# Transitionsmodellierung technischer Strömungen

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# Transition Modelling in Industrial CFD

## Effects

- Re number effects
- Heat transfer
- Wall shear stress
- Separation behaviour
- Efficiency of many technical devices

## Modelling

- Numerous developments:
  - Correlation based models
  - Low-Re models
  - $e^n$ linear stability
  - PSE models
  - LES
  - DNS

**~75% of all technical flows are in a Re range of $10^4$-$10^6$ and therefore in transitional regime**

**Almost all industrial CFD simulations are calculated without a transition model**

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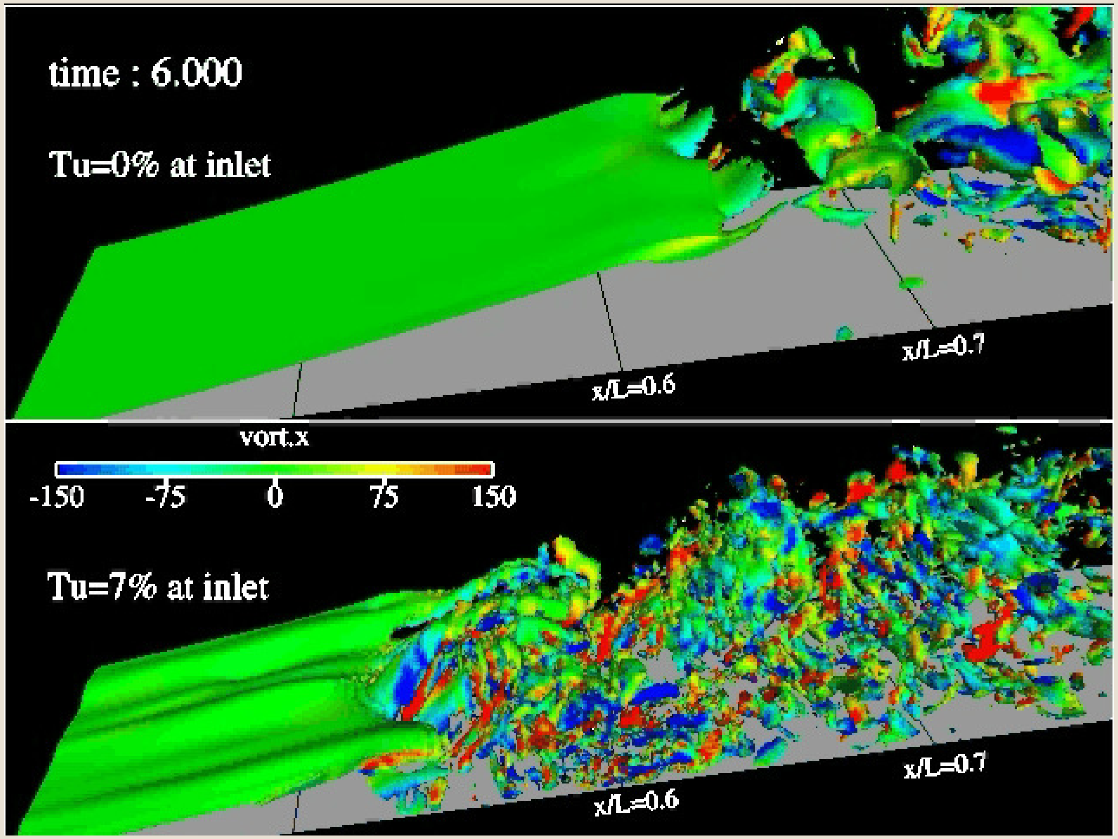
# DNS Rodi et al.

## Spanwise vorticity iso-surfaces (Sims. 1,2)

- Wakes impact on boundary layer cause bypass transition
- Re=60,000
- Periodic in spanwise direction
- No of grid nodes ~ $30x10^6$

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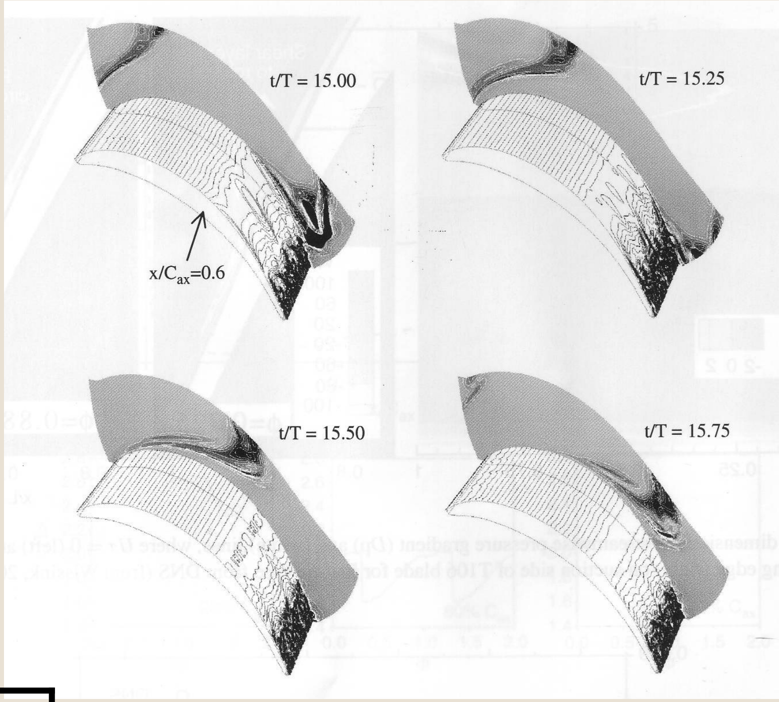
# Transition on T106 LPT blade (Re = 148000)

LES of
Michelassi et al (2003)

-10 mio grid points
Dynamic SGS model

- Isolines of vertical velocity

- Span/Chord ~ 0.15




| Full 3D | LES | Rans |
|---|---|---|
| Nodes | ~150-300x$10^6$ | ~3-5x$10^6$ |
| Dt- steady | ~$10^5$ | ~$10^2$ |
| Dt – unsteady | ~2x$10^5$ | ~2x$10^3$ |

## LES/RANS Ratio

| | |
|---|---|
| Ratio steady | ~ 50,000 |
| Ratio unsteady | ~ 5,000 |

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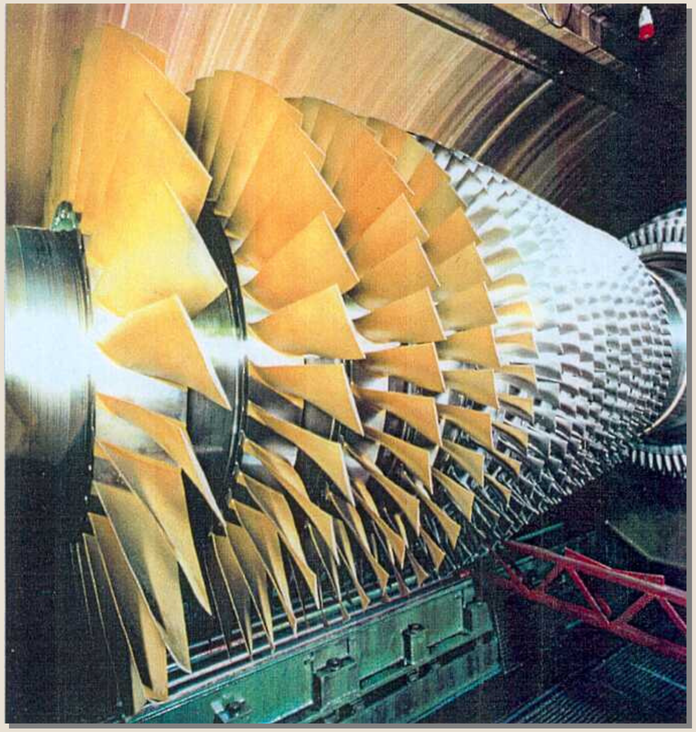
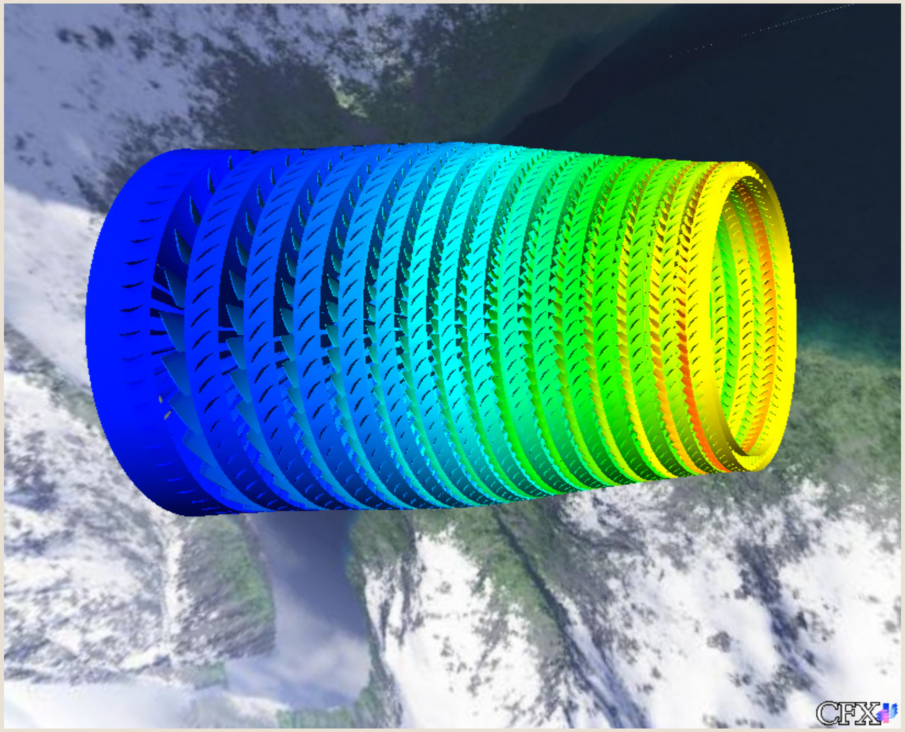
# Siemens 15 STAGE AXIAL COMPRESOR






- **15 rows x ~ 60 blades ~ 1000 blades**
- **Optimization (x 100 – 1000 configurations)**

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# Transition Modelling: Status Quo in Engineering

- **Low-Re models (only bypass transition)**
  - Based on transport equations for e.g. $k$ and $\varepsilon$ (compatible with modern CFD codes)
  - Cannot be calibrated independently of viscous sublayer model
  - Poor accuracy and robustness – not used in industry

- **$e^N$ method (only natural transition)**
  - Very accurate predictions for 2D airfoils (low FSTI)
  - N-S codes are not accurate enough to evaluate stability equations
  - Extension to generic 3D flows very difficult (impossible?)
  - Cannot account of non-linear effects (e.g. high FSTI, roughness)

- **Correlation based model**
  - Reasonably accurate
  - Correlations can be found for many different transition mechanisms (e.g. FSTI, dp/dx, Roughness)
  - Not compatible with 3D flows and unstructured/parallel CFD codes – non-local formulation

**Goal – correlation based model using transport equations**

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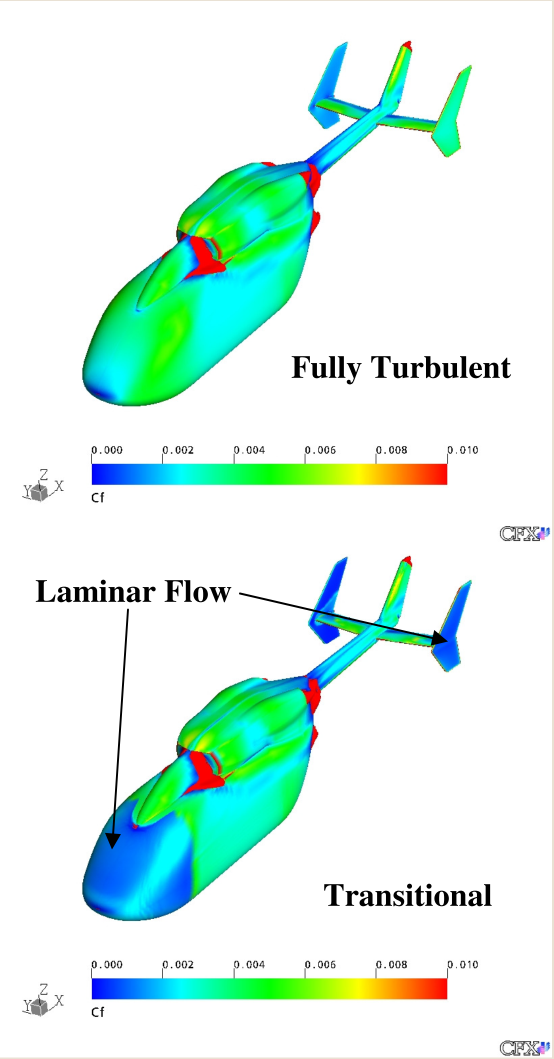
# Transition Model Requirements

- **Compatible with modern CFD code:**
  - Unknown application
  - Complex geometries
  - Unknown grid topology
  - Unstructured meshes (no search directions)
  - Parallel codes – domain decomposition
- **Requirements:**
  - Absolutely no search algorithms
  - Absolutely no integration along lines
  - Local formulation
  - Different transition mechanisms
  - Robust
  - No excessive grid resolution

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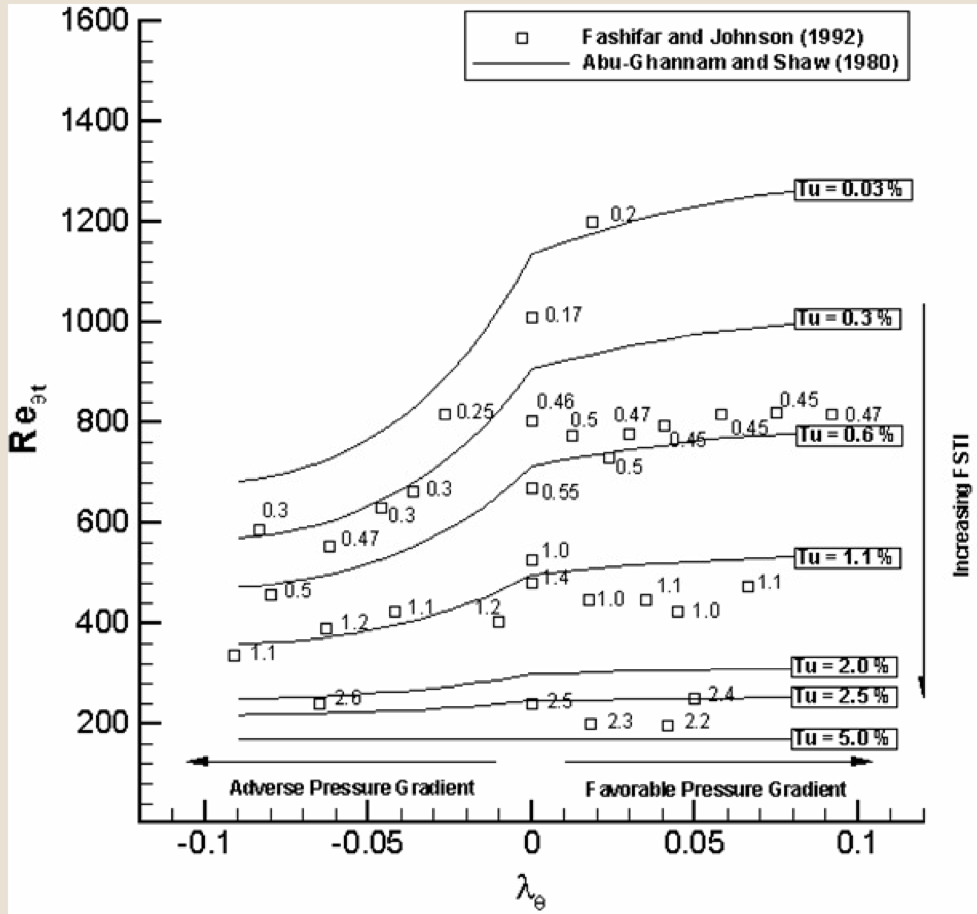
# Transition Onset Correlations

