Flat Plate Convection

Thermal Fluids and Energy Systems Lab

(ME EN 4650)

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Convective Heat Transfer

What we want to know:

→ $Nu = f(Re, Pr)$

→ q'' (heat flux)

→ T_s (surface temperature)

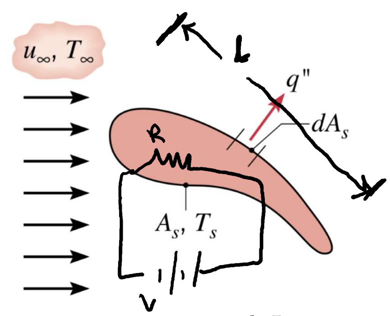
What we can measure:

→ P_{dyn} : Pitot-static probe → V_∞

→ $T_s(x)$: thermocouples

→ q'' : V, R multimeter

→ T_∞ : thermocouples



$$Nu = \frac{h\,L}{k}$$

$$Re = \frac{U_\infty\,L}{\nu}$$

$$Pr = \frac{\nu}{\alpha}$$

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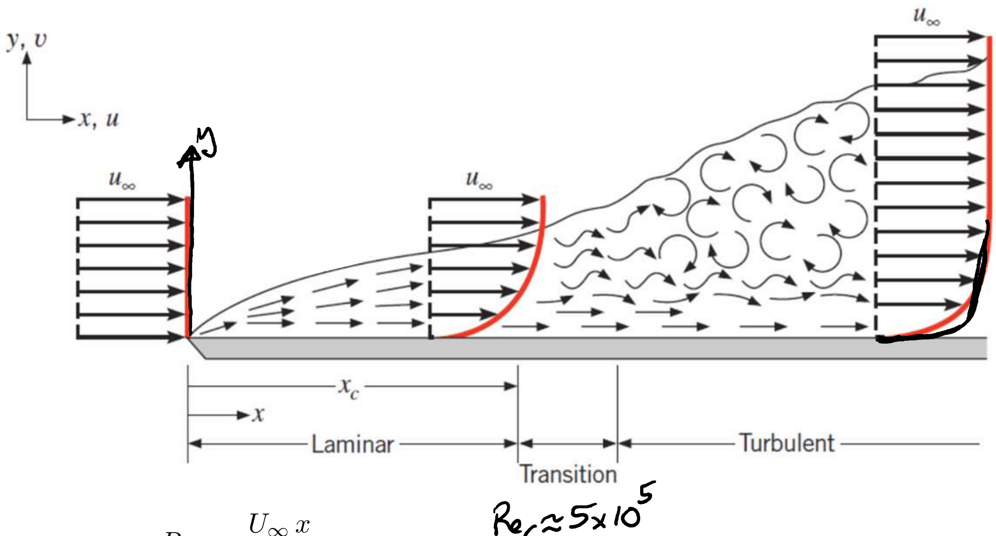
Flow over a Flat Plate



$$Re_x = \frac{U_\infty x}{\nu}$$

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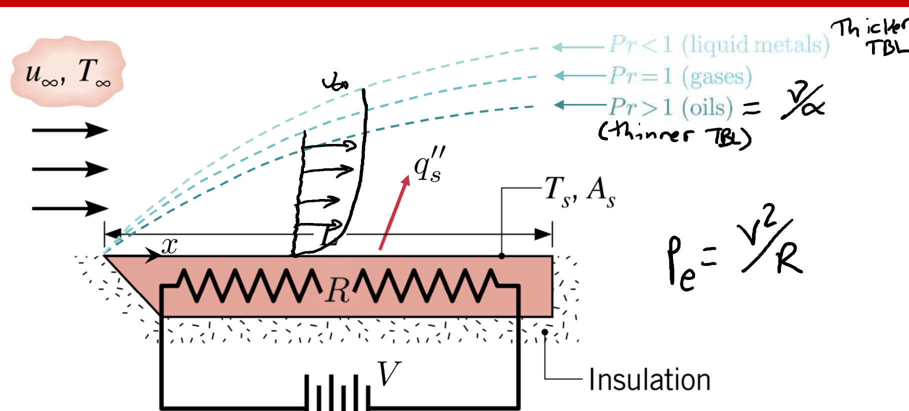
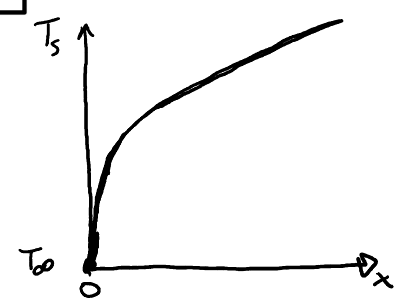
Heat Transfer from Heated Plate



