Shell & Tube Heat Exchanger

Thermal Fluids and Energy Systems Lab

(ME EN 4650)

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Based on Prof. M's slides

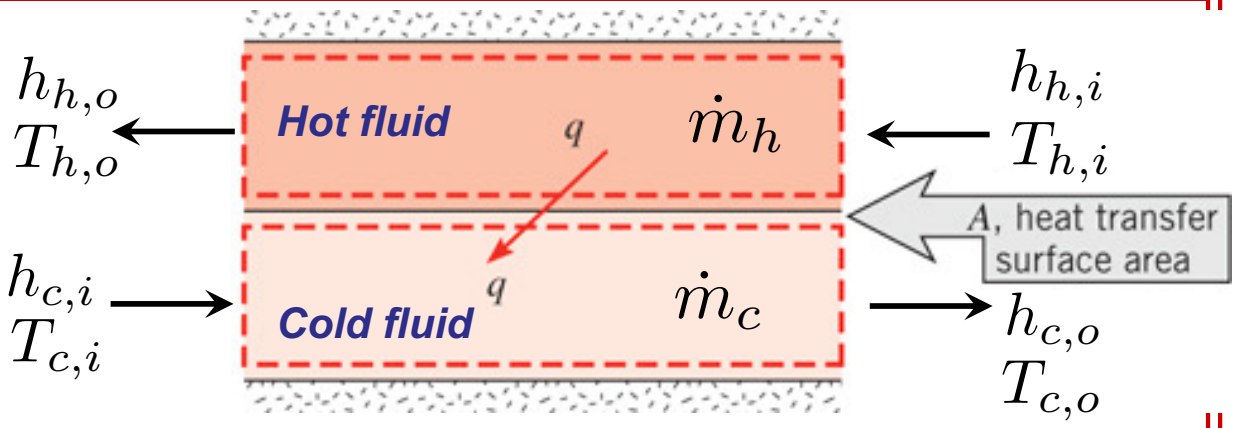
Objectives

1. Examine the performance of a shell and tube heat exchanger for a range of ow rates
2. Compare effectiveness values obtained from the experimental measurements to those predicted by the Effectiveness-NTU theory
3. Estimate the heat lost from the shell casing to the surroundings via convection and radiation.

Heat Exchanger Performance

What we want to know:

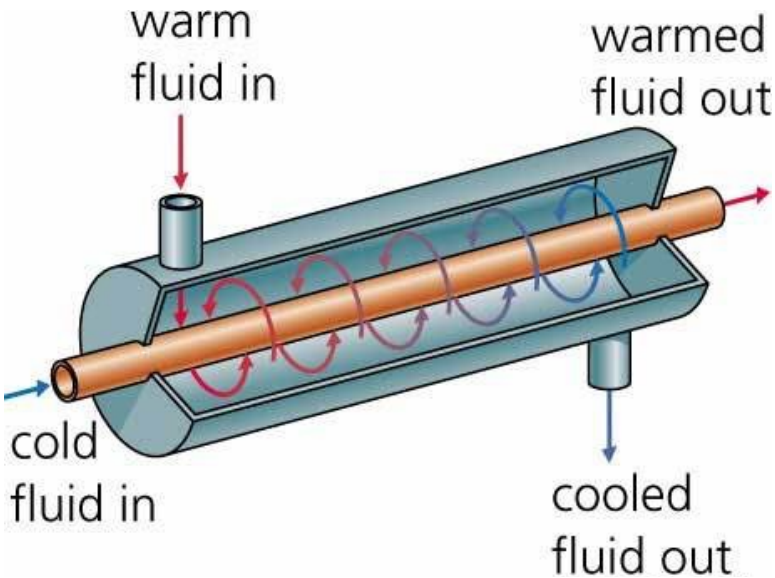
- Performance vs. flow rates
  - Heat transfer rate, q
  - Effectiveness, ε
  - Overall heat transfer coefficient, U



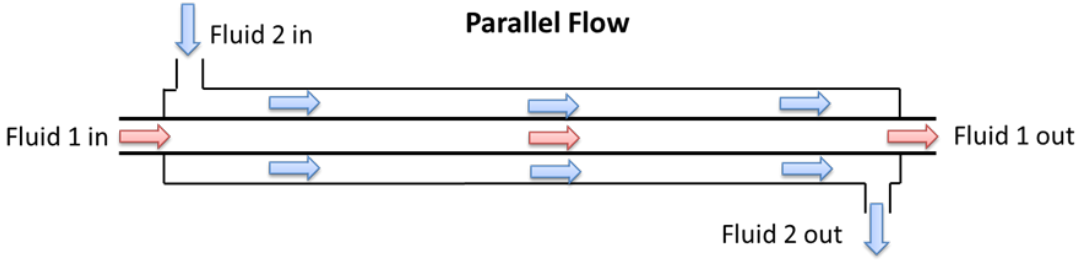
What we can measure:

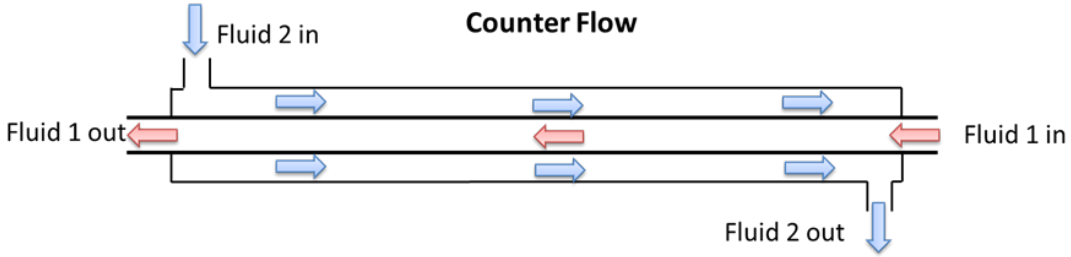
- Flow rates (rotameter)
- Temperatures at the inlets and outlets (thermocouples)
- Temperature of the casing of the heat exchanger
- Temperature of the ambient air

