Experimental Pulsatile Pertubations of Near Wall Thermal Transport

D. Biles, A. Ebadi, C.M. White
University of New Hampshire

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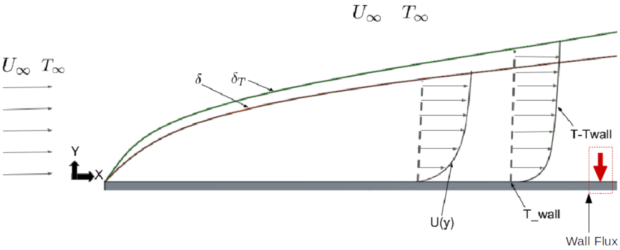
PARTNERSHIP
AWARD'S: 1258702, 1258594, 1258697

Thermal Boundary Layers 101

-2 field variables to study, Velocity and Temperature

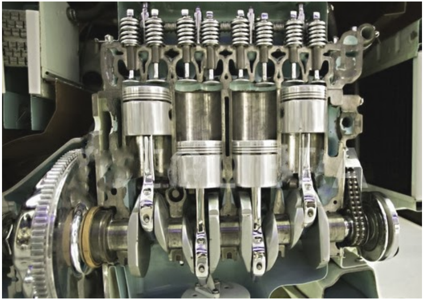


- U_∞ = Free-stream velocity
- $U(y)$ = Stream-wise velocity profile
- δ = Boundary layer thickness
- T_∞ = Free-stream temperature
- T_{wall} = Wall temperature
- δ_T = Thermal boundary layer thickness
- Pr=.707 =(viscous diff.)/(thermal diff.)

Engineering Systems

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

http://science.howstuffworks.com



http://me-mechanicalengineering.com

Important Parameters:

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

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

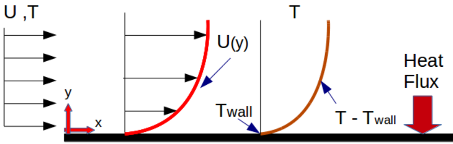
Complex Thermal Boundary Layers

Complex Boundary Layers brought about from;

- Induced pressure gradients
- Temperature gradients
- Separation
- Dynamic walls
- Unsteady flow

In many engineering applications one or several of these effects are important

Equilibrium Boundary Layer



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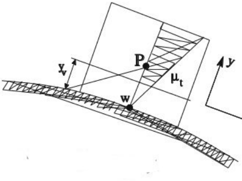
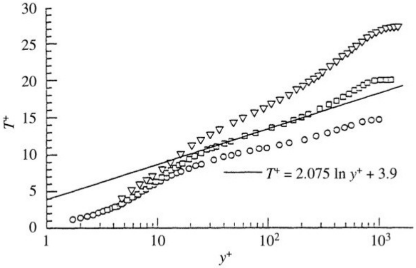
Modeling Non-Equilibrium Flows

- Computationally expensive to solve near wall dynamics
- Near wall dynamics extrapolated from log profile
- Reasonable estimate for equilibrium wall flows
- Fail when applied non-equilibrium boundary layers



P. Bradshaw and G. P. Huang



Bradshaw et al., *The law of the wall in turbulent flow*

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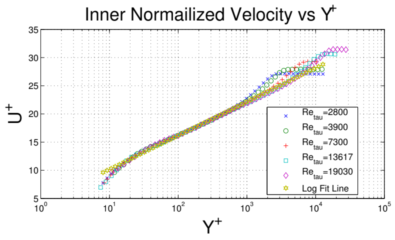

Hutchins et. al (2009)

- For $R_e = 9.7 \times 10^6$ ($\diamond$)
- $\delta = .302m$
- Scaling $y^+ = \frac{yu_\tau}{\nu}$, $u^+ = \frac{u}{u_\tau}$
- Viscous length scale $=$ 16 microns

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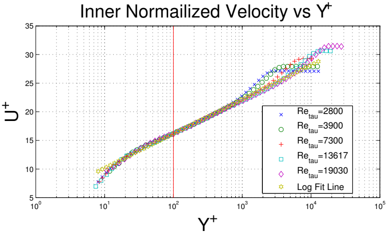
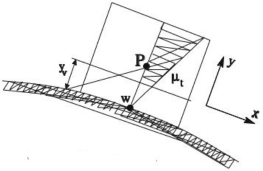


Hutchins et. al (2009)

