Heat Exchangers Keeps Things Cool

SPACE SHUTTLE TILES

MECH-420 Heat Transfer HEAT EXCHANGERS

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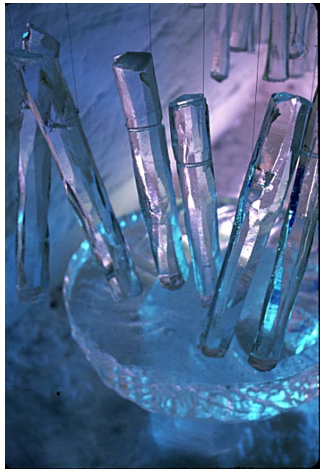
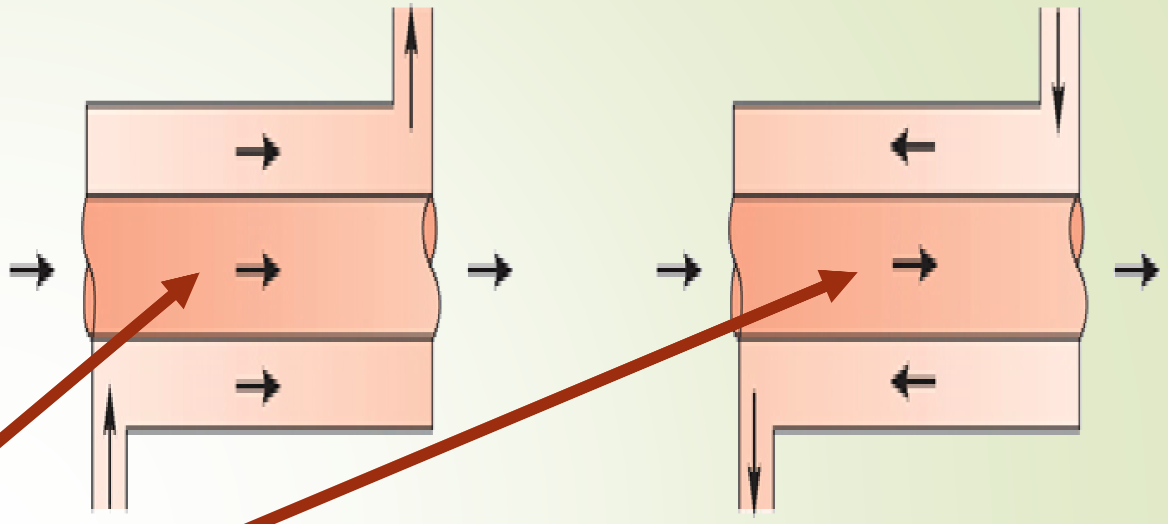
ASME FELLOW



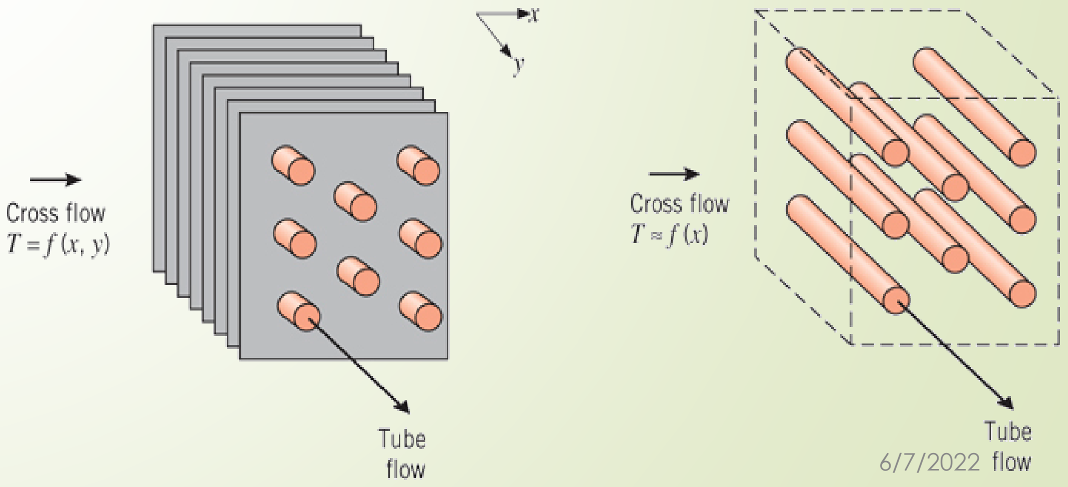
Heat Exchangers (HX) TYPES

- A device used to implement the exchange of heat transfer between TWO fluids that are separated by a solid wall, and flowing at different mass flow rates and temperatures
- COMMON HX TYPES
  - Double Pipe: Two Concentric pipes or tubes
    - Parallel Flow (hot/cold fluids in same direction)
    - Counter Flow (hot/cold fluids in opposite directions)



(a) (b)

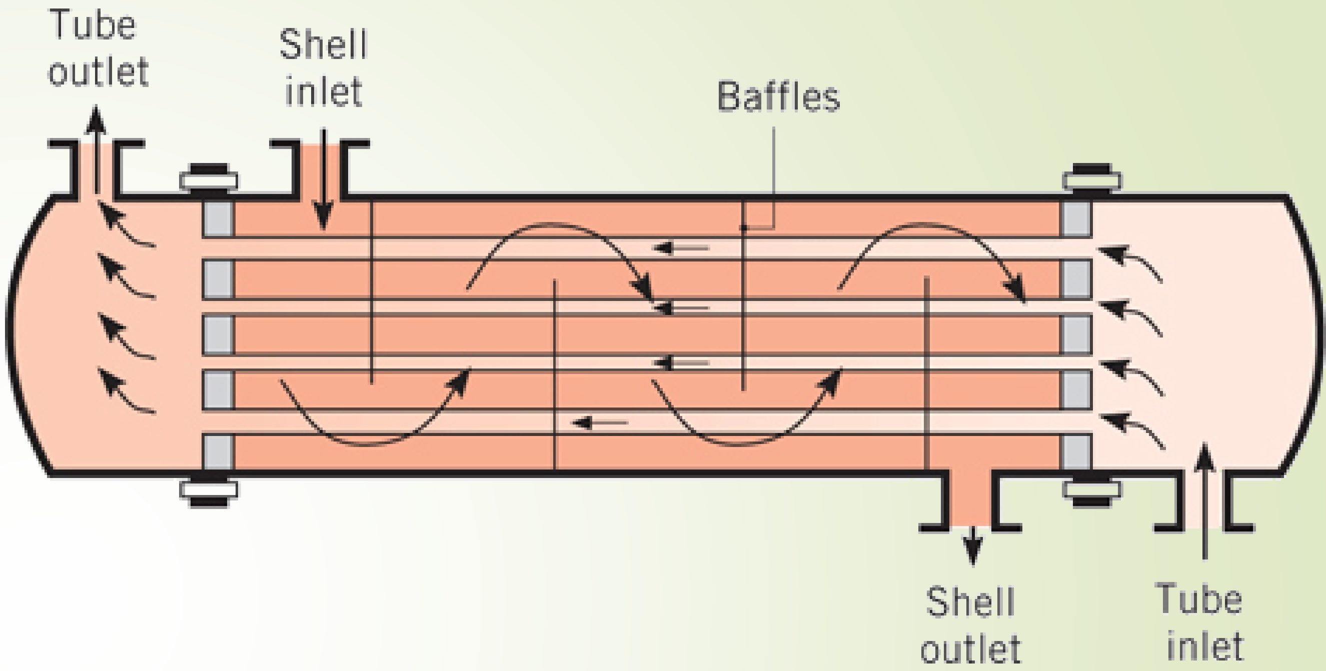
- CROSS FLOW HX
  - Two FLUIDS path cross each other, usually at right angles

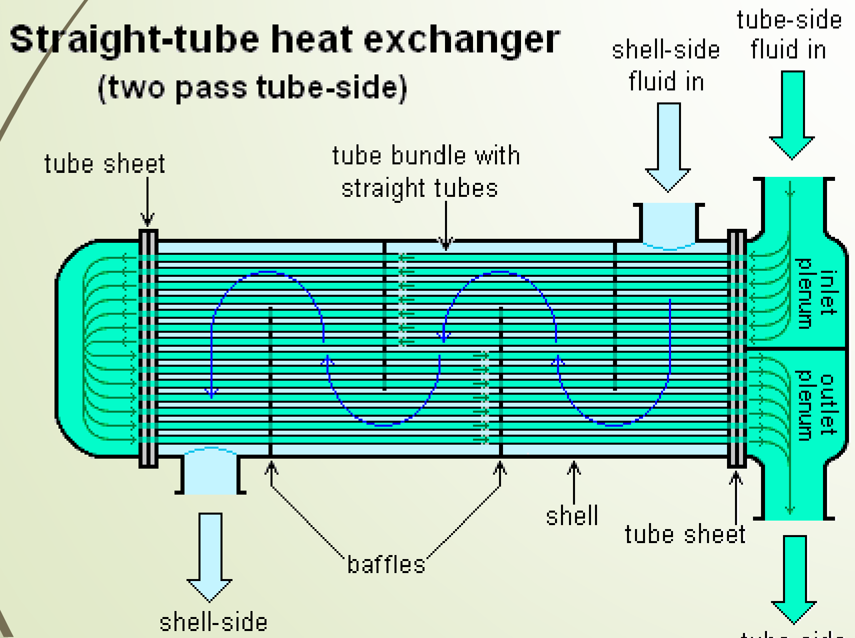


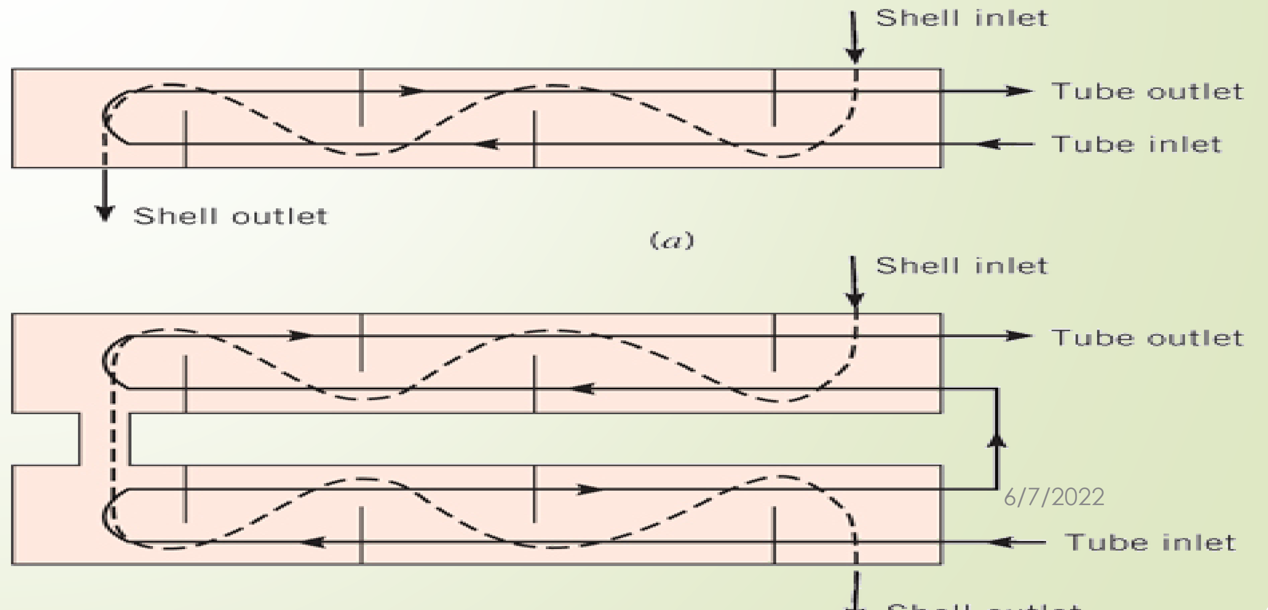
(a) (b)

Heat Exchangers Type: Shell-n-Tube

- Shell-n-Tube: A huge outer cylinder, or SHELL, which contains many tubes.
  - Can also have multiple shells and MULTIPLE tube passes per shell.

