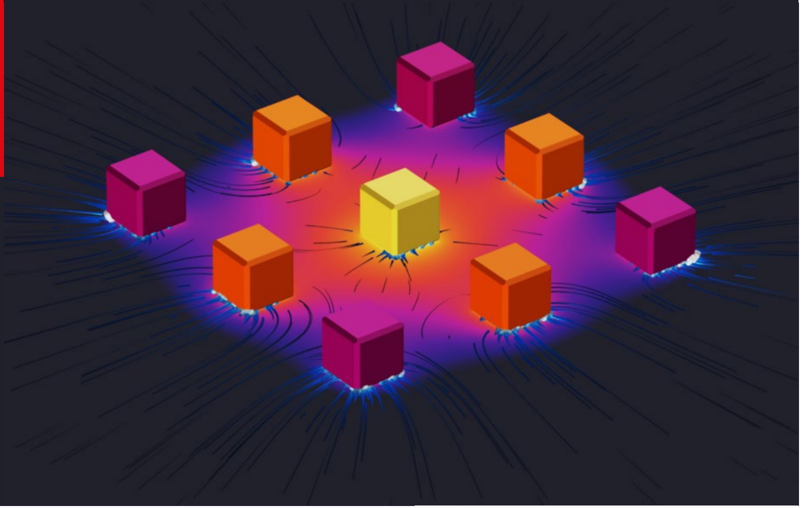
Heat and Mass Transfer ME-341

Instructor: Giulia Tagliabue



École polytechnique fédérale de Lausanne

Spring Semester

Previously

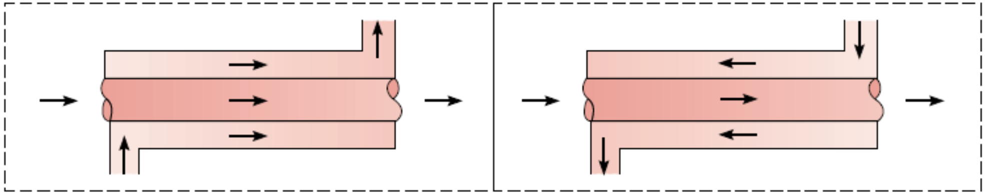
- ☑ Parallel Flow Design
  - ☑ Temperature Profile and Total Heat Transfer
- ☑ Counter-flow Design

Learning Objectives:

- ☑ Calculate the total heat transfer for parallel flow HE
- ☑ Calculate the total heat transfer for counter flow HE