- For $R_e = 9.7 \times 10^6$ (◇)
- $\delta = .302m$
- Scaling $y^+ = \frac{yu_\tau}{\nu}$, $u^+ = \frac{u}{u_\tau}$
- Viscous length scale = 16 microns
- $y^+ = 100 \rightarrow y = 1.6mm$

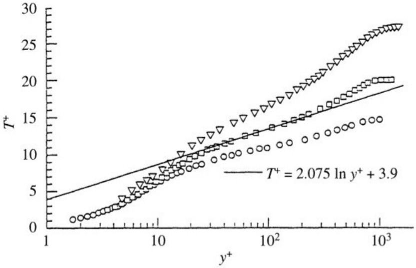
Modeling Non-Equilibrium Flows



P. Bradshaw and G. P. Huang

Question

How does time varying boundary conditions of U_∞ change the momentum and thermal boundary layer profiles?



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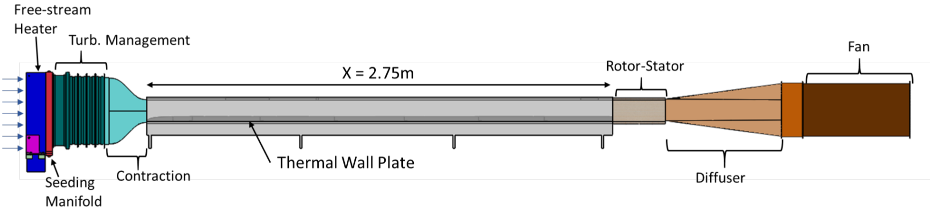
Experimental Facility

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

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



UNH Thermal Boundary Layer Wind Tunnel

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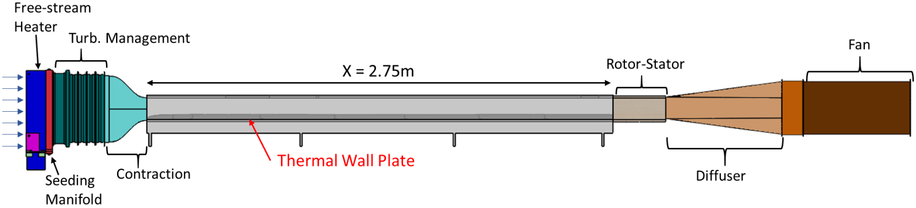

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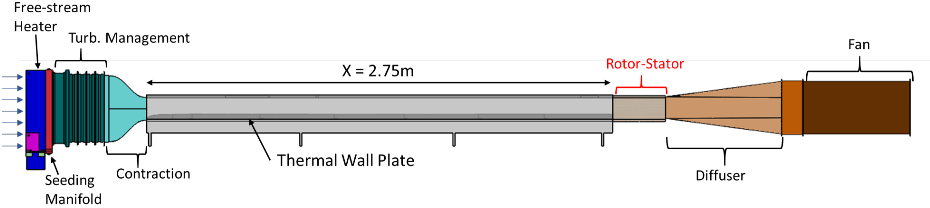
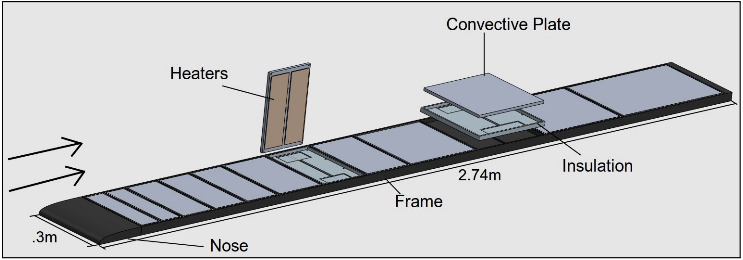


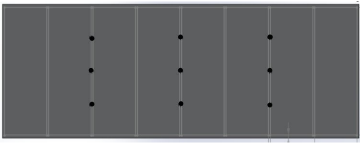
UNH Thermal Boundary Layer Wind Tunnel

Sectioned Thermal Wall Temperature Plate



- Size=0.3m x 2.74m
- Sectioned design*
- Independently heated/controlled*
- Individually Insulated