$P_e = V^2/R$

Heat flux (top surface): $q_s'' = P_e / A_s$



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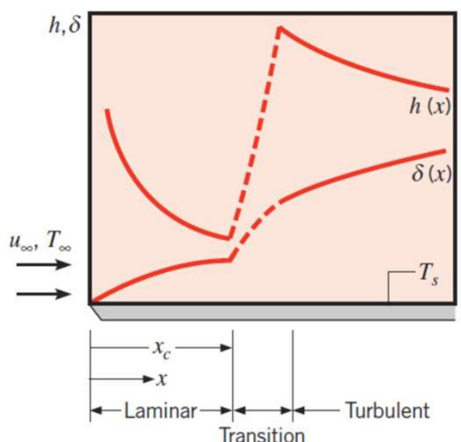
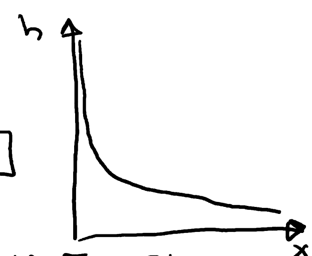
Heat Transfer from Heated Plate





Heat flux (top surface): $q_s'' = P_e / A_s$

Newton's Law of Cooling: $q_s'' = h_x(x)\,[T_s(x) - T_\infty]$

local heat transfer coefficient: $h_x(x) = q_s'' / [T_s(x) - T_\infty]$

local Nusslet number: $Nu_x = \dfrac{h_x(x)}{(k/x)}$

$T_f = \dfrac{T_s(x) + T_\infty}{2}$ Film temperature

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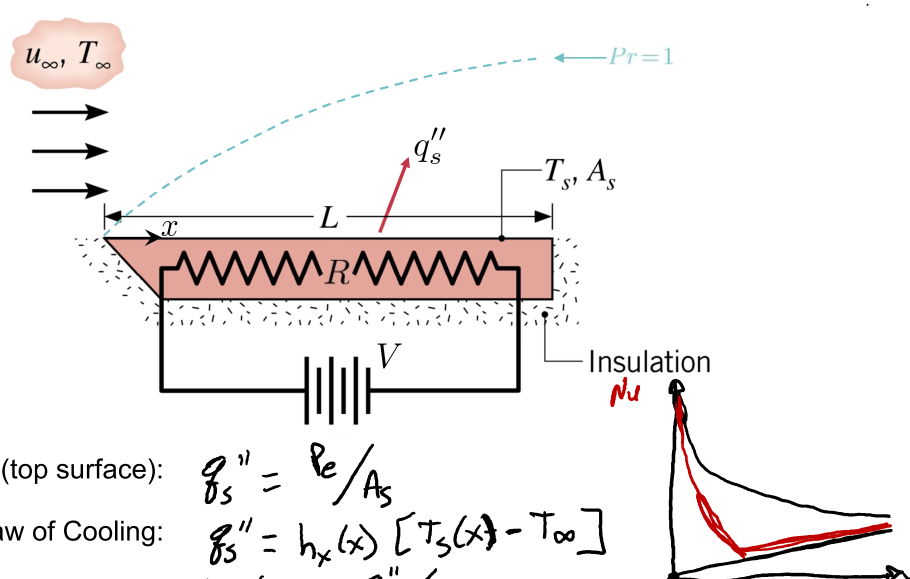
Heat Transfer from Heated Plate