Introduction to Heat Exchangers

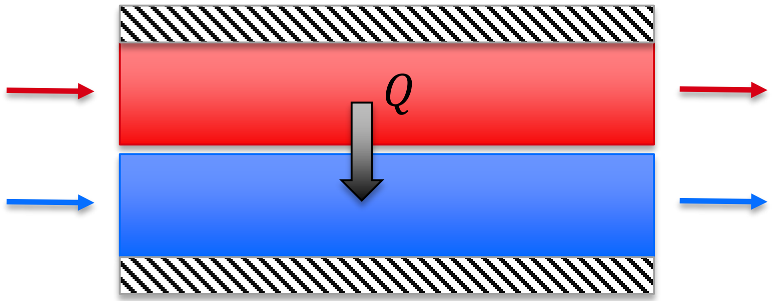
A. Concentric Flow

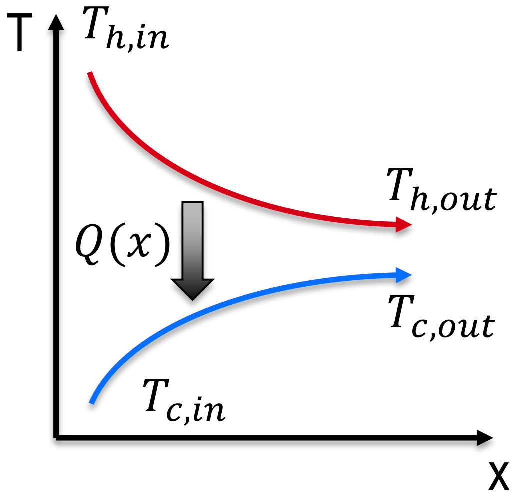


Parallel Flow	Counter Flow

Parallel Flow Heat Exchanger

Temperature Profile



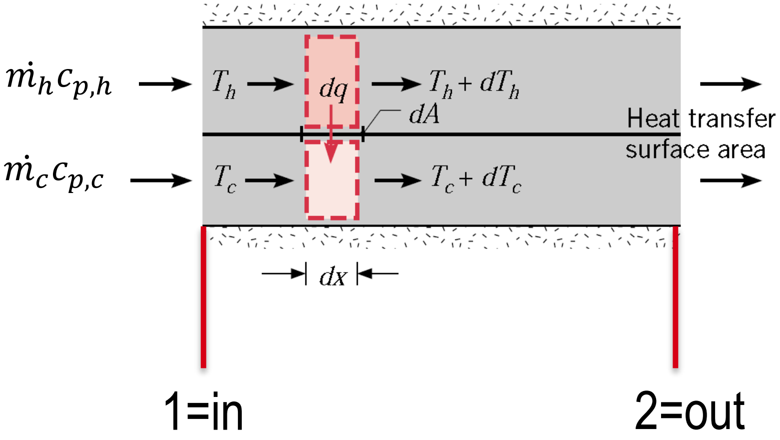


- What is an appropriate ΔT_m?

- Let's write a local energy balance, similar to what we did for internal forced convection

Parallel Flow heat Exchanger

Temperature Profile and Total Heat Transfer



$$Q = \mathrm{UA}\frac{\Delta T_2 - \Delta T_1}{ln\left(\Delta T_2/\Delta T_1\right)} = UA\Delta T_m$$

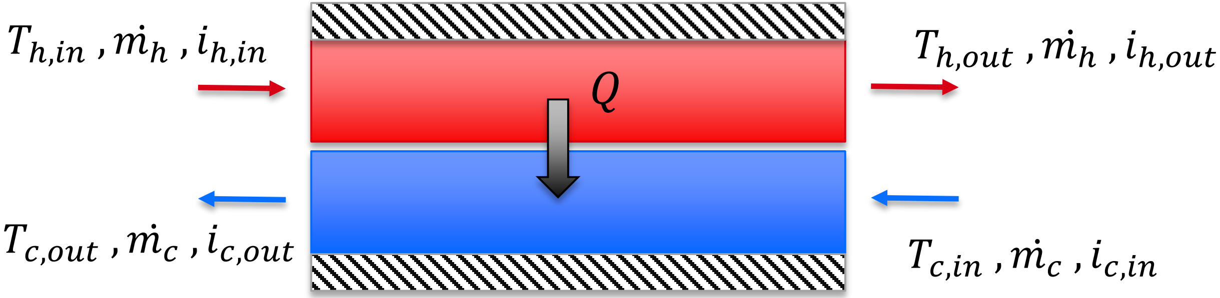
$$\Delta T_m = \frac{\Delta T_2 - \Delta T_1}{ln\left(\Delta T_2/\Delta T_1\right)}$$

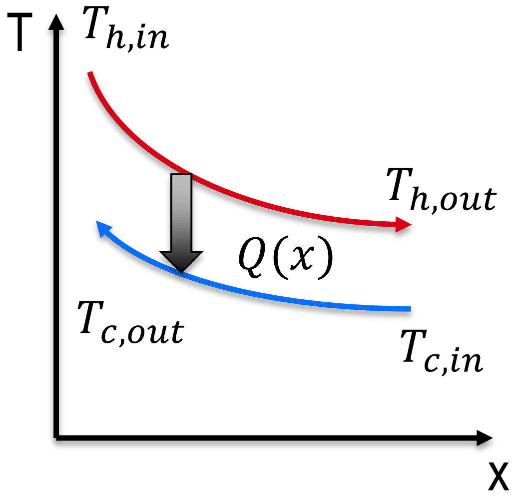
$$\Delta T_1 = \left(T_{h,1} - T_{c,1}\right) = \left(T_{h,in} - T_{c,in}\right)$$

$$\Delta T_2 = \left(T_{h,2} - T_{c,2}\right) = \left(T_{h,out} - T_{c,out}\right)$$