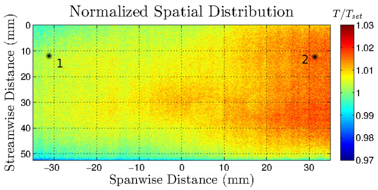
Front Convective Plate



* Blackwell, B. F., *The turbulent boundary layer on a porous plate*

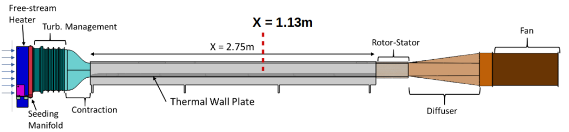
Validation of Wall Plate Design

- Control set Temperature to +-0.1^{o}C
- Produce spatially uniform temperature to +-2% in equilibrium flow
- Develop 2D equilibrium thermal boundary layer



Thermocouple #1 = 50^oC

Thermocouple #2 = 50.01^oC



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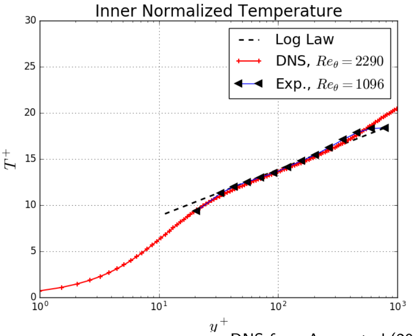
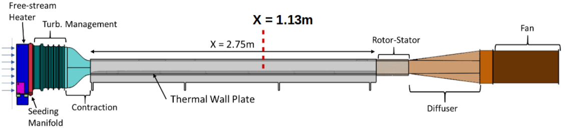


DNS from Araya et al.(2012)



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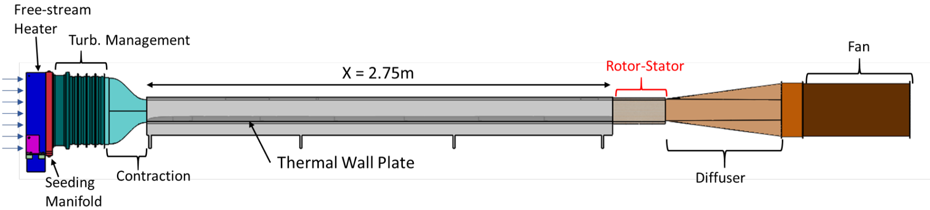

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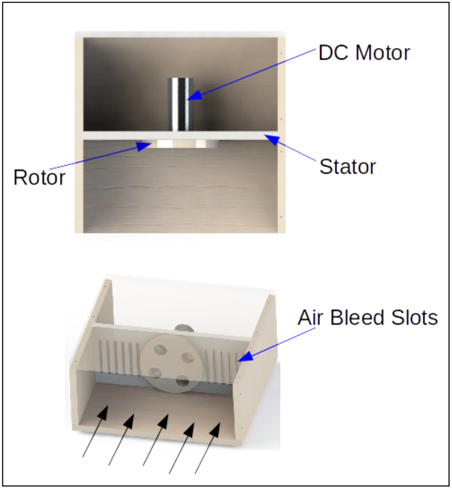
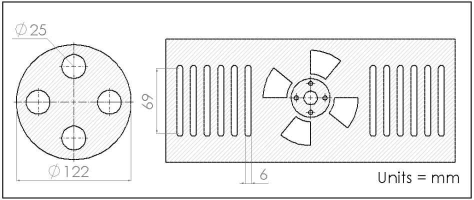
Rotor-Stator Design



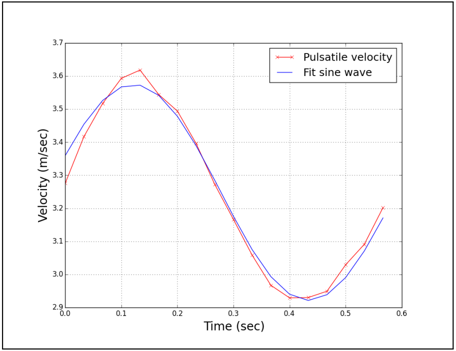
- Slotted Rotor-Stator design
- Rotor outer diameter = channel height
- Adjustable number of air-bleed slots
- Rotor speed adjustable from 1Hz to 85Hz



[1]

[1] K. Al-Asmi and I.P. Castro, *Production of oscillatory flow in wind tunnels*

Rotor-Stator Design



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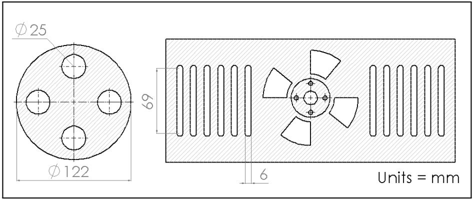

