# Shell & Tube Heat Exchanger

Thermal Fluids and Energy
Systems Lab

(ME EN 4650)

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*University of Utah*

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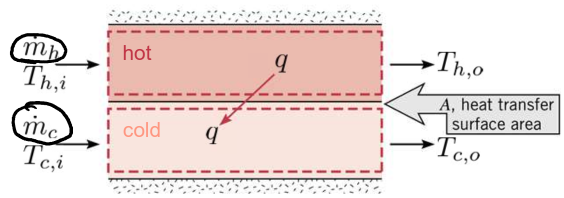
# Heat Exchanger Performance

What we want to know:




→ performance vs flow rates
- heat transfer rate, $q$
- effectiveness, $\varepsilon$
- overall heat transfer coefficient, $U$

→ predict outlet temperatures, $T_{h,o}$ & $T_{c,o}$

What we can measure:

→ flow rates (rotameter)
→ temperatures @ inlets & outlets (thermocouples)
→ temperature of casing
→ " of ambient air

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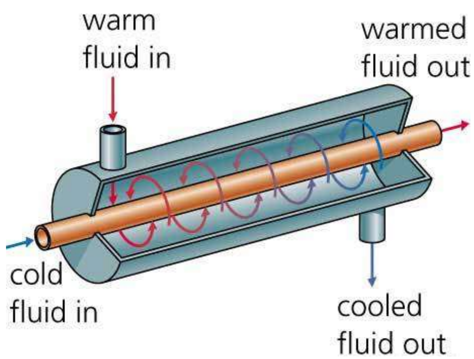
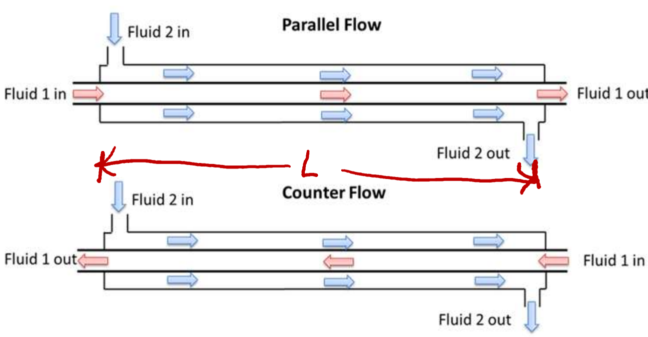
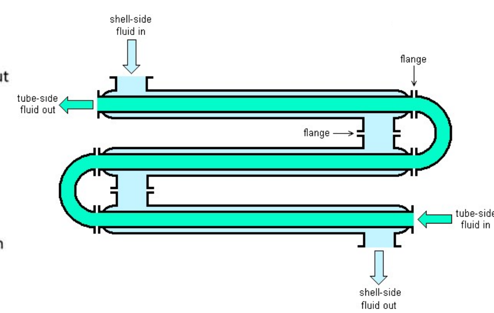
# Double Pipe Heat Exchanger







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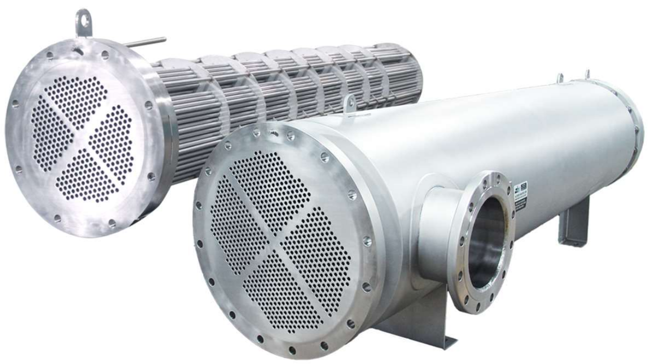
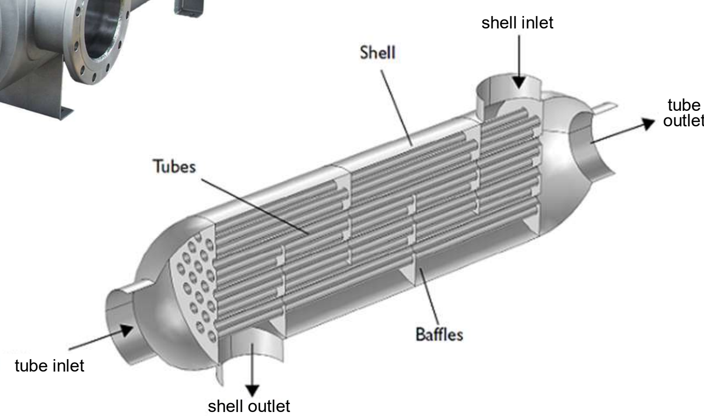
# Shell & Tube Heat Exchanger



