Turbulent Thermal Transport

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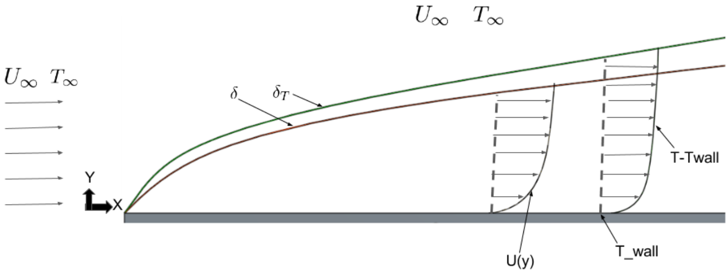
WAYNE STATE College of Engineering

Thermal Boundary Layers 101

-2 field variables to study, Velocity and Temperature

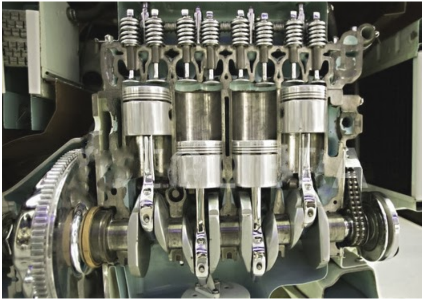


- U_∞ = Free-stream velocity
- $U(y)$ = Stream-wise velocity profile
- δ = Boundary layer thickness
- T_∞ = Free-stream temperature
- T_{wall} = Wall temperature
- δ_T = Thermal boundary layer thickness
- Pr=.707 =(viscous diff.)/(thermal diff.)

Engineering Systems

-Design of engineering systems relies on accurate models of real physics

http://science.howstuffworks.com



http://me-mechanicalengineering.com

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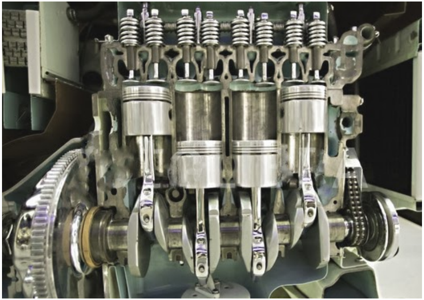

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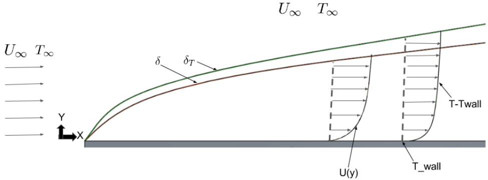
Important Parameters:

Wall shear stress $\rightarrow \tau_{wall}$

Wall heat flux $\rightarrow q''_{wall}$

Creating High Quality Boundary Layer Datasets



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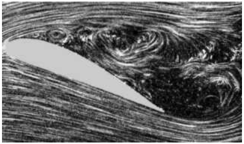


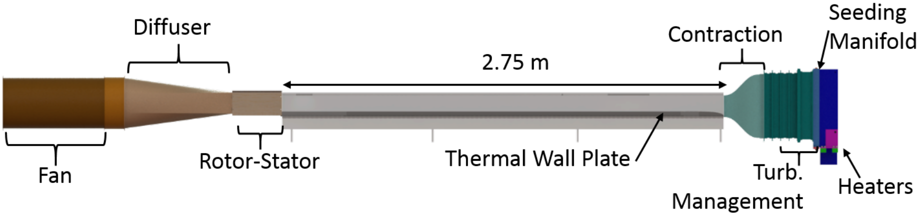
http://en.wikipedia.org/wiki/flow/separation

- Need to create test-bed for developing equilibrium/non-equilibrium flows
- Require experimental data sets to improve/validate models
- Requires controlling all boundary conditions

