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Investigating Non-Equilibrium Thermal Boundary Layers

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Michael Allard, Allen Ma, and Rza Ebadi

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PARTNERSHIP

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VACC VERMONT ADVANCED COMPUTING CENTER UNIVERSITY OF VERMONT

WAYNE STATE College of Engineering

Overview

1.Introduction to Boundary Layers

2.Background/Motivation

3.Experimental Setup

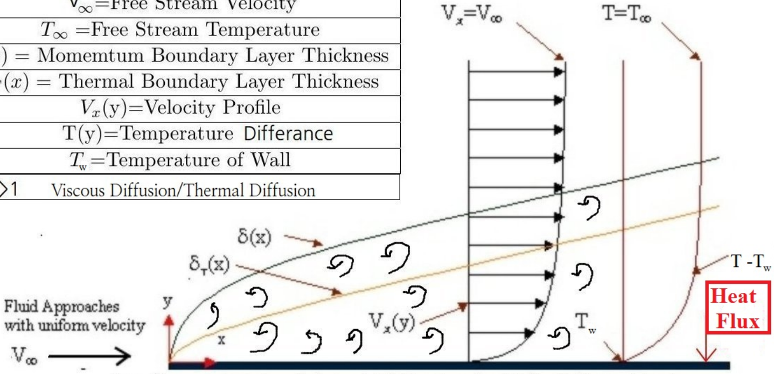
4. Experimental Validation

5. Future Work

Thermal Boundary Layers

Legend

V_∞=Free Stream Velocity	
T_∞ =Free Stream Temperature	
$\delta(x)$ = Momemtum Boundary Layer Thickness	
$\delta_T(x)$ = Thermal Boundary Layer Thickness	
V_x(y)=Velocity Profile	
T(y)=Temperature Differance	
T_w=Temperature of Wall	
Pr >1	Viscous Diffusion/Thermal Diffusion



http://www.owlnet.rice.edu/ ceng402/ed1projects/proj00/harris/feature2.html

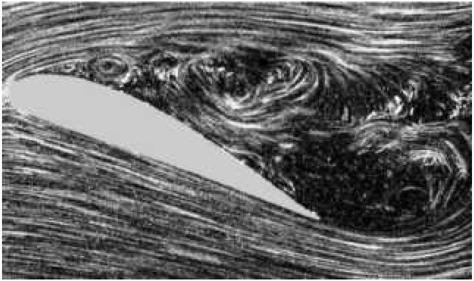
Non-Equilibrium Thermal Boundary Layers

Robust heat flux correlations do not exist

Brought about by:

- Pressure gradients
- Separation
- Dynamic walls
- Unsteady flow

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



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

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Engineering Systems With Non-Equilibrium Flows

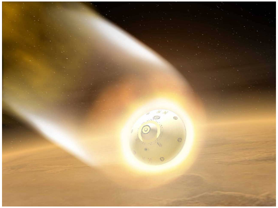
Gas Turbine

http://science.howstuffworks.com/

Internal Combustion Engine

http://www.zorly.com

Re-entry Vehicle



http://en.wikipedia.org

- Non-equilibrium flows exist in many environments
- Great need to further understand these complex flows for prediction and control

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Piston Engine as a Case Study to Demonstrate Research Needs

Standards for fuel mileage increasing to 40+mpg [3]

Cylinder Discretized with 1 Million Cells

Heat=Work+Heat Loss

Need to accurately model heat transfer in internal combustion engines

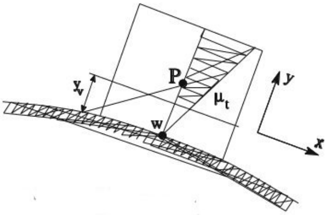
- Increase efficiency
- Reduce emissions
- Advance low temperature combustion modes

Heat loss numerically simulated in modern engines

- Simulation Integral component of engine design process
- Simulations can not accurately resolve boundary layer dynamics

3. Corporate Average Fuel Economy

CFD Wall models (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

Zero Pressure Gradient vs Adverse Pressure Gradient

P. Bradshaw and G. P. Huang

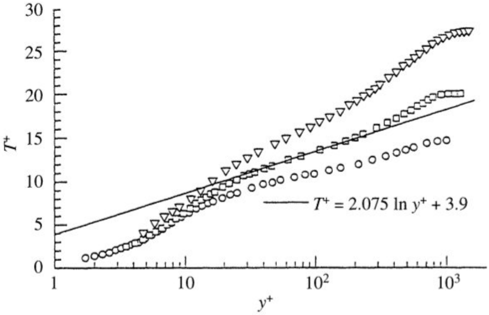


Figure 1. Temperature profiles in favourable (Thielbahr *et al.* 1969; ▽) and adverse (Blackwell *et al.* 1972; ○) pressure gradient. $T^+ \equiv (T_w - T)/T_\tau$. From Kays & Crawford (1993).