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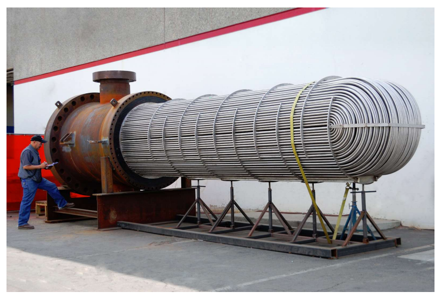
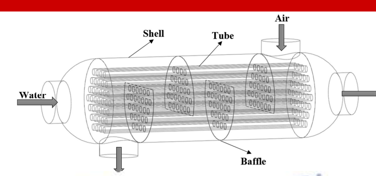
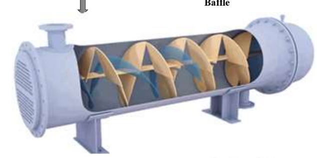
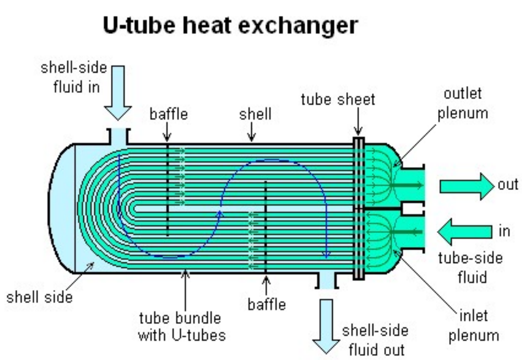
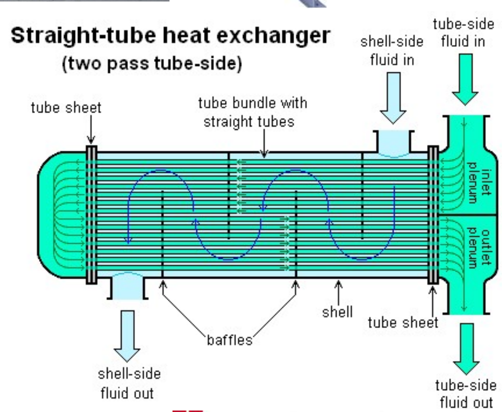
# Shell & Tube Heat Exchanger: One Shell Pass – Two Tube Passes







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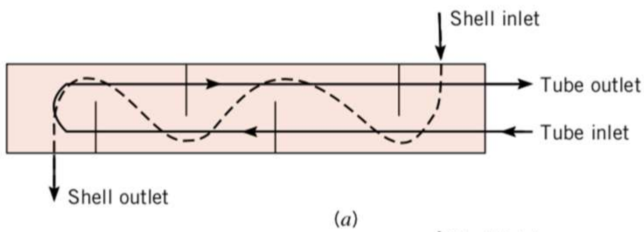
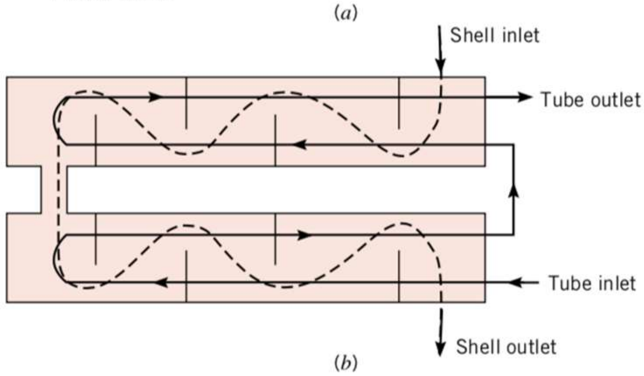
# Multiple Passes




One shell pass, two tube passes




Two shell passes, four tube passes

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# Other Types of Heat Exchangers