Experimental Facility

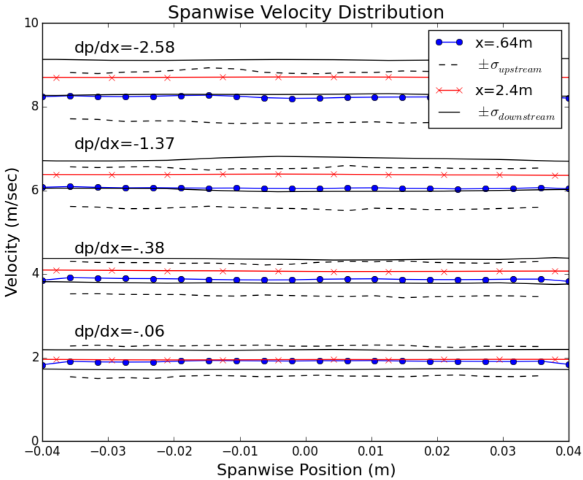
Non-Equilibirum And Thermal boundary layer Tunnel (N.E.A.T.)

- Length=2.75m $\longrightarrow$ Development Length
- Turbulent Management section $\longrightarrow$ Free Stream Turbulence
- VFD Controlled Motor $\longrightarrow$ U_∞
- Bank of Resistive Heaters $\longrightarrow$ T_∞
- Thermal Wall Plate $\longrightarrow$ T_{wall}
- Rotor-Stator Mechanism $\longrightarrow$ $\frac{\partial U_\infty}{\partial t}$

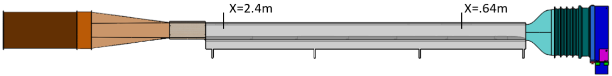


UNH Thermal Boundary Layer Wind Tunnel

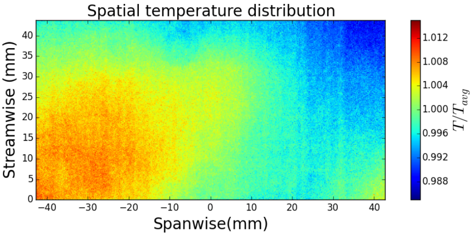
Pressure Gradient

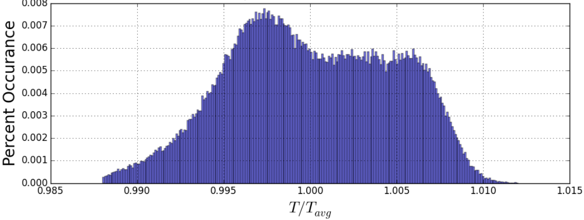


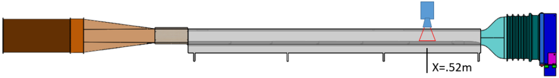
- Span-wise profile $\pm 12.5\%$
- dp/dx Parameter $K = \frac{\nu}{U_\infty^2} \frac{dU_\infty}{dx}$
- $K > 1.25 \times 10^{-6}$ [1]
- at 4m/sec $K = 1.0 \times 10^{-7}$