-Need models which can predict heat transfer in non-equilibrium flows

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

Experimental Approach to Investigating

Non-Equilibrium Thermal Boundary Layers

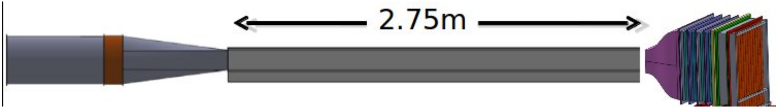
Systematic and Simple

Facility

- Length=2.75m
- Turbulent Management section (screens/honeycomb)
- Velocity .25 to 12m/sec (frequency controlled motor)

Design Constraints

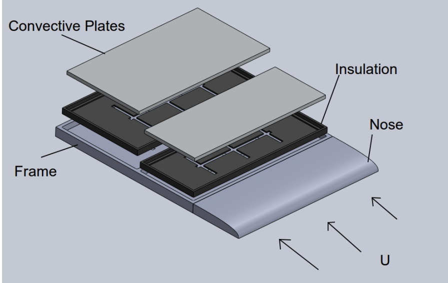
- Control Boundary Conditions
  - -Control T_∞
  - -Control T_o/heat flux
- Maintain attached boundary Layer



UNH Thermal Boundary Layer Wind Tunnel

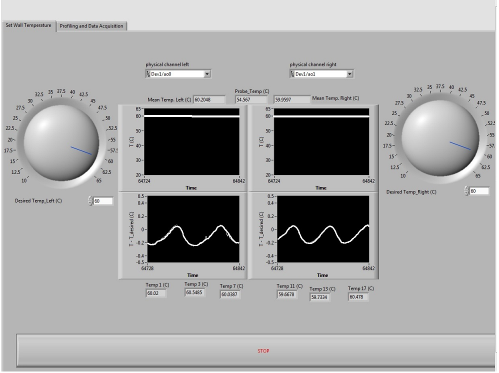
Sectioned Constant Wall Temperature Plate

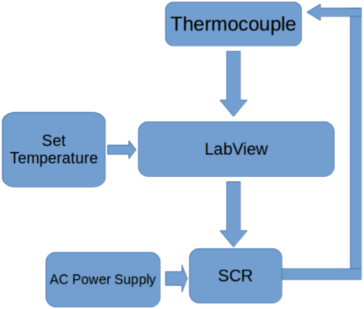
- Size=18"x25.5"
- Sectioned design[2]
- Independently heated/controlled[2]
- Individually Insulated
- Thermocouple monitored temperature



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

Temperature Controller





- Maintain temperature within $+-.1^o$ C
- Independently monitor and control each plate

Designed/Created by:Ebadi, Reza

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Spatial Temperature Distribution

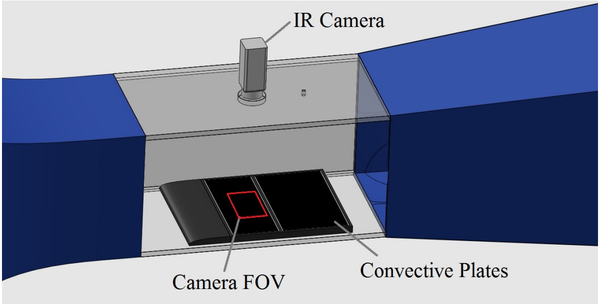
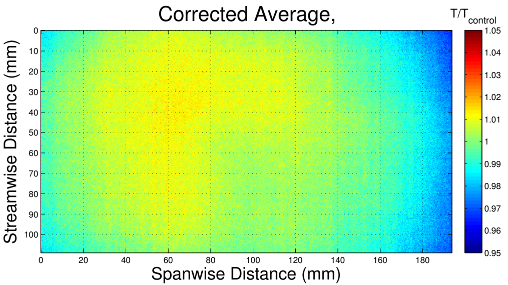
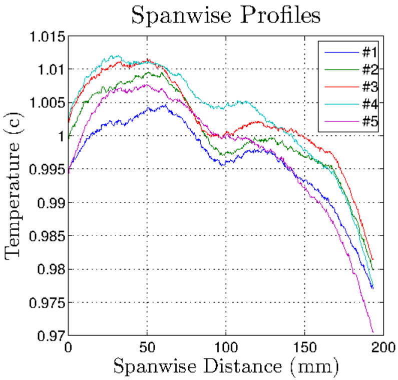


Image Correction Scheme

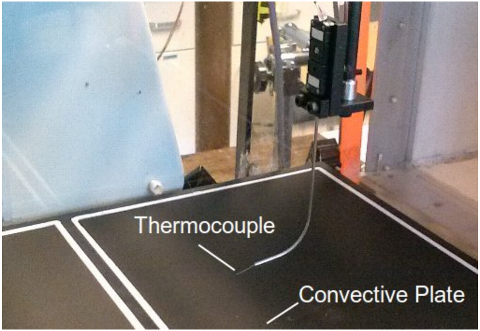
- Acquire Flat Field Image
- Average and find correction matrix
- Acquire images