- Transition onset is affected by:
  - Free-stream turbulence turbulence intensity (FSTI)
  - Pressure gradients ($\lambda_\theta$)
  - Separation
  - Reynolds number ($Re_\theta$)
  - Mach number
  - Freestream length scale
  - Surface conditions:
    - Roughness
    - Temperature
    - Curvature
  - The history of the above parameters




$$Re_{\theta t} = f(Tu, \lambda_\Theta)$$

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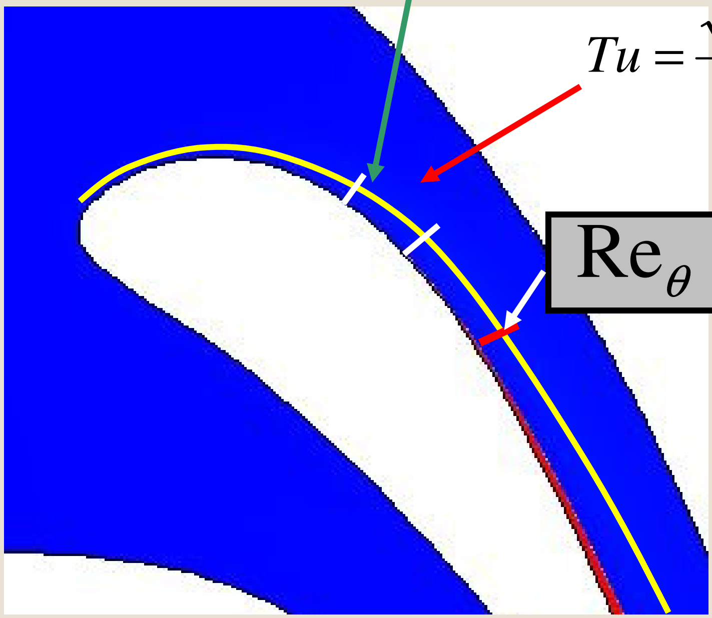
# Non-local formulations

- Transition onset:
  - Compute $Re_\Theta$ for all laminar bl-profiles and compare with $Re_{\Theta t}$
- Length of transition
  - Trigger turbulence model with ramp-function
- Correlation
  - Evaluated at edge of the boundary layer

$$\theta = \int_0^\delta \frac{u}{U}\left(1-\frac{u}{U}\right)dy \rightarrow \mathrm{Re}_\theta = \frac{\rho U \theta}{\mu}$$

$$Tu = \frac{\sqrt{2k/3}}{U}$$

$$\mathrm{Re}_\theta \geq \mathrm{Re}_{\theta t}$$



$$\mathrm{Re}_{\theta t} = f(Tu, \lambda_\Theta)$$

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# Transport Equation for Intermittency γ

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

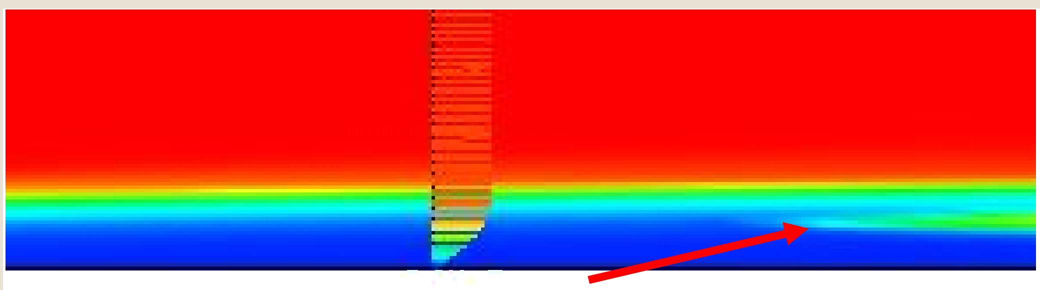
***Transition Sources***

$$P_\gamma = F_{length} c_{a1}\rho S\left[\gamma F_{onset}\right]^{0.5}\left(1-c_{e1}\gamma\right)$$

**$F_{onset}$ transition onset when** $\mathrm{Re}_\theta \geq \mathrm{Re}_{\theta t}$

$$E_\gamma = c_{a2}\rho\Omega\gamma F_{turb}\left(c_{e2}\gamma-1\right)$$

**$F_{length}$ length of transition**

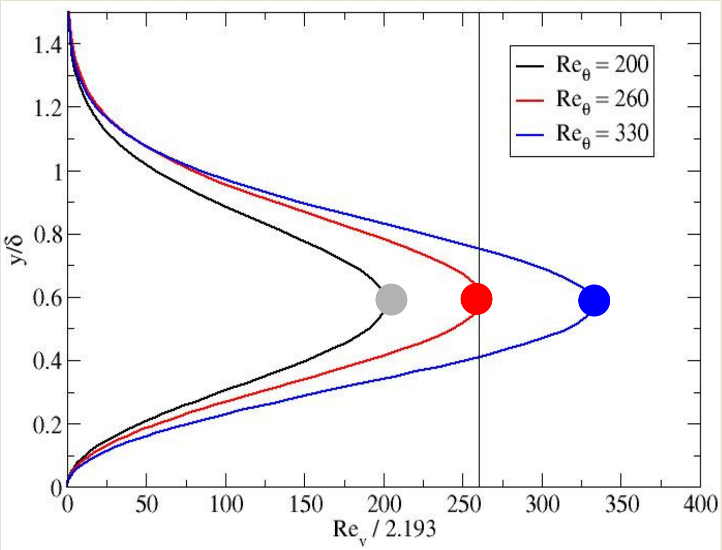


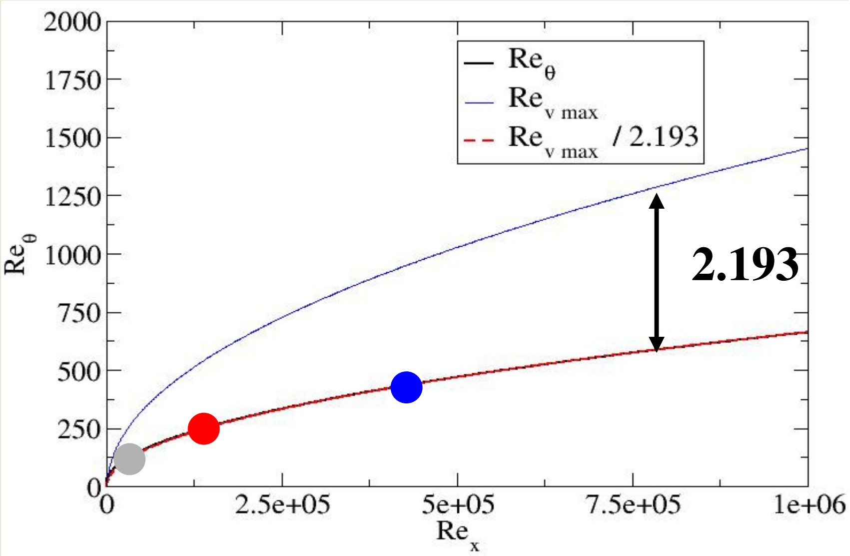
**Onset**

# New Idea: Vorticity Reynolds Number

$$\mathrm{Re}_v = \frac{\rho y^2}{\mu}\left|\frac{\partial u}{\partial y}\right|$$

**Blasius Boundary Layer**




$$(\mathrm{Re}_v)_{\max} = (\mathrm{Re}_\Theta)\cdot 2.193$$

- **Maximum value of $\mathrm{Re}_v$ in the B.L. is proportional to $\mathrm{Re}_\theta$**
- **Can relate $\mathrm{Re}_{\theta t}$ from correlation to $\mathrm{Re}_v$**
- **Allows empirical correlations to be used with 3d, unstructured parallel solvers**

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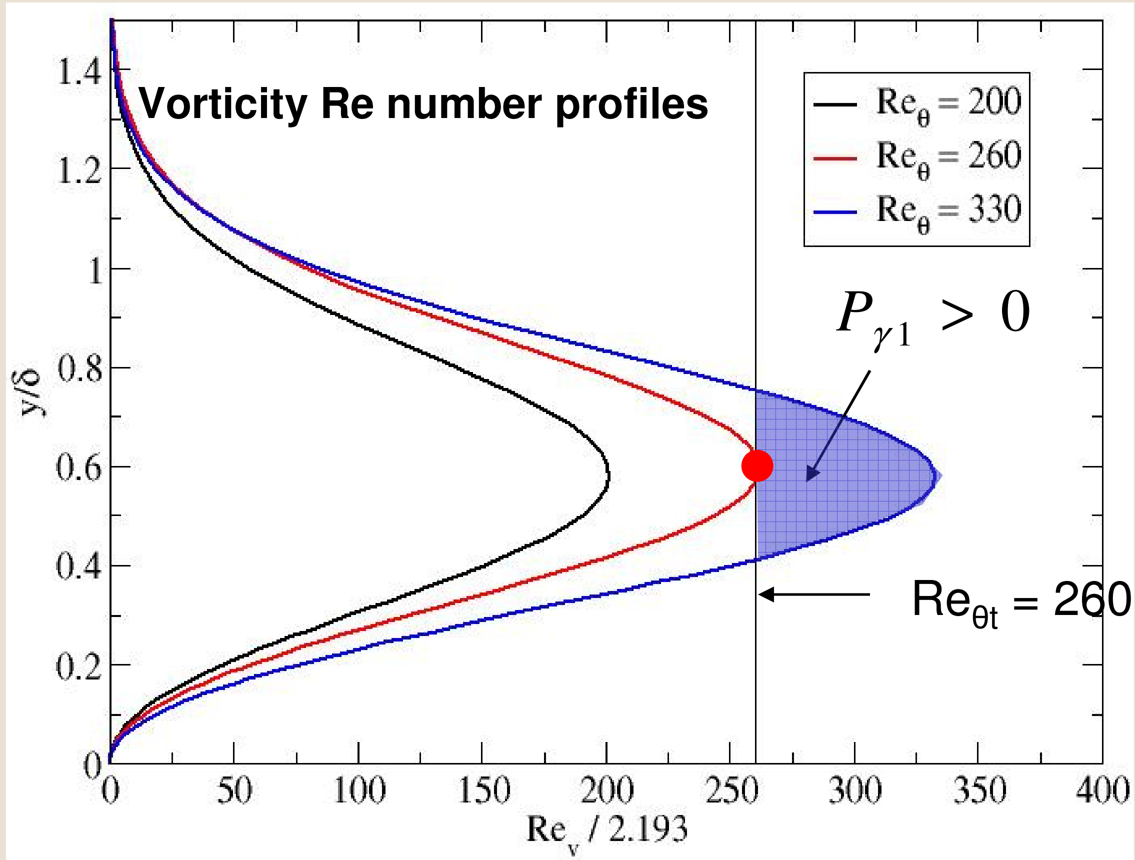
# Production of Intermittency

$$\mathrm{Re}_v = \frac{\rho y^2}{\mu}\left|\frac{\partial u}{\partial y}\right|$$

$$F_{onset} \sim \max\left(\frac{\mathrm{Re}_v}{2.193\,\mathrm{Re}_{\theta t}} - 1, 0\right)$$

$$\mathrm{Re}_{\theta t} = f(Tu, \lambda_{\theta t})$$

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# Modification to SST Turbulence Model

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho U_j k)=\tilde{P}_k-\tilde{D}_k+\frac{\partial}{\partial x_j}\left((\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right)$$

$$P_k=\mu_t S^2 \qquad D_k=\beta^*\rho k\omega$$

$$\tilde{P}_k=\gamma_{eff}P_k \qquad \tilde{D}_k=\min\left(\max(\gamma_{eff},0.1),1.0\right)D_k$$