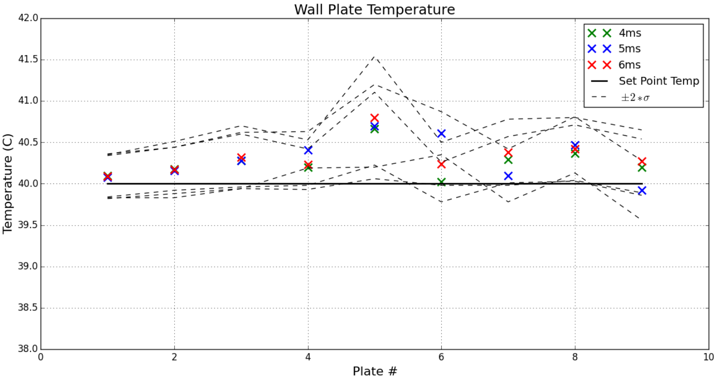
Spatial Wall Temperature Distribution



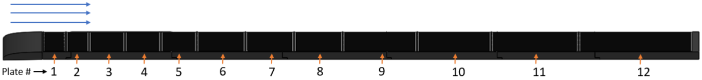




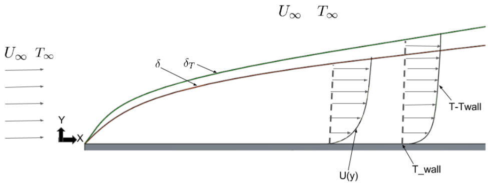
Mean Plate Temperature

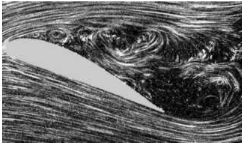


- Set Temperature=40^{o}C
- Controller loop at 20Hz



Creating High Quality Boundary Layer Datasets



→ 

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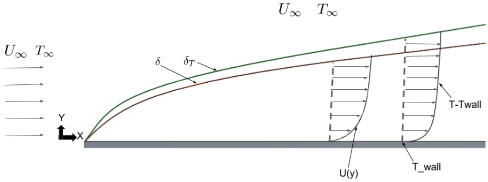

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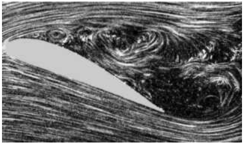

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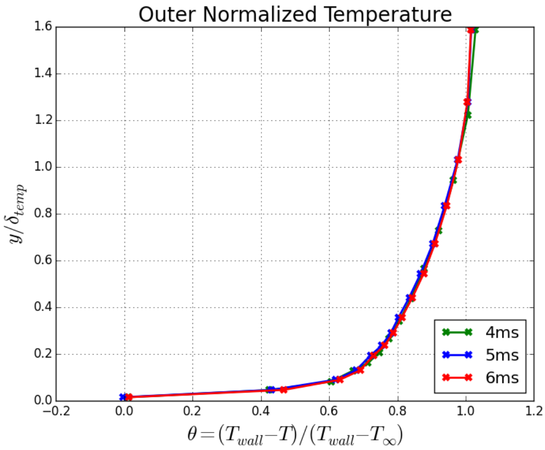
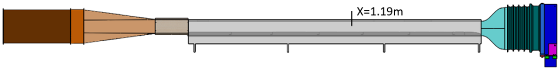
$\rightarrow$ Equilibrium momentum and thermal boundary layer measurements

Temperature Profile



- Type J thermocouple
- δ_T/Probe Diam = 33
- 30 Points
- $T_{wall} = 40^o C$
- Sample Freq = 2Hz
- Sample length=120sec



Governing Equations

Examine Navier Stokes and Energy Equation

$$\frac{d\vec{u}}{dt} + \vec{u}\nabla\vec{u} = \nu\nabla^2\vec{u} + -\frac{1}{\rho}\nabla P$$
$$\frac{dT}{dt} + u\nabla T = Pr\nabla^2 T$$

- Temporal Change
- Convection/Advection
- Diffusion
- Pressure Gradient

Assumptions:

- Steady
- 2D
- Incompressible

Laminar Analysis

Similarity scaling transforms PDE $\rightarrow$ ODE

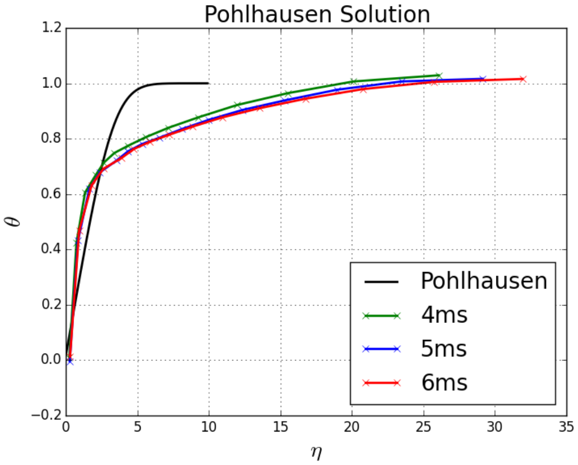
Similarity variable: $\eta = y\sqrt{\frac{U_\infty}{\nu x}}$