Spatial Temperature Distribution Results



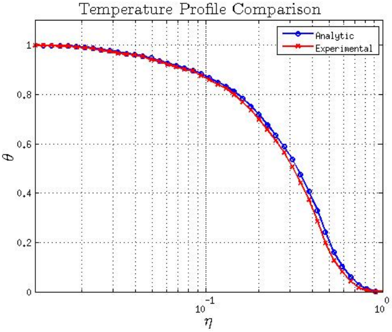


Temperature Profile



- Type K thermocouple
- Probe diameter = .254 mm
- Downstream position=.3 m
- Wall temperature= 60^{o}C
- 30 points logarithmicly spaced
- Sampled at 2 Hz for 2 min

Temperature Profile Results

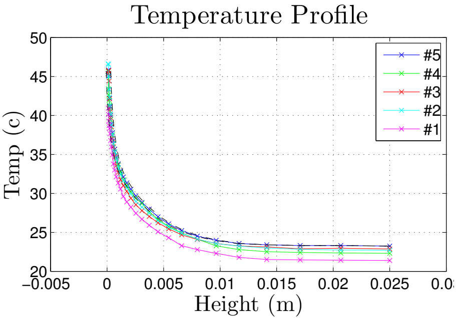


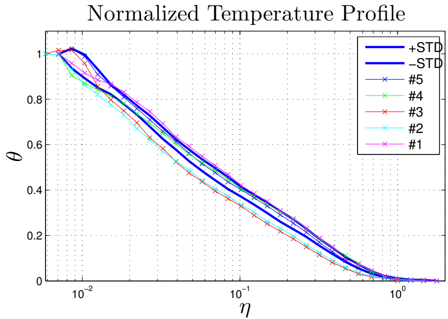
Non-dimensional variables[1]:

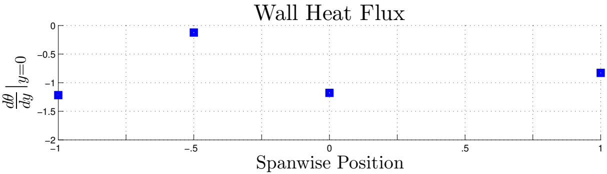
- $\theta = \frac{T - T_\infty}{T_{wall} - T_\infty}$
- $\eta = \frac{y}{\delta_T}$
- $\theta_A = 1 - 1.5\eta + .5\eta^3$

1. Faghri, Amir, *Advanced Heat and Mass Transfer*

Spanwise Variability







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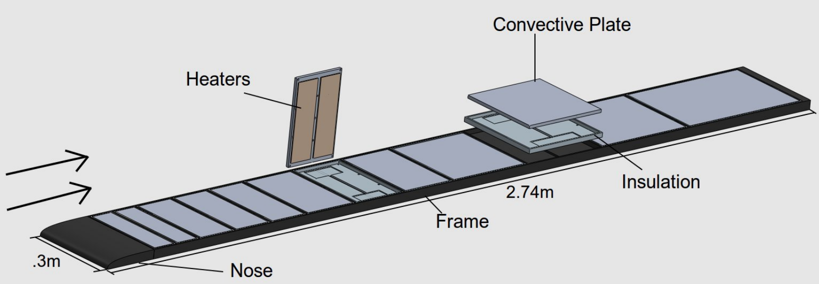
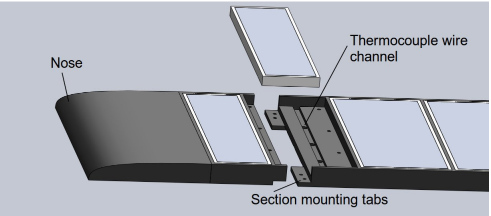
Final Wall Plate Design

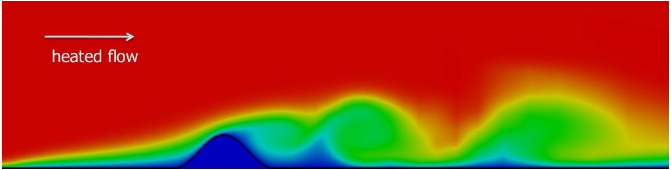




Future Work Student Wind Tunnel (next week)

- Examine spatial wall plate temperature distribution due to flow around an obstacle

DNS



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Future Work BL Wind Tunnel

- Validate plate design
- Systematically investigate non-equilibrium boundary layers

References

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- Fox and McDonald *Intro to Fluid Mechanics. John Wiley & Sons, 2011. Print.*
- Jiji, Latif M. *Heat Convection. Springer, 2006. Print.*
- Blackwell, B. F. *The turbulnet boundary layer on a porous plate. Stanford, 1972. Print.*
- Faghri, Amir, *Advanced Heat and Mass Transfer*

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Questions??