Counter Flow Heat Exchanger

Temperature Profile

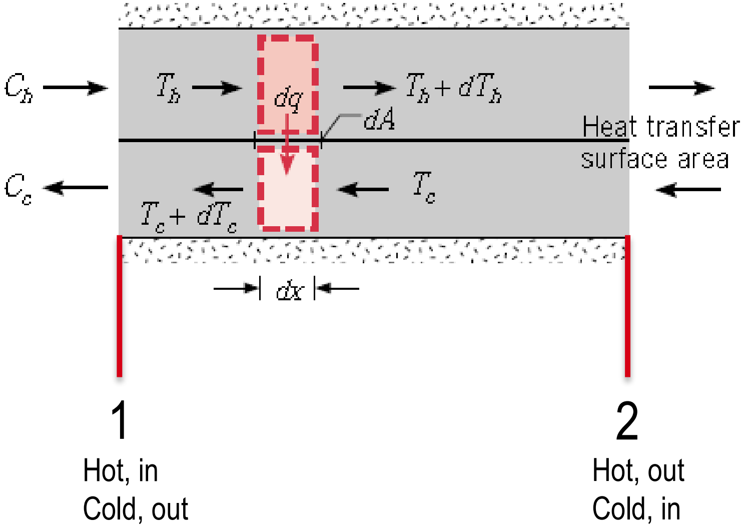




➡ What is an appropriate ΔT_m?

Counter Flow heat Exchanger

Temperature Profile and Total Heat Transfer



$$Q = \text{UA}\frac{\Delta T_2 - \Delta T_1}{ln\left(\Delta T_2 / \Delta T_1\right)} = UA\Delta T_m$$

$$\Delta T_m = \frac{\Delta T_2 - \Delta T_1}{ln\left(\Delta T_2 / \Delta T_1\right)}$$

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This Lecture

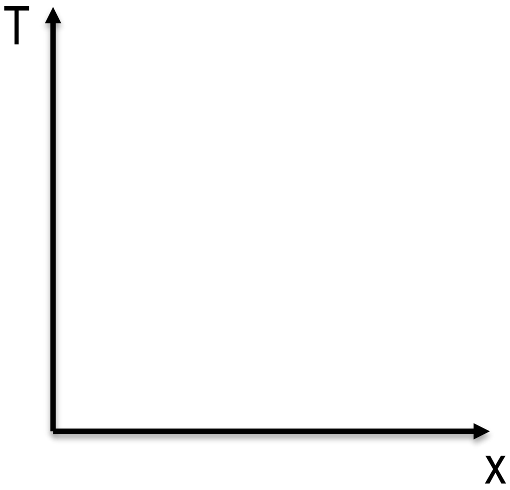
- ❑ Special Operating Conditions
- ❑ Exercises

Learning Objectives:

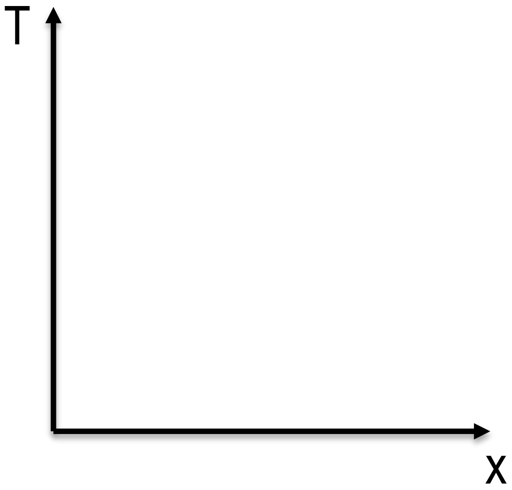
- ❑ Recognize specific conditions

Special Operating Conditions

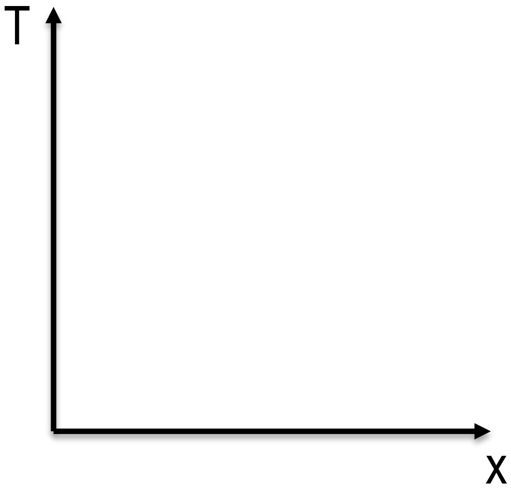
Representations Based on Counter Flow



- Condensing vapor on the hot-side
- $C_h \gg C_c$



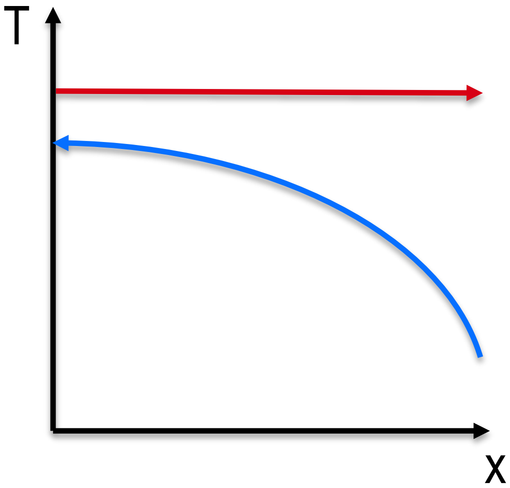
- Evaporating liquid on the cold side
- $C_h \ll C_c$



- $C_h \sim C_c$

Special Operating Conditions

Representations Based on Counter Flow



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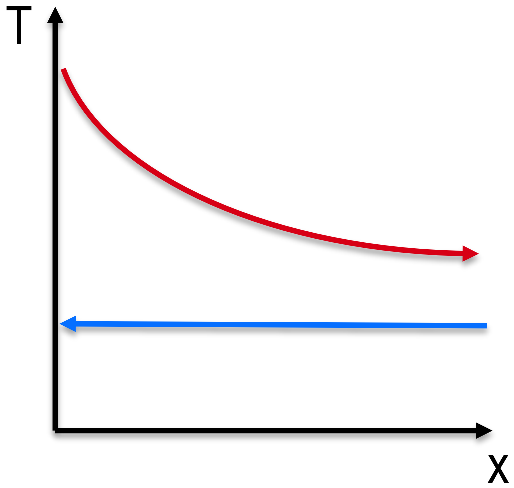

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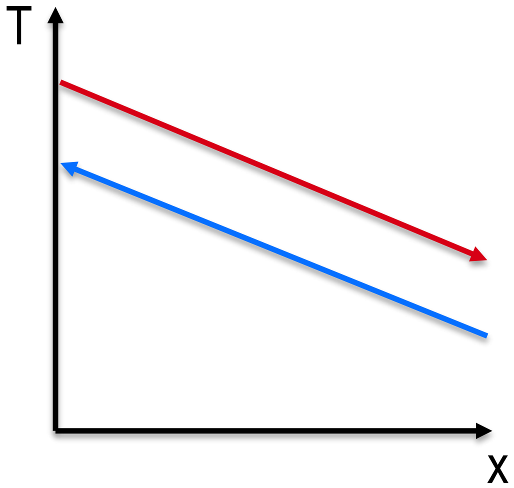


- $C_h \sim C_c$

This Lecture

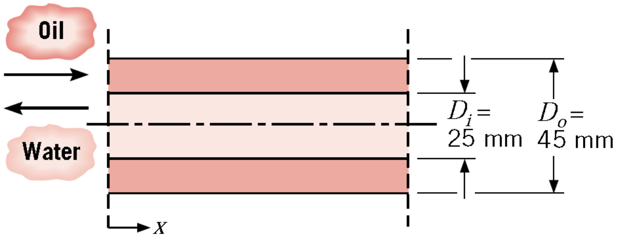
- [x] Special Operating Conditions
- [ ] Exercises

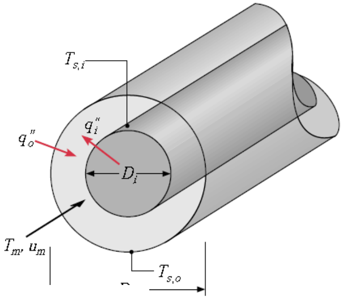
Learning Objectives:

- [x] Recognize specific conditions

Example

A counterflow, concentric tube heat exchanger is used to cool the lubricating oil for a large industrial gas turbine engine. The flow rate of cooling water through the inner tube (D_i = 25 mm) is 0.2 kg/s, while the flow rate of oil through the outer annulus (D_o = 45 mm) is 0.1 kg/s. The oil and water enter at temperatures of 100 and 30°C, respectively. How long must the tube be made if the outlet temperature of the oil is to be 60°C?