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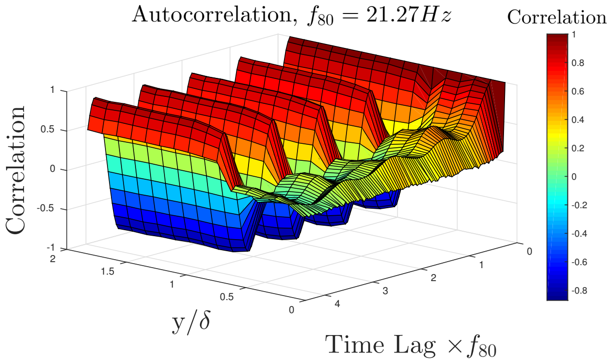
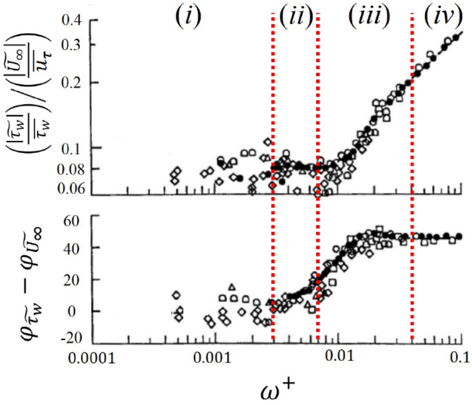
Rotor-Stator Testing: Auto-correlation



- Induced pulsatile flow in free stream
- Correlation drops off within boundary layer
- Correlation peaks still visible in boundary layer

Non-Equilibrium Classification



Markers from Brereton and Mankbadi (1995)

Modulation Amplitude (top), Phase Shift (bottom) of perturbation wall shear stress

- (*i*) - Quasi-steady region
- (*ii*) - Low frequency region
- (*iii*) - Intermediate frequency region
- (*iv*) - High frequency region

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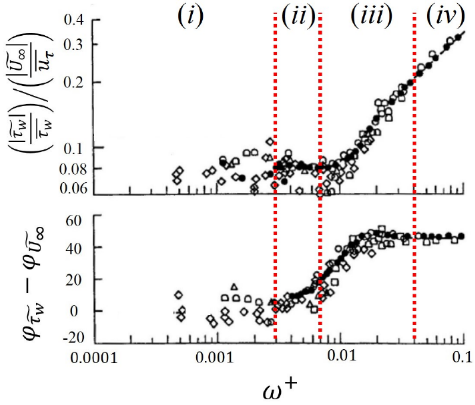

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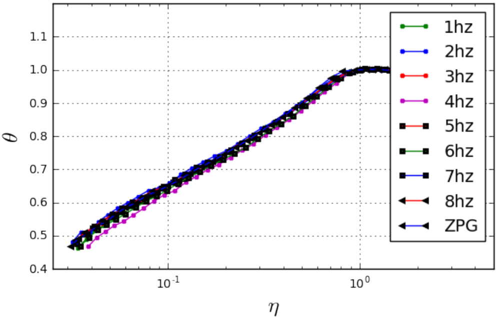
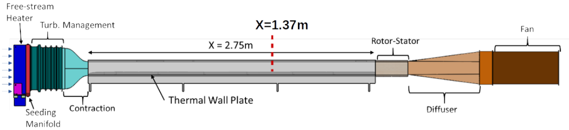
Pulsatile Mean and Integral Parameters



- δ_T / TC_{diam}=28
- $\theta = \frac{T_{wall} - T(y)}{T_{wall} - T_\infty}$
- $\eta = y/\delta_T$
- $Re = 2.6 \times 10^5$
- $T_{wall} = 40^o C$
- Frequency = 1Hz $\rightarrow$ 8Hz



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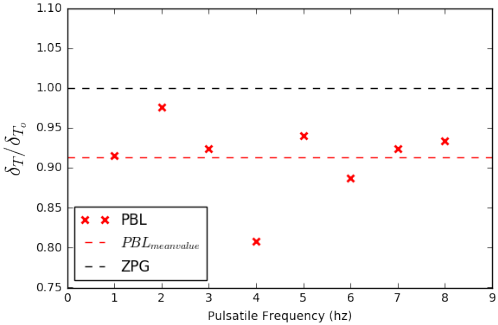