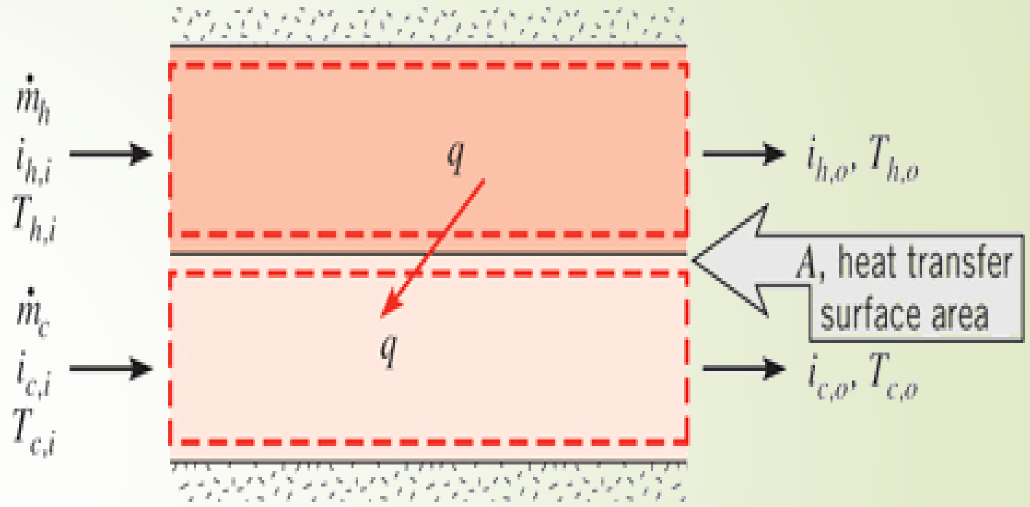






Overall Heat Transfer Coefficient and Fouling Factors

- An essential part of any heat exchanger analysis is determination of the overall heat transfer coefficient.
- During normal operations, HOT and COLD surfaces are often subject to fouling by fouling impurities, rust formation, or their reactions between the fluid and the wall material.



$$UA = \frac{1}{\sum R_{th}} = \frac{1}{\frac{1}{h_c A_c} + \frac{R_c''\, \frac{m^2-K}{W}}{A_c} + R_{t_{CONDUCTION}} + \frac{1}{h_h A_h} + \frac{R_h''\, \frac{m^2-K}{W}}{A_h}}$$

TABLE 11.1 Representative Fouling Factors [1]

Fluid	R''_f ($m^2 \cdot K/W$)
Seawater and treated boiler feedwater (below 50°C)	0.0001
Seawater and treated boiler feedwater (above 50°C)	0.0002
River water (below 50°C)	0.0002–0.001
Fuel oil	0.0009
Refrigerating liquids	0.0002
Steam (nonoil bearing)	0.0001

ANALYSIS: METHOD #1: PARALLEL-FLOW LOG MEAN TEMPERATURE DIFFERENCE

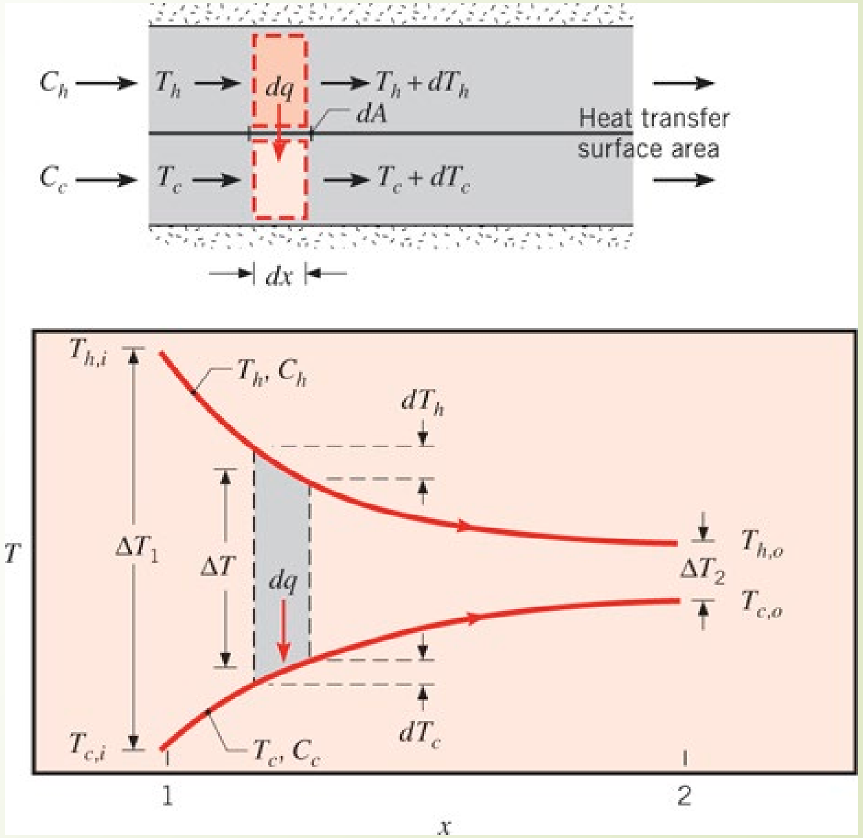
- Assumptions
  - Insulation from surroundings.
  - Axial conduction is small
  - Potential and kinetic energy changes are small
  - Cp and Overall Heat Transfer Coefficient is constant
- 3 of 4 temperatures are **KNOWN**.

$$q = UA\Delta T_{LM} = (\dot{m}cp)_{cold}\,\Delta T_{cold} = (\dot{m}cp)_{hot}\,\Delta T_{hot}$$

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln \dfrac{\Delta T_1}{\Delta T_2}}$$

PARALLEL-FLOW HX

$$\Delta T_1 = T_{h,in} - T_{c,in} \quad , \Delta T_2 = T_{h,out} - T_{c,out}$$



ANALYSIS: METHOD #1: COUNTER-FLOW LOG MEAN TEMPERATURE DIFFERENCE

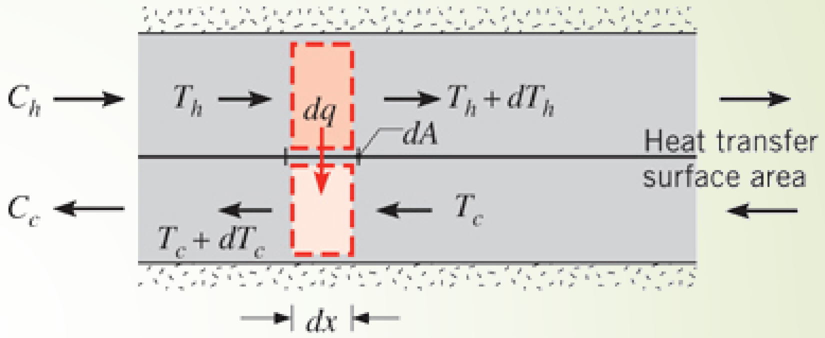
- Assumptions
  - Insulation from surroundings.
  - Axial conduction is small
  - Potential and kinetic energy changes are small
  - Cp and Overall Heat Transfer Coefficient is **constant** **(may really be a function of Temp**)
- 3 of 4 temperatures are **KNOWN**.

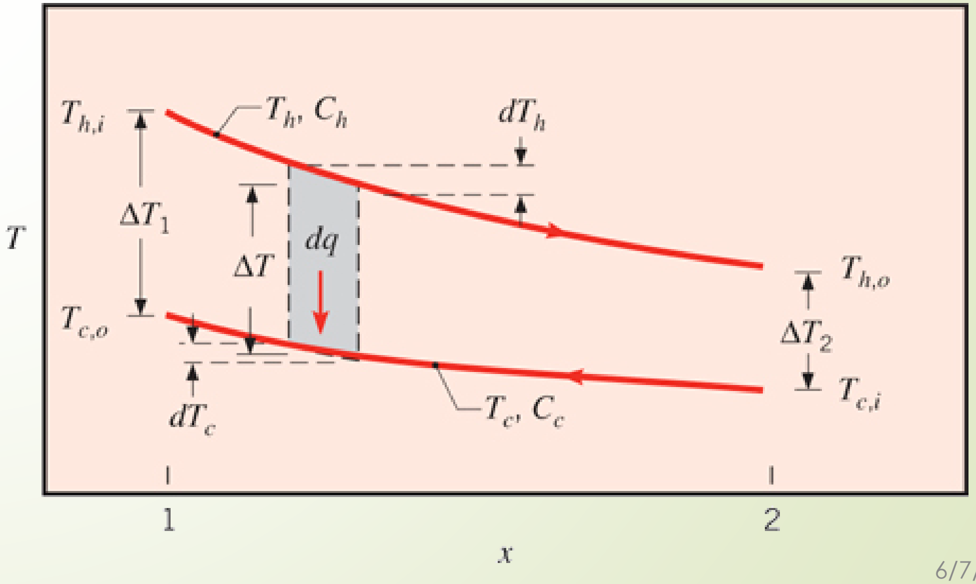
$$q = UA\Delta T_{LM} = \left(\dot{m}cp\right)_{cold} \Delta T_{cold} = \left(\dot{m}cp\right)_{hot} \Delta T_{hot}$$

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln \dfrac{\Delta T_1}{\Delta T_2}}$$

COUNTER-FLOW HX

$$\Delta T_1 = T_{h,in} - T_{c,out} \quad , \Delta T_2 = T_{h,out} - T_{c,in}$$

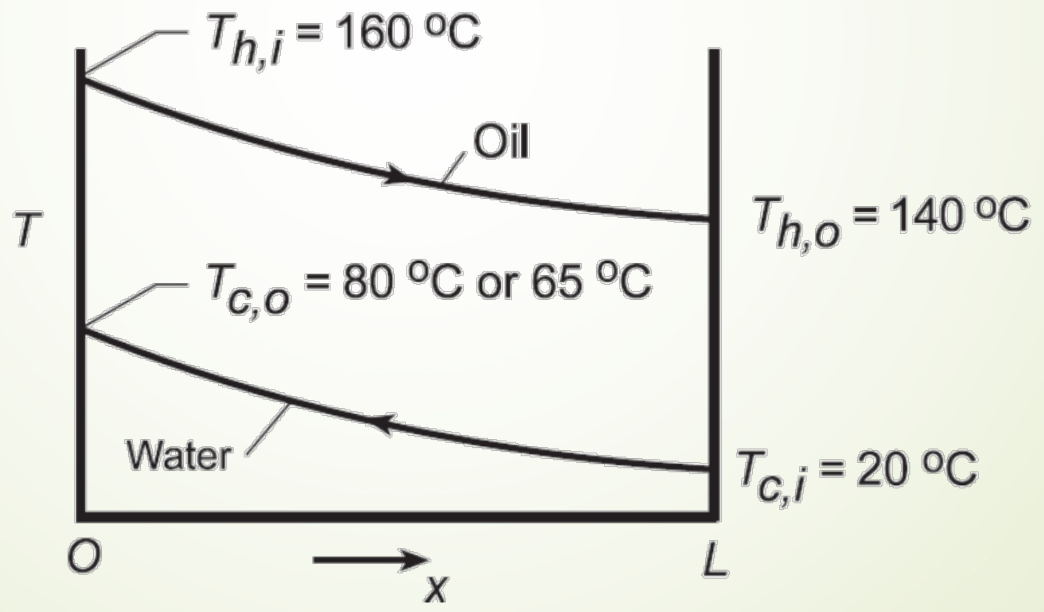




Known: Inner D=0.02, counterflow, concentric tube heat exchanger, thin wall. **U=500W/m2-K**, q=3000W. Cold outlet temperature after 3 years, (Tc,o=65C).