Assumptions:

1. Negligible heat loss to the surroundings.
2. Negligible kinetic and potential energy changes.
3. Constant properties.
4. Negligible tube wall thermal resistance and fouling factors.
5. Fully developed conditions for the water and oil (U independent of x).

For the cold side estimate the physical properties at T =35C

Forced Convection in an Annular Passage:

Note that separate convection coefficients are associated with the inner and outer surfaces. The corresponding Nusselt numbers are of the form

$$Nu_i \equiv \frac{h_i D_h}{k} \tag{8.69}$$

$$Nu_o \equiv \frac{h_o D_h}{k} \tag{8.70}$$

the hydraulic diameter D_h is

$$D_h = \frac{4(\pi/4)(D_o^2 - D_i^2)}{\pi D_o + \pi D_i} = D_o - D_i$$

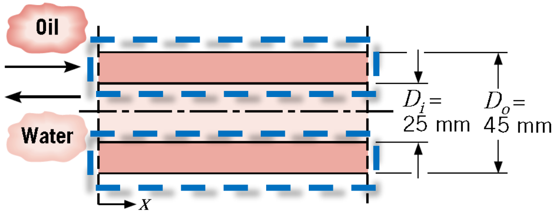
For the case of fully developed laminar flow with one surface insulated and the other surface at a constant temperature, Nu_i or Nu_o may be obtained from Table 8.2.

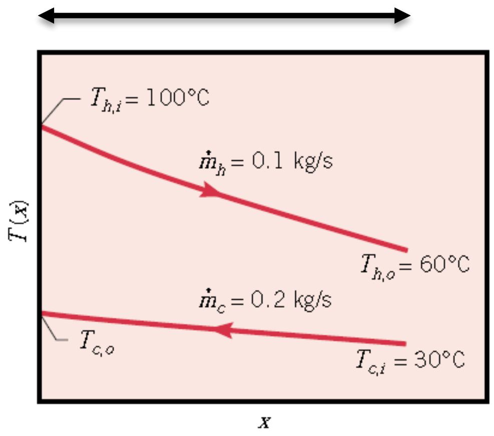
TABLE 8.2 Nusselt number for fully developed laminar flow in a circular tube annulus with one surface insulated and the other at constant temperature

D_i/D_o	Nu_i	Nu_o	*Comments*
0	—	3.66	See Equation 8.55
0.05	17.46	4.06	
0.10	11.56	4.11	
0.25	7.37	4.23	
0.50	5.74	4.43	
≈1.00	4.86	4.86	See Table 8.1, $b/a \to \infty$

Used with permission from W. M. Kays and H. C. Perkins, in W. M. Rohsenow and J. P. Hartnett, Eds., *Handbook of Heat Transfer*, Chap. 7, McGraw-Hill, New York, 1972.

Example





Properties: Table A.5, unused engine oil ($\overline{T}_h = 80°C = 353$ K): $c_p = 2131$ J/kg · K, $\mu = 3.25 \times 10^{-2}$ N · s/m^2, $k = 0.138$ W/m · K. Table A.6, water ($\overline{T}_c \approx 35°C$): $c_p = 4178$ J/kg · K, $\mu = 725 \times 10^{-6}$ N · s/m^2, $k = 0.625$ W/m · K, $Pr = 4.85$.

For the hot fluid we know both inlet and outlet temperatures hence we can determine the overall heat that must be removed as it flows through the heat exchanger by applying the energy balance to the hot side:

$$q = \dot{m}_h c_{p,h}(T_{h,i} - T_{h,o})$$

$$q = 0.1 \text{ kg/s} \times 2131 \text{ J/kg} \cdot \text{K } (100 - 60)°\text{C} = 8524 \text{ W}$$

All this heat must be transferred to the cold side, therefore we can immediately determine the exit temperature of the cold fluid:

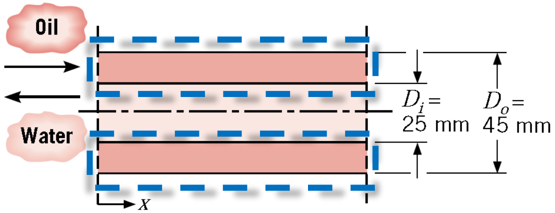
$$T_{c,o} = \frac{q}{\dot{m}_c c_{p,c}} + T_{c,i}$$