Fin and tube heat exchanger

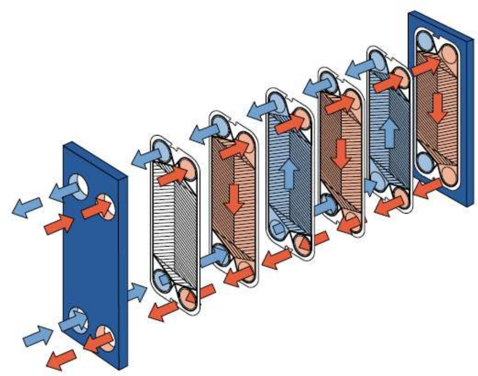

Plate heat exchangers

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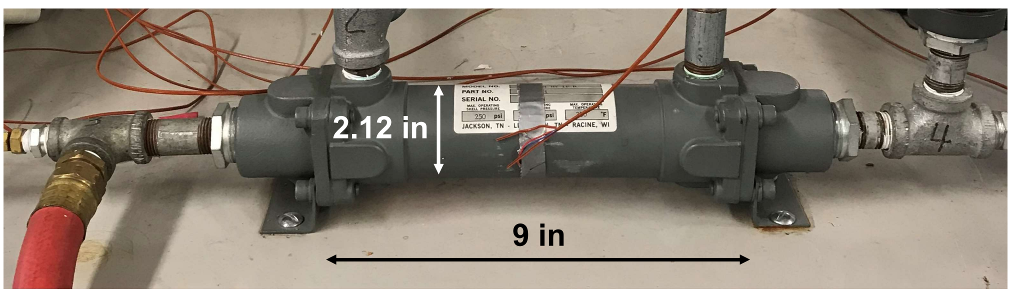
# Experimental Apparatus

Crossflow, One Shell-Pass, One Tube-Pass




| | |
|---|---|
| Shell Outside Diameter (in) | 2.12 |
| Shell (and Tube) Length (in) $= L$ | 9.00 |
| Baffle Spacing (in) | 1.13 |
| Tube Outside Diameter (in) $= D_o$ | 0.250 |
| Tube Wall Thickness (in) $= t$ | 0.028 |
| Number of Tubes $= N$ | 31 |
| Number of Tube Passes | 1 |
| Tube Material | copper |
| Shell Material | brass |

heat transfer surface area
(based on tube inside diameter)

$A_i = N \pi D_i L$

$D_i = D_o - 2t = 0.194''$

$A_i = 170.04\ in^2\ (0.1097 m^2)$

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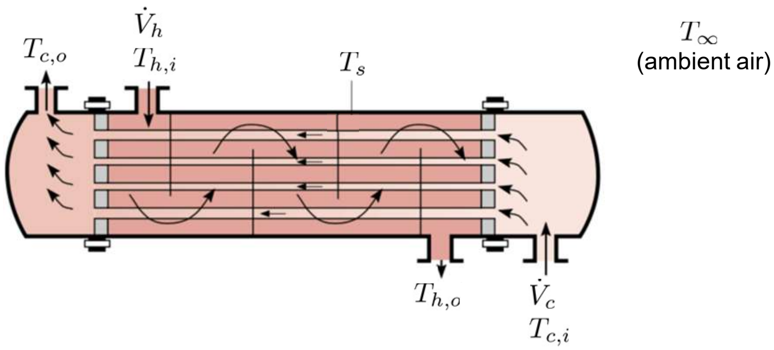
# Measurements




| Quantity | Symbol | Units | Instrument |
|---|---|---|---|
| Temperature of hot-side | $T_{h,i}$, $T_{h,o}$ | °F | thermocouple |
| Temperature of cold-side | $T_{c,i}$, $T_{c,o}$ | °F | thermocouple |
| Temperature of shell casing | $T_s$ | °F | thermocouple |
| Temperature of ambient air | $T_\infty$ | °F | thermocouple |
| Volume flow rate | $\dot{V}_c$, $\dot{V}_h$ | gpm | rotameter |