Find; a) L, b)q, hot fluid out, U and FF after three years.

SCHEMATIC:



LMTD METHOD

$$q = UA\Delta T_{LM} = (\dot{m}cp)_{cold}\,\Delta T_{cold} = (\dot{m}cp)_{hot}\,\Delta T_{hot}$$

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln\frac{\Delta T_1}{\Delta T_2}} = \frac{80-120}{\ln\left[\frac{80}{120}\right]} = 98.7C$$

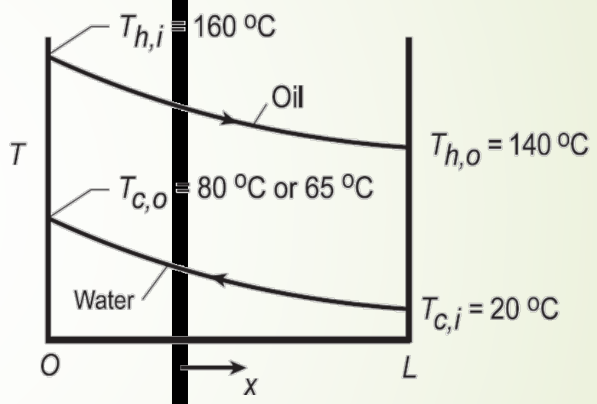
COUNTER-FLOW HX

$$\Delta T_1 = T_{h,in} - T_{c,out} \quad , \Delta T_2 = T_{h,out} - T_{c,in}$$

$$A = \pi DL$$

$$L = \frac{q}{(\pi D)U\Delta T_{LM}} = \frac{3000W}{(\pi \times 0.02m)500\frac{W}{m^2-K}\times 98.7C} = 0.968m$$

SCHEMATIC:



After 3 years, Tc,o Drops from 80C to 65C. Find q and U. (*FOULING COLD SIDE*)

$$q = UA\Delta T_{LM} = (\dot{m}cp)_{cold}\,\Delta T_{cold} = (\dot{m}cp)_{hot}\,\Delta T_{hot}$$

$$\frac{q_1}{q_3} = \frac{\left[(\dot{m}cp)_{cold}\,\Delta T_{cold}\right]_1}{\left[(\dot{m}cp)_{cold}\,\Delta T_{cold}\right]_3} = \frac{80-20}{65-20} = \frac{60C}{45C} = 1.333$$

$$q_3 = \frac{q_1}{1.333} = 2250W$$

$(T_{\text{HOT OUT}})_{\text{Year 3}}$

$$\frac{q_1}{q_3} = 1.333 = \frac{\left[(\dot{m}cp)_{hot}\,\Delta T_{hot}\right]_1}{\left[(\dot{m}cp)_{hot}\,(T_{h,i}-T_{h,o})\right]_3} = \frac{160-140}{160-T_{h,o}} \rightarrow T_{h,o} = 145C$$

$(U)_{\text{YEAR 3}}$

$$q_3 = (UA\Delta T_{LM})_3 \rightarrow U_3 = \frac{q_3}{(A\Delta T_{LM})_3} = \frac{q_3}{(\pi DL\Delta T_{LM})_3}$$

$$\Delta T_{LM} = \frac{125-95}{\ln\left[\frac{125}{95}\right]} = 109.3C$$

$$U_3 = \frac{q_3}{(\pi DL\Delta T_{LM})_3} = \frac{2250W}{\pi 0.02m \times 0.968m \times (109.3C)} = 338W/m^2-K$$

FOULING FACTOR: COLD SIDE

$$UA = \frac{1}{\sum R_{th}} = \frac{1}{\frac{1}{h_c A_c} + \frac{R_c'' \frac{m^2-K}{W}}{A_c} + R_{t_{CONDUCTION}} + \frac{1}{h_h A_h} + \frac{R_h'' \frac{m^2-K}{W}}{A_h}}$$

$$R_{t_{CONDUCTION}} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k_{wall} L} \rightarrow 0 \rightarrow \text{THIN WALL} \rightarrow \ln(1) \rightarrow 0$$

$$(\text{UA})_{cold} = U_c A_c = \frac{1}{\sum R_{th}} = \frac{1}{\frac{1}{h_c A_c} + \frac{R_c'' \frac{m^2-K}{W}}{A_c} + \frac{1}{h_h A_h}}$$

$$U_c = \frac{1}{A_c\left(\frac{1}{h_c A_c} + \frac{R_c'' \frac{m^2-K}{W}}{A_c} + \frac{1}{h_h A_h}\right)} = \frac{1}{\frac{1}{h_c} + R_c'' \frac{m^2-K}{W} + \frac{A_c}{h_h A_h}}$$

$$\text{THIN WALL} \rightarrow \frac{A_c}{A_h} = 1$$

$$U_{3c} = \frac{1}{\frac{1}{h_c} + R_c'' \frac{m^2-K}{W} + \frac{A_c}{h_h A_h}}$$

$$\frac{1}{U_{3c}} = \frac{1}{h_c} + R_c'' \frac{m^2-K}{W} + \frac{1}{h_h}$$

$$R_c'' \frac{m^2-K}{W} = \frac{1}{U_{3c}} - \left(\frac{1}{h_c} + \frac{1}{h_h}\right)$$

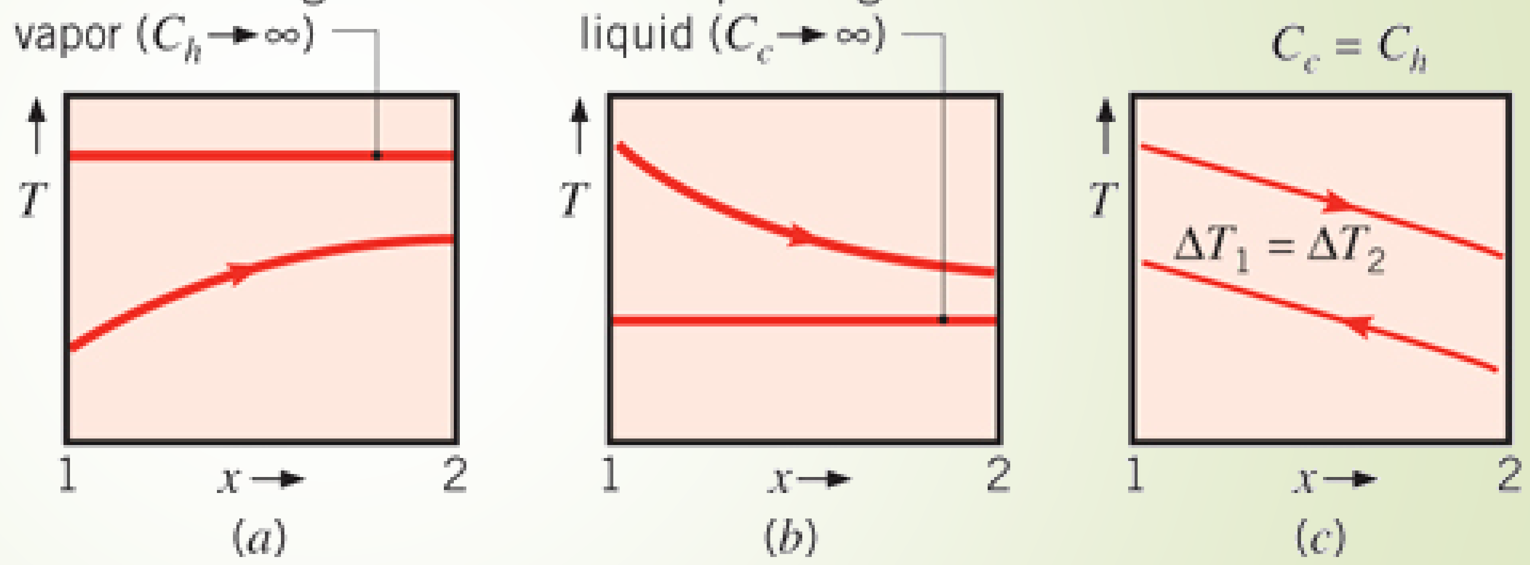
$$= \frac{1}{U_{c-Year3}} - \frac{1}{U_{c-Year1}} = \frac{1}{338} - \frac{1}{500} = 9.59x10^{-4} \frac{m^2-K}{W}$$

Special Operating Conditions Condensation and Evaporation

- ***CONDENSATION*** occurs at a constant temperature (i.e. ***THERMODYNAMICS***)
  - Implies a ***VERY LARGE*** THERMAL CAPACITY OF ***HOT*** FLUID (Ch).