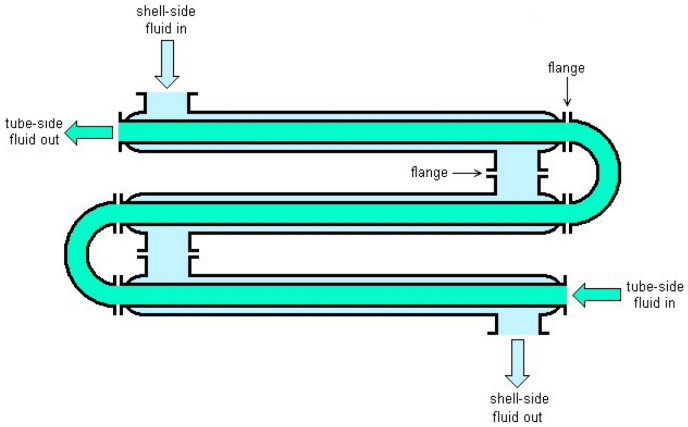
Double Pipe Heat Exchanger



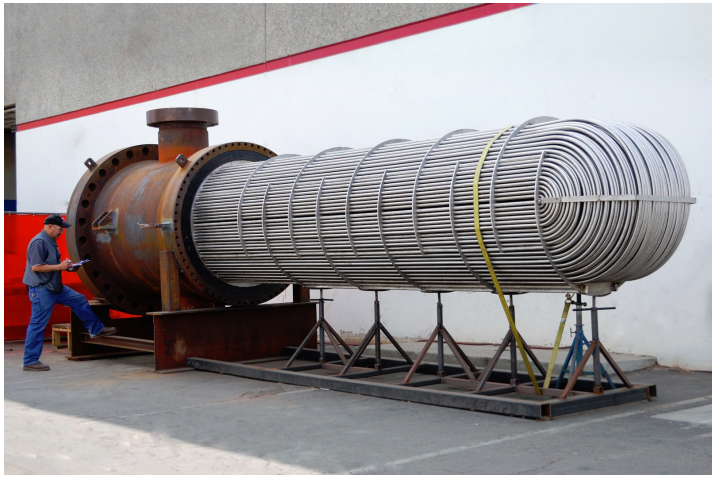
cascade of double pipe heat exchangers

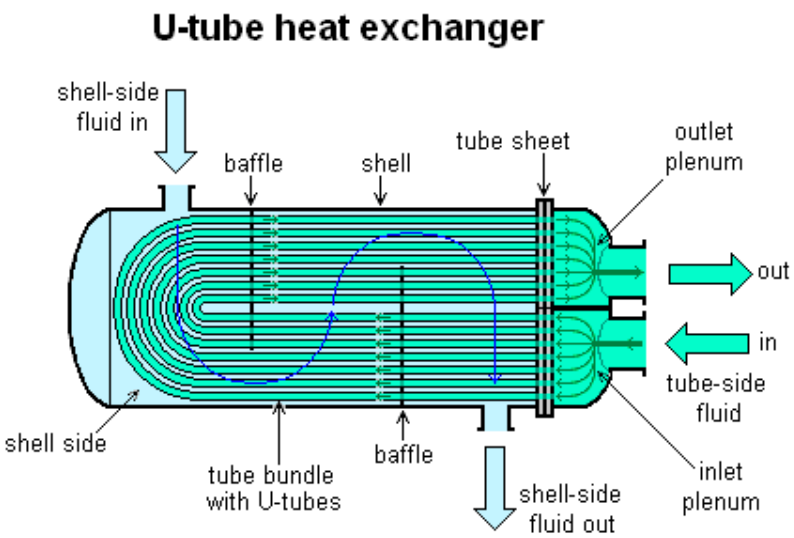


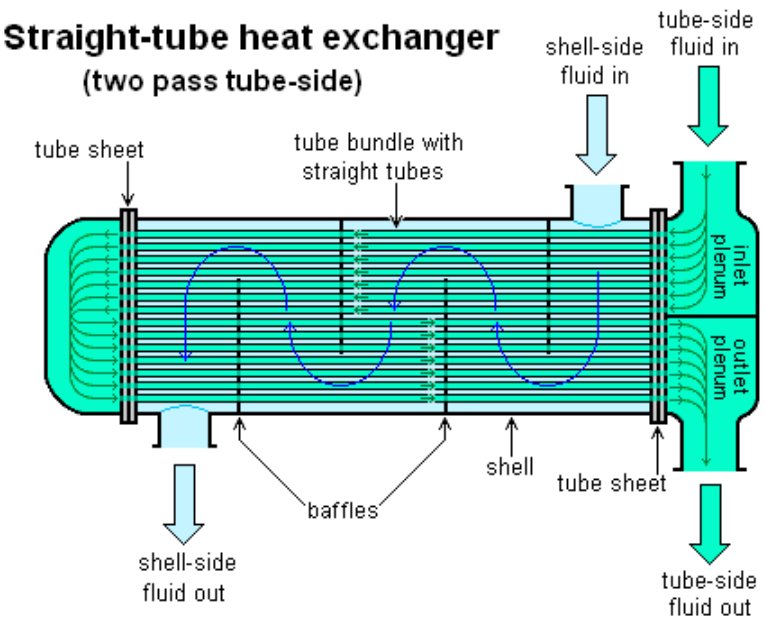




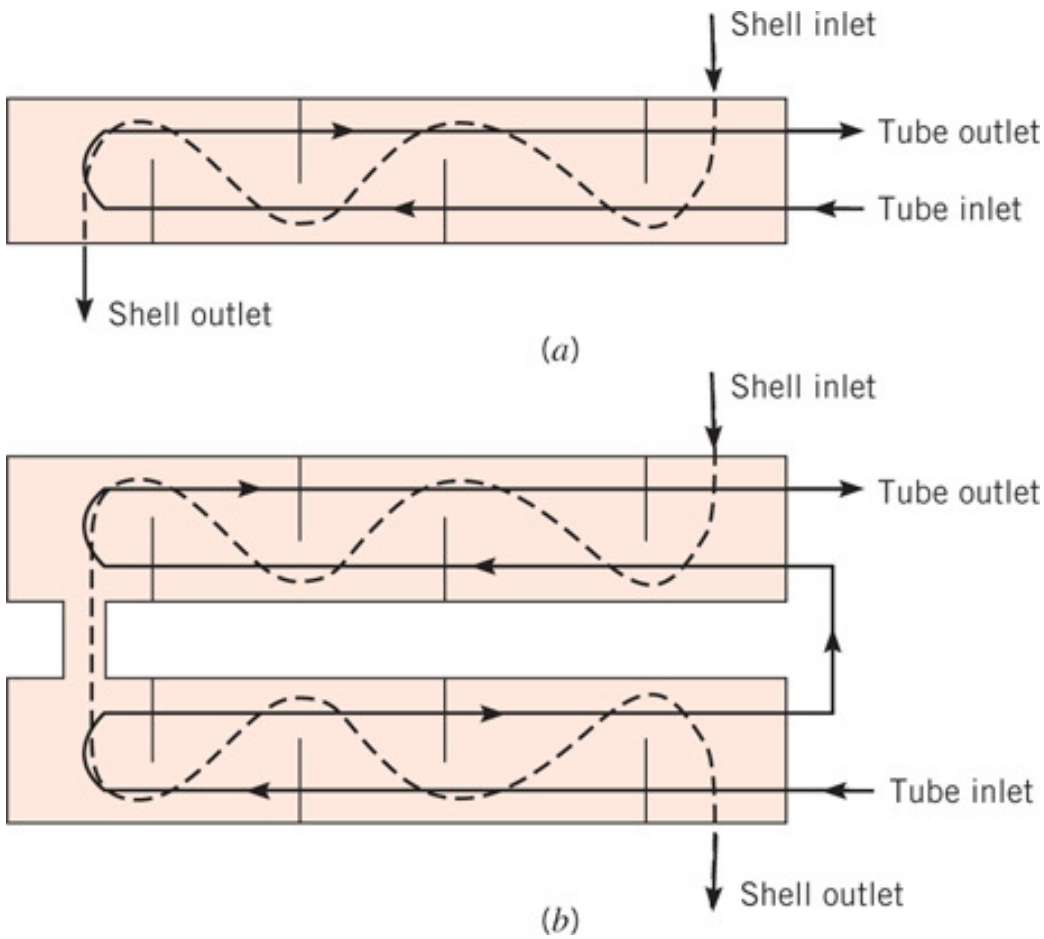
Shell & Tube Heat Exchanger







Multiple Passes – Shell & Tube



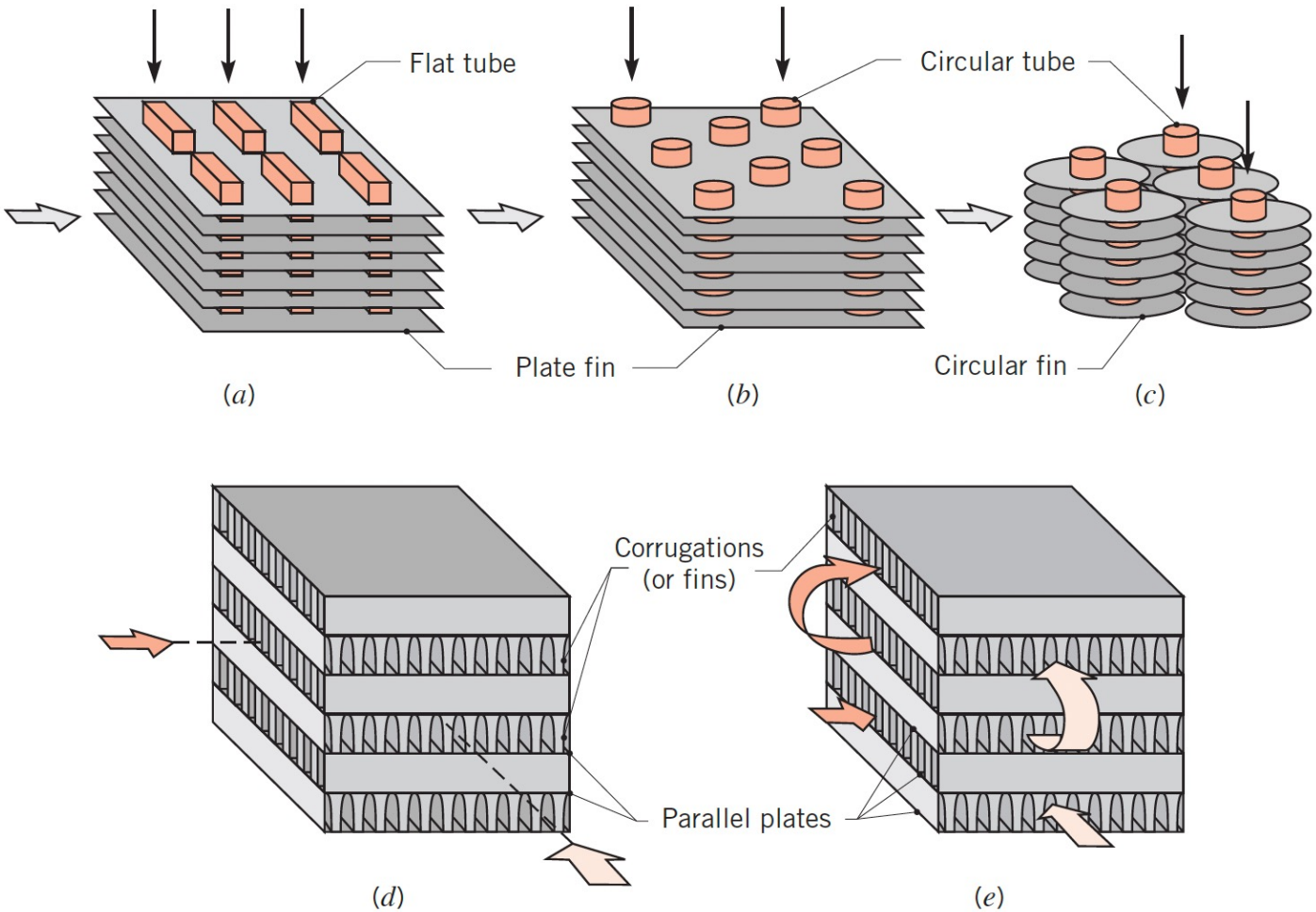
One shell pass and two tube passes

Two shell passes and four tube passes