***S* – invariant form of strain-rate**

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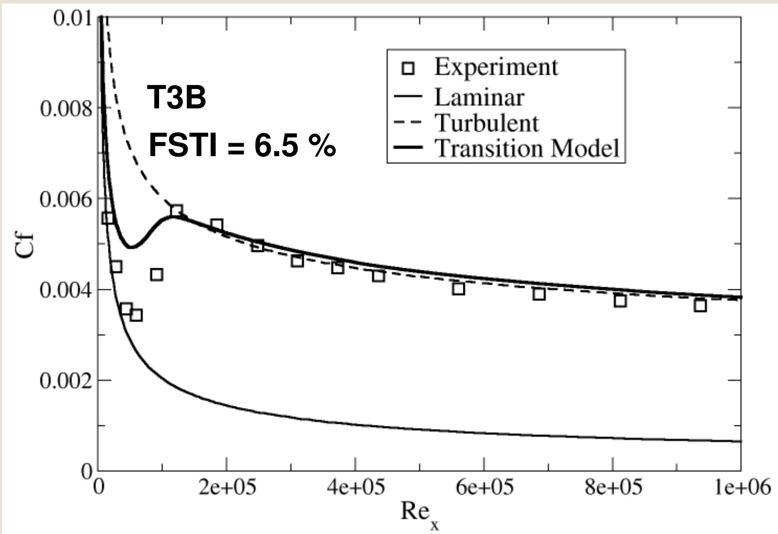
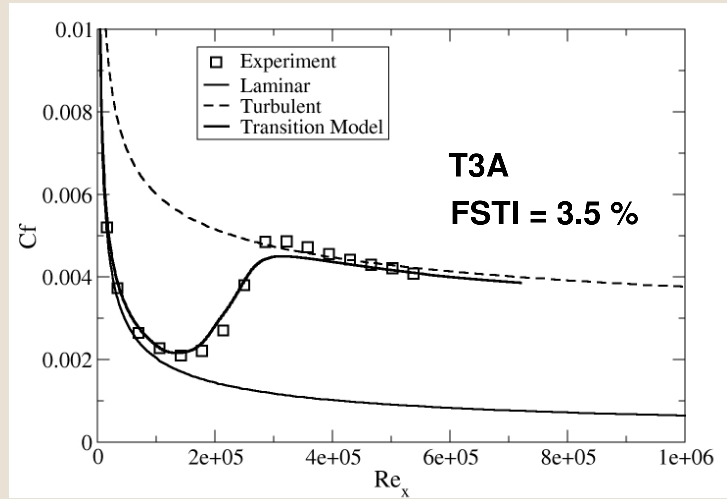
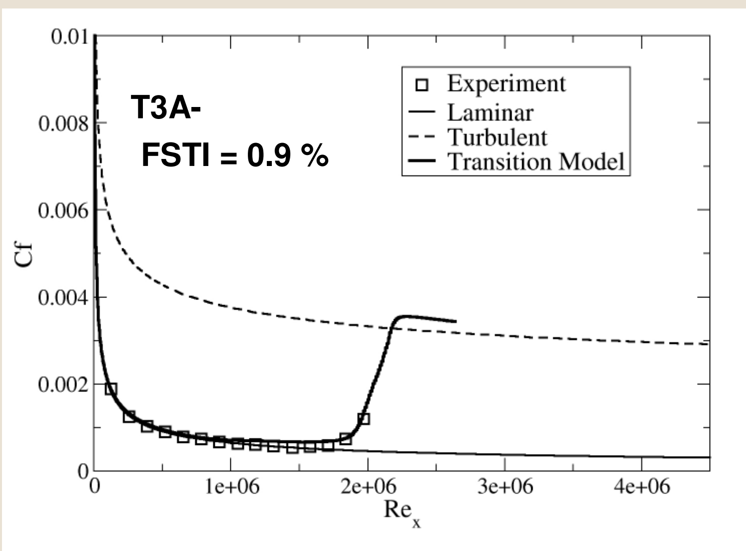
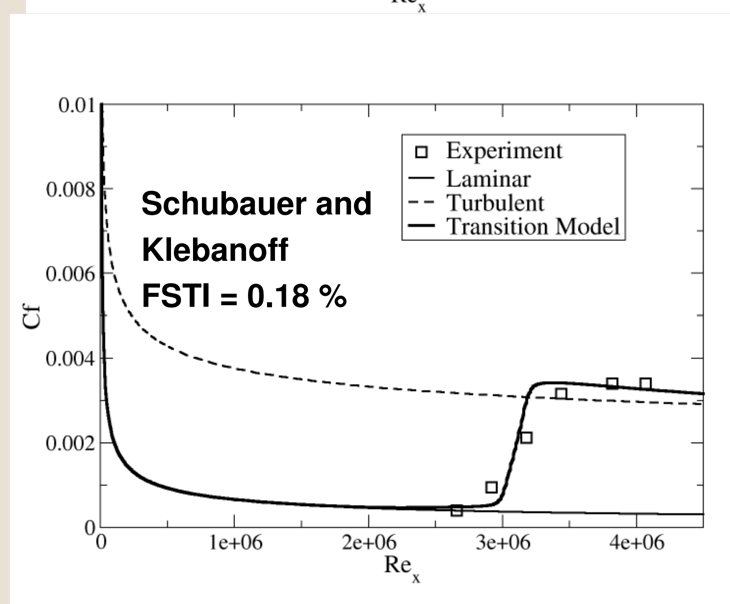
# Flat Plate Results: dp/dx=0

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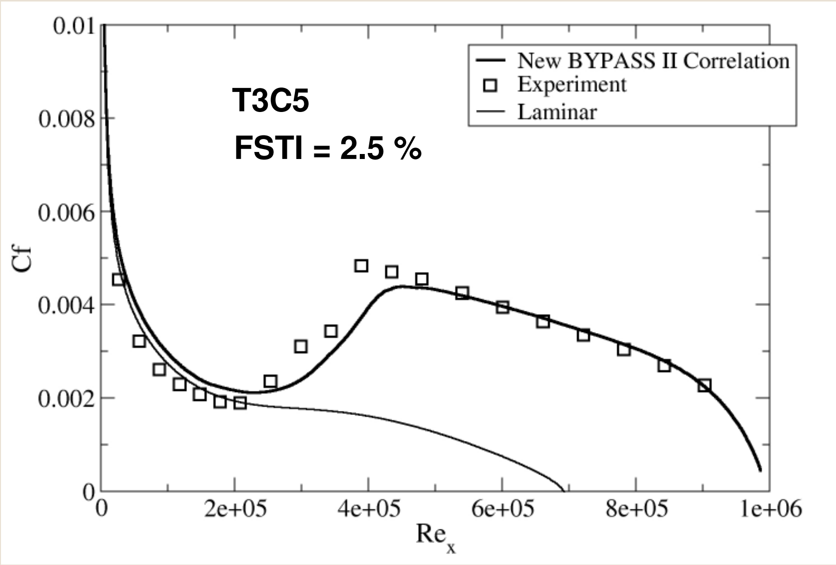
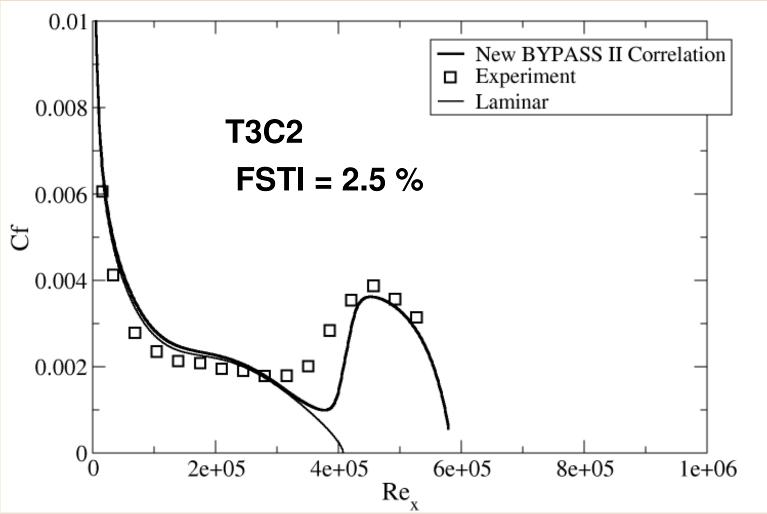
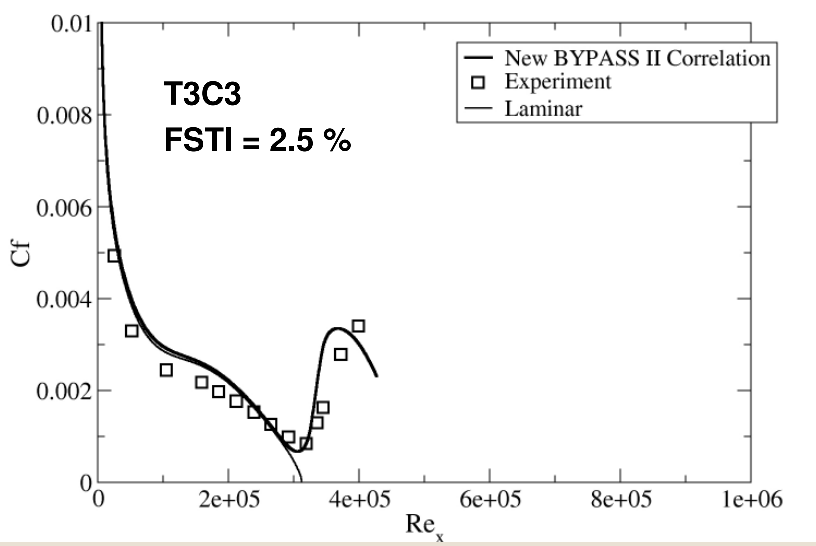
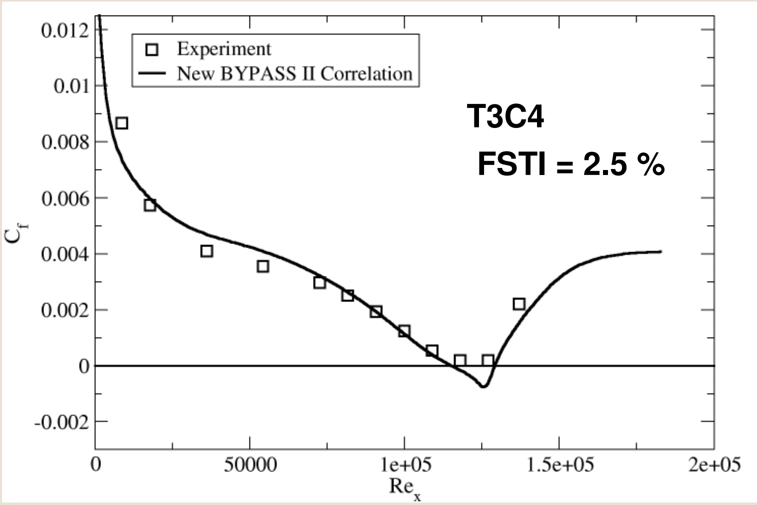
# Flat Plate Results: dp/dx (change in Re number)

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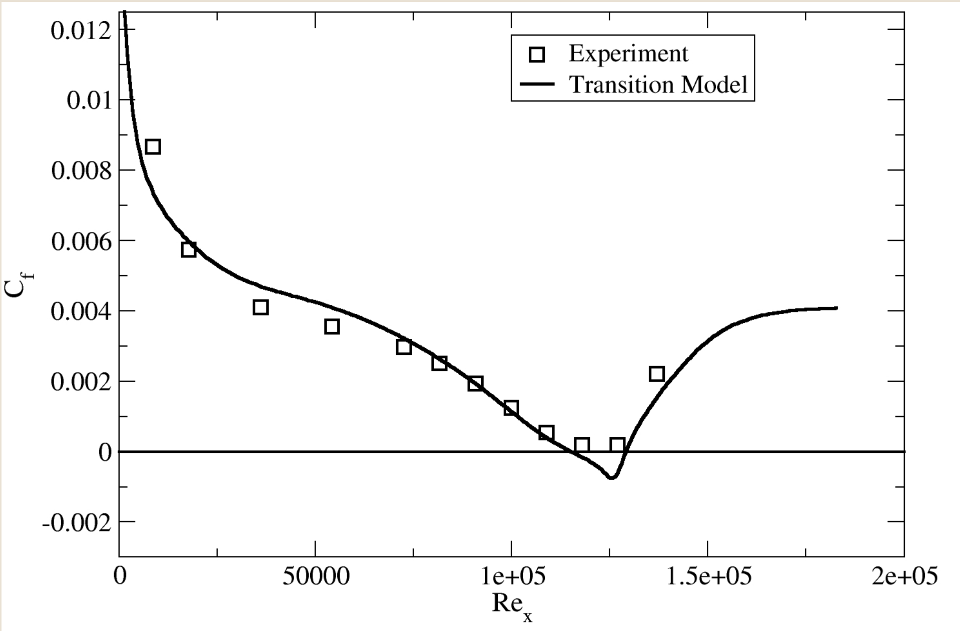
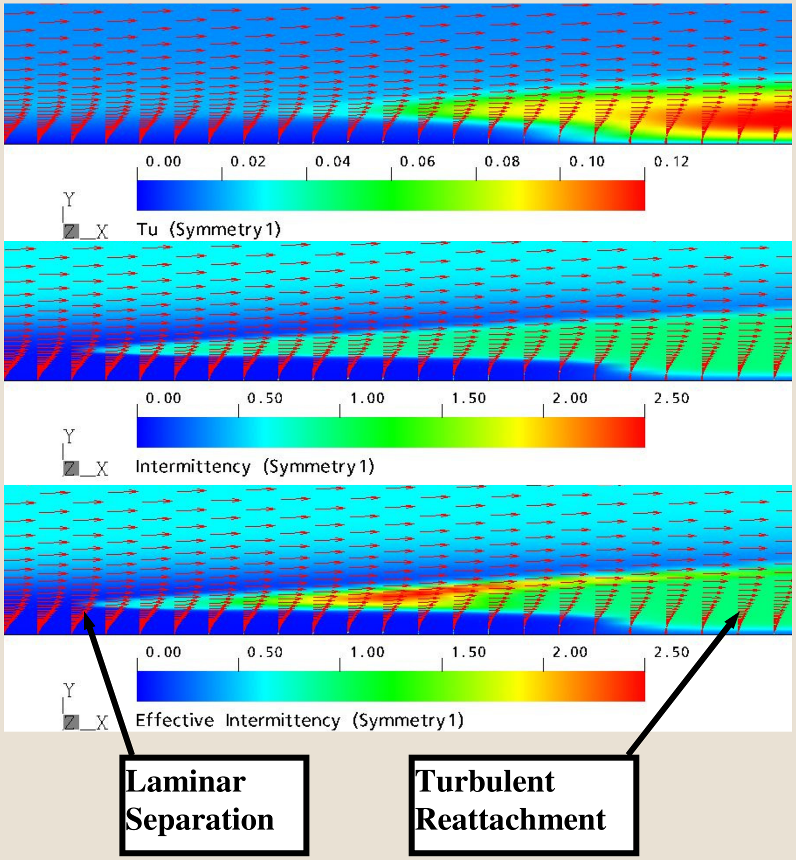
# Separation Induced Transition




- **Previous versions predicted separation induced transition too late**
- **Solution: Allow intermittency to increase above 1.0 in laminar separation bubbles**