- ***EVAPORATION*** occurs at a constant temperature (i.e. THERMODYNAMICS)
  - Implies a ***VERY LARGE*** THERMAL CAPACITY OF ***COLD*** FLUID (Cc).

$$q = C_c \Delta T_c = C_h \Delta T_h$$



$$q = \dot{m}_h (kg/s) h_{fg} (J/kg)$$

$$q = \dot{m}_c (kg/s) h_{fg} (J/kg)$$

$$C \equiv \text{THERMAL CAPACITY} = \dot{m} c p$$

ANALYSIS: METHOD #2: EFFECTIVENESS--NTU

- ONLY **TWO** TEMPERATURES ARE REQUIRED **(Thi and Tci)**
  - MAJOR ADVANTAGE
- Definition: Heat Exchanger Effectiveness

$$C \equiv \text{THERMAL CAPACITY} = \dot{m}cp$$

$$C_h = (\dot{m}cp)_h, C_c = (\dot{m}cp)_c \rightarrow q = (\dot{m}cp)_{cold} \Delta T_{cold} = (\dot{m}cp)_{hot} \Delta T_{hot}$$

$$C_{\min} = \text{MINIMUM}(C_h, C_c)$$

$$\varepsilon \equiv \text{ HX EFFECTIVENESS}$$

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

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

$$= \frac{C_c(T_{c,o} - T_{c,i})}{C_{\min}(T_{h,i} - T_{c,i})} = \frac{q_c}{C_{\min}(T_{h,i} - T_{c,i})}$$

$$C_{\min}(T_{h,i} - T_{c,i}) \rightarrow \text{MAXIMUM POSSIBLE FLUID HEAT TRANSFER}$$

$$\varepsilon \rightarrow F(NTU, \frac{C_{\min}}{C_{\max}}), NTU \equiv \text{Number of Transfer Units (Dimensionless)}$$

PHASE CHANGE

(constant pressure and temperature heat transfer)

$CONDENSATION, C_h \rightarrow \infty$

$$\varepsilon \equiv \frac{q}{q_{\max}} = \frac{q}{C_{\min}(T_{h,i}-T_{c,i})} = \frac{C_c(T_{c,o}-T_{c,i})}{C_{\min}(T_{h,i}-T_{c,i})}, C_{\min} = C_c$$

$$= \frac{(T_{c,o}-T_{c,i})}{(T_{h,i}-T_{c,i})}$$

$$q[W] = \dot{m}_h(kg/s) \bullet h_{fg}(J/kg)$$

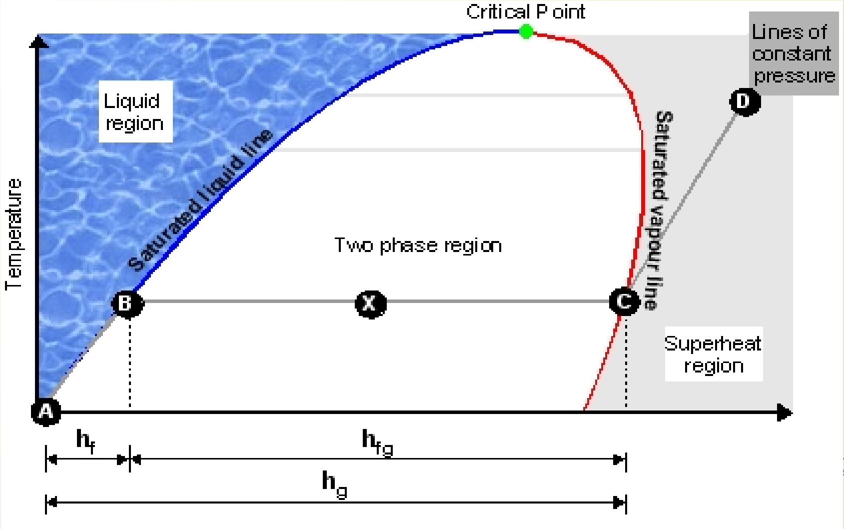
$VAPORIZATION, C_c \rightarrow \infty$

$$\varepsilon \equiv \frac{q}{q_{\max}} = \frac{q}{C_{\min}(T_{h,i}-T_{c,i})} = \frac{C_h(T_{h,i}-T_{h,o})}{C_{\min}(T_{h,i}-T_{c,i})}, C_{\min} = C_h$$

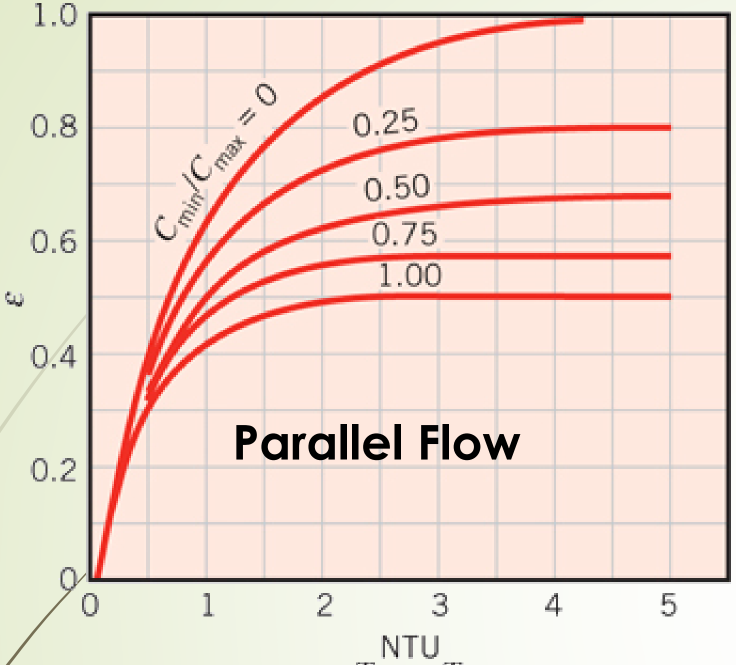
$$= \frac{(T_{h,i}-T_{h,o})}{(T_{h,i}-T_{c,i})}$$

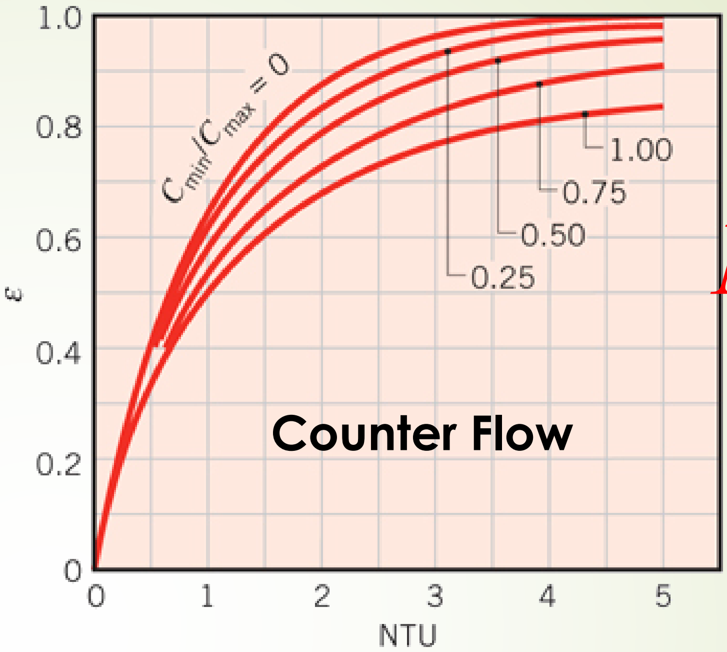
$$q[W] = \dot{m}_c(kg/s)h_{fg}(J/kg)$$

h_{fg} = latent heat of vaporization = $h_g - h_f$

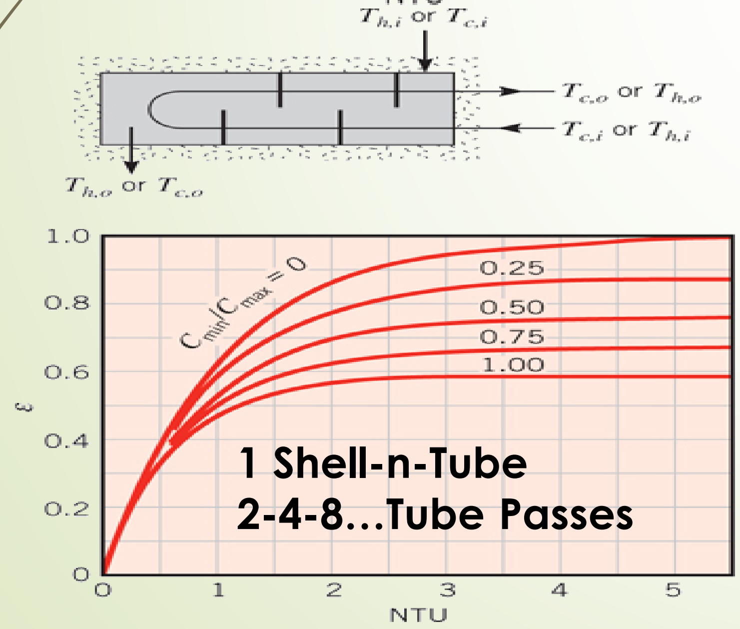


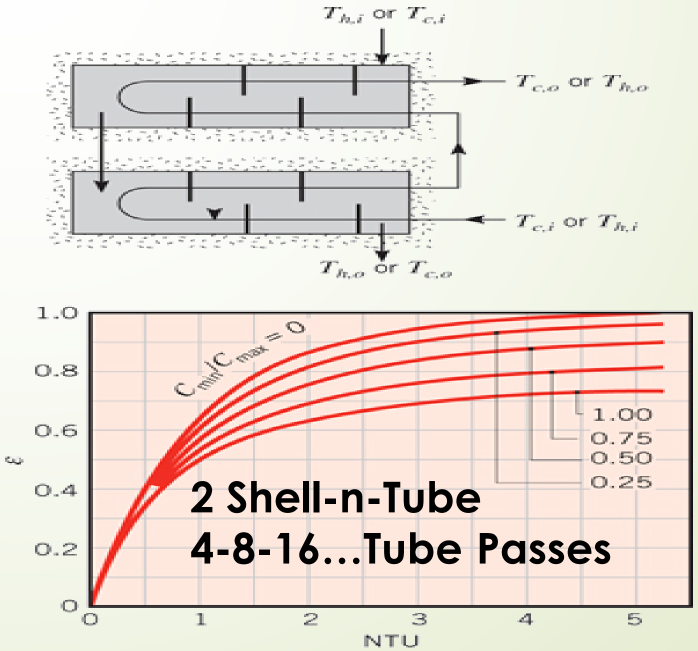
EFFECTIVENESS





$$NTU \equiv \frac{UA}{C_{\min}}$$





NTU RELATIONSHIPS (sometimes easier)

$$C_r = \frac{C_{min}}{C_{max}} = 0 \rightarrow \text{ALL EXCHANGERS w/PHASE CHANGE}$$

$$\varepsilon = 1 - \exp(-NTU), NTU = -\ln(1-\varepsilon)$$

COUNTER FLOW$(C_r = 1.0)$

$$\varepsilon = \frac{NTU}{1+NTU}, NTU = \frac{\varepsilon}{1-\varepsilon}$$

Parallel Flow

$$\varepsilon = \frac{1-\exp\left[-NTU(1+C_r)\right]}{1+C_r}$$

COUNTER FLOW$(C_r < 1.0)$

$$\varepsilon = \frac{1-\exp\left[-NTU(1-C_r)\right]}{1-C_r\exp\left[-NTU(1-C_r)\right]}, NTU = \frac{1}{C_r - 1}\ln\left(\frac{\varepsilon - 1}{\varepsilon C_r - 1}\right)$$

ONE SHELL PASS (n=2,4,8,16..tube passes)

$$NTU_1 = -(1+C_r^2)^{-1/2}\ln\left(\frac{E-1}{E+1}\right), E = \frac{\frac{2}{\varepsilon_1} - (1+C_r)}{(1+C_r^2)^{+1/2}}, \varepsilon_1 = \frac{F-1}{F-C_r}, F = \left(\frac{\varepsilon C_r - 1}{\varepsilon - 1}\right)^{1/n} NTU = n(NTU)_1$$

NTU Relationships (CROSS FLOW HEAT EXCHNAGERS)

Cross-Flow (single pass)