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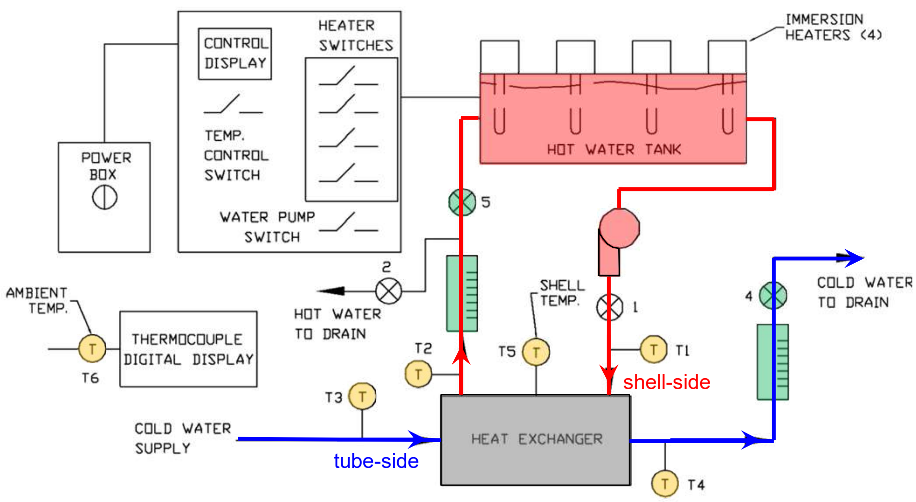
# Experimental Apparatus

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# Figures and Tables

**Table 1a**

| Case | Flow Rate (kg/s) | | Temperature (°C) | | $U_i$ | Heat Transfer Rate (kW) | | |
|---|---|---|---|---|---|---|---|---|
| | $\dot{m}_c$ | $\dot{m}_h$ | $\Delta T_h$ | $\Delta T_c$ | (W/K m$^2$) | $q_c$ | $q_h$ | $\Delta q$ (%) |
| 1a | (fast) | (fast) | | | | | | |
| 1b | (fast) | (slow) | | | | | | |
| 2a | (slow) | (f | | | | | | |
| 2b | (slow) | (s | | | | | | |

$\Delta T_h = T$ $\Delta T_c = T_{c,o} - T_{c,i}$ nsfer coefficient

Avg temp: $T_{avg} = \frac{T_i + T_o}{2}$

Density: $\rho_w = f(T_{avg})$ "WaterProperties.m"

mass flow rate: $\dot{m} = \rho_w \dot{V}$ CHECK UNITS!

**Table 1b**

| Case | Flow Rate (kg/s) | | $C_r$ | $NTU$ | ε | | |
|---|---|---|---|---|---|---|---|
| | $\dot{m}_c$ | $\dot{m}_h$ | | | measured | theory | Δε (%) |
| 1a | (fast) | (fast) | | | | | |
| 1b | (fast) | (slow) | | | | | |
| 2a | (slow) | | | | | | |
| 2b | (slow) | (slow) | | | | | |

heat capacity ratio ransfer units effectiveness

heat capacity: $C_c = \dot{m}_c c_{p_c}$ & $C_h = \dot{m}_h c_{p_h}$ @ $T_{avg}$

heat capacity ratio: $C_r = \frac{C_{min}}{C_{max}}$ where $C_{min} = \min(C_c, C_h)$ & $C_{max} = \max(C_c, C_h)$

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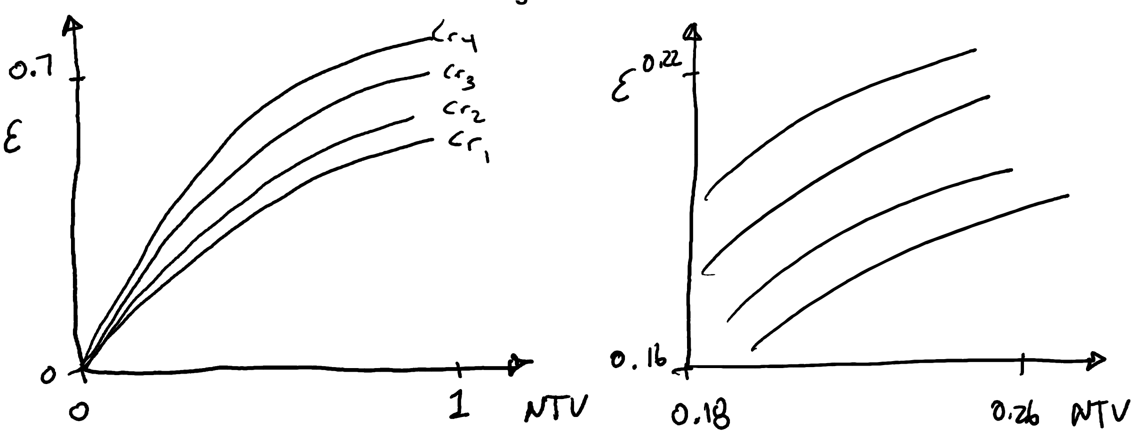
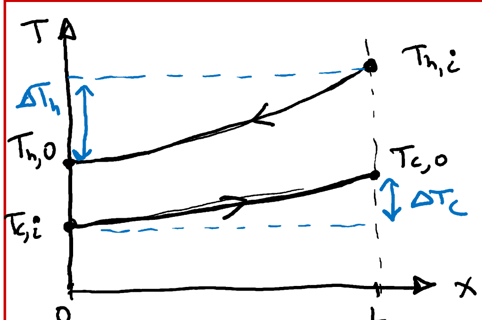
# Figures and Tables (cont)