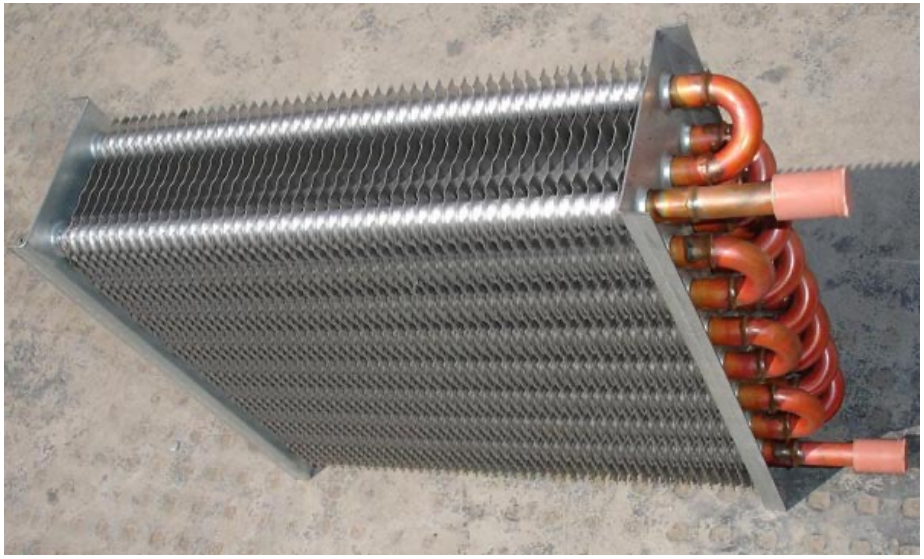
Compact Heat Exchangers

Compact heat exchanger: Large heat transfer surface area per unit volume

- *Highly efficient*
- *Flows can be separated*
- *Often laminar flow*
- *pressure drops are significantly less than for a conventional concentric tube*



Other Types of Heat Exchangers



Fin and tube heat exchanger

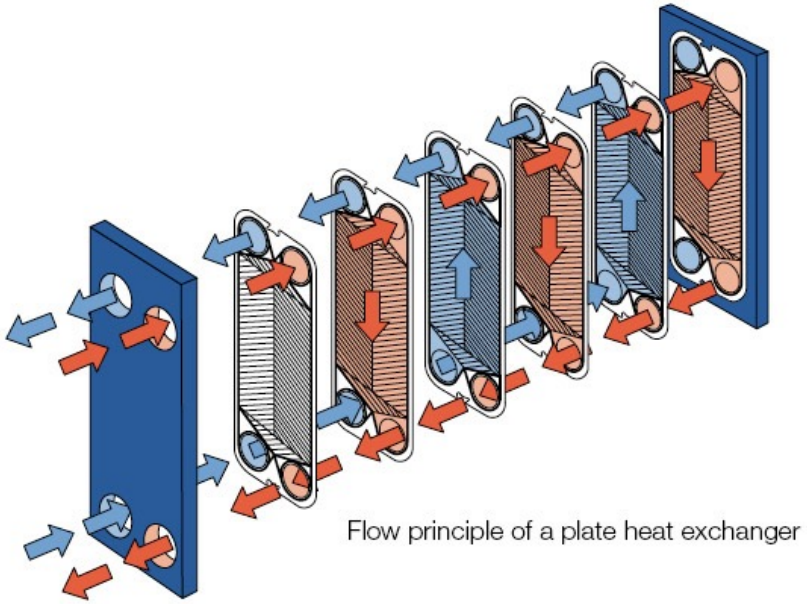
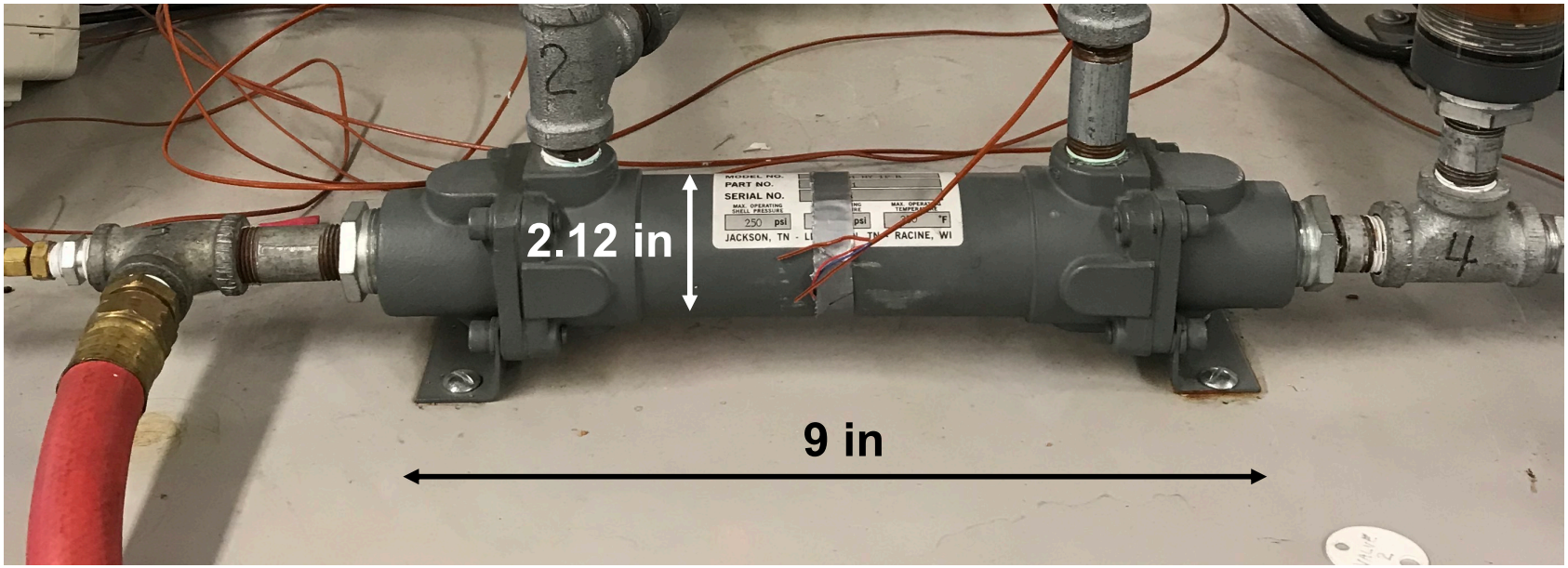