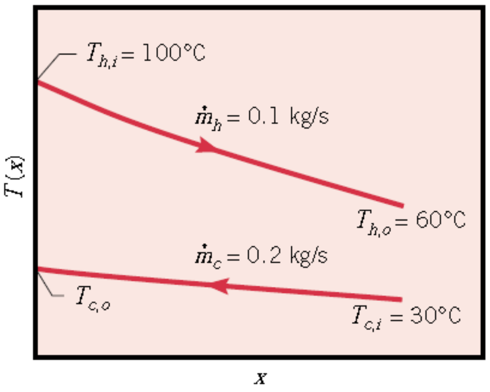
$$T_{c,o} = \frac{8524 \text{ W}}{0.2 \text{ kg/s} \times 4178 \text{ J/kg} \cdot \text{K}} + 30°\text{C} = 40.2°\text{C}$$

Now that we know all the inlet/outlet temperatures we can estimate the length of the heat exchanger by considering the overall energy balance:

$$q = UA\,\Delta T_{\text{lm}} \qquad \text{where } A = \pi D_i L$$

Example





We calculate the logarithmic mean temperature for a counter-flow heat exchanger:

$$\Delta T_{\text{lm}} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln\left[(T_{h,i} - T_{c,o})/(T_{h,o} - T_{c,i})\right]} = \frac{59.8 - 30}{\ln(59.8/30)} = 43.2°\text{C}$$

Assuming negligible conduction resistance of the wall, the overall heat transfer is affected only by the convection on the cold and hot side:

$$\frac{1}{UA} = R_{conv,cold} + R_{conv,cold} = \frac{1}{h_{cold}A_{cold}} + \frac{1}{h_{hot}A_{hot}}$$

As the thickness of the tube wall is negligible, the areas are the same both for hot and cold convection, therefore:

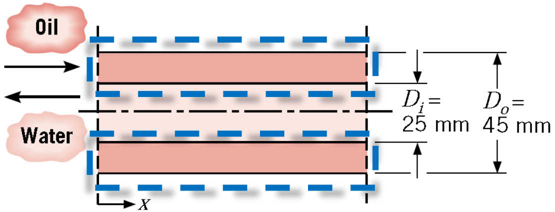
$$\frac{1}{U} = \frac{1}{h_{cold}} + \frac{1}{h_{hot}}$$

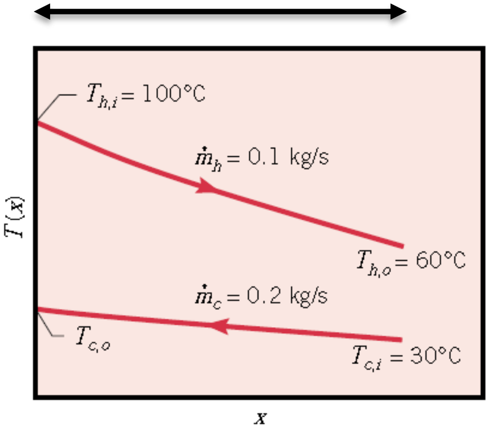
The convection conditions for the two sides are:

- Cold side: internal forced convection, circular tubes, fully developed flow
- Hot side: internal forced convection, annular passage, fully developed flow

Example

$$\frac{1}{U} = \frac{1}{h_{cold}} + \frac{1}{h_{hot}}$$





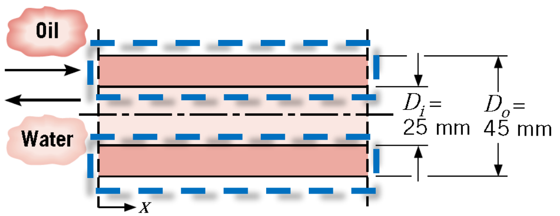
Cold side:

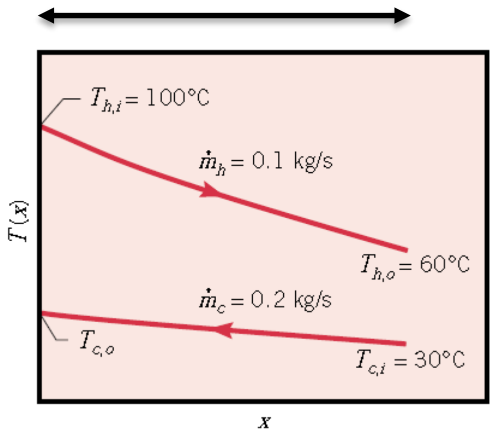
$$Re_D = \frac{4\dot{m}_c}{\pi D_i \mu} = \frac{4 \times 0.2\ \text{kg/s}}{\pi (0.025\ \text{m}) 725 \times 10^{-6}\ \text{N} \cdot \text{s/m}^2} = 14{,}050$$ > 10000 > 2300, turbulent flow

$$Nu_D = 0.023\ Re_D^{4/5}\ Pr^{0.4}$$
$$Nu_D = 0.023\ (14{,}050)^{4/5}\ (4.85)^{0.4} = 90$$

$$h_i = Nu_D \frac{k}{D_i} = \frac{90 \times 0.625\ \text{W/m} \cdot \text{K}}{0.025\ \text{m}} = 2250\ \text{W/m}^2 \cdot \text{K}$$

Example





$$\frac{1}{U} = \frac{1}{h_{cold}} + \frac{1}{h_{hot}}$$

Hot side:

$$D_h = D_o - D_i = 0.02 \text{ m},$$

$$Re_D = \frac{\rho u_m D_h}{\mu} = \frac{\rho(D_o - D_i)}{\mu} \times \frac{\dot{m}_h}{\rho\pi(D_o^2 - D_i^2)/4}$$

$$\dot{m} = \rho\dot{V} = \rho u A_c$$

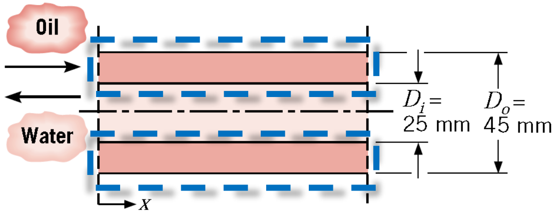
$$Re_D = \frac{4\dot{m}_h}{\pi(D_o + D_i)\mu} = \frac{4 \times 0.1 \text{ kg/s}}{\pi(0.045 + 0.025) \text{ m} \times 3.25 \times 10^{-2} \text{ kg/s} \cdot \text{m}} = 56.0$$

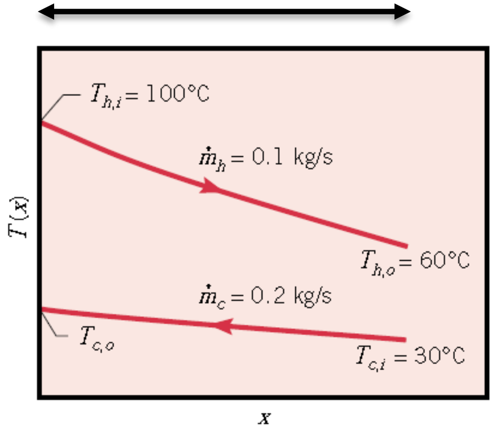
Re_D< 2300, laminar flow

$$\frac{D_i}{D_o} = 0.56 \quad \Rightarrow \quad Nu_i = \frac{h_o D_h}{k} = 5.63$$

$$h_o = 5.63 \frac{0.138 \text{ W/m} \cdot \text{K}}{0.020 \text{ m}} = 38.8 \text{ W/m}^2 \cdot \text{K}$$

Example





$$\frac{1}{U} = \frac{1}{h_{cold}} + \frac{1}{h_{hot}}$$

$$U = \frac{1}{(1/2250\ \mathrm{W/m^2 \cdot K}) + (1/38.8\ \mathrm{W/m^2 \cdot K})} = 38.1\ \mathrm{W/m^2 \cdot K}$$

$$L = \frac{q}{U \pi D_i \Delta T_{\mathrm{lm}}} = \frac{8524\ \mathrm{W}}{38.1\ \mathrm{W/m^2 \cdot K}\ \pi\ (0.025\ \mathrm{m})\ (43.2°\mathrm{C})} = 65.9\ \mathrm{m}$$

Comments:

1. The hot side convection coefficient controls the rate of heat transfer between the two fluids, and the low value of h_o is responsible for the large value of L. Incorporation of heat transfer enhancement methods, such as described in Section 8.8, could be used to decrease the size of the heat exchanger.
2. Because $h_i \gg h_o$, the tube wall temperature will follow closely that of the coolant water. Accordingly, the assumption of uniform wall temperature, which is inherent in the use of Table 8.2 to obtain h_o, is reasonable.