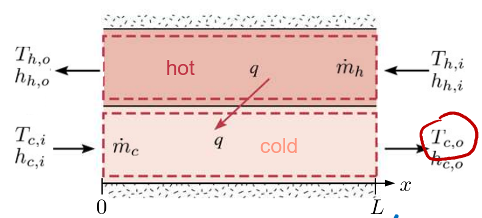
**Figure 1c**




$0 \le \varepsilon \le 1$

# Temperature Profiles



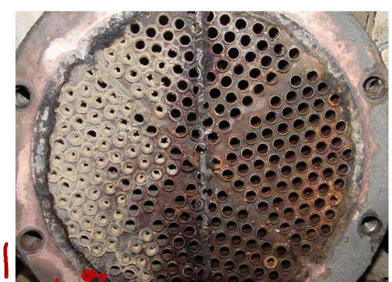

USE $q_h$ in theoretical calculations

Steady Energy Equation (no changes in KE or PE, no work, no losses to surroundings)

$$q_h = \dot{m}_h \Delta h_h = \dot{m}_h c_{p_h} \Delta T_h$$

$$q_h = \dot{m}_h c_{p_h} (T_{h,o} - T_{h,i}) \quad [W]$$

$$q_c = \dot{m}_c c_{p_c} (T_{c,o} - T_{c,i})$$



MUST : $q_c = q_h \Rightarrow \Delta q = \dfrac{|q_h - q_c|}{\frac{1}{2}(q_h + q_c)} \times 100\%$

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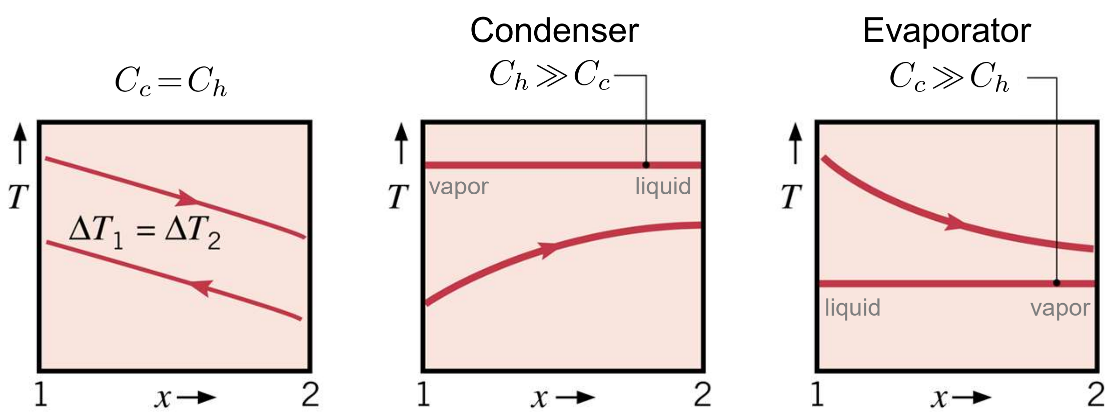
# Temperature Profiles:
## Special Heat Exchangers