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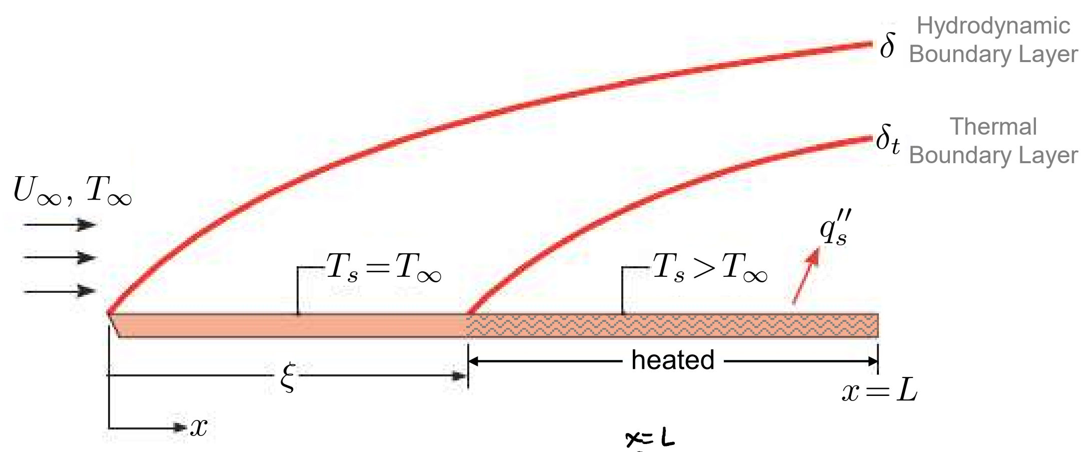
Flat Plate with Unheated Starting Length



average heat transfer coefficient: $\bar{h}_L = \frac{1}{L-\xi} \int_{x=\xi}^{x=L} h_x(x)\,dx$

average Nusslet number: $\overline{Nu}_L = \bar{h}_L \cdot L/k$

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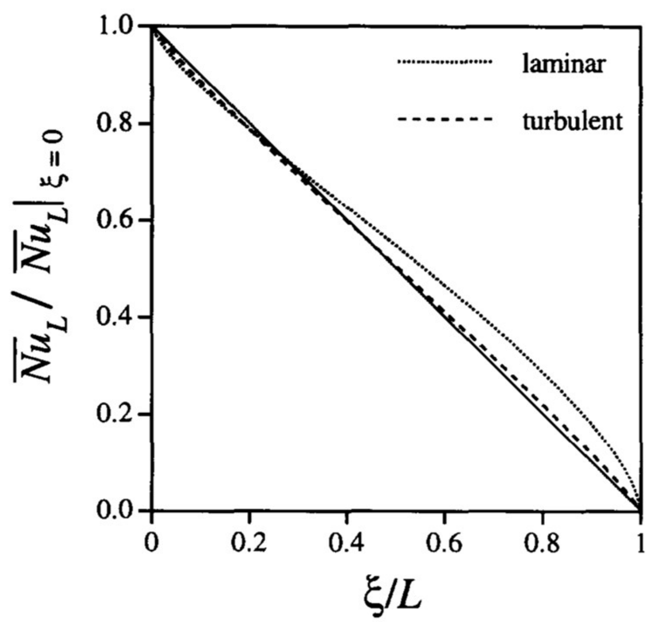
Effect of Unheated Starting Length on Average Nusselt Number



$\bar{N}u_2 = \frac{\bar{h}_2 \cdot L}{k}$

Ameel, *Int. Comm. Heat Mass Transfer* (1997)

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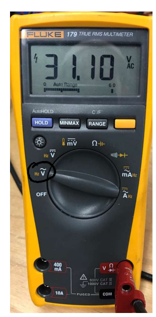
Measurements