Plate & Frame heat exchangers

Experimental Apparatus



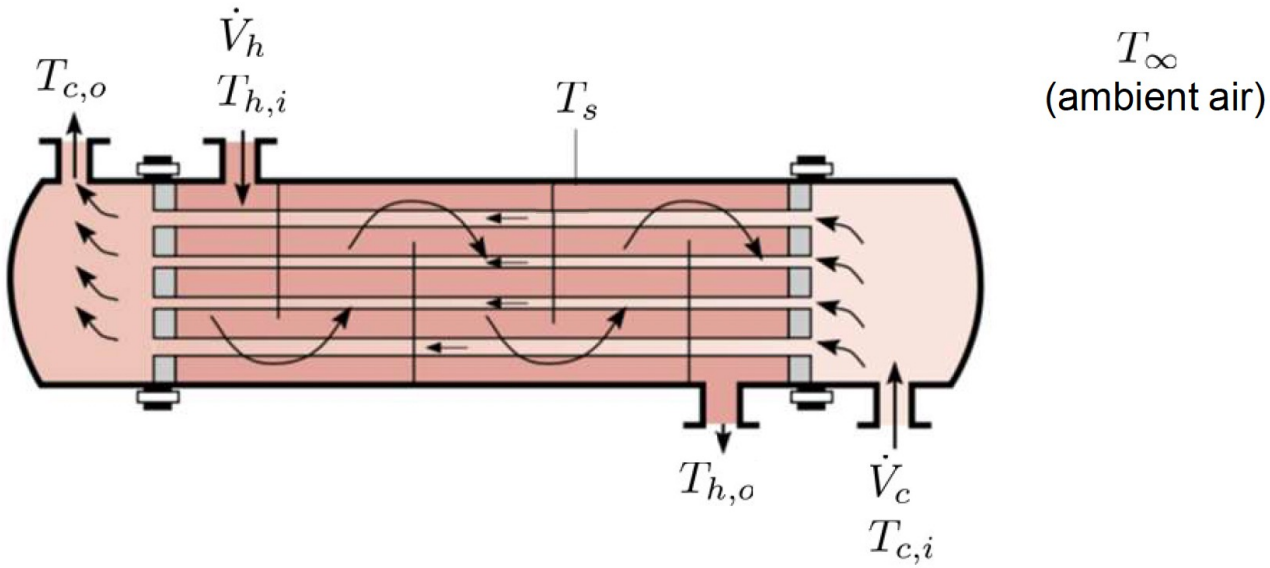
Shell Outside Diameter (in)	2.12	D_s
Shell (and Tube) Length (in)	9.00	L
Baffle Spacing (in)	1.13	
Tube Outside Diameter (in)	0.250	D_o
Tube Wall Thickness (in)	0.028	t
Number of Tubes	31	N
Number of Tube Passes	1	
Tube Material	copper	
Shell Material	brass	

Heat transfer surface area
(based on tube inside diameter)

$$A_i = N\pi D_i L$$

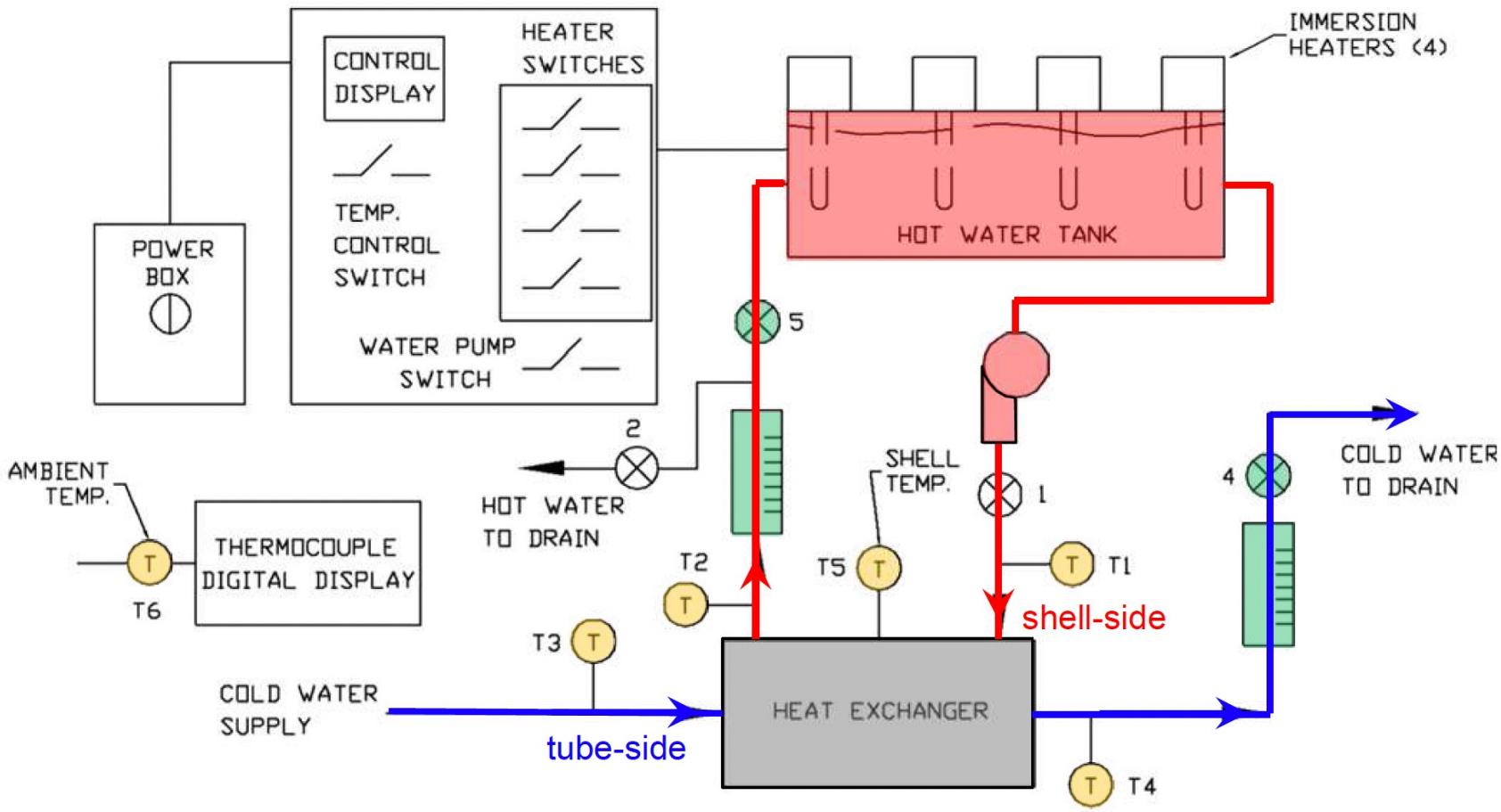
$$D_i = D_o - 2t$$

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_∞	°F	thermocouple
Volume flow rate	$\dot{V}_c$, $\dot{V}_h$	gpm	rotameter

Experimental Apparatus



Figures and Tables

TFES Lab (ME EN 4650)

Heat Exchanger Experiment: Raw Data Sheet

P_{atm} : 661 (mm Hg)

Case	Volume Flow Rate (gpm)		Temperatures (°F)					
	cold-side	hot-side	hot-side inlet (T_1)	hot-side outlet (T_2)	cold-side inlet (T_3)	cold-side outlet (T_4)	shell casing (T_5)	ambient air (T_6)
1a	3.8	4.6	114.2	104.9	51.8	64.0	95.6	70.4
1b	3.7	3.0	115.7	103.1	51.5	63.7	96.8	70.5
2a	3.2	5.2	113.9	106.7	51.5	64.4	97.2	70.4
2b	3.4	3.0	116.3	103.9	51.2	63.8	97.1	70.2

4 different hot-side flow rates

Figures and Tables

Table 1a

Case	Flow Rate (kg/s)		Temperature (°C)		U_i (W/K m^2)	Heat Transfer Rate (kW)		
	$\dot{m}_c$	$\dot{m}_h$	ΔT_h	ΔT_c		q_c	q_h	Δq (%)
1a	(fast)	(fast)						
1b	(fast)	(slow)						
2a	(slow)	(fast)						
2b	(slow)	(slow)						

Table 1b

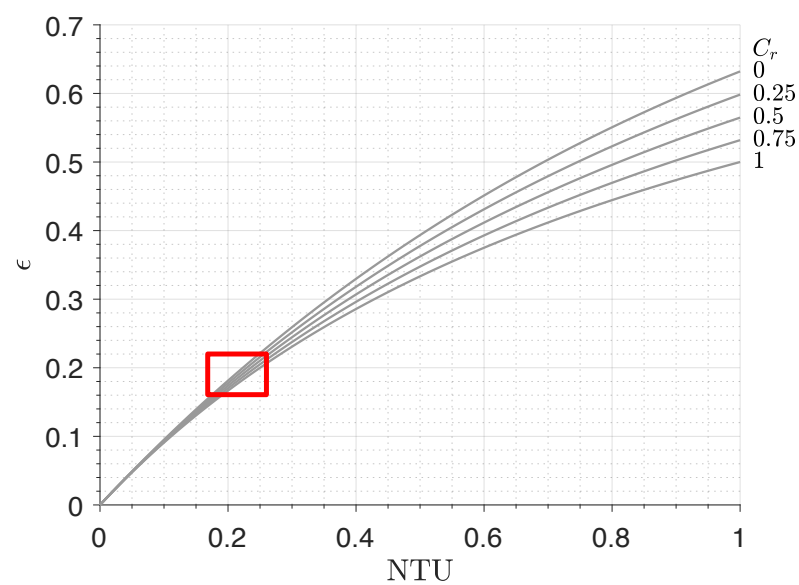
Case	Flow Rate (kg/s)		C_r	NTU	ε		
	$\dot{m}_c$	$\dot{m}_h$			measured	theory	$\Delta\varepsilon$ (%)
1a	(fast)	(fast)					
1b	(fast)	(slow)					
2a	(slow)	(fast)					
2b	(slow)	(slow)					