$C_h \rightarrow \infty$     $C_c \rightarrow \infty$

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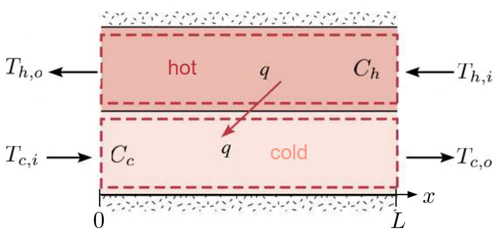
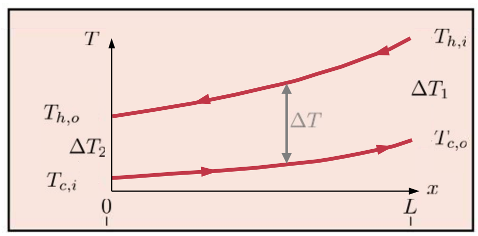
# Log Mean Temperature Difference (LMTD)




Modified Newton's Law of Cooling

$$q = U_i A_i F \Delta T_{LM}$$

$$\Delta T_{LM} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)}$$

$\Delta T_1 = T_{h,i} - T_{c,o}$ & $\Delta T_2 = T_{h,o} - T_{c,i}$

$U_i \equiv$ overall heat transfer coefficient

$A_i \equiv$ total inside tube surface area

$$A_i = N \pi D_i L$$

$F \equiv$ correction factor (= 1 for counter-flow, single tube, single pass)

Overall heat transfer coefficient

$$U_i = \frac{q}{A_i F \Delta T_{LM}}$$

use $q_h$ from calculation

use measurements

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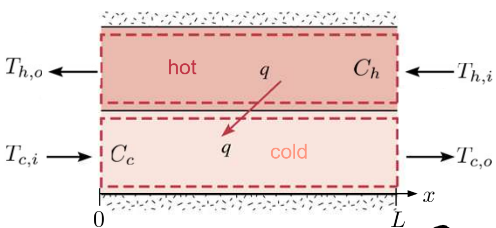
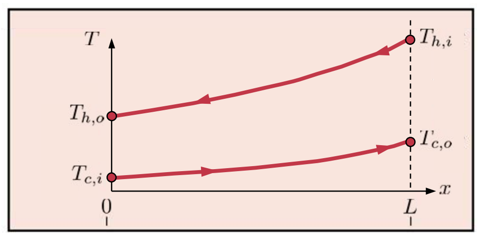
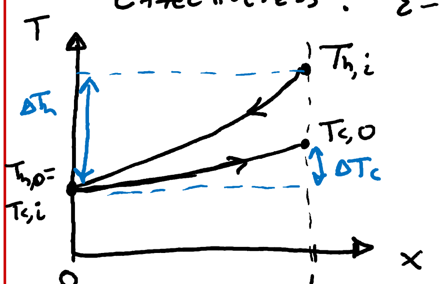
# Effectiveness



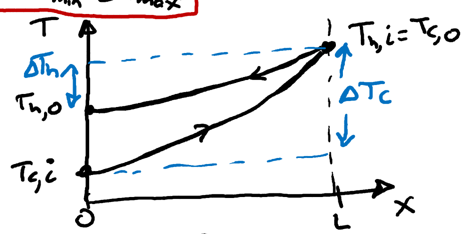




effectiveness : $\varepsilon = \dfrac{q}{\boxed{q_{max}} = \dfrac{q}{C_{min}\,\Delta T_{max}}}$ $0 \leq \varepsilon \leq 1$




$q_c = C_c \Delta T_c$
$q_h = C_h \Delta T_h$

$C_c \underbrace{\Delta T_c}_{< \Delta T_h} = \underbrace{C_h}_{C_{min}} \underbrace{\Delta T_h}_{= \Delta T_{max}}$




$q_c = C_c \Delta T_c$
$q_h = C_h \Delta T_h$

$\underbrace{C_c}_{C_{min}} \underbrace{\Delta T_c}_{\Delta T_{max}} = C_h \underbrace{\Delta T_h}_{< \Delta T_c}$