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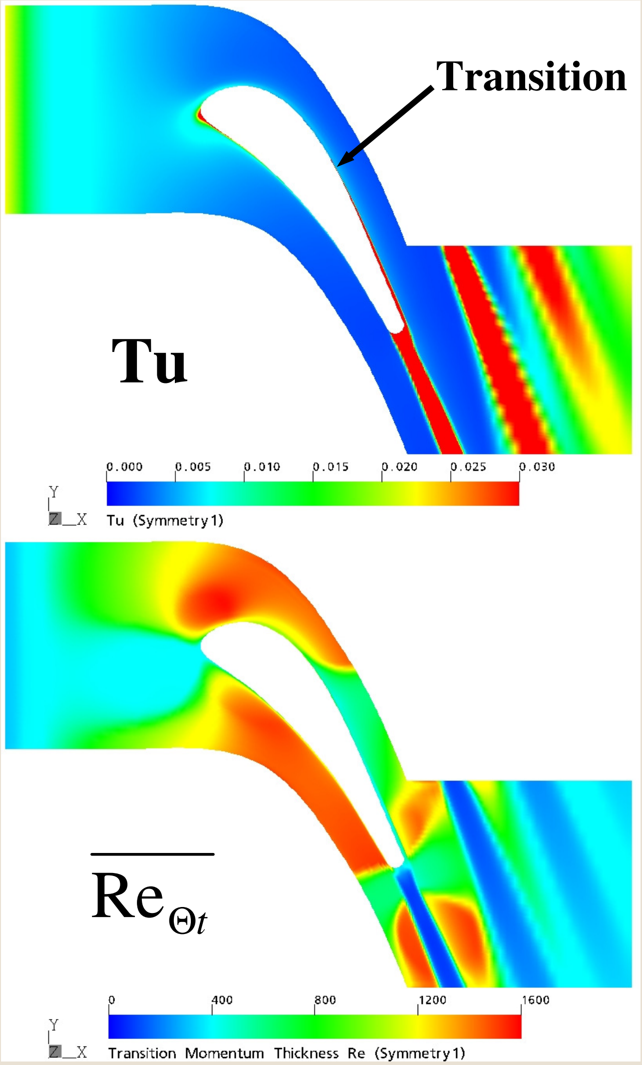
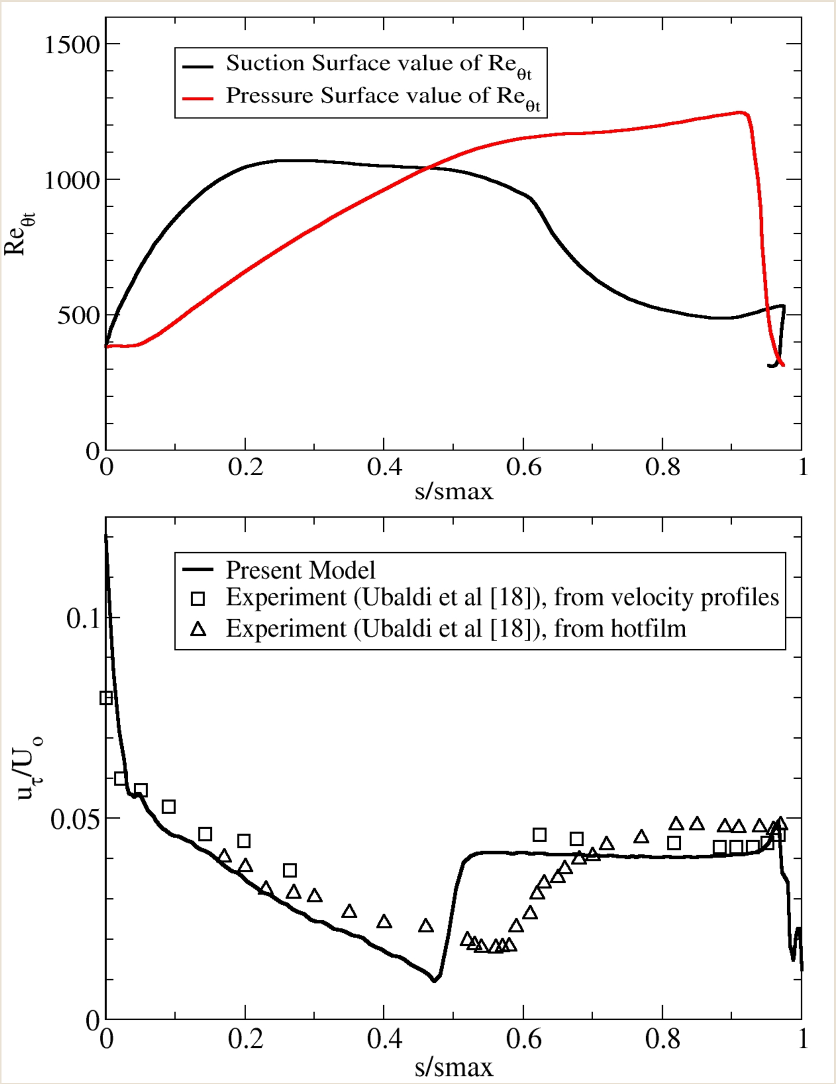
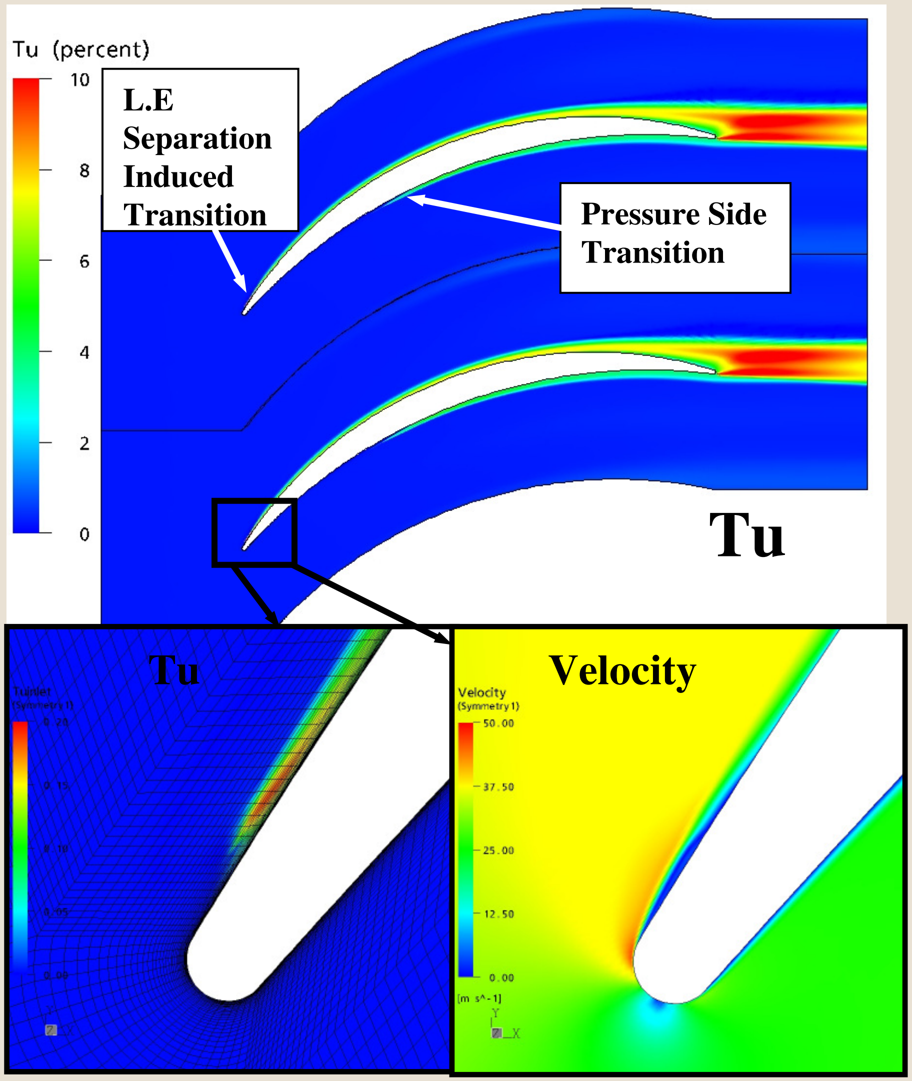
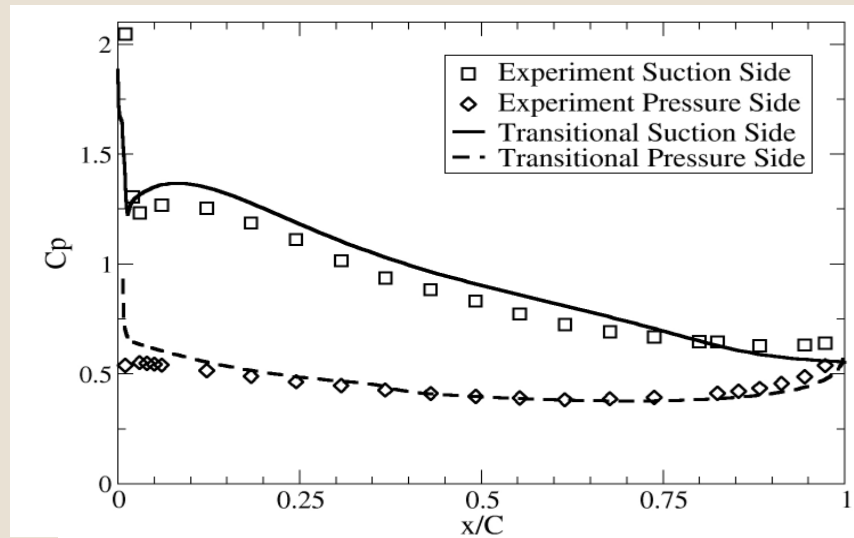
# Test Cases: Genoa Turbine Blade

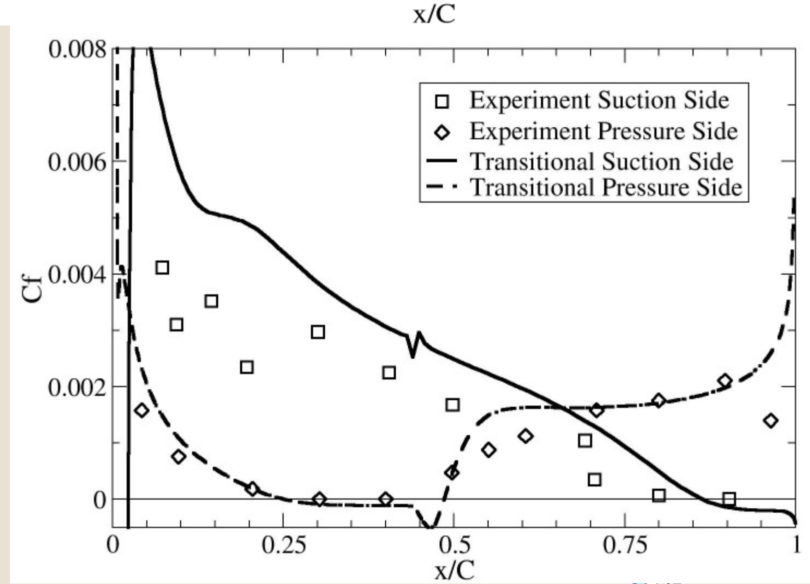


# Test Cases: Zierke (PSU) Compressor Blade

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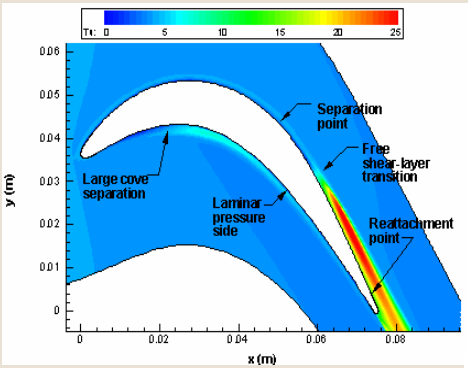
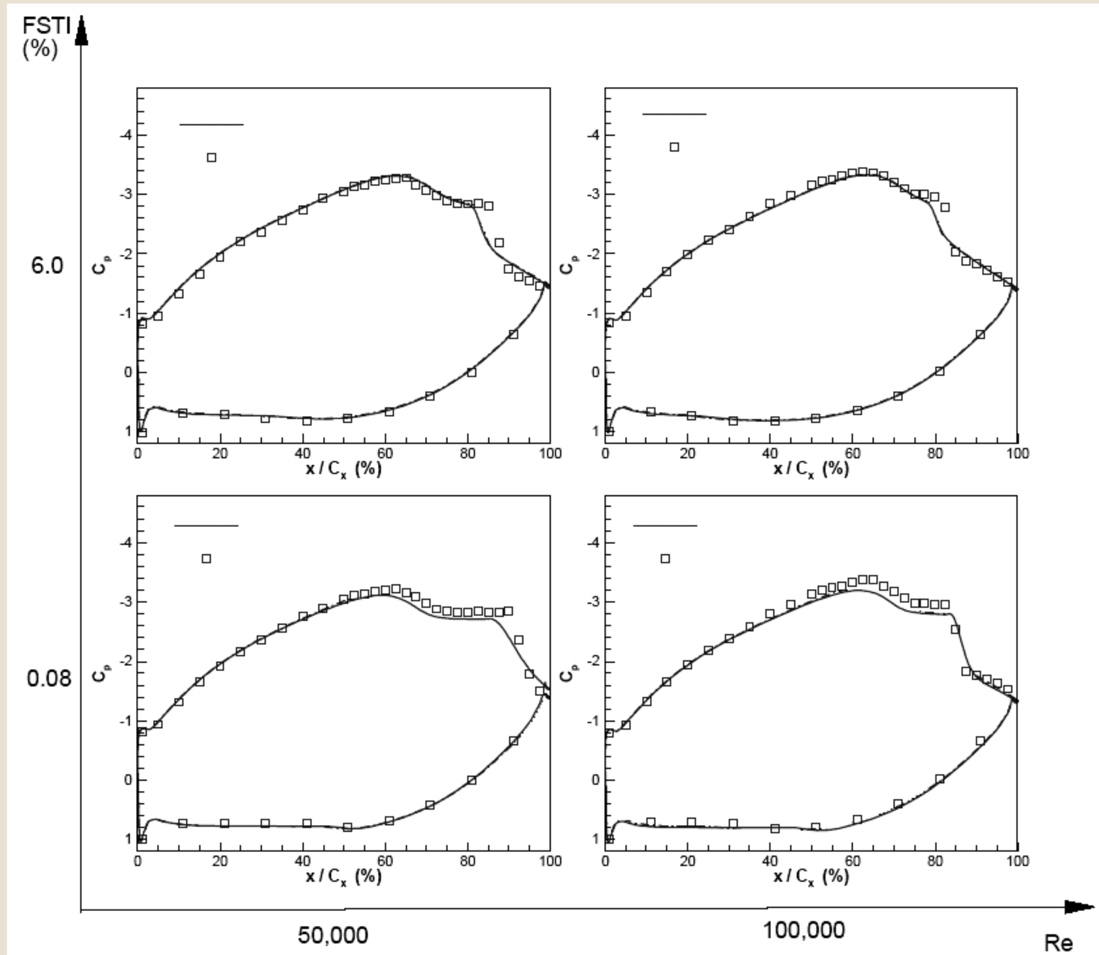
# Separation Induced Transition On an LP-Turbine




- Pratt and Whitney Pak-B LP turbine blade
- $Re_x$= 50 000, 75 000 and 100 000
- FSTI = 0.08, 2.25, 6.0 percent
- Computations performed by Suzen and Huang, Univ. of Kentucky