Table templates are posted on CANVAS

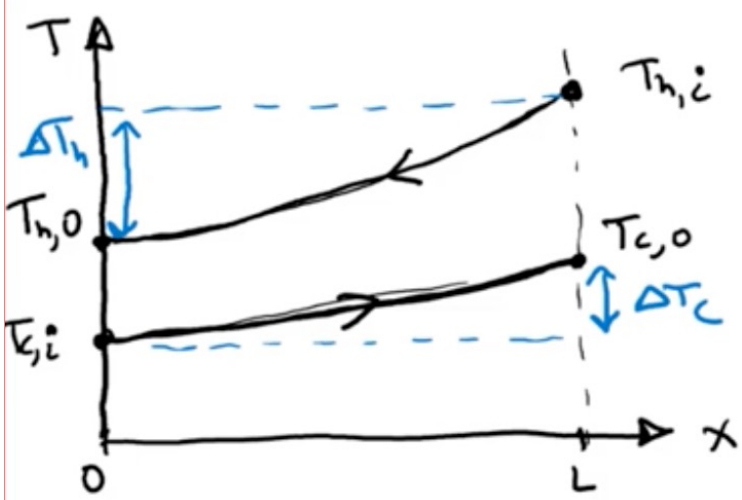
Figures and Tables

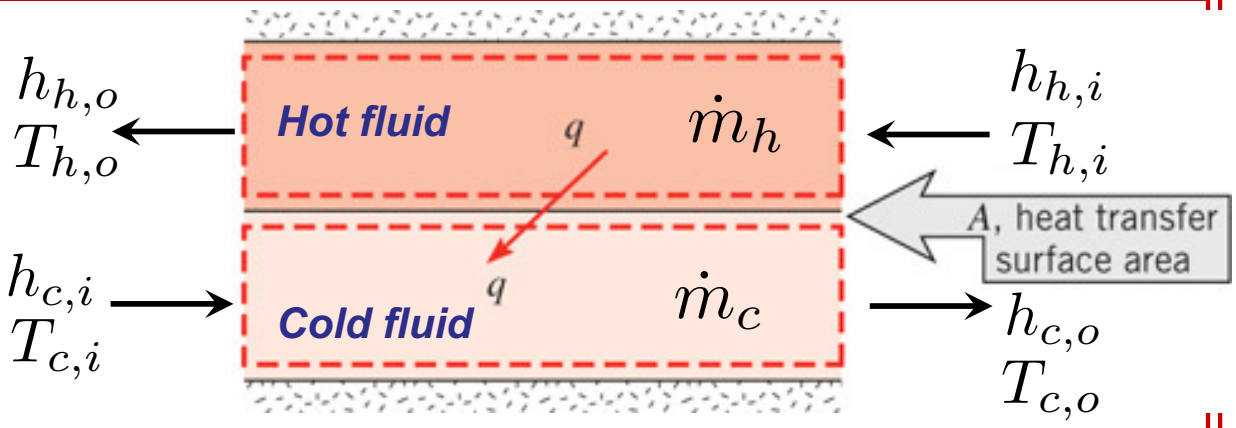
Two subplots

- Effectiveness (0 to 0.7) vs NTU (0 to 1)
- Zoom in of the same plot with effectiveness (0.16 to 0.22) vs NTU (0.18 to 0.26) to see agreement/disagreement better between data better



Heat Transfer Rates





Energy balance for the hot and cold fluids: $\dot{E}_{in} = \dot{E}_{out}$

- Negligible heat transfer between exchanger and surroundings
- No phase change and constant specific heats, incompressible liquid or ideal gas

Hot fluid: $q_h = \dot{m}_h c_{p,h}(T_{h,i} - T_{h,o}) = C_h(T_{h,i} - T_{h,o})$

Cold fluid: $q_c = \dot{m}_c c_{p,c}(T_{c,o} - T_{c,i}) = C_c(T_{c,o} - T_{c,i})$

C_c and C_h are the <u>heat capacity rates</u> for the cold and hot fluids [W/K]

$q_c = q_h$

$$\Delta q = \frac{|q_h - q_c|}{\frac{1}{2}(q_h + q_c)} \cdot 100\%$$

Use q_h in analysis!

Uncertainty in Heat Transfer Rates

Uncertainty propagation (start from Taylor-Series expansion)

$$\frac{\sigma_{q_c}}{q_c} = \left[\left(\frac{\sigma_{\dot{V}_c}}{\dot{V}_c} \right)^2 + \left(\frac{\sigma_{\Delta T_c}}{\Delta T_c} \right)^2 \right]^{1/2} \cdot 100\% \,;$$

$$\frac{\sigma_{q_h}}{q_h} = \left[\left(\frac{\sigma_{\dot{V}_h}}{\dot{V}_h} \right)^2 + \left(\frac{\sigma_{\Delta T_h}}{\Delta T_h} \right)^2 \right]^{1/2} \cdot 100\%$$

$$\Delta T_c = T_{c,o} - T_{c,i}$$

$$\Delta T_h = T_{h,i} - T_{h,o}$$

From your data

For T-type thermocouples:

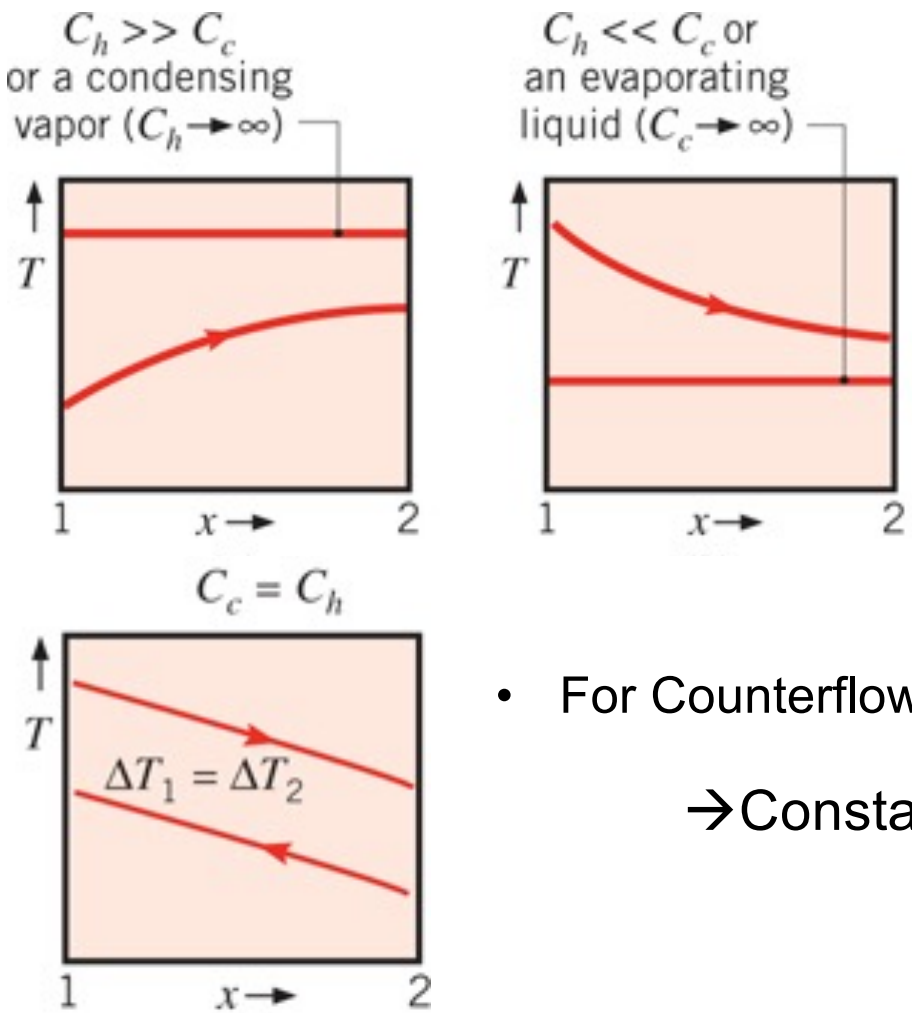
$$\sigma_{\Delta T} = \pm 0.1°\mathrm{C}.$$