Blasius Solution (momentum) $\rightarrow$ $$2\frac{d^3 f}{d\eta^3} + f(\eta)\frac{d^2 f}{d\eta^2} = 0$$

Polhausen Solution (energy)$\rightarrow$ $$\frac{d^2\theta}{\eta^2} + \frac{Pr}{2}f(\eta)\frac{d\theta}{d\eta} = 0$$

$$f' = \frac{U}{U_\infty},\ \theta = \frac{T_{wall} - T}{T_{wall} - T_\infty}$$

Temperature Profile - Pohlhausen



- Temperature profiles deviate from laminar solution

Laminar Analysis

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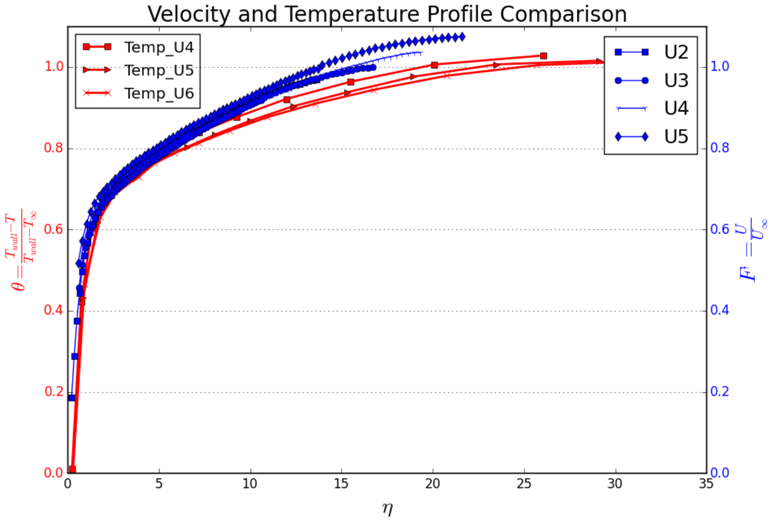
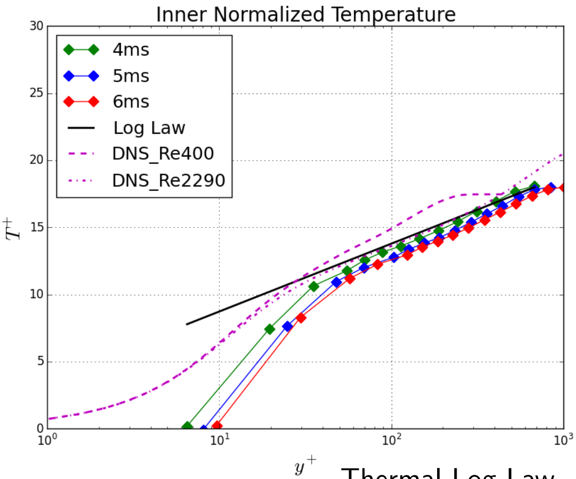
Temperature Profile - Velocity Profile



Thermal Profile - DNS



DNS (Araya et al.)

- $R_\theta 1 = 400$
- $R_\theta 2 = 2290$
- Constant wall temperature BC
- Pr = .71