Increasing FSTI




Increasing $Re_x$

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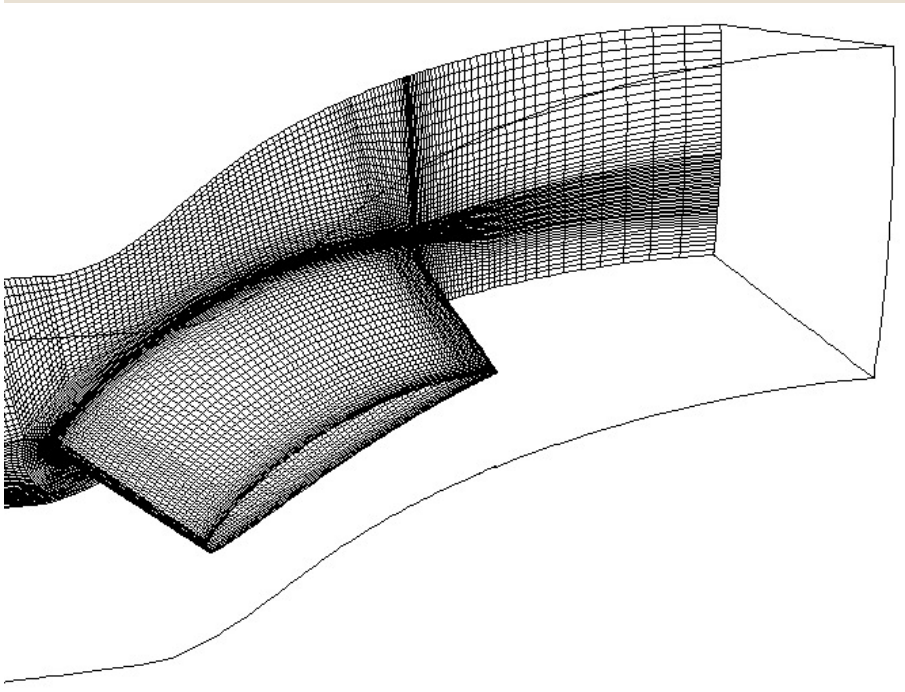
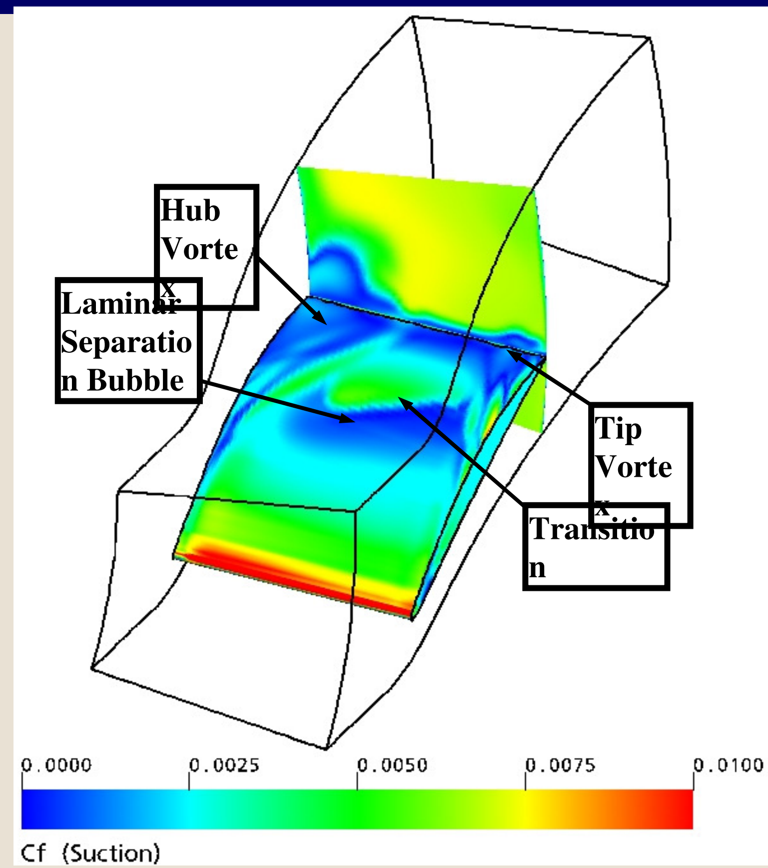
# Test Cases: 3D RGW Compressor Cascade






RGW Compressor (RWTH Aachen)

FSTI = 1.25 %

$Re_x$ = 430 000

Loss coefficient, (Yp) = 0.097

Yp = (poinlet - pooutlet)/pdynoutlet

Schulz, H.D., Gallus, H.D., 1988, “Experimental Investigation of the Three-Dimensional Flow in an Annular Compressor Cascade”, ASME *Journal of Turbomachinery*,

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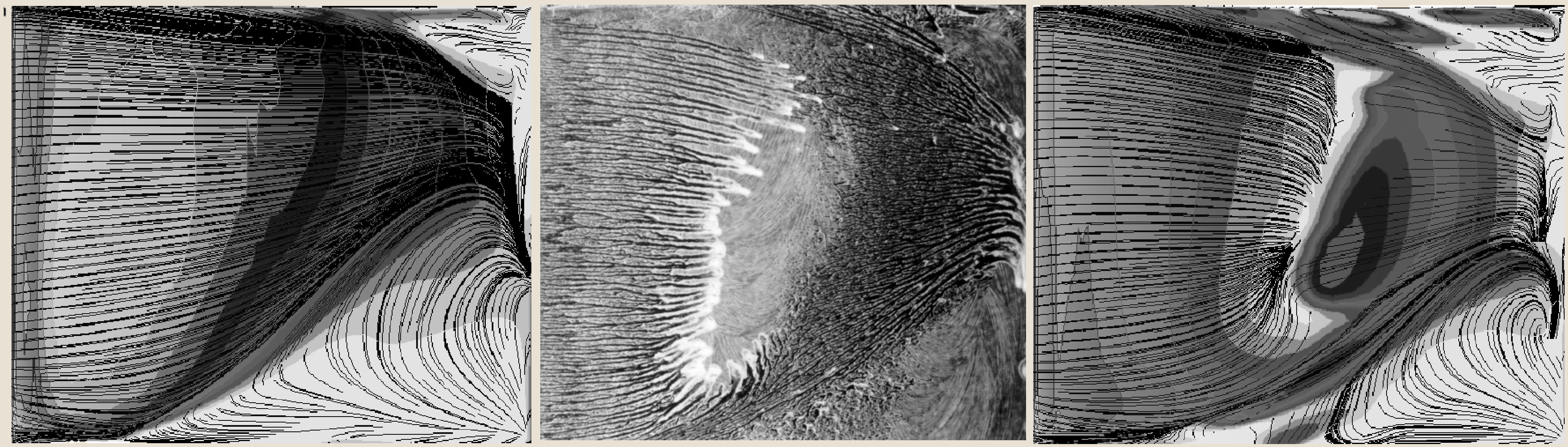
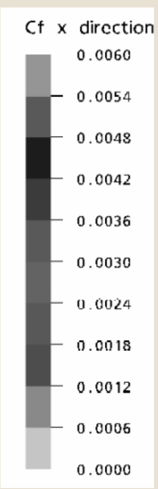
# Test Cases: 3D RGW Compressor Cascade






**Fully Turbulent**

**Yp = 0.19**

**Experimental Oil Flow**

**Yp = 0.097**

**Transition Model**

**Yp = 0.11**

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# Unsteady Wake Induced Transition (George Huang)

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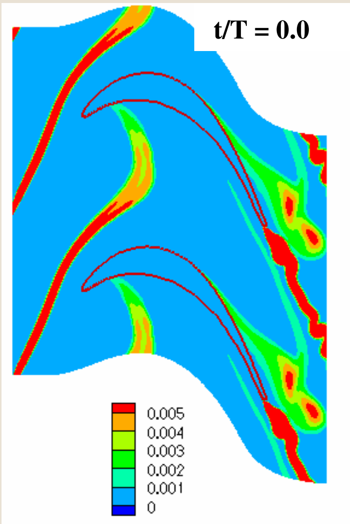