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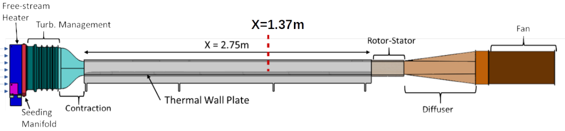
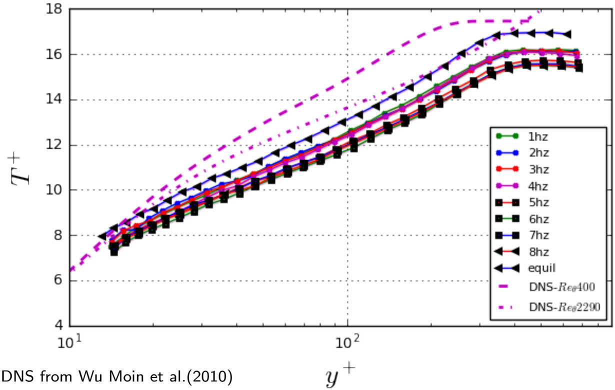


Inner Normalized Profiles



DNS from Wu Moin et al.(2010)

ZPG

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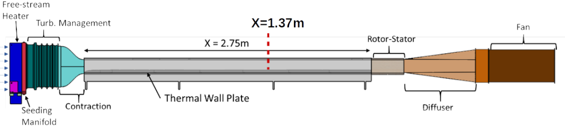
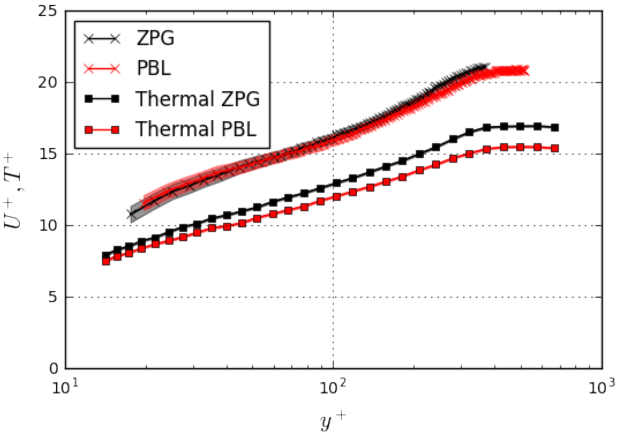


ZPG vs Pulsatile Flow

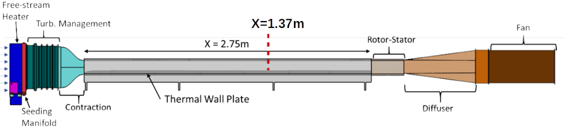


ZPG

- $Re_\theta = 1139$

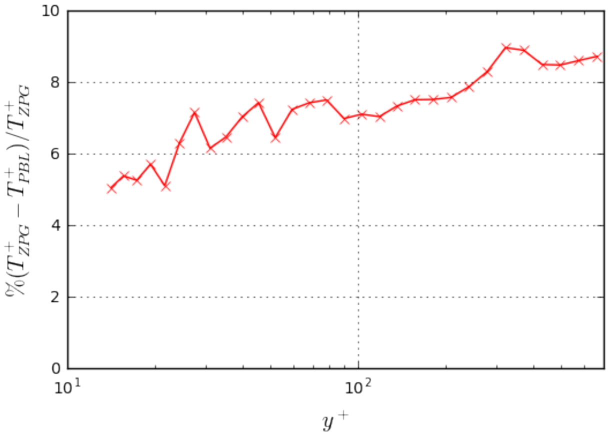
Pulsatile

- $Re_\theta = 874$
- Freq = 6Hz



  drummond.biles@gmail.com

ZPG vs Pulsatile Flow



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Pulsatile

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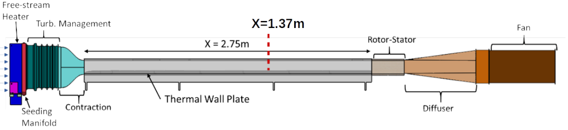

Conclusions

- Pulsatile forcing of outer velocity boundary condition results in pressure gradient like influence on temperature field
- Since the effect of a favorable pressure gradient is most evident in the inner-normalized profiles it is possible that pulsatile forcing modifies the wall heat flux or causes a phase lag between the wall shear stress and the wall heat flux.
- Both results suggest a breakdown of Reynolds analogy in pulsatile flow in the intermediate non-equilibrium region. Perhaps not surprising since Bradshaw showed that Reynolds analogy breaks down in adverse and favorable pressure gradient flows

Future Work

- Phase averaged wall heat flux
- Coupled temperature and velocity measurements to investigate $v'T'$ correlation

Thank you for Your Attention!