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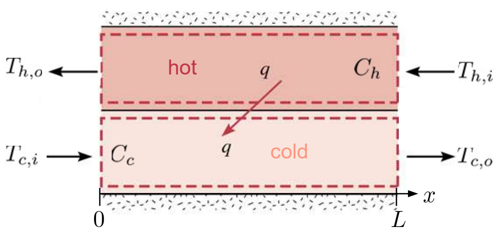
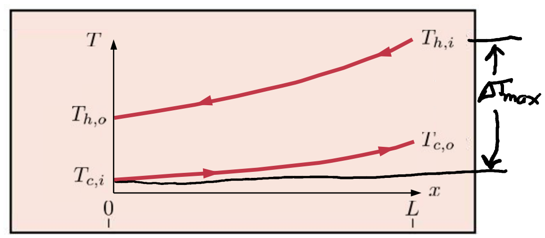
# Effectiveness – NTU Method




effectiveness: $\varepsilon = \dfrac{q}{(C_{min}\,\Delta T_{max})}$ , $\Delta T_{max} = T_{h,i} - T_{c,i}$

Theory: $\varepsilon = f(NTU, C_r)$ where $C_r = \dfrac{C_{min}}{C_{max}}$ $(C_r \leq 1)$

Number of transfer units: $NTU = \dfrac{U_i A_i}{C_{min}}$

use calculation from measurements

Theoretical effectiveness (counterflow, single tube-pass, single shell-pass)

$$\varepsilon = \begin{cases} \dfrac{1-\exp[-NTU(1-C_r)]}{1-C_r\exp[-NTU(1-C_r)]}, & C_r < 1 \\ NTU/(1+NTU), & C_r = 1 \end{cases}$$

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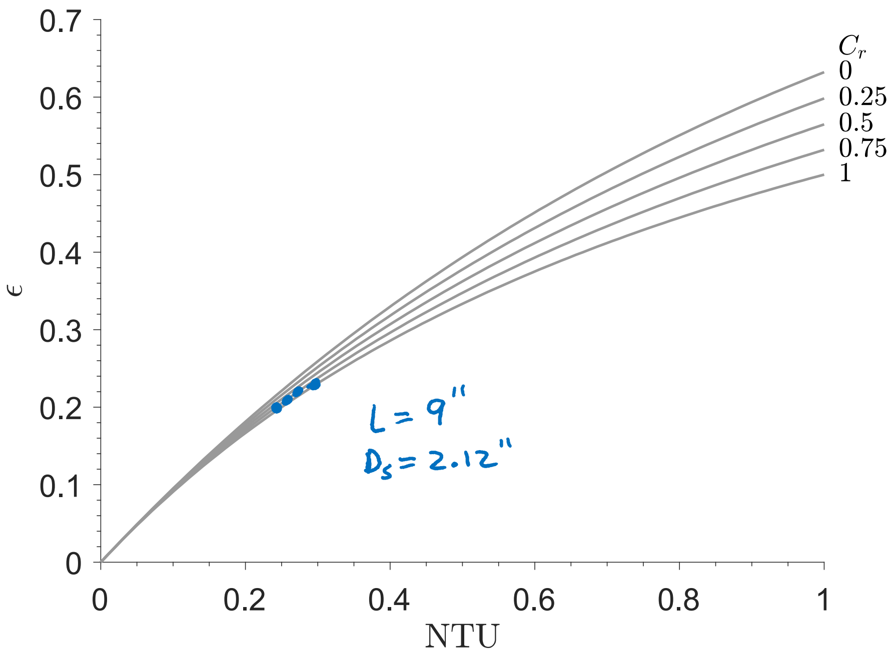
# Theoretical Effectiveness vs NTU
## (single tube-pass, single shell-pass, counterflow)

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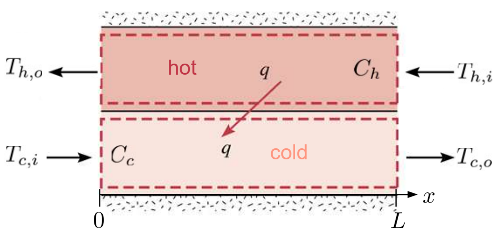
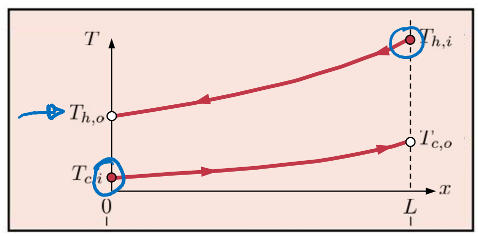
# Heat Exchanger Design:
## Predicting Hot-Side Outlet Temperature