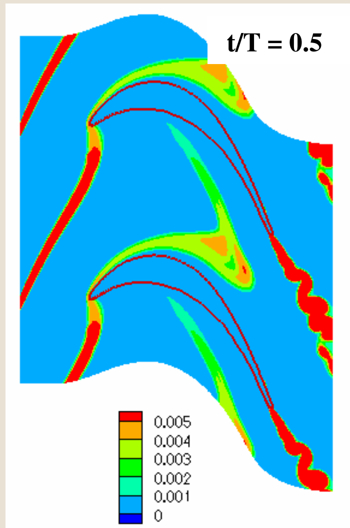


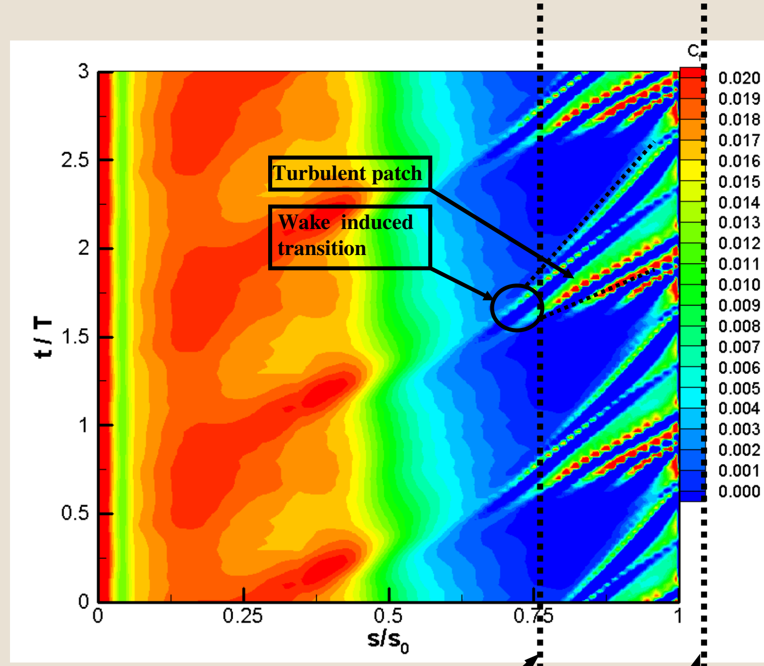


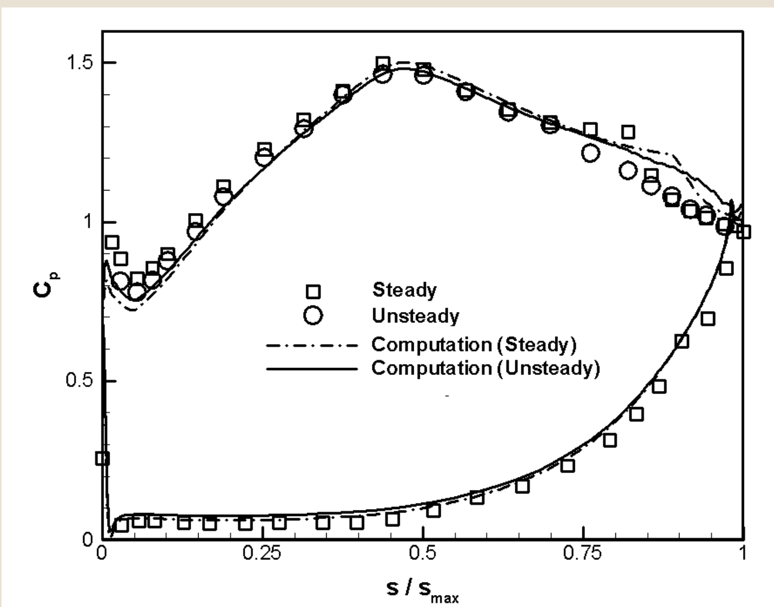


Steady Laminar Separation

Steady Turbulent Reattachment

## Stieger et al. (2003)

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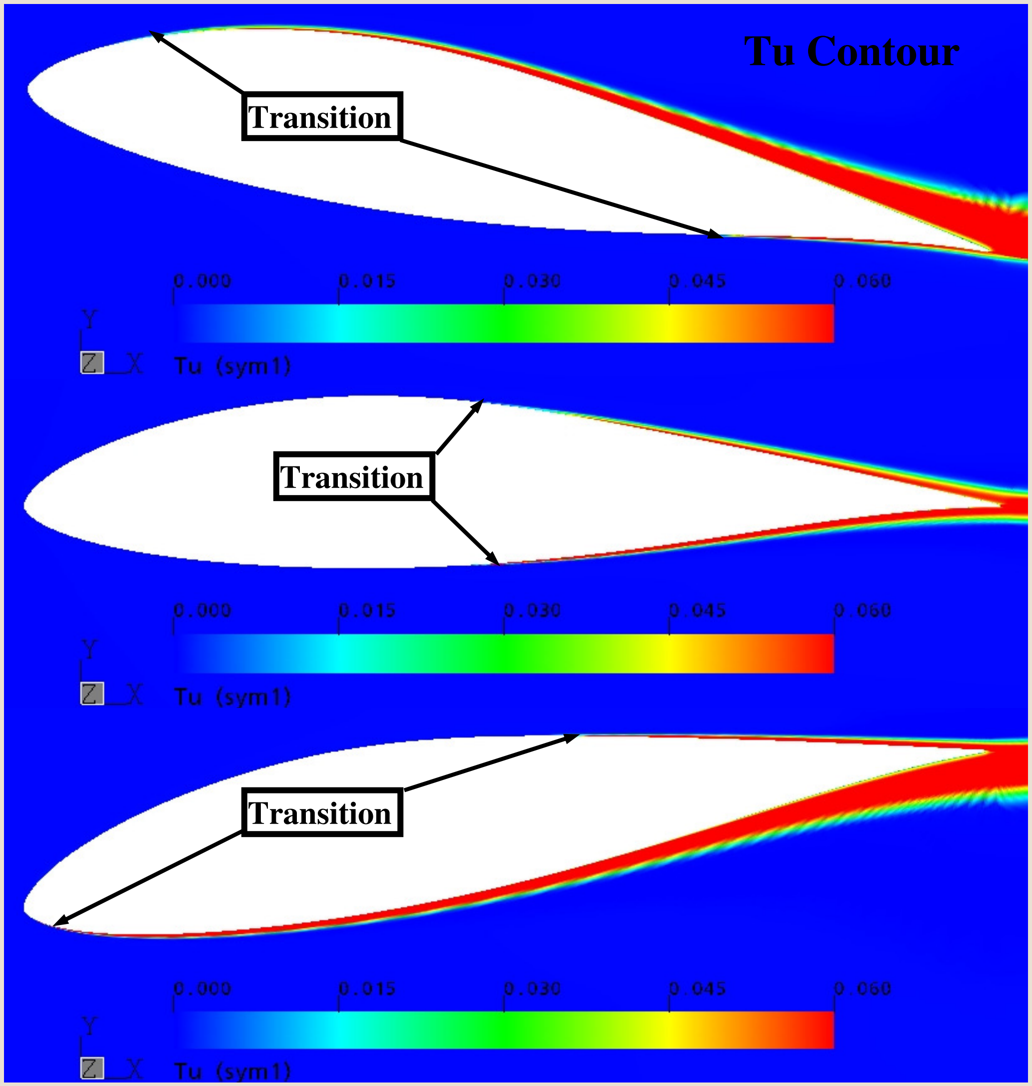
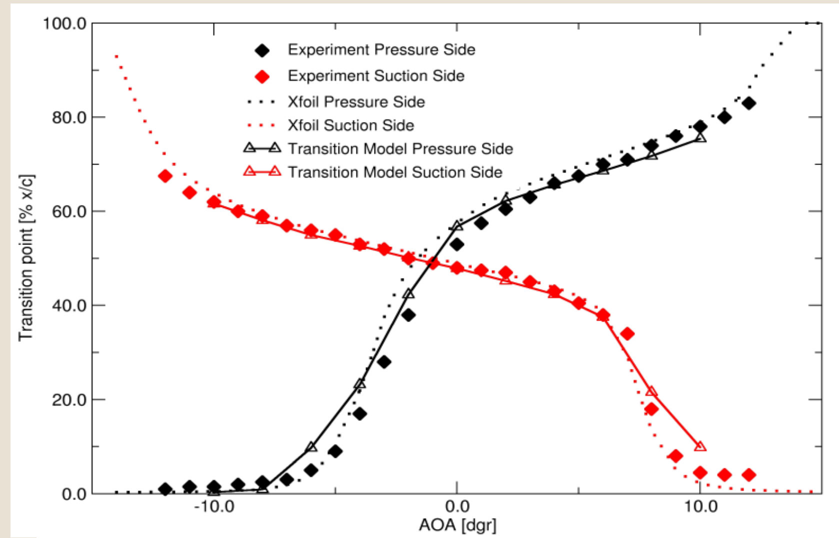
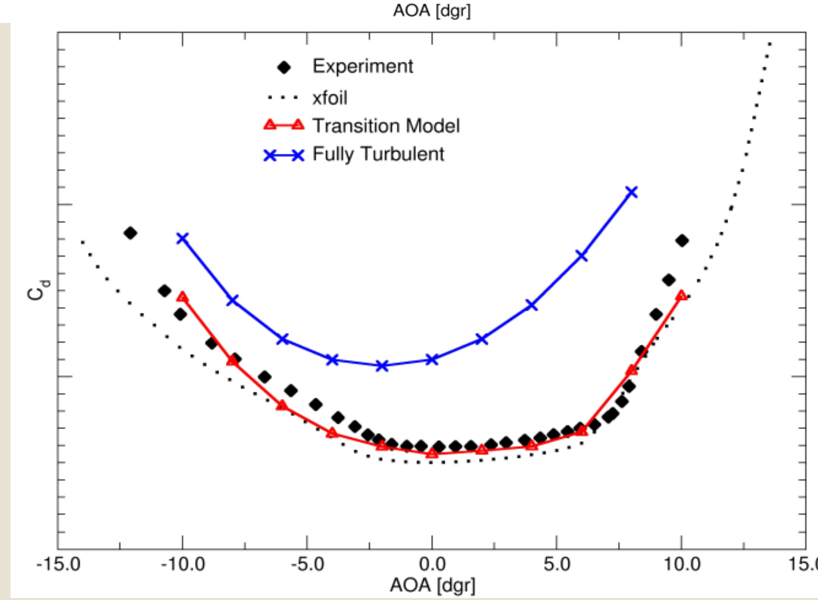
# Wind Turbine Airfoil

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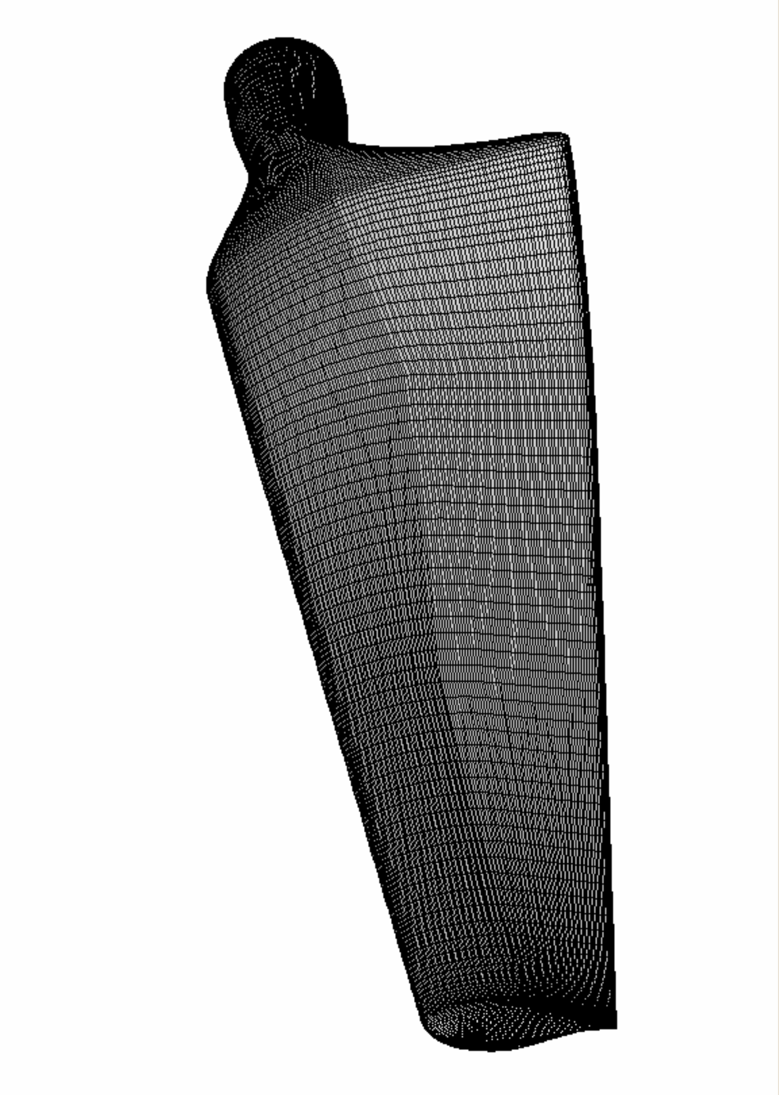
# 3D NREL Wind Turbine (S809 Airfoil)

- Full 3D Wind Turbine
- Wind Speeds = 7 to 25 m/s
- S809 airfoil profile for the NREL Phase IV full wind turbine experiment, (Simms, 2001)
- All CFD computations performed with ANSYS CFX 10
  - Transitional and Fully Turbulent
  - Grid = 10 million Nodes
  - Each run made overnight on a 16 CPU Linux cluster
  - Max y+ = 1



**Simms, D., Schreck, S., Hand, M, and Fingersh, L.J. (2001). "NREL Unsteady Aerodynamics Experiment in the NASA-Ames Wind Tunnel: A Comparison of Predictions to Measurements", *NREL Technical report, NREL/TP-500-29494.***

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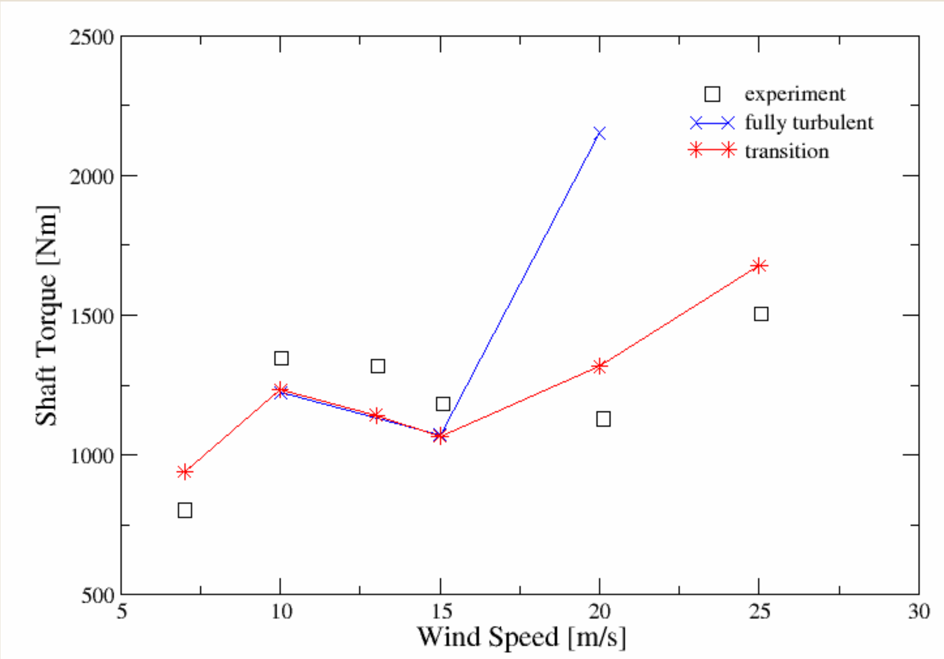
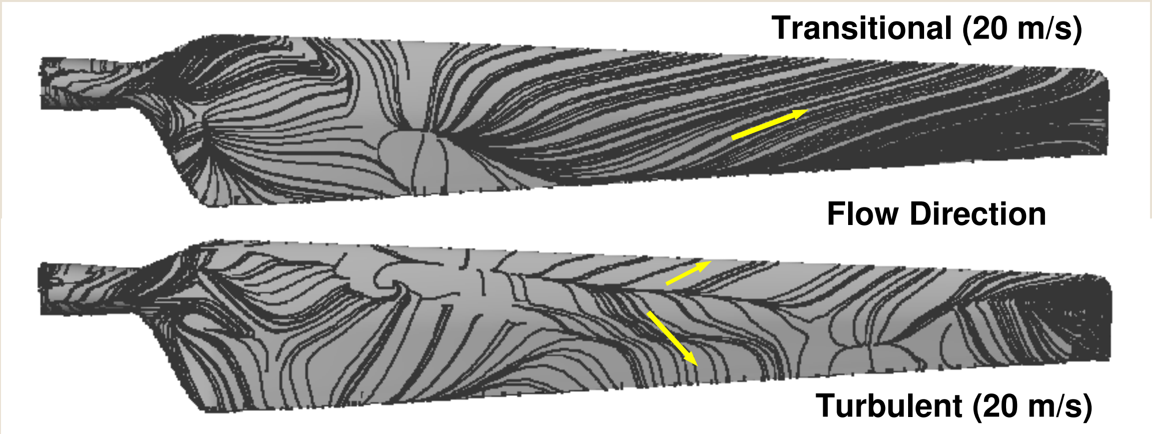
# NREL Wind Turbine: Shaft Torque

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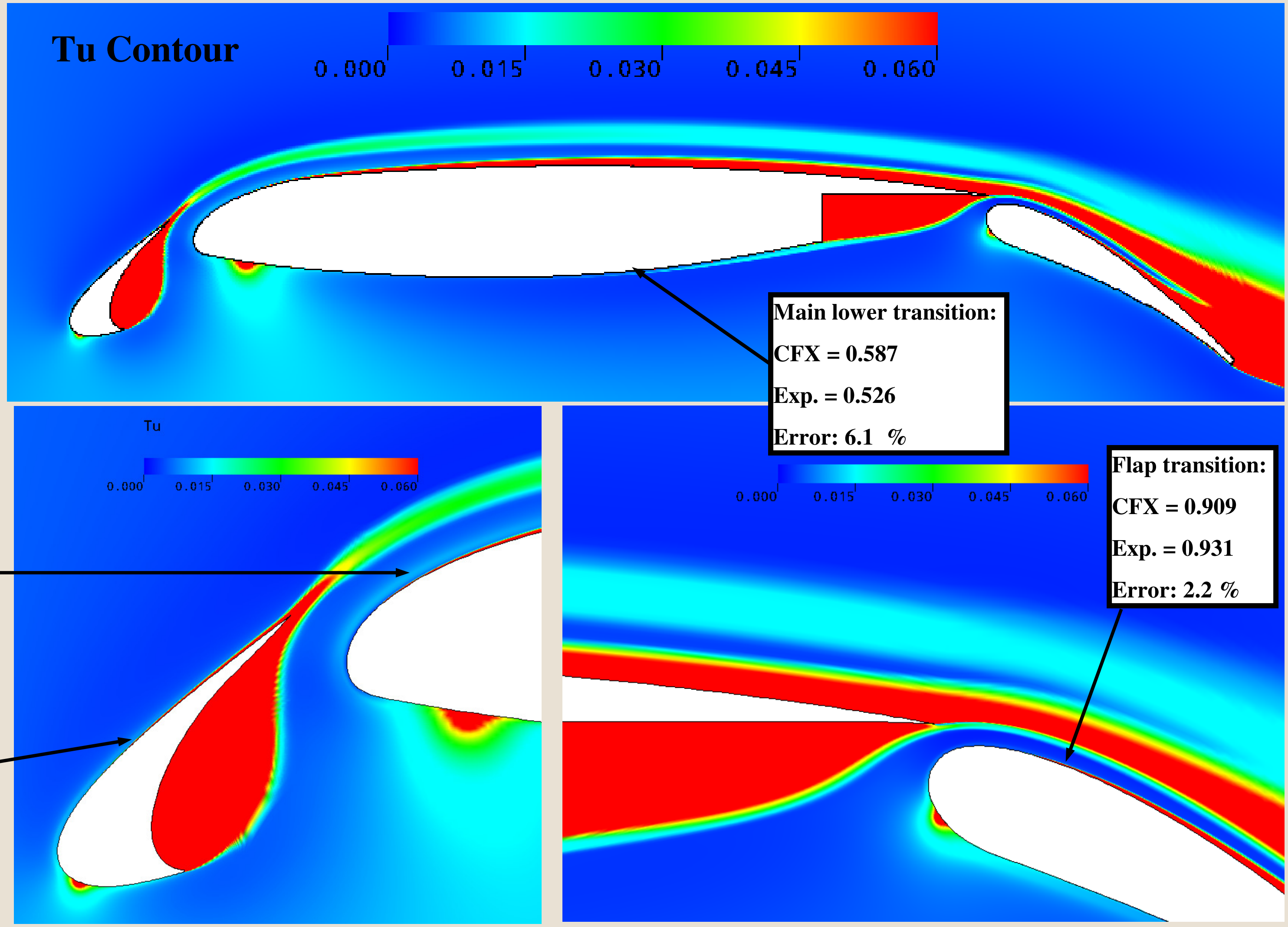
# McDonnell Douglas 30P-30N 3-Element Flap

Re = 9 million
Mach = 0.2
C = 0.5588 m
AoA = 8°

Exp. hot film transition location measured as f(x/c)