For the rotameters:

$$\sigma_{\dot{V}} = \pm 0.2 \text{ gpm}$$

See Lecture Friday on Uncertainty Propagation

Special Cases



Energy Balance for two-streams

$$C_h(T_{h,i} - T_{h,o}) = C_c(T_{c,o} - T_{c,i})$$

- For Counterflow heat exchangers with: $C_c = C_h$

  →Constant ΔT throughout the heat exchanger

Log Mean Temperature Difference

Modified Newton's Law of Cooling

$$q = U_i\, A_i\, F\, \Delta T_{\mathrm{lm}}$$

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

$$\Delta T_1 = T_{h_i} - T_{c_o}$$

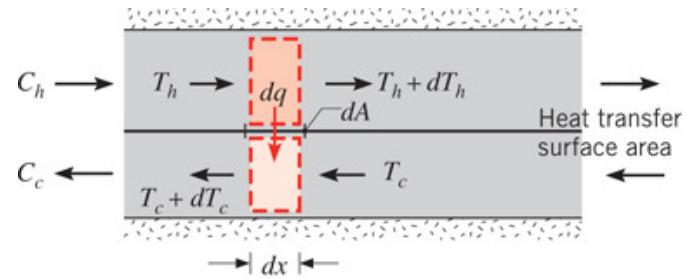
$$\Delta T_2 = T_{h,o} - T_{c,i}$$

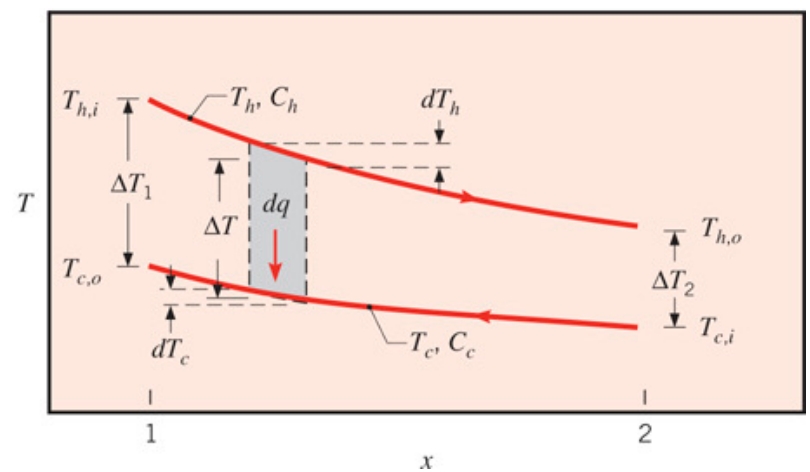
$$U_i = \frac{q}{A_i F \Delta T_{\mathrm{lm}}}$$

Use q_h

U_i overall heat transfer coefficient
A_i total tube inside HT area
F_i Correction factor (~1) for our case

ΔT_{lm} is determined by applying an energy balance to the differential elements in the hot and cold fluids





Effectiveness-NTU or NTU method

Effectiveness ε of a heat exchanger ($0 \le \varepsilon \le 1$):

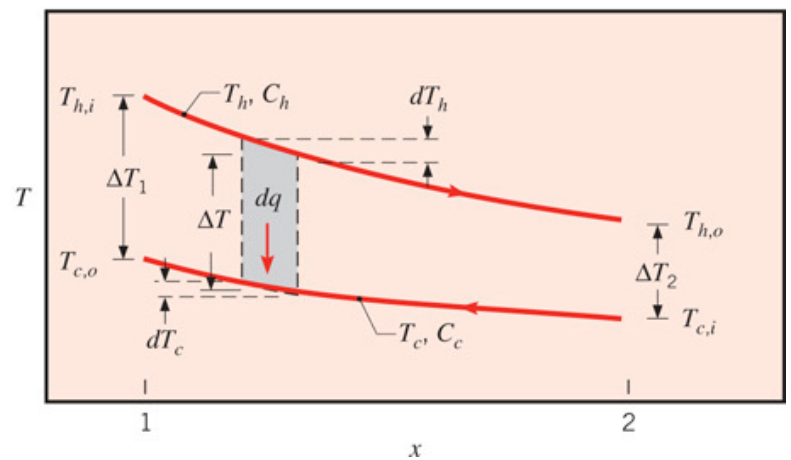
$$\varepsilon = \frac{q}{q_{\max}}$$

$q_{\max} \longrightarrow$ ***Maximum heat transfer rate***

- The maximum heat rate can be achieved in a counterflow heat exchanger of infinite length
- One of the fluids will experience the maximum temperature difference $T_{h,i} - T_{c,i}$

Hot fluid: $q = C_h(T_{h,i} - T_{h,o})$

Cold fluid: $q = C_c(T_{c,o} - T_{c,i})$



Effectiveness-NTU or NTU method

- $C_c < C_h$: The cold fluid experiences the largest temperature gradient

$$L \rightarrow \infty \Rightarrow T_{c,o} = T_{h,i}$$

$$\therefore q_{\max} = C_c(T_{h,i} - T_{c,i})$$

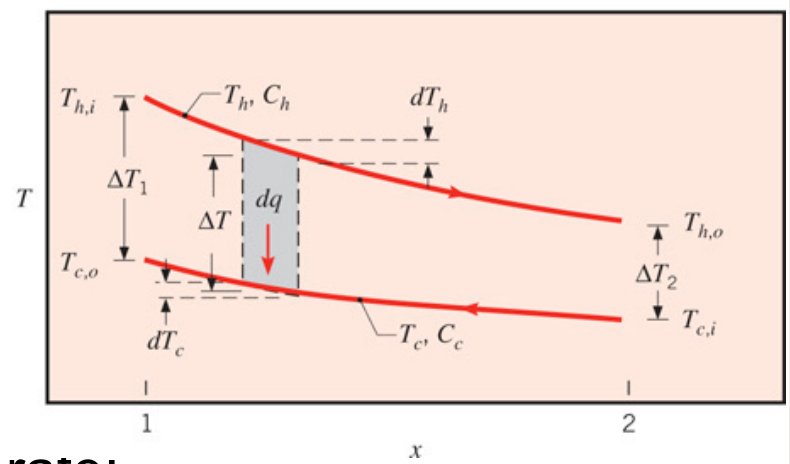
Energy Balance for two-streams

$$C_h(T_{h,i} - T_{h,o}) = C_c(T_{c,o} - T_{c,i})$$

- $C_h < C_c$: The hot fluid experiences the largest temperature gradient

$$L \rightarrow \infty \Rightarrow T_{h,o} = T_{c,i}$$

$$\therefore q_{\max} = C_h(T_{h,i} - T_{c,i})$$



- General expression for the maximum heat rate:

$$\boxed{\therefore q_{\max} = C_{\min}(T_{h,i} - T_{c,i})}$$

Effectiveness-NTU or NTU method

- Knowing ε and the inlet temperatures, the heat rate can easily be calculated:

$$\boxed{q = \varepsilon q_{\max} = \varepsilon C_{\min}(T_{h,i} - T_{c,i})}$$

What is an expression for ε ?

- NTU (**Number of Transfer Units**) is a dimensionless parameter:

$$NTU = \frac{UA}{C_{\min}} \quad \frac{\text{Ability of a HX to transfer heat}}{\text{Fluid's minimum ability to absorb heat}}$$

NTU is the non-dimensional size of a heat exchanger

$$NTU = \frac{U_i A_i}{C_{\min}}$$

- For any heat exchanger, it can be shown that:

$$\varepsilon = f\left(NTU, C_r\right)$$

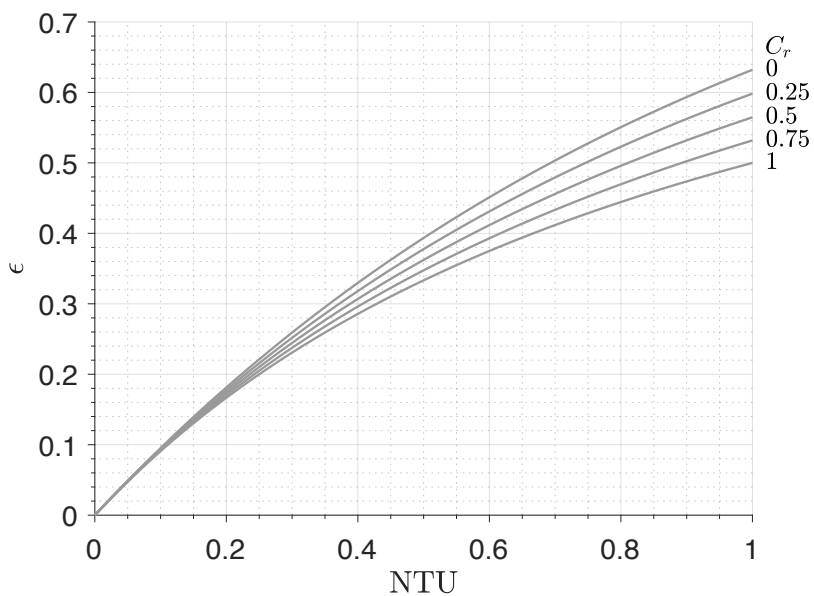
The functional form depends on the flow arrangement