$q_h = C_h(T_{h,i} - T_{h,o})$ and $q = \varepsilon C_{min}(T_{h,i} - T_{c,i})$

Set equal: $\frac{C_h(T_{h,i} - T_{h,o})}{C_h} = \frac{\varepsilon C_{min}(T_{h,i} - T_{c,i})}{C_h}$

Solve for $T_{h,o}$: $T_{h,o} = -\varepsilon \frac{C_{min}}{C_h}(T_{h,i} - T_{c,i}) + T_{h,i}$

or

$T_{h,o} = T_{h,i}\left(1 - \varepsilon \frac{C_{min}}{C_h}\right) + T_{c,i}\left(\varepsilon \frac{C_{min}}{C_h}\right)$

theory

measured

$C_c, C_h$: specified flow rates & inlet temperatures

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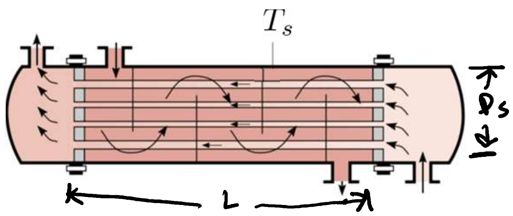
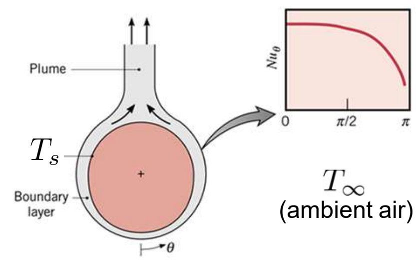
# Heat Lost to Surroundings:
## Natural Convection from Shell Casing




Newton's Law of Cooling

$$q_{conv} = \bar{h}\,(T_s - T_\infty)\,\pi D_s L$$

$$\bar{h} = \frac{k}{D_s}\overline{Nu}_D, \quad k \equiv \text{thermal conductivity of air @ } T_{film} = (T_s + T_\infty)/2$$

Empirical Nusselt Number Relationship

$$\overline{Nu}_D = f(Ra_D, Pr), \quad Ra_D = \frac{g\beta (T_s - T_\infty) D_s^3}{\nu\alpha}, \quad Pr = \frac{\nu}{\alpha}, \quad \alpha = \frac{k}{\rho c_p}$$

For ideal gases, $\beta = \frac{1}{T_{film}}$

$$\overline{Nu}_D = \left[0.6 + \frac{0.387\, Ra_D^{1/6}}{\left[1 + \left(0.559/Pr\right)^{9/16}\right]^{8/27}}\right]^2, \text{ for } Ra_D < 10^{12}$$

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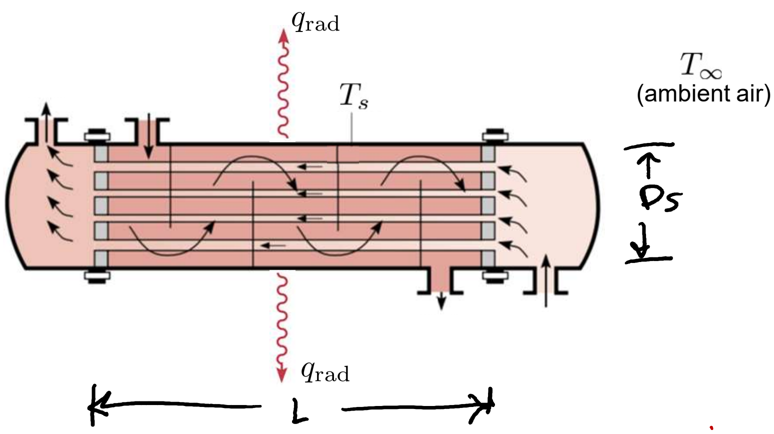
# Heat Lost to Surroundings:
## Thermal Radiation




are in Kelvin!

$$q_{rad} = \varepsilon \sigma (T_s^4 - T_\infty^4) \underbrace{\pi D_s L}_{\text{heat transfer surface area}}$$

~0.95 (guess)

$5.6703 \times 10^{-8}$ $W/m^2K^4$

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# Questions??

**Thank you for your attention!**

Let me or the TAs know if you have questions

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