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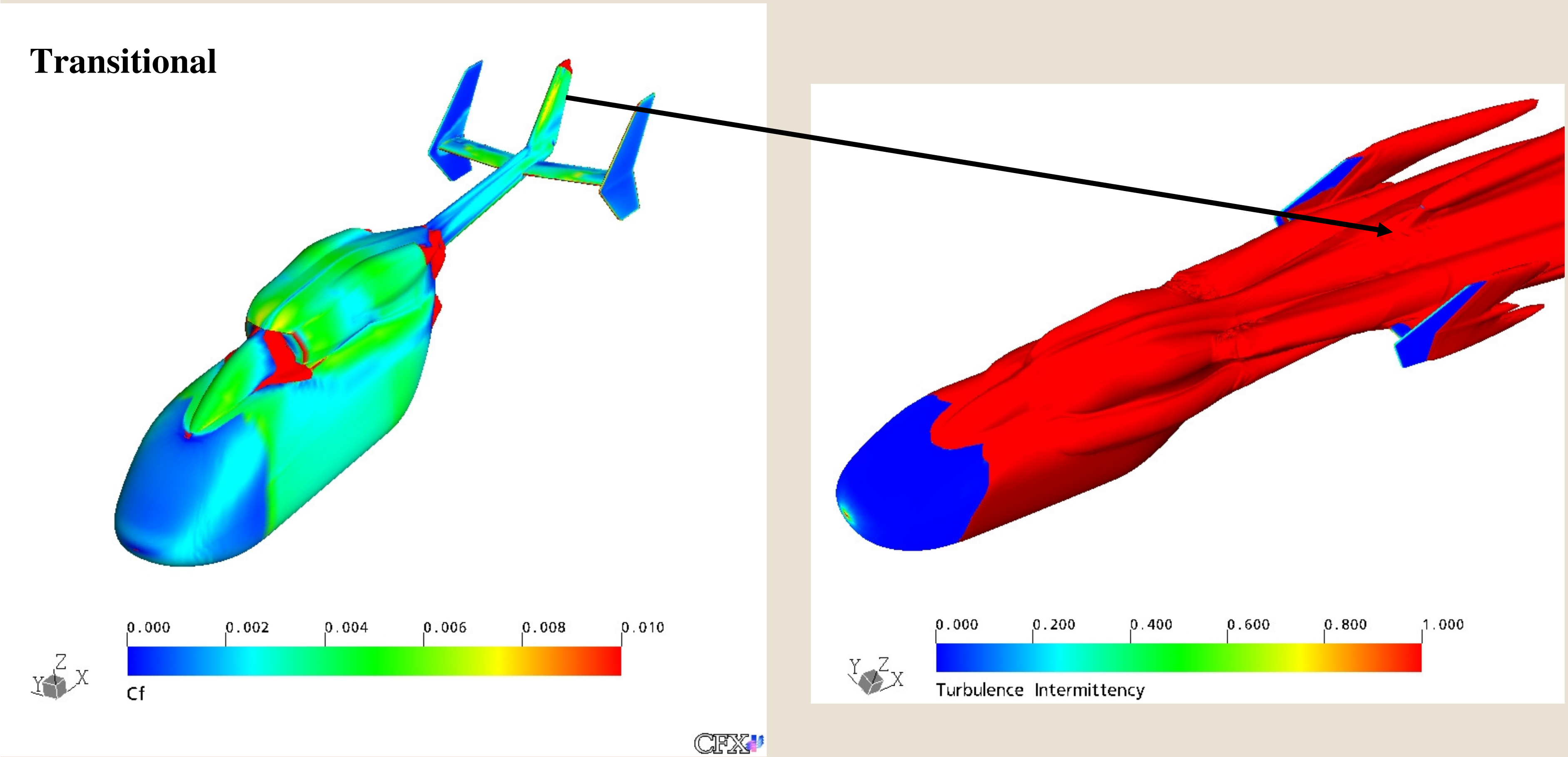
# Eurocopter – Wake induced transition




$Re_x = 30$ million

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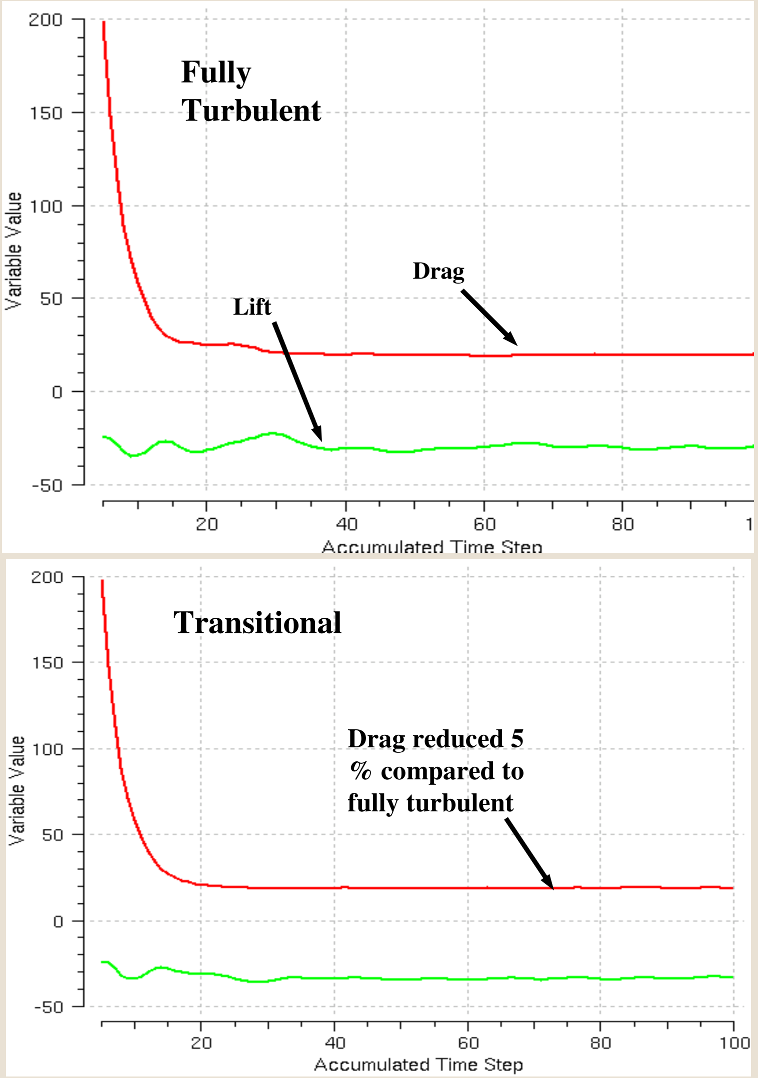
# Convergence and Cost of using the transition model

- Eurocopter configuration
- 6 million nodes
- Max y+ = 1
- 16 CPU's
- Total Additional CPU cost 17%
  - Discritization (High Res) 12%
  - Linear Solution 5%

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# Team Alinghi in Action

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# Wind Tunnel Facility

Wind Tunnel testing carried out at NRC's 9m x 9m wind tunnel in Ottawa (Canada)

- 1.5:1 model scale (to match Re)
- measure of force on the whole appendage and on each appendage component (keel, bulb, winglets)
- transition location study (with thermography)
- Study on the dependency on inflow turbulence levels

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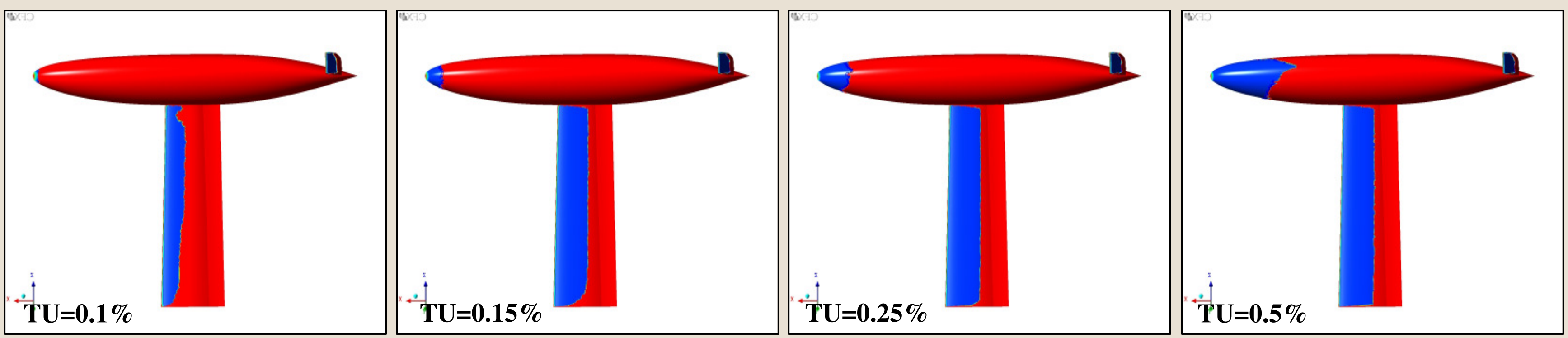
# Transition Modelling Calibration

Inflow turbulence intensity calibration:

- Comparison with high turbulence wind tunnel run
- Good force and transition location matching for TU=0.5%

| TU | Global Drag | Error | Bulb Lam % | Keel Lam % |
|---|---|---|---|---|
| 0.10% | -0.0460 | 16% | 18-26 | 57 |
| 0.15% | -0.0483 | 12% | 8-12 | 57 |
| 0.25% | -0.0495 | 10% | 5-6 | 54 |
| 0.50% | -0.0558 | 1% | 2-2.5 | 29-36 |
| Wind Tunnel | -0.0550 | | 2 | 27-30 |

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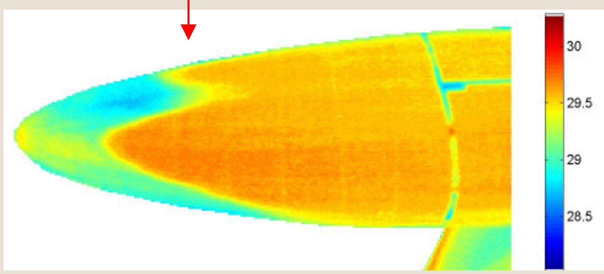
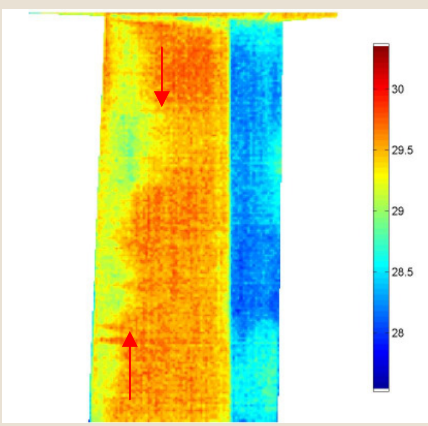
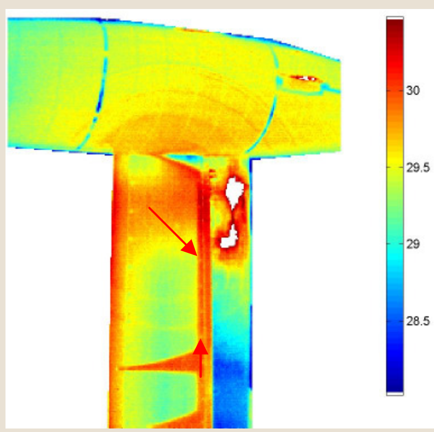
# Transition Modelling Testing

## Wind Tunnel Thermography




Bulb: 7%-15%

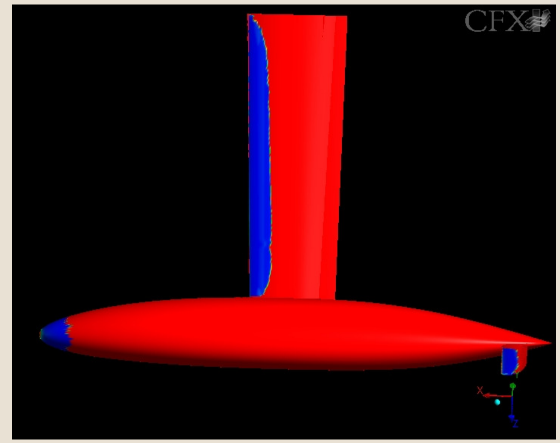


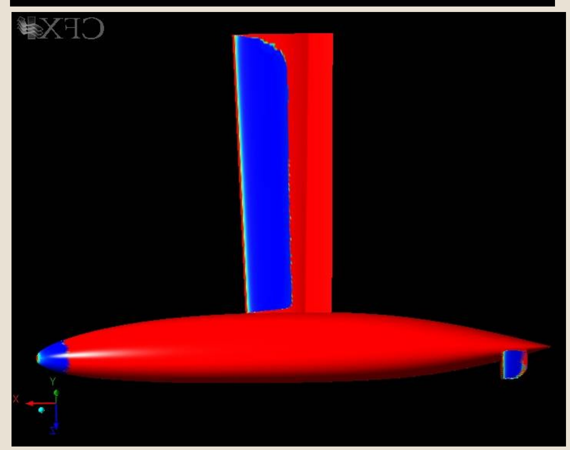




Keel (suction side): 12.5% - 23.5%
Keel (pressure side): 62%

## CFD Analysis

Bulb: 8%



Keel (suction side): 24%
Keel (pressure side): 57%

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# Summary

- New correlation based transition model has been developed
  - Based strictly on local variables
  - Applicable to unstructured massively parallelized codes
- Onset prediction is completely automatic
  - User must specify correct values of inlet Tu and $R_T$
- Validated for a wide range of 2-D and 3-D turbomachinery and aeronautical test cases – one set of correlations for all flows
- Strong potential that 1$^{st}$ Order effects of transition can be captured in everyday industrial CFD simulations
- Opens many new opportunities in industrial CFD – Implementation into Fluent 6.4 – Formula One teams …