Next Lecture

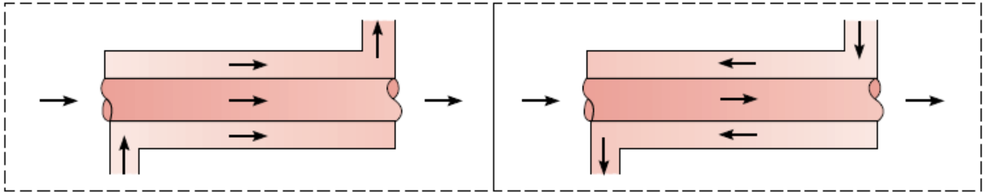
- ❑ Heat Exchanger Analysis/Design/Performance Calculation
  - ❑ Effectiveness-NTU method

Learning Objectives:

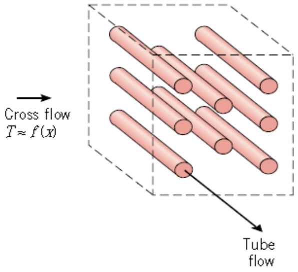
- ❑ Identify the design parameter for a heat exchanger
- ❑ Analyze the performance of a heat exchanger

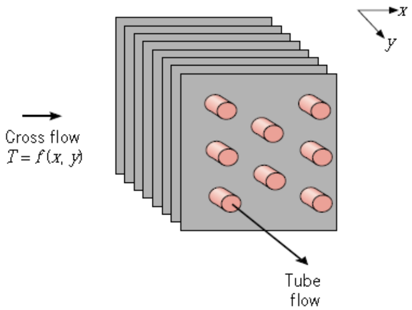
Introduction to Heat Exchangers

A. Concentric Flow

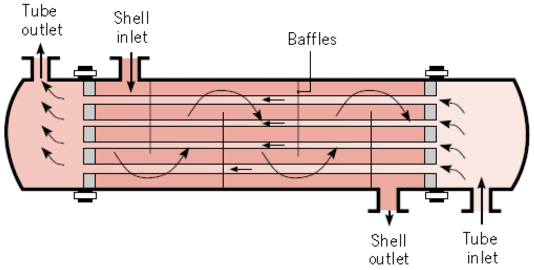


B. Cross-Flow

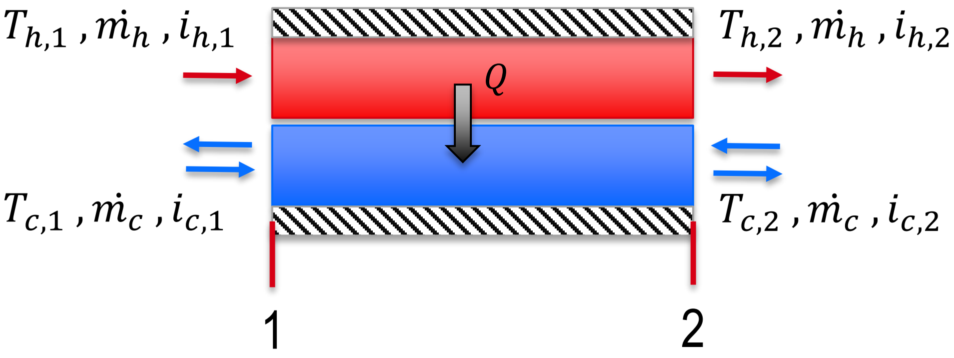




C. Shell-and-Tube



Effectiveness-NTU Method



$$Q = -Q_h = -C_h(T_{h,out} - T_{h,in})$$

$$Q = Q_c = C_c(T_{c,out} - T_{c,in})$$

$$\Delta T_m = \frac{\Delta T_2 - \Delta T_1}{ln\left(\Delta T_2 / \Delta T_1\right)}$$

$$Q = \mathrm{UA}\frac{\Delta T_2 - \Delta T_1}{ln\left(\Delta T_2 / \Delta T_1\right)} = UA\Delta T_m$$

How do we design the heat exchanger if we do NOT know all the four temperatures ?
What about shell-tube heat exchangers where there are various flow configurations?