$C_{max}\,(mixed), C_{min}\,(unmixed)$

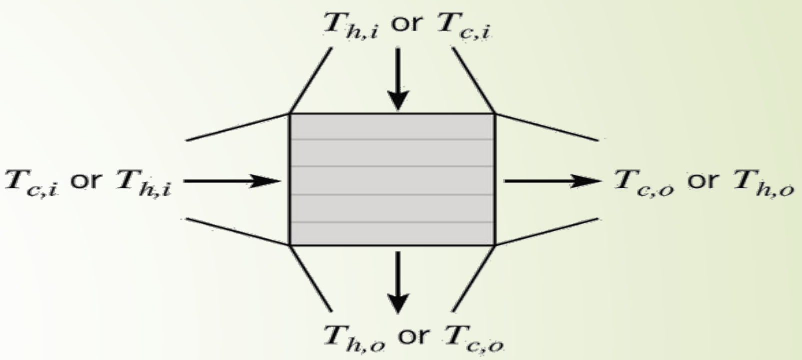
$$NTU = -\ln\left[1+\left(\frac{1}{C_r}\right)\ln(1-\varepsilon C_r)\right]$$

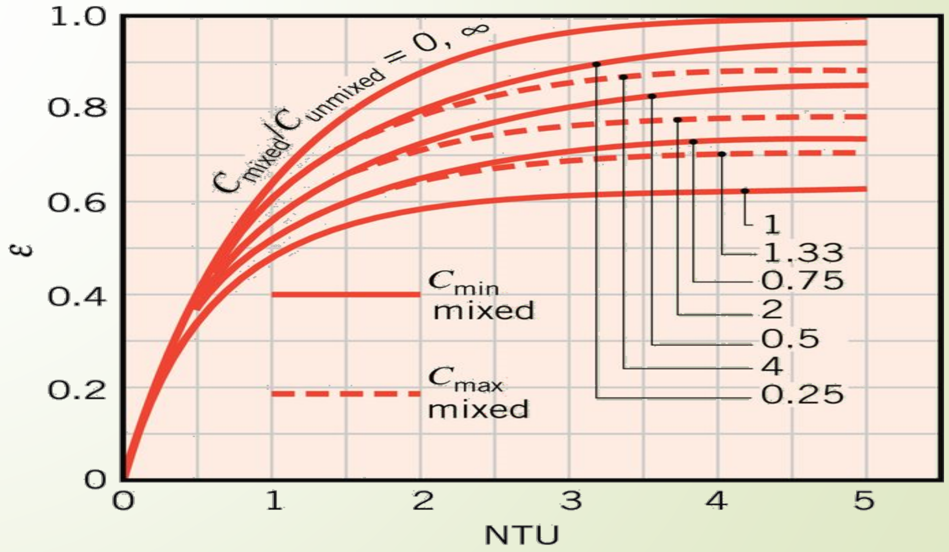
$$a = C_r\left(e^{-NTU}-1\right), \varepsilon = \frac{1-e^{a}}{C_r}$$

$C_{min}\,(mixed), C_{max}\,(unmixed)$

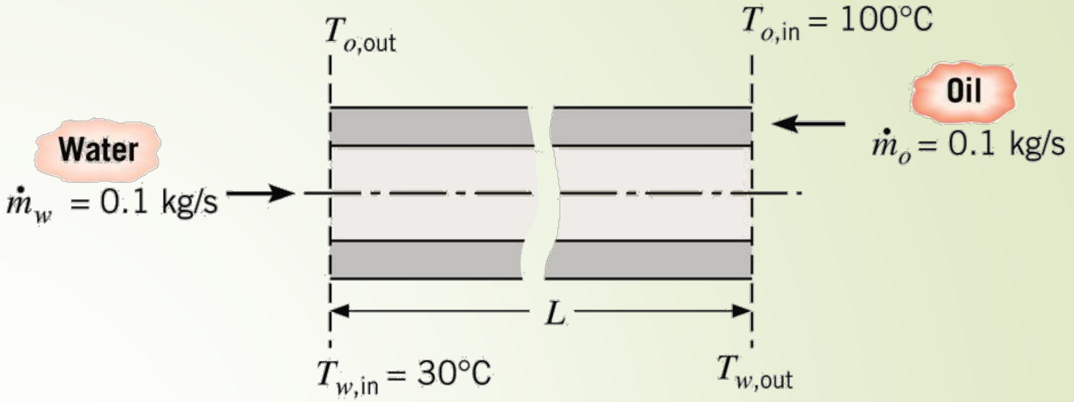
$$NTU = -\left(\frac{1}{C_r}\right)\ln\left[C_r\ln(1-\varepsilon)+1\right]$$

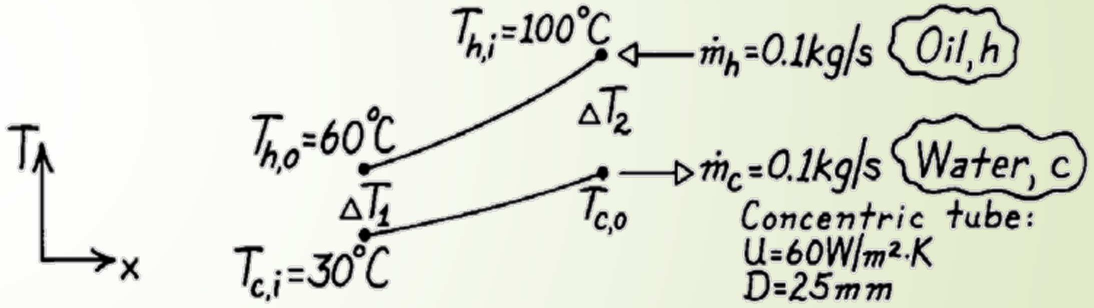
$$a = \frac{e^{-NTU \bullet C_r}-1}{C_r}, \varepsilon = 1-e^{a}$$





Concentric Tube Heat Exchanger. Thin walled inner tube of 25mm with water, and 45mm outer tube with oil.
Counter flow with U=60W/m2-K





Find:

a. Total Heat Transfer and water outlet temperature if Toil out is 60C
b. Tube Length.

PROPERTIES: (given):

	ρ (kg/m^3)	c_p (J/kg·K)	ν (m^2/s)		k (W/m·K)
Water	1000	4200	7×10^{-7}	0.64	4.7
Oil	800	1900	1×10^{-5}	0.134	140

Properties

OVERALL ENERGY BALANCE

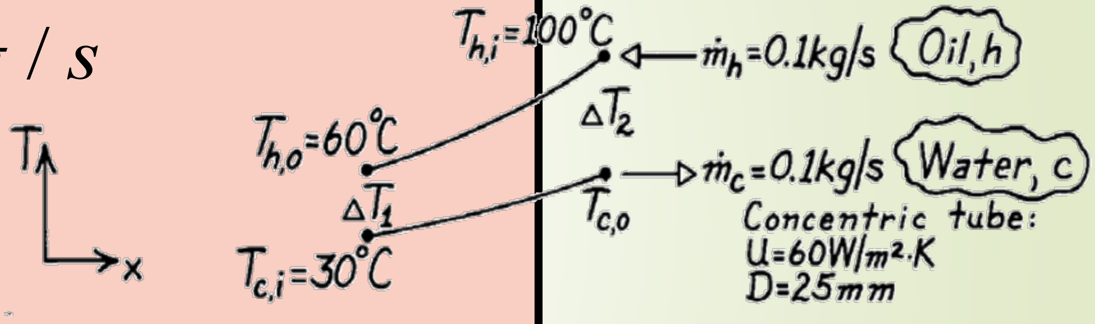
$$q = (\dot{m}cp)_{hot}(T_{h,i} - T_{h,o}) = (\dot{m}cp)_{cold}(T_{c,o} - T_{c,i})$$

$HOT : OIL$

$$T_{h,i} = 100C, T_{h,o} = 60C, \dot{m}_h = 0.1kg/s$$

$COLD : WATER$

$$T_{c,i} = 30C, T_{c,o} = ?, m_c = 0.1kg/s$$



$$T_{c,o} = \frac{(\dot{m}cp)_{hot}(T_{h,i} - T_{h,o})}{(\dot{m}cp)_{cold}} + T_{c,i}$$

$$= \frac{0.1kg/s \bullet 1900J/kg-K(100-60)C}{0.1kg/s \bullet 4200J/kg-K} + 30C$$

$$= 48.1C$$

LMTD METHOD #1

L=?

$$q = UA\Delta T_{\log mean,CF} = U(\pi DL)\Delta T_{\log mean,CF}$$

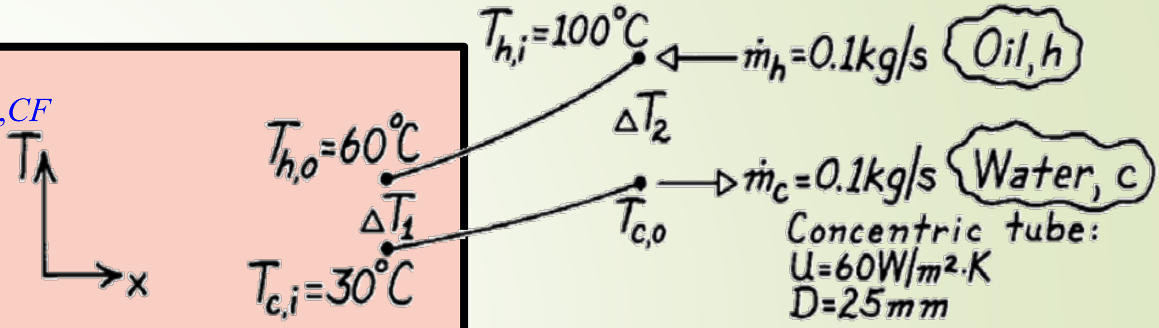
$$L = \frac{q}{U(\pi D)\Delta T_{\log mean,CF}}$$

$$\Delta T_{\log mean,CF} = \frac{\Delta T_1 - \Delta T_2}{\ln\left[\frac{\Delta T_1}{\Delta T_2}\right]} = \frac{(60-30)C-(100-48.1)C}{\ln(30/51.9)} = 40.0C$$

$$q = (\dot{m}cp)_{hot}(T_{h,i} - T_{h,o}) = (\dot{m}cp)_{cold}(T_{c,o} - T_{c,i}) = 7600W$$

$$L = \frac{q}{U(\pi D)\Delta T_{\log mean,CF}} = \frac{7600W}{60\frac{W}{m^2-K}\bullet\pi\bullet 0.025m\bullet 40.0C}$$

$$L = 40.3m$$



COUNTER FLOW

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

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

PARALLEL FLOW

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

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

e-NTU METHOD #2

L=?