Quantity	Symbol	Units	Instrument
Freestream dynamic pressure	P_{dyn}	mmHg	Pitot-static probe
Plate surface temperature	$T_s(x)$	°C	thermocouple
Freestream temperature	T_∞	°C	thermocouple
Heater voltage	V	VAC	multimeter
Heater resistance	Ω	Ohm	multimeter

14 + 2

$$U_\infty = \sqrt{2 P_{dyn}/\rho}$$



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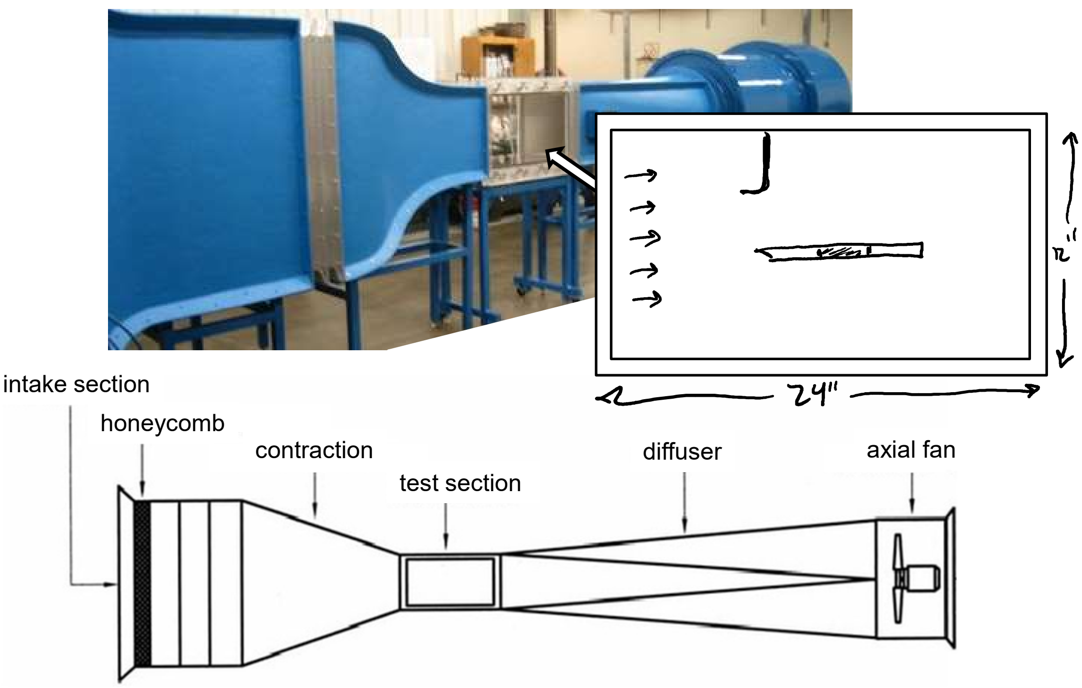
Wind Tunnel Experiment



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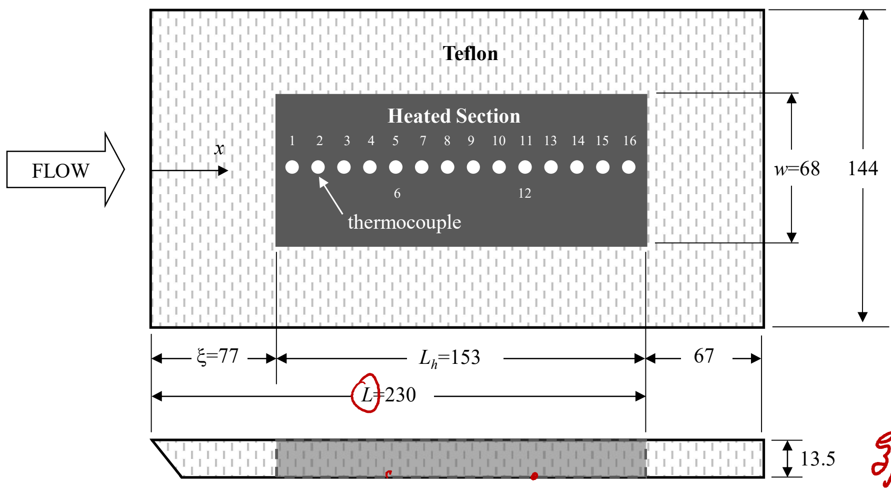
Flat Plate with Heated Section in Middle



