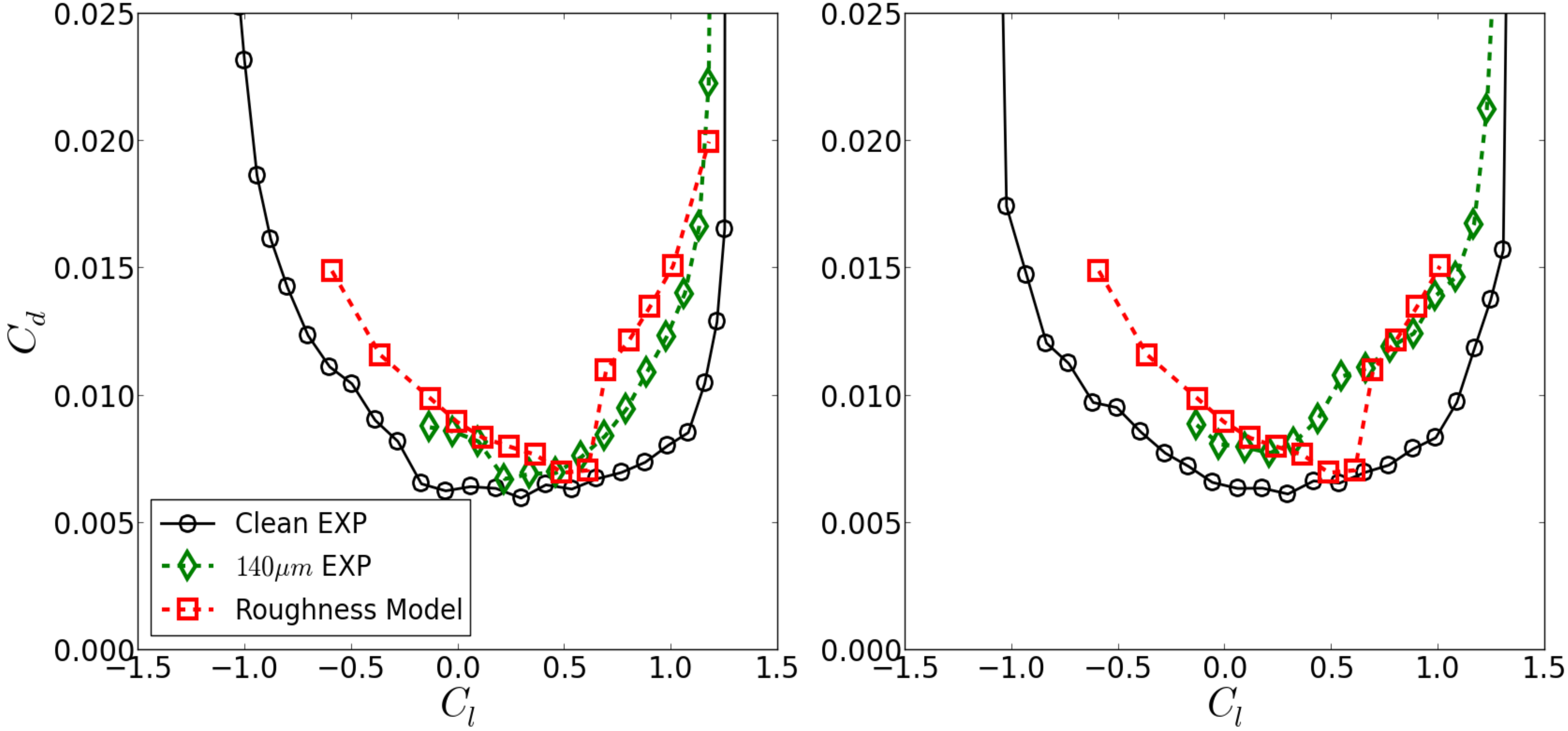


$Re_c = 2.4 \times 10^6$



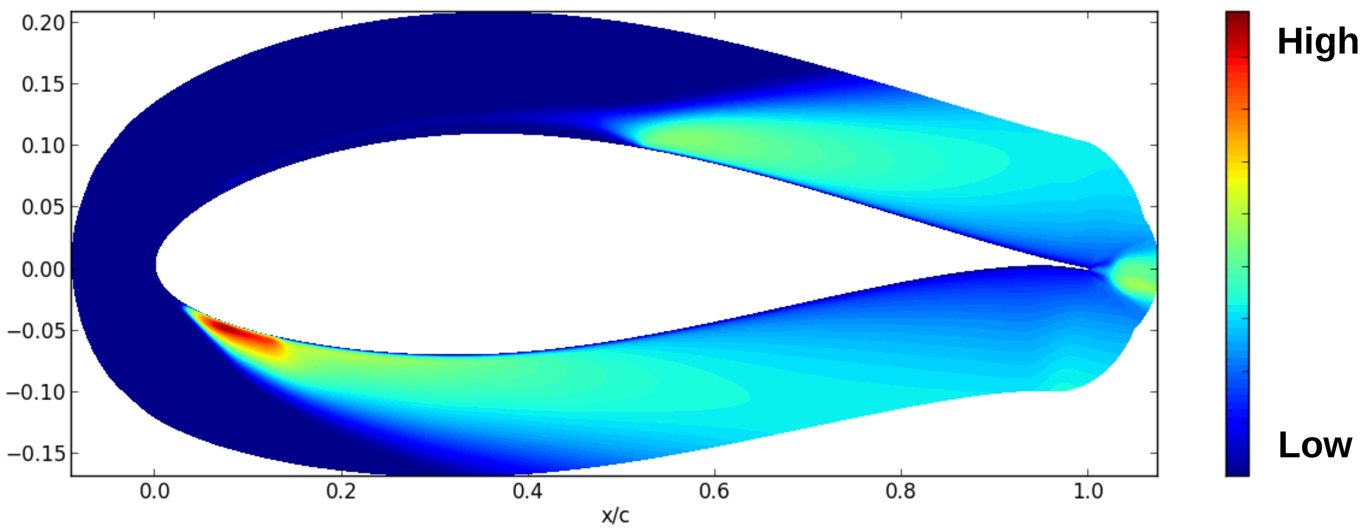
NACA 63_3- 418 Drag Polar with Roughness

$Re_c = 1.6 \times 10^6$ $Re_c = 2.4 \times 10^6$



Early Model Findings

- Errors in drag prediction traced back to over production of turbulent kinetic energy (TKE) on lower surface
- Strong pressure gradient effects not well captured



Contours of TKE, NACA $63_3 - 418$, Rey = 2.4×10^6, Axis expanded 15x in wall normal direction for clarity

Planned Model Development

- Langtry-Menter pressure gradient correction dominated by roughness model function
- Reformulate roughness model to depend on pressure gradient parameter (λ_θ) and non-dimensional velocity magnitude ($\widetilde{U}$)
- Previously solely a function of A_r, the change to the transition criteria is now assumed to be:

Local pressure gradient parameter

$$\Delta Re_{\theta t} = f\left(A_r, \lambda_\theta, \widetilde{U}\right)$$

Information about roughness height / velocities at roughness

Reduce influence of modification near wall

Ongoing and Future Work

- Continue calibration of model with data set produced in Texas A&M experiments
- Refine new formulation with pressure gradient effects and continue validation
- Add density parameter to boundary condition input and A_r function
- New experimental investigations planned on different airfoils
- Explore modifications to Langtry-Menter to improve high Reynolds number predictions

Conclusions

- Generalized nature of transport equation
  - Three dimensional
  - Overset extensible
- Localized formulation very desirable for parallelization
- Still bound by underlying limitations of Langtry-Menter transition model
- Modification of transition onset criteria more manageable than physically representing all scales