$C_h = (\dot{m}cp)_{hot} = 190W/K, C_c = (\dot{m}cp)_{cold} = 420W/K$

$C\min = C_h$

$C\max = C_c$

$q_{\max} = C_{\min}(T_{h,i} - T_{c,i}) = 190W/K(100-30) = 13,300W$

$q = (\dot{m}cp)_{hot}(T_{h,i} - T_{h,o}) = (\dot{m}cp)_{cold}(T_{c,o} - T_{c,i}) = 7600W$

$$\varepsilon = \frac{q}{q_{\max}} = \frac{7600W}{13,300W} = 0.571$$

FIND NTU--EQN: 11.29b

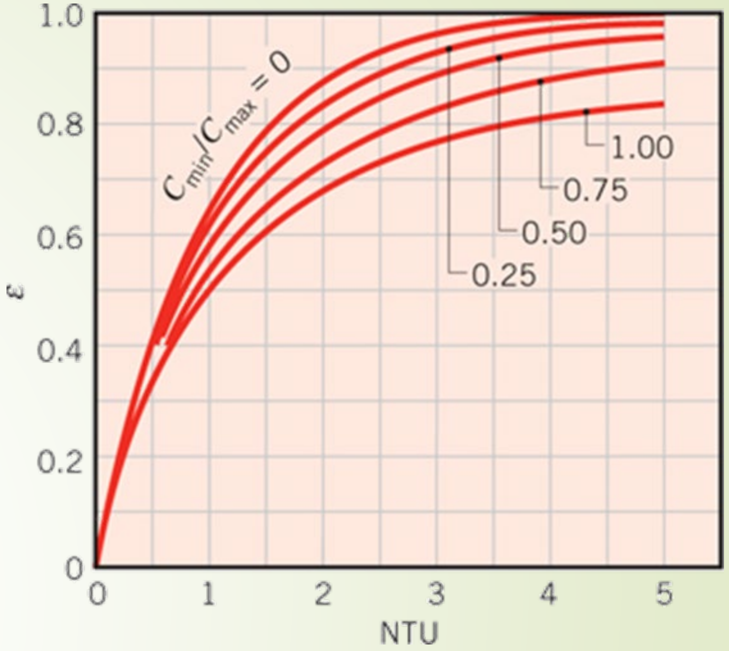
$$\text{NTU}=\frac{1}{C_r - 1}\ln\left(\frac{\varepsilon - 1}{\varepsilon C_r - 1}\right) = \frac{UA}{C_{\min}}$$

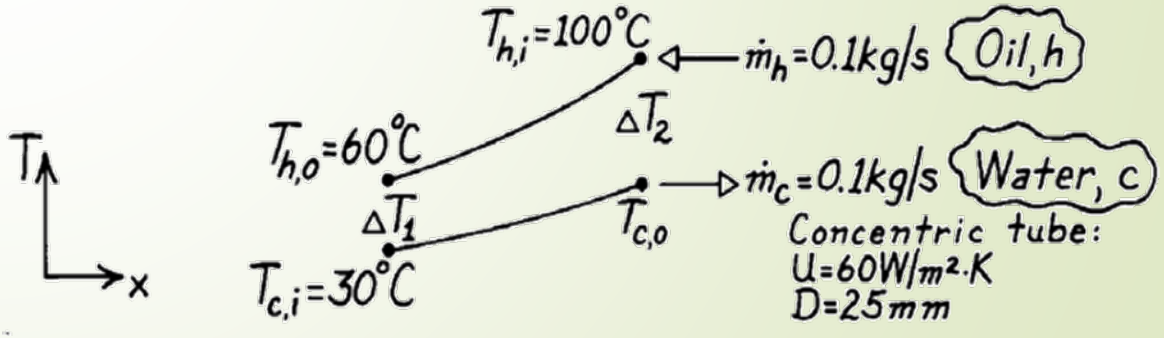
$$C_r = \frac{C_{\min}}{C_{\max}} = \frac{190}{420} = 0.452$$

$$\text{NTU}=\frac{1}{0.452-1}\ln\left(\frac{0.571-1}{0.571\bullet 0.452-1}\right) = 1.00$$

$$1.00 = \frac{UA}{C_{\min}} = \frac{U\pi DL}{C_{\min}}$$

$$L = \frac{NTU\bullet C_{\min}}{U\pi D} = \frac{1.0\bullet 190W/K}{60W/m^2-K\bullet\pi\bullet 0.025m} = 40.3m$$





PARALLEL VS COUNTER FLOW

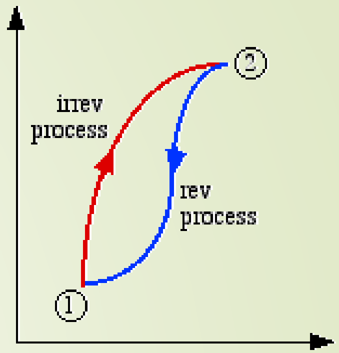
COUNTER FLOW is MORE EFFECTIVE: MORE HEAT TRANSFER w/SAME AREA

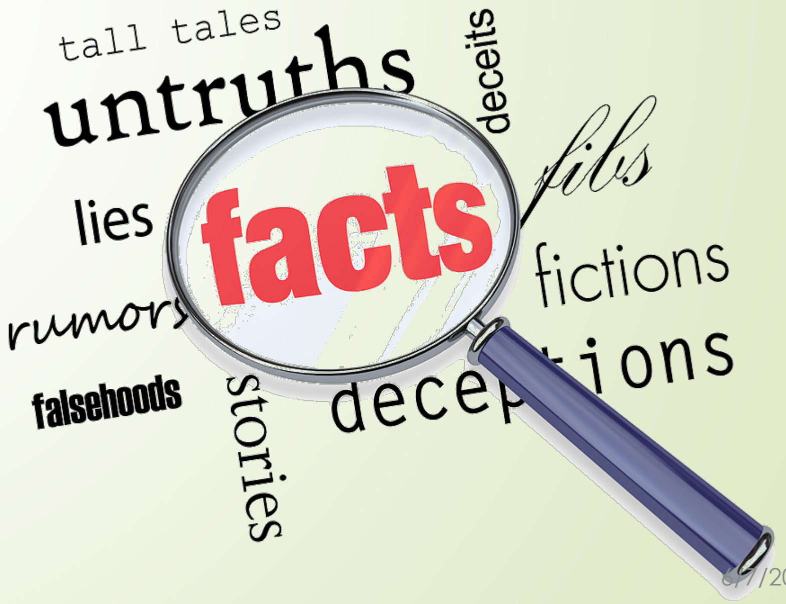
$$\oint \frac{\delta Q}{T} = \int_{1,\,irrev}^{2} \frac{\delta Q}{T} + \int_{2,\,rev}^{1} \frac{\delta Q}{T} < 0$$

$$\int_{1,\,irrev}^{2} \frac{\delta Q}{T} + \int_{2}^{1} dS = \int_{1,\,irrev}^{2} \frac{\delta Q}{T} + (S_1 - S_2) < 0$$

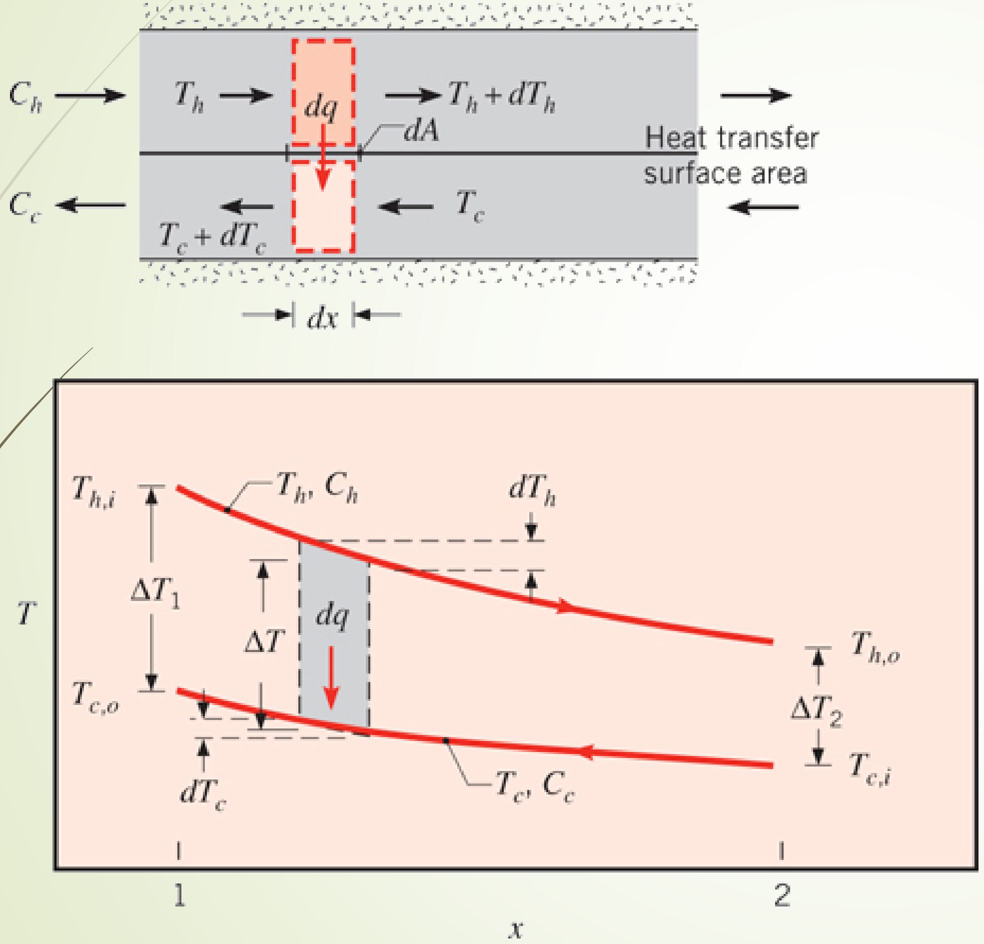
$$\Delta S = (S_2 - S_1) > \int_{1}^{2} \frac{\delta Q}{T}$$

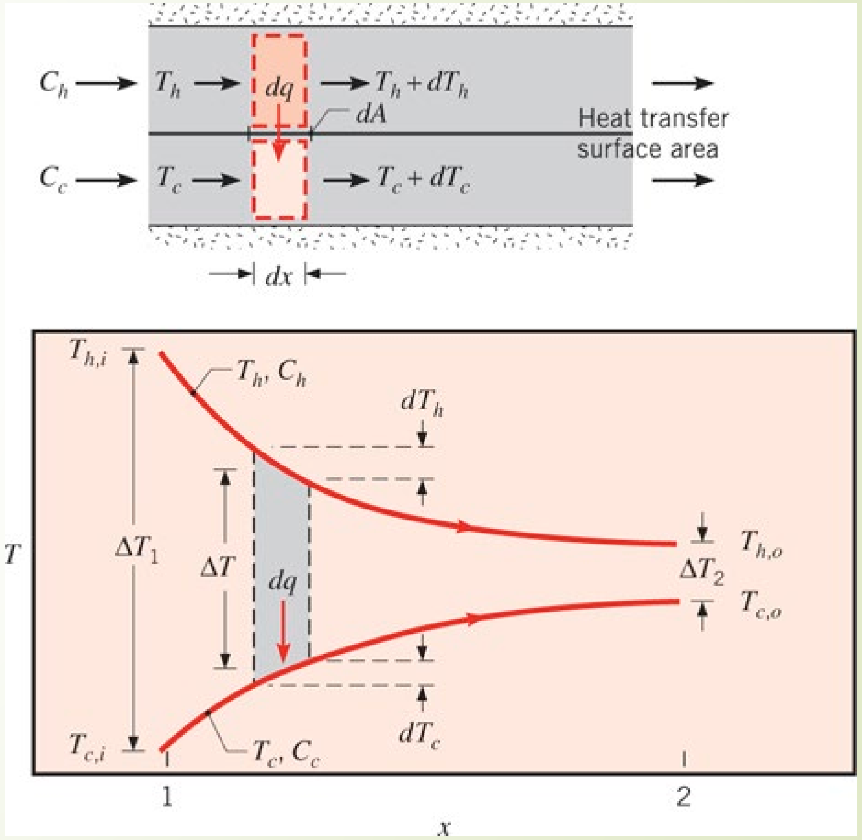
For adiabatic processes ($\delta Q = 0$) $\Rightarrow$ $\Delta S \geq 0$