$\xi/L \approx 33\%$

Laminar Flow: $Re_L < 5\times10^5$

$\frac{U_\infty L}{\nu} < 5\times10^5 \Rightarrow U_\infty < \frac{5\times10^5 (1.85\times10^{-5} m^2/s)}{0.23 m} \rightarrow U_\infty < 40 \frac{m}{s}$

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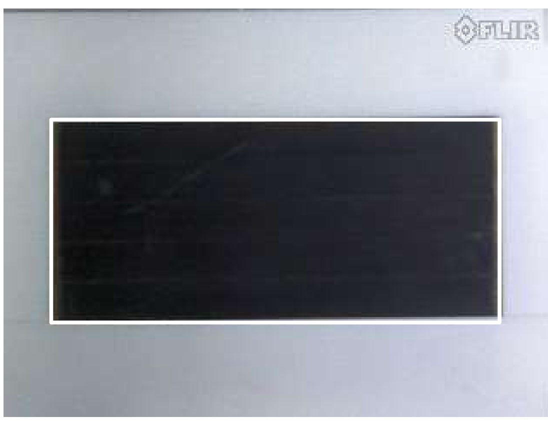
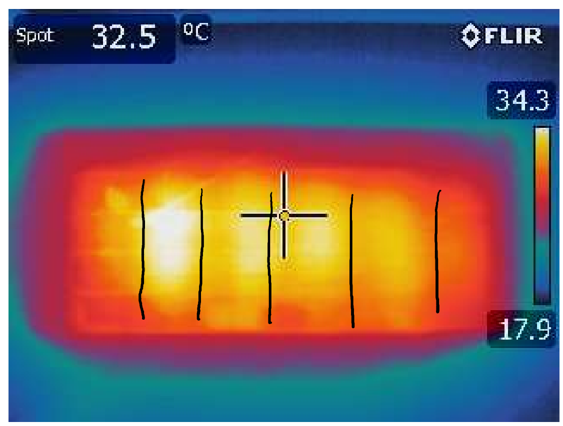
Photographs of Heated Plate





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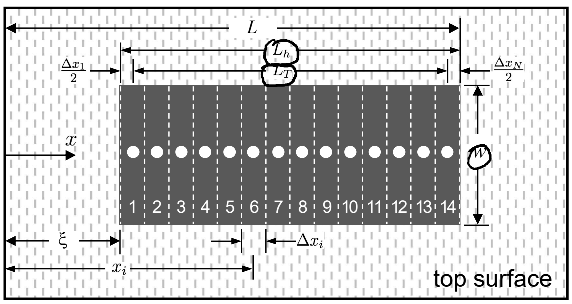
Data Analysis: Measurements



$L_T = x_{14} - x_1$

Heat flux from top surface: $q_s'' = \frac{V^2}{R_2 L_h w}$

Local heat transfer coefficient: $h_x(x_i) = q_s'' / [T_s(x_i) - T_\infty]$ for $i = 1, \ldots, 14$

Avg heat transfer coefficient: $\bar{h}_L = \frac{1}{L_T} \int_{x=x_1}^{x_{14}} h_x(x)\, dx$ Trapezoidal Rule