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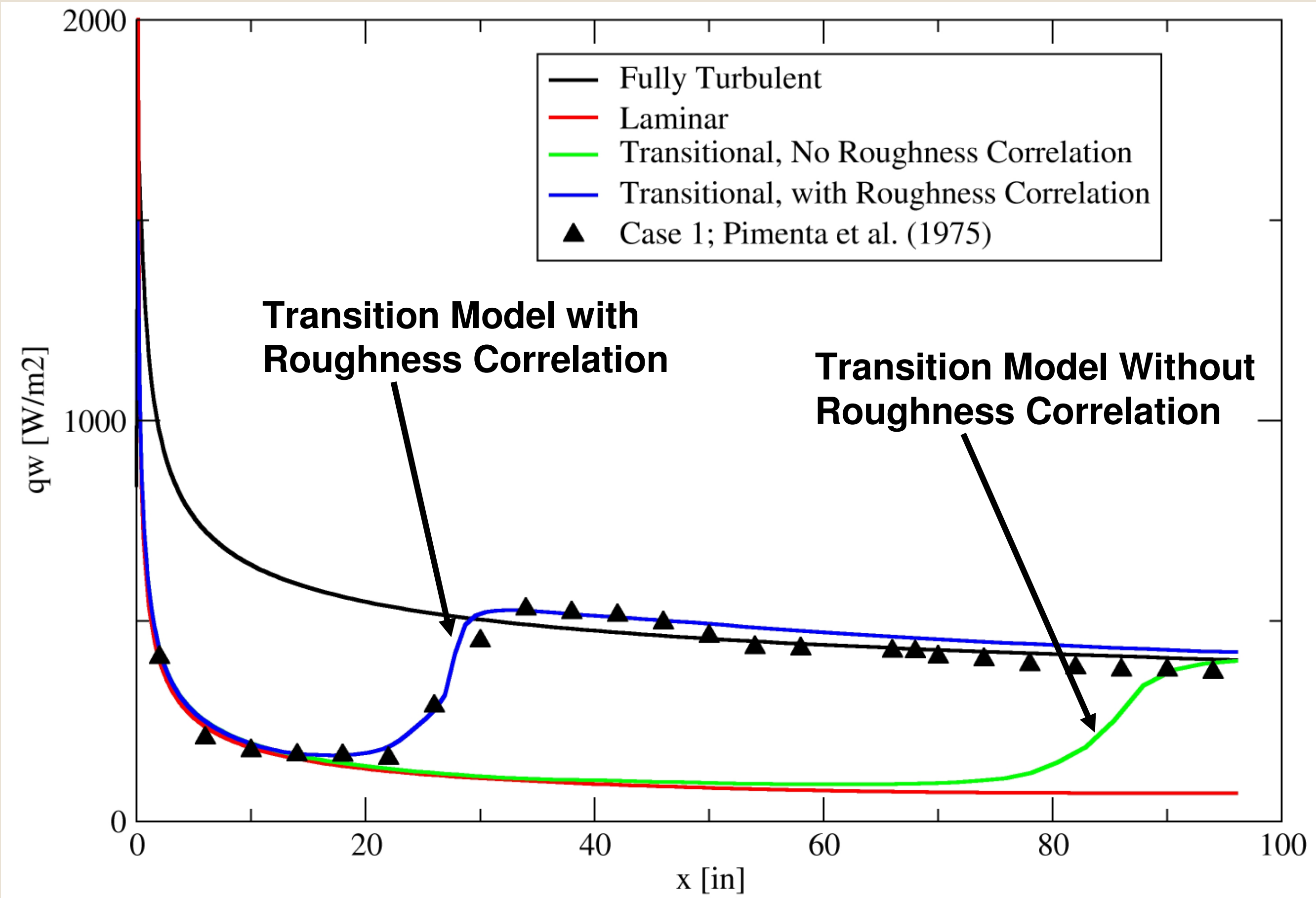
# Flat Plate Transition with Roughness

- **Included Correlations for the effect of Roughness on transition onset**

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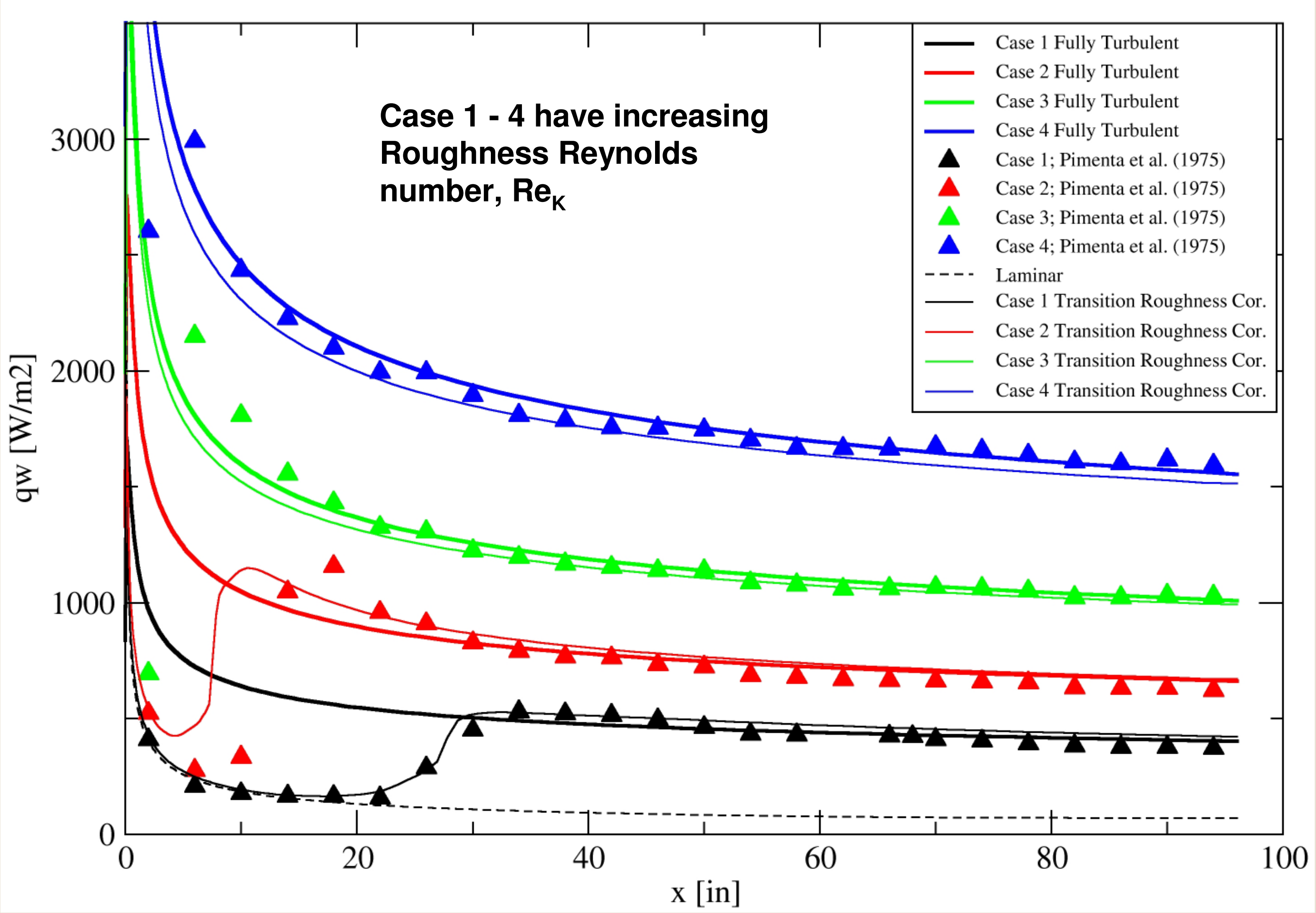
# Flat Plate
# Transition with Roughness

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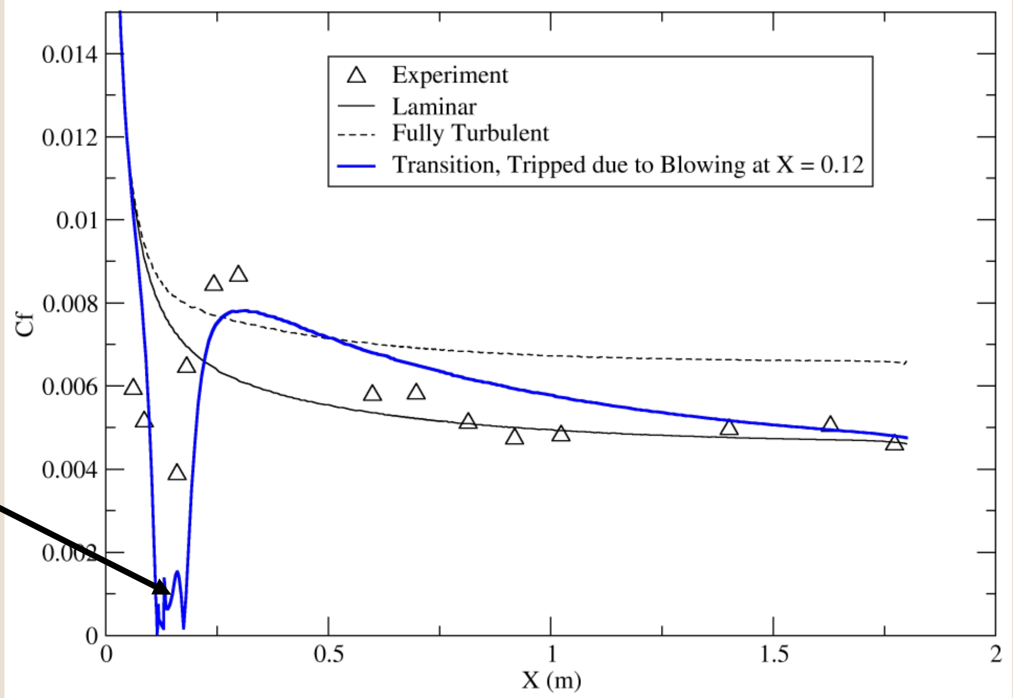
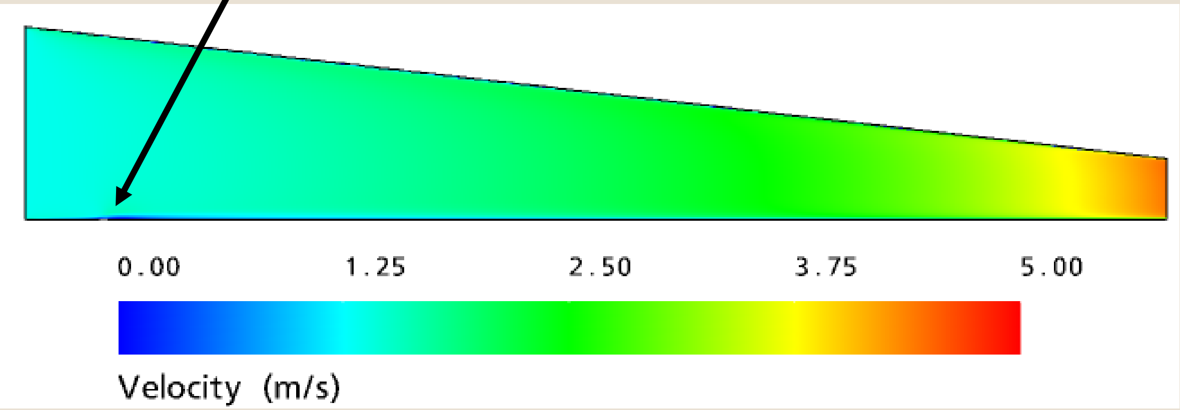
# Flat Plate Relaminarization




**Trip due to Blowing**

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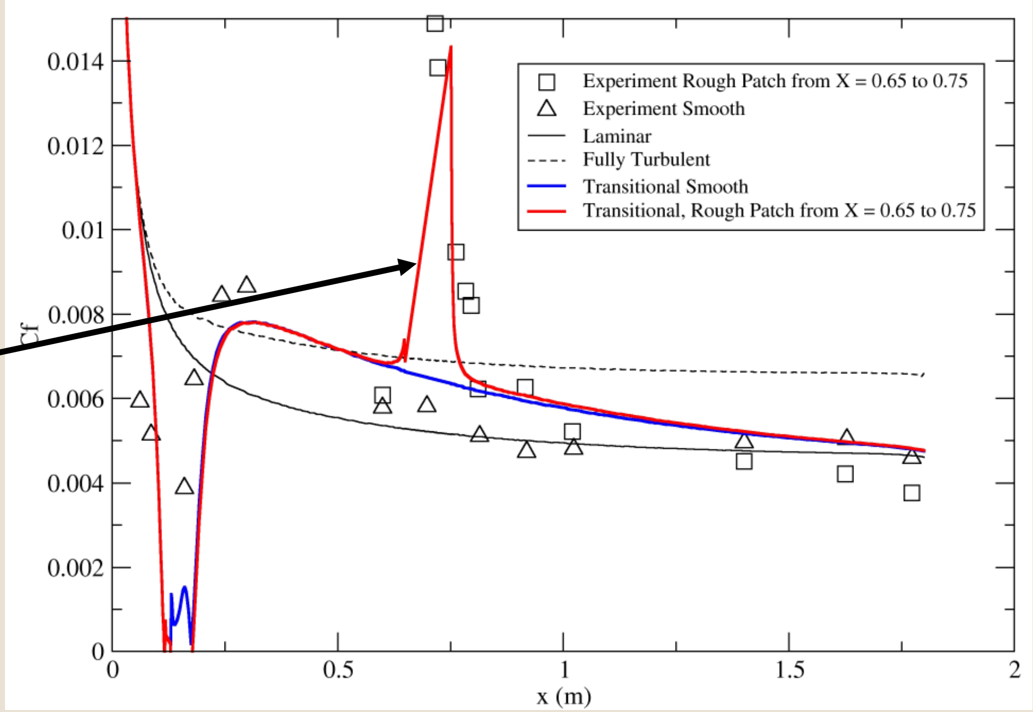
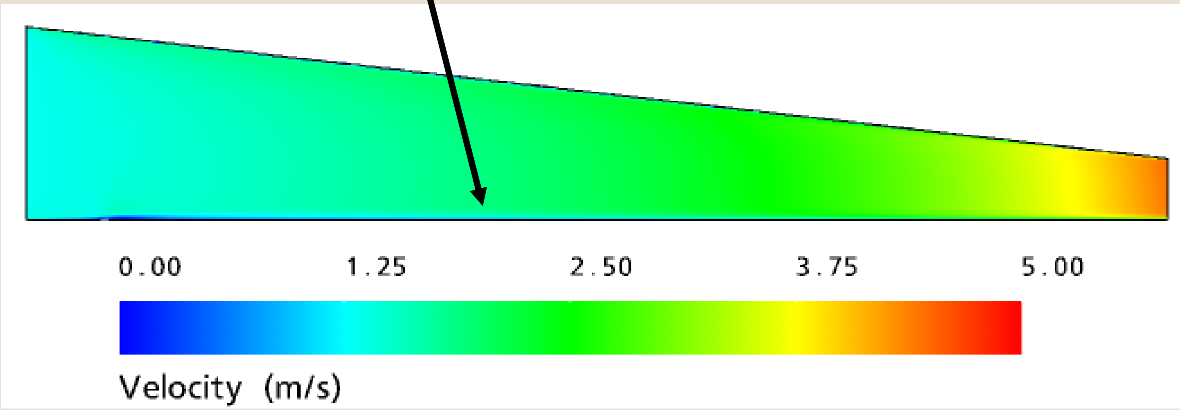
# Flat Plate Relaminarization with Roughness Strip




Roughness Strip

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