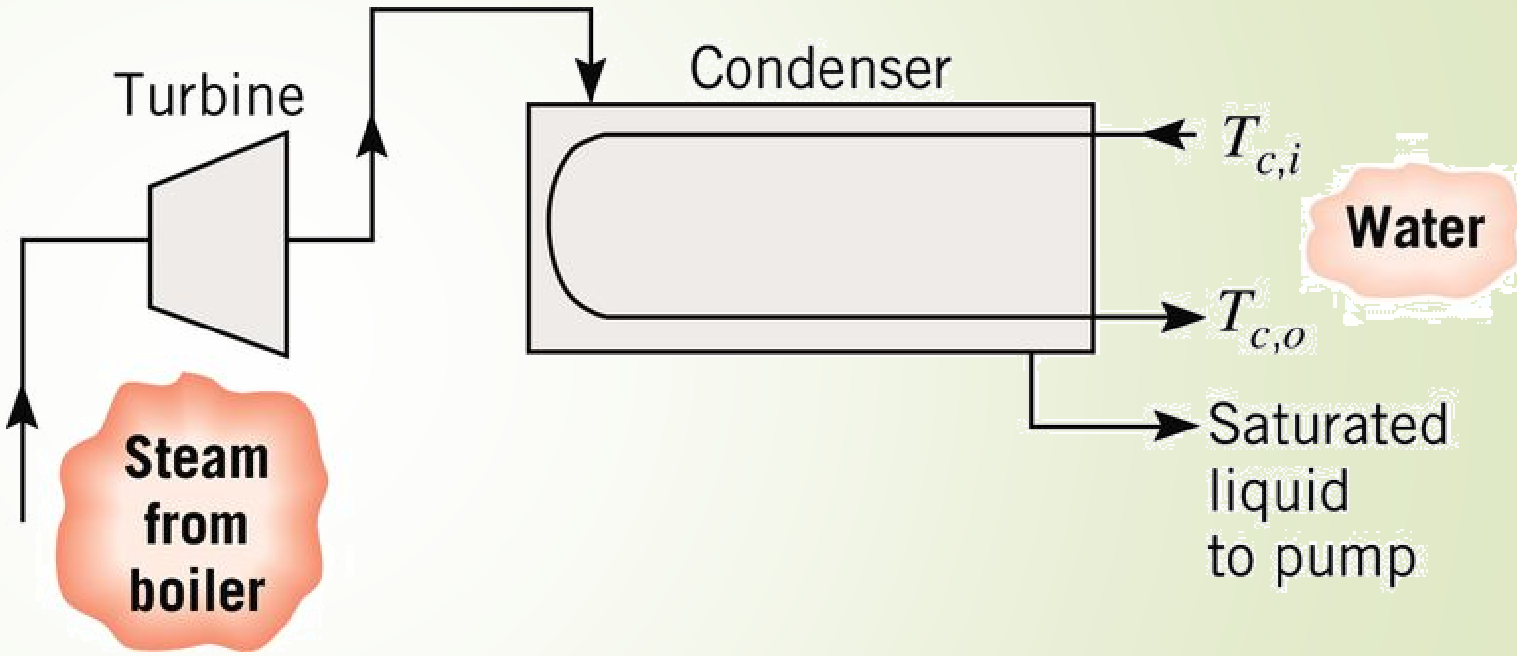


SMALLER dT OVER LENGTH and THUS LOWER THERMAL LOSSES DUE TO LOWER ENTROPY PRODUTION


C_h
T_h
dq
$T_h + dT_h$
dA
Heat transfer
surface area
C_c
T_c
$T_c + dT_c$
dx
$T_{h,i}$
T_h, C_h
dT_h
ΔT_1
ΔT
dq
T
$T_{h,o}$
ΔT_2
$T_{c,o}$
$T_{c,i}$
dT_c
T_c, C_c
1
2
x

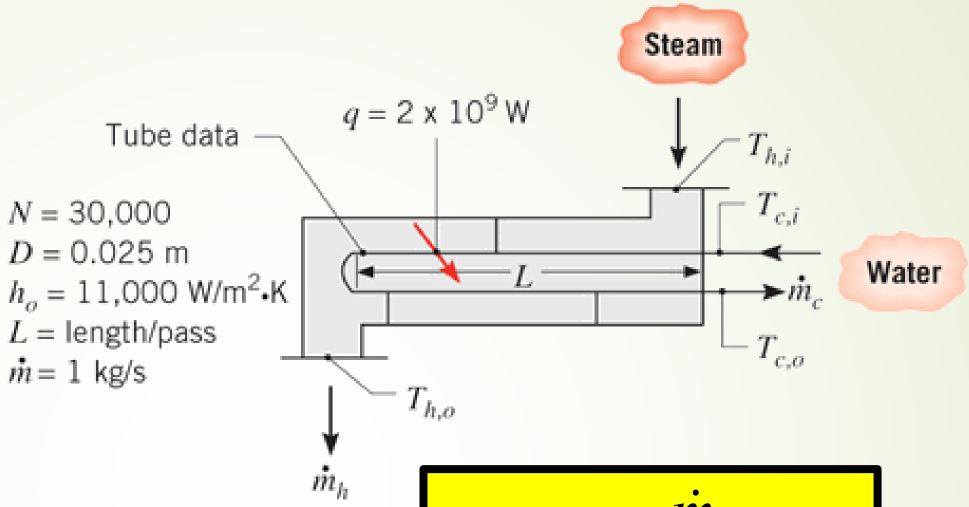

C_h
T_h
dq
$T_h + dT_h$
dA
Heat transfer
surface area
C_c
T_c
$T_c + dT_c$
dx
$T_{h,i}$
T_h, C_h
dT_h
ΔT_1
ΔT
dq
T
$T_{h,o}$
ΔT_2
$T_{c,o}$
$T_{c,i}$
T_c, C_c
dT_c
1
2
x

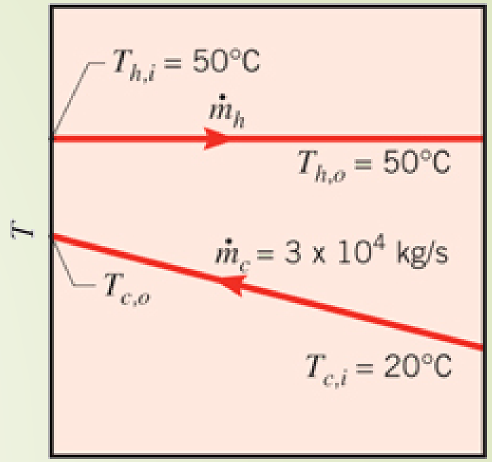
Steam Power Plant Condenser Design



Problem
Large Power Plant with Steam Condenser

- Find T cold out, and Tube Length ("L") Per Pass for required Heat Transfer





$$\dot{m}_{TUBE} = \frac{\dot{m}_{TOTAL}}{\#TUBES}$$

PROPERTIES

$$\mathrm{T}_{c_{FILM}} = \frac{T_{c,i} + T_{c,o}}{2} = \frac{20+?}{2} \rightarrow \text{GUESS } T_{c,o} = 34C \rightarrow \mathrm{T}_{c_{FILM}} = 300K$$

$$water: \rho = 997 kg/m^3, cp = 4179 J/kg-K, \mu = 855x10^{-6} N-s/m^2, k = 0.613 W/m-K, \Pr = 5.83$$

COLD ENERGY BALANCE

$$\mathrm{q=C}_c(T_{c,o} - T_{c,i}) \rightarrow T_{c,o} = \frac{q}{C_c} + T_{c,i} = \frac{2x10^9 W}{3x10^4 kg/s \bullet 4179 J/kg-K} + 20C = 36C$$

UA and Effectiveness

NTU DESIGN PROBLEM, Need UA (NO FOULING FACTORS)

$$UA=\left(\frac{1}{h_iA_i}+\frac{1}{h_oA_o}\right)^{-1}=\left(\frac{1}{A}\left[\frac{1}{h_i}+\frac{1}{h_o}\right]\right)^{-1}\rightarrow \text{THIN WALL TUBE}\rightarrow A=A_i=A_o$$

$$U=\frac{1}{\frac{1}{h_i}+\frac{1}{h_o}},\ h_o=11,000W/m^2-K\rightarrow GIVEN$$

INTERNAL FLOW

$$Re_D=\left(\frac{4\dot{m}}{\pi D\mu}\right)_{\text{ONE TUBE}}=\frac{4\bullet\frac{1kg/s}{tube}}{\pi\bullet 0.025\bullet 855x10^{-6}N-s/m2}=59,567\rightarrow \text{TURBULENT}$$

$$\overline{NU}_D=0.023Re_D^{4/5}Pr^{0.4}=\frac{\overline{h}_iD}{k_{fluid}}=308\rightarrow \overline{h}_i=7543W/m^2-K$$

$$U=\frac{1}{\frac{1}{h_i}+\frac{1}{h_o}}=\frac{1}{\frac{1}{7543W/m^2-K}+\frac{1}{11,000W/m^2-K}}=4474W/m^2-K$$

$$\varepsilon=1-\exp(-NTU),\ NTU=-\ln(1-\varepsilon)$$

Because of STEAM CONDENSING

$$C_h\rightarrow C_{max}\rightarrow\infty\rightarrow CMAX\rightarrow\frac{C_{min}}{C_{max}}=0$$

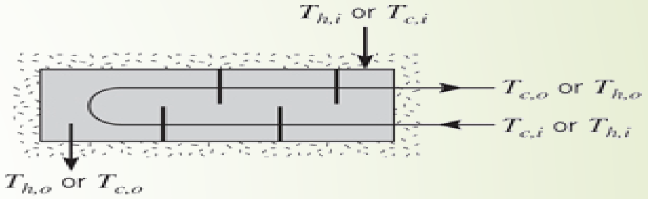
Max Possible Heat Transfer

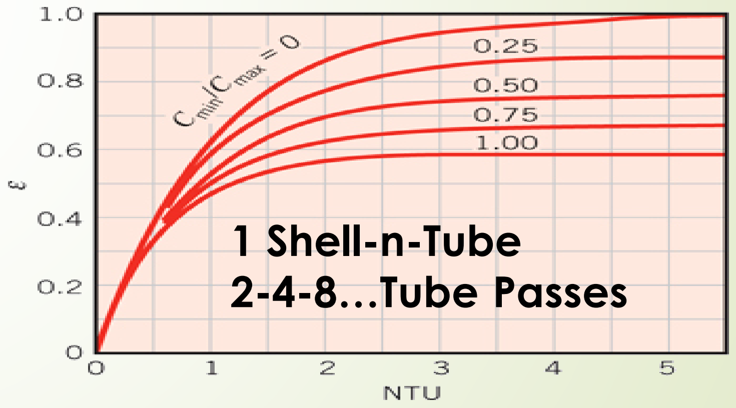
$$q_{max}=C_{min_{TOTAL}}(T_{h,i}-T_{c,i})=C_c(T_{h,i}-T_{c,i})$$

$$=3x10^4kg/s\bullet 4179J/kg-K(50-20)K=3.76x10^9W$$

Effectiveness

$$\varepsilon=\frac{q}{q_{max}}=\frac{2x10^9W}{3.76x10^9W}=0.532$$





$$NTU\left(\frac{C_{min}}{C_{max}}=0,\varepsilon=0.532\right)\rightarrow 0.759=\frac{UA}{C_{min}}$$