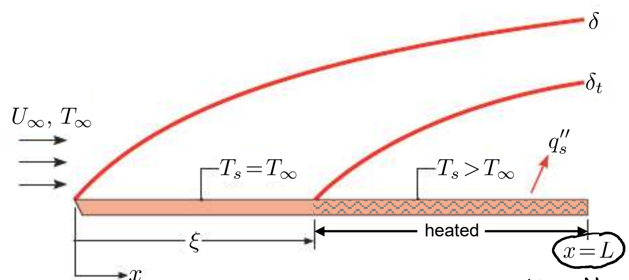
Do NOT use mean()

Local Nusselt number: $Nu_x(x) = h_x(x) \cdot x / k_x$ ← use local $T_f(x)$ "AirProperties.m"

Avg Nusselt number: $\overline{Nu}_L = \frac{\bar{h}_L \cdot L}{\bar{k}}$ ← can use mean()

Data Analysis: Theoretical Formulas

(Kays & Crawford, 1993; Ameel, 1997)



Local Nusselt number: $Nu_{x,th}(x) = \dfrac{0.453\, Re_x^{1/2} Pr^{1/3}}{\left[1-(\xi/x)^{3/4}\right]^{1/3}}$

for laminar flow

*use avg film temp. for fluid properties

Local heat transfer coefficient: $h_{x,th}(x) = \left(\bar{k}/x\right) Nu_{x,th}(x)$

for $\xi \le x \le L$

Avg heat transfer coefficient: $2\left(\dfrac{\bar{k}}{L-\xi}\right)\left(0.453\, Re_L^{1/2} Pr^{1/3}\right)\left[1-(\xi/L)^{3/4}\right]^{2/3} = \bar{h}_{L,th}$

Avg Nusselt number: $\overline{Nu}_{L,th} = \bar{h}_{L,th} \cdot L/\bar{k}$

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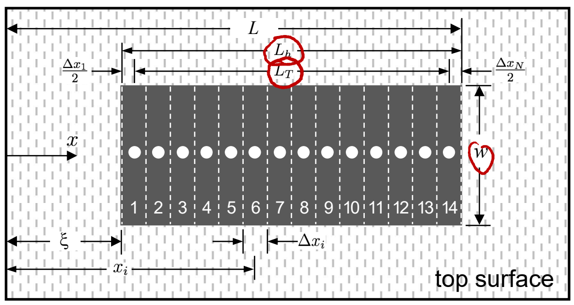
Data Analysis: Predictions from Theory



Newton's Law of Cooling

Estimate Heat Flux

(given measurements of surface temperature)

$$q''_{s,th} = h_{x,th}(x_i)\underbrace{\left[T_s(x_i) - T_\infty\right]}_{\text{measurements}}$$

$$q_{s,th} = \frac{L_h \cdot W}{L_T}\int_{x=x_1}^{x_{14}} q''_{s,th}(x)\,dx$$

use trapezoidal rule

Estimate Surface Temperature

(given measurements of heat flux)

$$T_{s,th}(x) = T_\infty + \frac{q_s''}{h_{x,th}(x)}$$

measured

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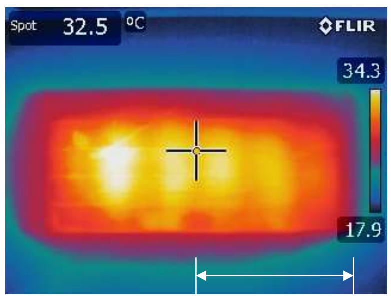
Effect of Thermal Radiation



in Kelvin!

Radiation heat flux (top surface): $q''_{rad}(x_i) = \varepsilon \sigma \left(T_s^4(x_i) - T_\infty^4\right)$

$\varepsilon = 0.7$, $\sigma = 5.6703 \times 10^{-8}\ W/m^2 \cdot K^4$

Corrected surface temperature: $T_{s,th}(x) = T_\infty + \dfrac{q_s'' - q''_{rad}}{h_{x,th}(x)}$

Radiation heat transfer rate: $\dfrac{L_h \cdot w}{L_T} \displaystyle\int_{x=x_1}^{x_{14}} q''_{rad}(x)\, dx$

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Questions??

Thank you for your attention!

Let me or the TAs know if you have questions

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