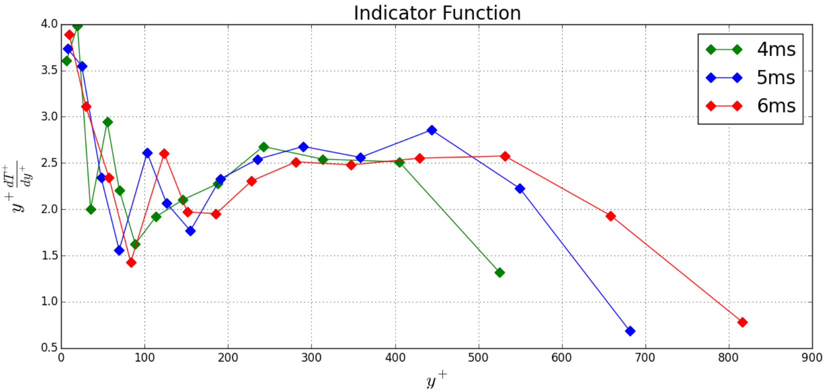
Experiment

- $T^+ = \theta \frac{U_\infty}{u_\tau} Pr^{2/3}$
- $y^+ = \frac{y u_\tau}{\nu}$
- Probe Diam = 12.5y$^+$

Thermal Log-Law

- $T^+ = 2.195 ln(y^+) + 13.2Pr - 5.66$ [3]

Thermal Profile - DNS



Thermal Log-Law

- $T^+ = 2.195 ln(y^+) + 13.2Pr - 5.66$
- differentiate both side $\rightarrow$ $y^+ \frac{dT^+}{dy^+} = constant$

Conclusions/Capabilities

- Maintain T_{wall} in equil/non-equil flow
- Pressure gradient is to weak to change mean dynamics
- Turbulent thermal profiles are observed

Future Work

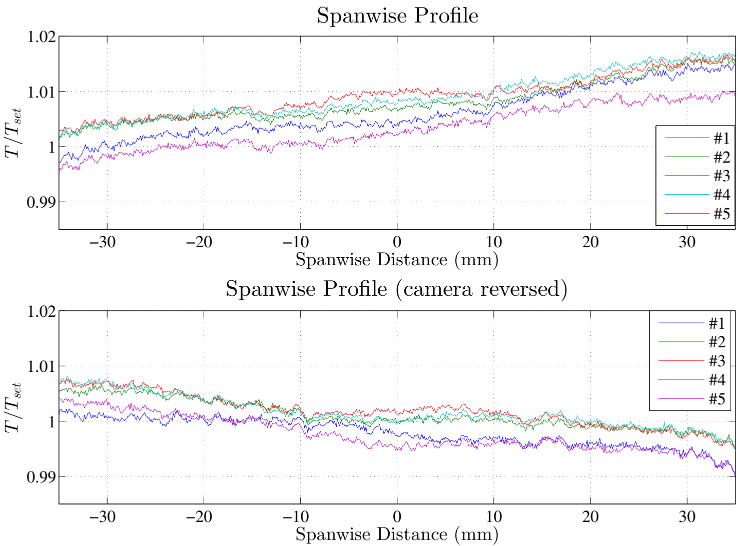
- Diagnose TC noise issues
- Thermocouple measurements in non-equilibrium flow
- Coupled temperature and velocity measurements in equilibrium environments

Questions??

References

- 1. Philippe R. Spalart, Jonathan H. Watmuff (1992). "Experimental and Numerical study of a turbulent boundary layer with pressure gradients". J. FLuid Mech. 337-371.
- 2. Marusic I, Monty JP, Hultmark M, Smits AJ (2013). "On the logarithmic region in wall turbulence". J Fluid Mech 716:R3
- 3. Kays WIlliam Morrow, Crawford Michael E. (1980). "Convective Heat and Mass Transfer". McGraw-Hill Series in Mechanical Engineering. 210-211.
- 4. Araya Guillermo, Castillo Luciano (2012). "DNS of turbulent thermal boundar layers up to $Re_\theta = 2300$". Int Journal of Heat and Mass Transfer. 4003- 4019.

IR Plot


Spanwise Profile
1.02
1.01
1
0.99
T/T_set
−30
−20
−10
0
10
20
30
Spanwise Distance (mm)
#1
#2
#3
#4
#5
Spanwise Profile (camera reversed)
1.02
1.01
1
0.99
T/T_set
−30
−20
−10
0
10
20
30
Spanwise Distance (mm)
#1
#2
#3
#4
#5