TUBE LENGTH

$$NTU\left(\frac{C_{\min}}{C_{\max}} = 0, \varepsilon = 0.532\right) \rightarrow 0.759 = \frac{\frac{U}{tube} \bullet \# tubes \bullet A_{TOTAL}}{C_{\min}}$$

$$A_{TOTAL} = \pi D \frac{L_{TOTAL}}{pass} \bullet \frac{\# passes}{shell} \bullet \# shells$$

$$\frac{L_{TOTAL}}{pass} = \frac{0.759 \bullet C_{\min}}{\frac{U}{tube}\left(\pi D \bullet \frac{\# passes}{shell} \bullet \# tubes \bullet \# shells\right)}$$

$$\frac{\# passes}{shell} = 2$$

$$\# tubes = 30{,}000$$

$$\# shells = 1$$

$$\frac{L_{TOTAL}}{pass} = 4.51m \text{ per pass}$$

PHASE CHANGE

$$q = \dot{m}_h h_{fg} = (\dot{m}cp)_{cold}\, \Delta T_{cold}$$

$$\dot{m}_h = \frac{(\dot{m}cp)_{cold}\, \Delta T_{cold}}{h_{fg}}$$

Because of STEAM CONDENSING

$$C_h \rightarrow C_{\max} \rightarrow \infty \rightarrow CMAX \rightarrow \frac{C_{\min}}{C_{\max}} = 0$$

Max Possible Heat Transfer

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

$$= 3x10^4\, kg/s \bullet 4179 J/kg - K(50-20)K = 3.76x10^9 W$$

Effectiveness

$$\varepsilon = \frac{q}{q_{\max}} = \frac{2x10^9 W}{3.76x10^9 W} = 0.532$$

$$NTU_{TOTAL} \equiv \frac{UA(TOTAL)}{C_{\min}(TOTAL)}$$

$UA \equiv$ TOTAL RESISTANCE--ALL TUBES

$C_{\min} \equiv$ TOTAL CAPACITANCE--ALL TUBES

$$NTU_{TOTAL} = \left(\frac{(U_{one-tube} \bullet \#\text{ tubes} \bullet A_{TOTAL}}{C_{\min-TOTAL}}\right)$$

Pressure Drop, Power, and COST

TURBULENT

$Re_D > 2300$

$$\frac{1}{\sqrt{f}} = -1.8\log_{10}\left(\left(\frac{\varepsilon / D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right)$$

Smooth ε=0

f=0.0376,

$$L_{TOTAL} = \frac{L_{TOTAL}}{pass} \bullet \#passes=9m$$

$$\frac{\Delta P}{TUBE} = \frac{fL}{D}\frac{\rho\frac{u_m^2}{TUBE}}{2} = \frac{28,764Pa}{TUBE}, \rightarrow \frac{\dot{m}}{TUBE} = \rho_{fluid} A_c \frac{u_m}{TUBE} \rightarrow A_c = \frac{\pi D^2}{4}$$

POWER

$$\dot{P}_{ower} = \frac{\frac{\Delta P}{TUBE}\dot{m}_{TOTAL}}{\rho_{water}} = \frac{\frac{28,764Pa}{TUBE}30,000kg/s}{997kg/m3} = 0.87MW \rightarrow \text{TOTAL POWER REQUIRED-PUMP}$$

COST – –Electric Pump

$$\eta_{pump} = 0.87$$

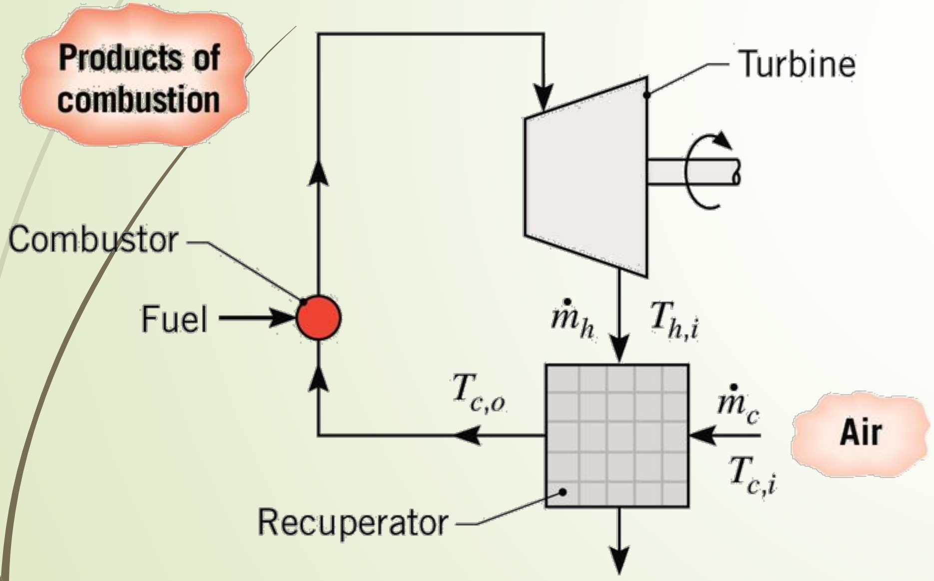
$$Electric = \frac{\$0.05}{kWh}$$

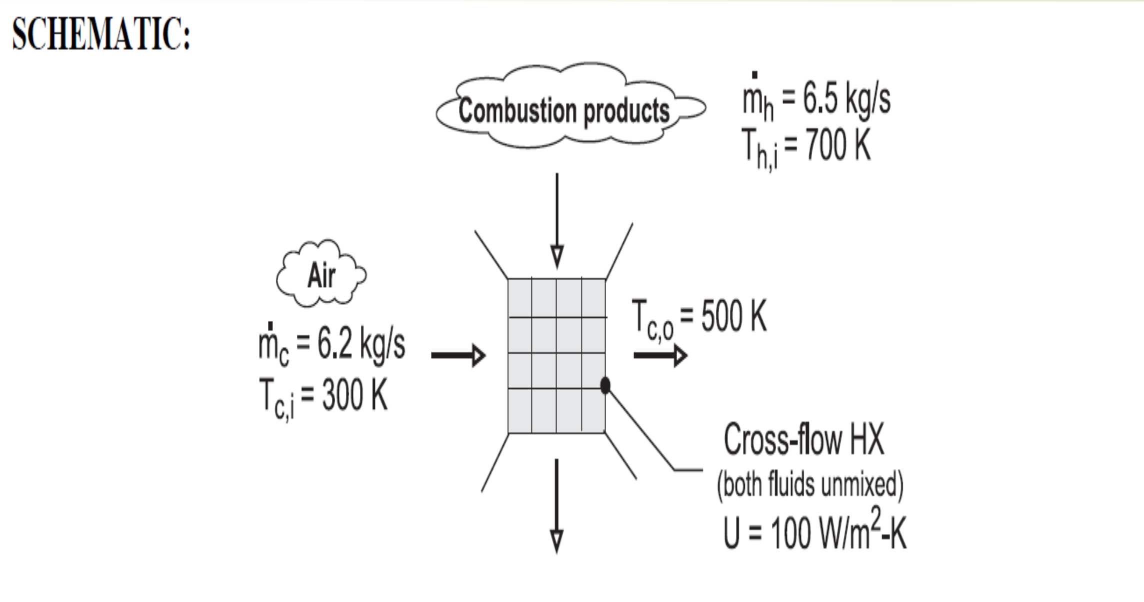
$$\text{Operating Cost} = \frac{0.87x10^6 W \bullet \frac{\$0.05x10^{-3}}{Whr} \bullet 8,760\frac{hr}{yr}}{0.87}$$

$$= \$438,000 / year$$

A recuperator is a heat exchanger that heats air used in a combustion process by extracting energy from the products of combustion as shown below. (air and combustion products have cp=1040 J/kg-K)

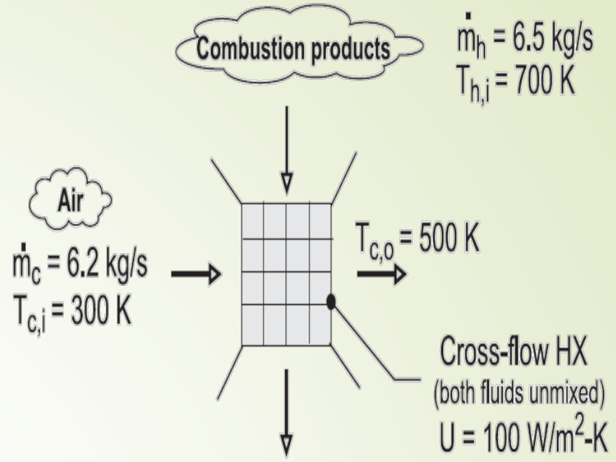
Find: Surface Area as function of Tc,o.





How do you MAXIMIZE heat transfer rates?

SCHEMATIC:



Properties

$$cp,_c = cp,_h = 1040 J/kg-K$$

Analysis

$$C_{min} = C_c = 6.2 kg/s \bullet 1040 J/kg-K = 6,448 W/k$$

$$C_{max} = C_h = 6.5 kg/s \bullet 1040 J/kg-K = 6,760 W/K$$

$$C_r = \frac{C_{min}}{C_{max}} = 0.954$$

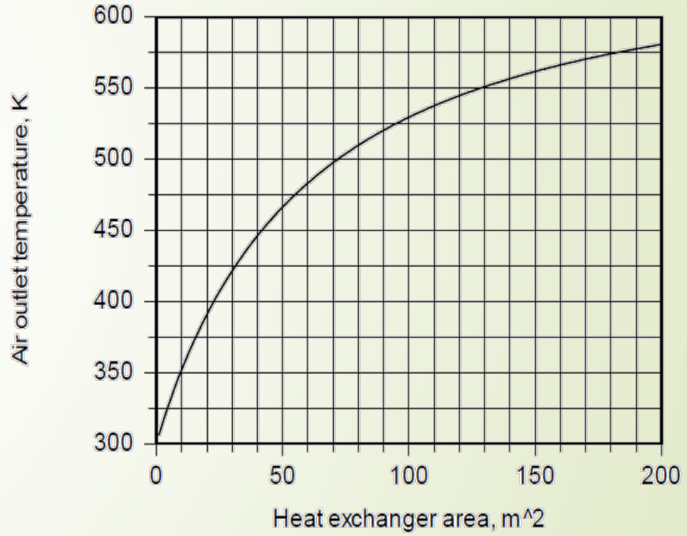
$$q_{max} = C_{min}(T_{h,i} - T_{c,i}) = 6,448 W/K(400K) = 2.58x10^6 W$$

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

$$\varepsilon = \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})} = \frac{6,448 W/K(500-300)}{6,448 W/K(700-300)} = 0.50$$

$$NTU \approx 1.10 = UA/C_{min} \rightarrow FIG: 11.14(\text{both unmixed})$$

$$A = \frac{NTU \bullet C_{min}}{U} = 70.9 m^2$$



NOTE: As area **increases**, Tco increases but the % increase is less and less as you approach Th,i. To maximize Tco (and q) would require large heat exchanger and costly.

PROBLEMS

11.10, 11.14, 11.18,
11.23, 11.32, 11.35

11.63a, 11.64,
11.76abc