- $C_r = C_{min}/C_{max}$ ***Heat capacity ratio***

Effectiveness

For a single tube pass, single shell counterflow shell and tube heat exchanger

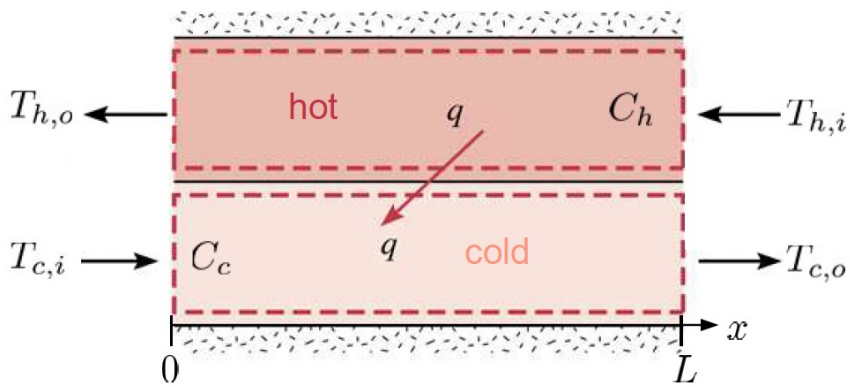
$$\varepsilon_{\text{theory}} = \begin{cases} \dfrac{1-\exp[-NTU\,(1-C_r)]}{1-C_r\,\exp[-NTU\,(1-Cr)]}, & C_r < 1, \\ \dfrac{NTU}{1+NTU}, & C_r = 1, \end{cases}$$

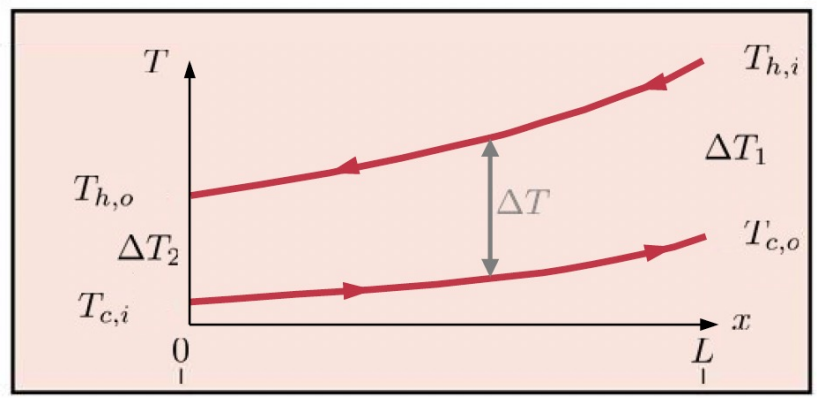


Actual Effectiveness

$$\varepsilon = \frac{C_{\max}\,(T_{h,i}-T_{h,o})}{C_{\min}\,(T_{h,i}-T_{c,i})} = \frac{1}{C_r}\frac{(T_{h,i}-T_{h,o})}{(T_{h,i}-T_{c,i})}$$

Heat Exchanger Design (Predicting Hot-side Outlet Temperature)





Energy balance: $q_h = C_h\left(T_{h,i} - T_{h,o}\right) \qquad q = C_{\min}\varepsilon\left(T_{h,i} - T_{c,i}\right)$

Set these equal to each other:

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

Divide both sides by Ch and solve for Th,o

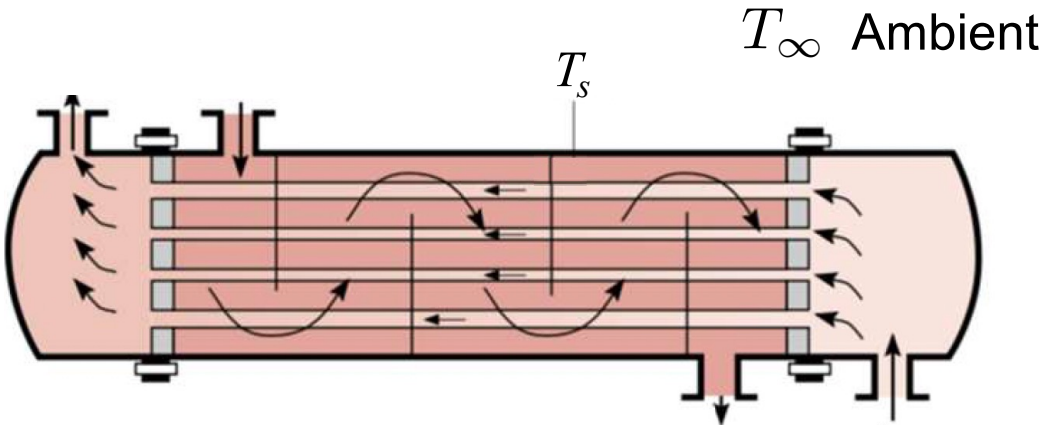
$$T_{h,0} = T_{h,i} - \varepsilon\frac{C_{\min}}{C_h}\left(T_{h,i} - T_{c,i}\right)$$

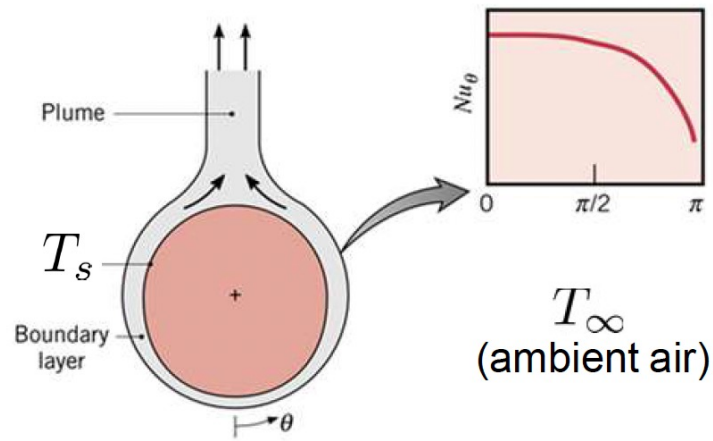
Or,

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

ε is from theory and the T's on the RHS are from data

Heat Loss to Surroundings (1. Natural Convection from Casing)





Newton's Law of Cooling

$$q_{\text{conv}} = \overline{h}(T_s - T_\infty)A_s = \overline{h}(T_s - T_\infty)\pi D_s L$$

$$\overline{h} = \frac{\kappa\,\overline{Nu}_D}{D_s}$$

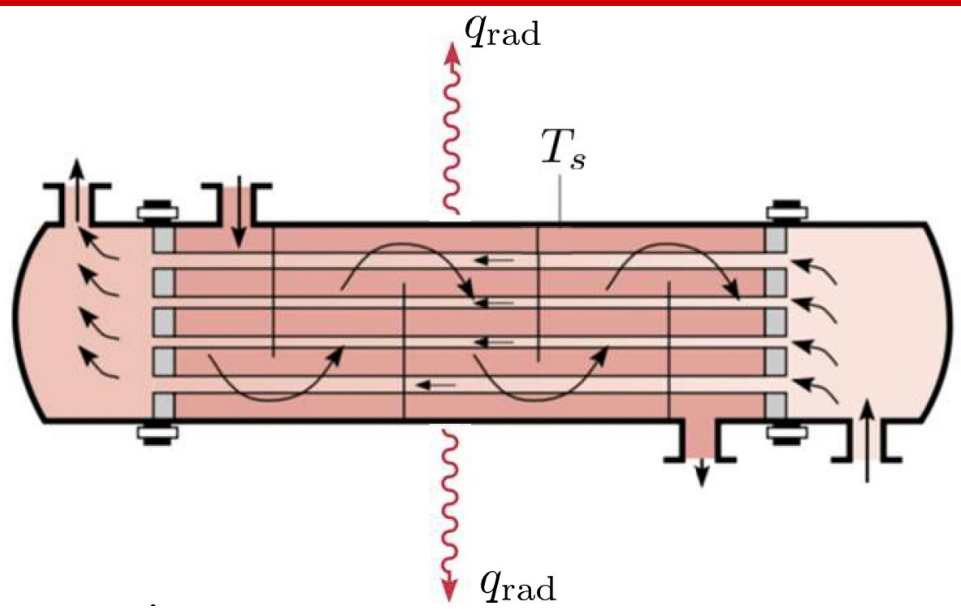
Compute properties at film temp: $T_f = \frac{1}{2}(T_s + T_\infty)$

Empirical Nusselt Number Relationship

$$\overline{Nu}_D = 0.48\,Ra_D^{1/4} \qquad Ra_D = \frac{g\,\beta\,(T_s - T_\infty)\,D_s^3}{\nu\,\alpha} \qquad \beta = \frac{1}{T_f}$$

Kelvin

Heat Loss to Surroundings (2. Thermal Radiation from Casing)



$$q_{\mathrm{rad}} = \epsilon\sigma(T_s^4 - T_\infty^4)\pi D_s L$$

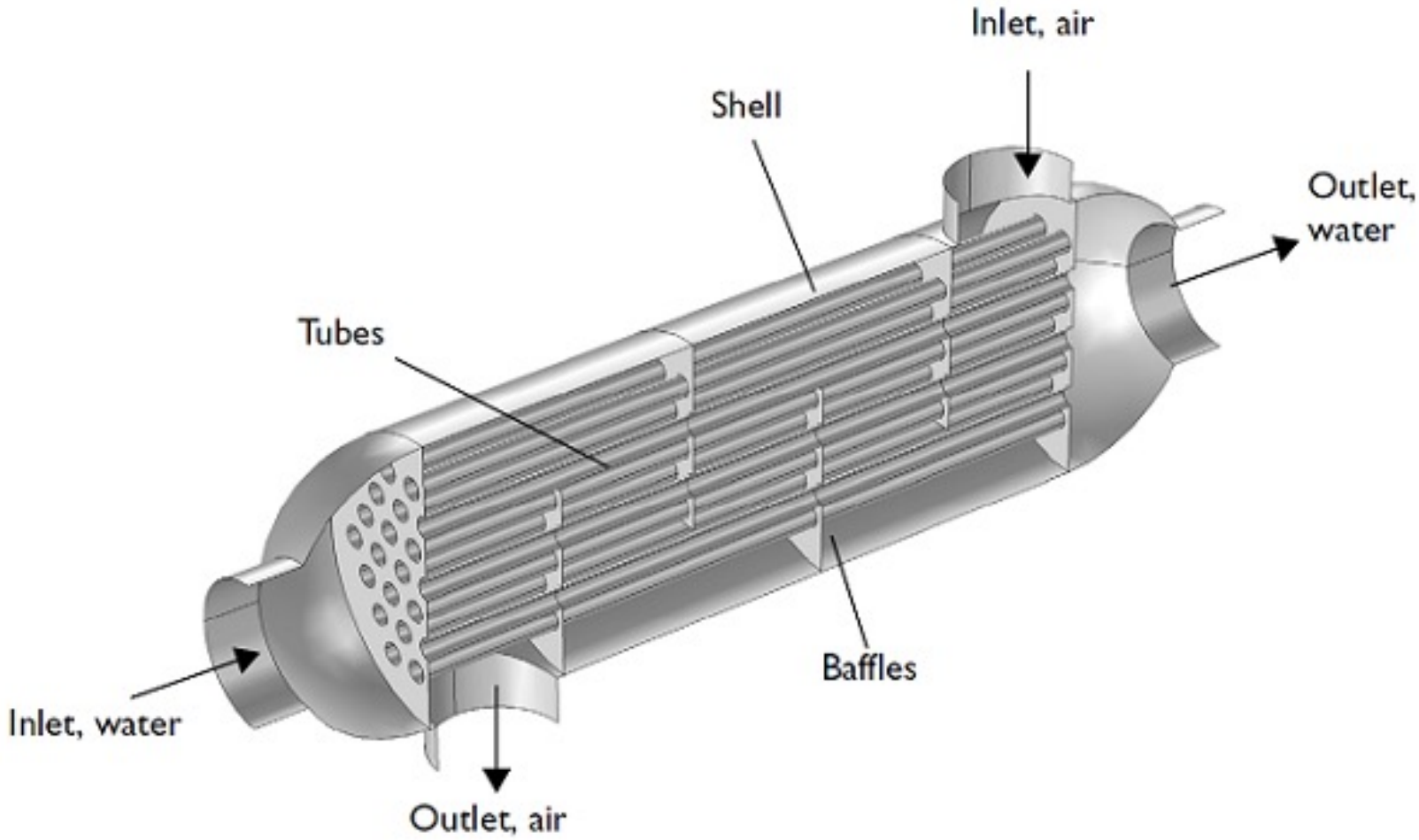
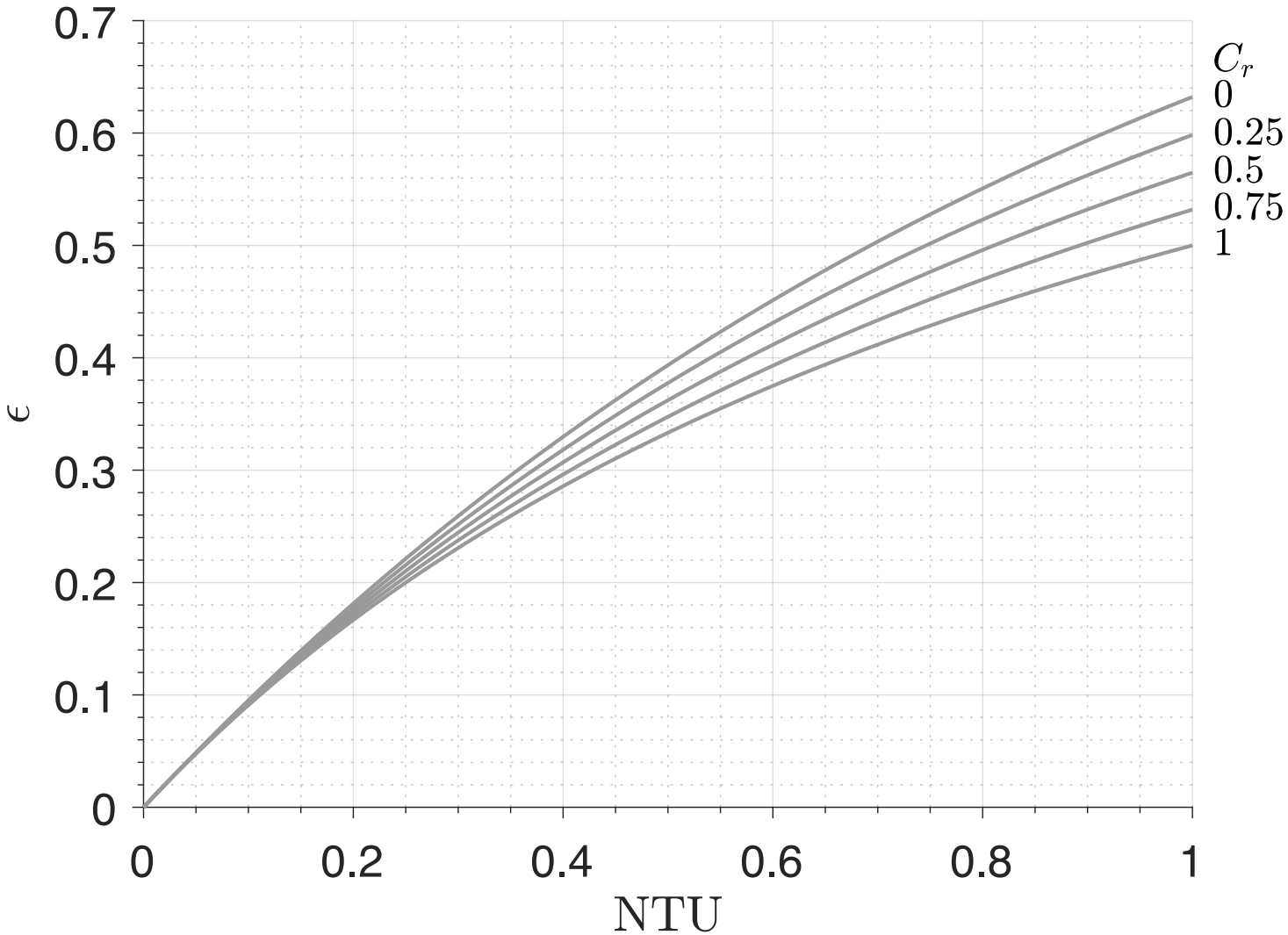
$$\epsilon \approx 0.95$$

Don't forget that temperatures here are absolute, i.e. in Kelvin

Coding and Data Analysis Tools

- See code for computing properties for air and water posted on CANVAS
- Matlab fig-file for effectiveness-NTU
- HeatExchangerTables-Blank.xlsx (Excel spreadsheet for required tables)

Crossflow: One Shell Pass, One Tube Pass



Effectiveness vs NTU