Before turning to radiation (last topic) we will discuss a few practical applications.

How can we use Fundamental Heat Transfer to understand real devices like heat exchangers?
The heat transfer from the outside to the inside is just heat flux in an annular shell.

The Simplest Heat Exchanger:
Double-Pipe Heat exchanger - counter current

Example 4: Heat flux in a cylindrical shell

Assumptions:
• long pipe
• steady state
• $k =$ thermal conductivity of wall
• $h_1, h_2 =$ heat transfer coefficients

Maybe we can use heat transfer coefficient to understand forced-convection heat exchangers. . .

BUT . . .
**BUT:** The temperature difference between the fluid and the wall **varies** along the length of the heat exchanger.

**The Simplest Heat Exchanger:**
Double-Pipe Heat exchanger - counter current

The temperature difference between the fluid and the wall varies along the length of the heat exchanger.

How can we adapt $h$ so that we can use the concept to characterize heat exchangers?

Let's look at the solution for radial conduction in an annulus

Example 4: Heat flux in a cylindrical shell

**Solution:**

$$q_r = \frac{c_1}{A} \cdot \frac{r}{r}$$

$$T = -\frac{c_1}{k} \ln r + c_2$$

Boundary conditions?
Example 4: Heat flux in a cylindrical shell, Newton’s law of cooling boundary Conditions

Results: Radial Heat Flux in an Annulus

\[ T - T_{b2} = \frac{(T_{b1} - T_{b2}) \left( \ln \left( \frac{R_2}{r} \right) + \frac{k}{h_2 R_2} \right)}{\frac{k}{h_2 R_2} + \ln \left( \frac{R_2}{R_1} \right) + \frac{k}{h_1 R_1}} \]

\[ q_r = \frac{A}{R_2} \left( \frac{T_{b1} - T_{b2}}{1 + \frac{1}{k} \ln \left( \frac{R_2}{R_1} \right) + \frac{1}{h_1 R_1}} \right) \]

Note that total heat flow is proportional to bulk \( \Delta T \) and (almost) area of heat transfer
Overall Heat Transfer Coefficient, $U$

$$Q = UA \Delta T$$

$$= UA(T_{b1} - T_{b2})$$

this equation serves as the definition of $U$

$A =$ area of heat transfer (not always unambiguous)

$\Delta T =$ driving temperature difference

Example: in a pipe

$\text{Do we use inner or outer area?}$

$$\tau_{2} \Delta U = \text{driving temperature difference}$$

$$\tau_{2} \Delta U = \text{driving temperature difference}$$

Area must be specified when $U$ is reported
Heat flux in a cylindrical shell: \( Q = UA(T_{b1} - T_{b2}) \)

But, in an actual heat exchanger, \( T_{b1} \) and \( T_{b2} \) vary along the length of the heat exchanger.

What kind of average do we use?

The Simplest Heat Exchanger:
Double-Pipe Heat exchanger - counter current

We will do an open-system energy balance on a differential section to determine the correct average temperature difference to use.
The Simplest Heat Exchanger: Double-Pipe Heat exchanger - counter current

Another way of looking at it:

\[ Q_{\text{inside}} = Q = -Q_{\text{outside}} \]

Can do three balances:

1. Balance on the inside system

\[ Q_{\text{inside}} = Q = -Q_{\text{outside}} \]
The Simplest Heat Exchanger:
Double-Pipe Heat exchanger - counter current

Another way of looking at it:

Can do three balances:
1. Balance on the inside system
2. Balance on the outside system
3. Overall balance

\[
Q_{\text{inside}} = Q = -Q_{\text{outside}}
\]

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The Simplest Heat Exchanger: Double-Pipe Heat exchanger - counter current

Another way of looking at it:

$$Q_{inside} = Q = -Q_{outside}$$

We can do:
- a macroscopic balances over the entire heat exchanger, or
- a pseudo microscopic balance over a slice of the heat exchanger

All the details of the algebra are here:
www.chem.mtu.edu/~fmorriso/cm310/double_pipe.pdf

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Pseudo Microscopic Energy Balance on a slice of the heat exchanger

Open system energy balance on a differential control volume:

\[ \Delta E_p + \Delta E_k + \Delta H = Q_{in} + W_{s,\text{net}} \]

\[ \Delta H = Q_{in} \]

\[ \Delta Q_{in,\text{inter}} \]

INSIDE BALANCE

\[ \hat{H}_x \quad \Delta x \quad \hat{H}_{x+\Delta x} \]

recall: \( \Delta \) is out-in

Pseudo Microscopic Energy Balance on a slice of the heat exchanger

\[ \Delta H = Q_{in} \]

\[ \Delta Q_{in,\text{outer}} \]

OUTSIDE BALANCE

\[ \hat{H'}_x \quad \Delta x \quad \hat{H'}_{x+\Delta x} \]

recall: \( \Delta \) is out-in

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Pseudo Microscopic Energy Balance on a slice of the heat exchanger

\[ \Delta E_p + \Delta E_k + \Delta H = Q_{in} + W_{in,\text{net}} \]

OVERALL BALANCE

\[ \Delta Q_{m,\text{outer}} \]

\[ \Delta Q_{m,\text{inner}} \]

\[ \Delta x \]

\[ \Delta H = 0 \]

This expression characterizes the rate of change of heat transferred with respect to distance down the heat exchanger.

\[ \Delta H = 0 \]

energy balance on overall differential system

\[ \Delta H_{\text{inner system}} + \Delta H_{\text{outer system}} = 0 \]

heat into inner differential system

\[ \Delta Q_{m,\text{inner}} \]

heat into outer differential system

\[ \Delta Q_{m,\text{outer}} \]

divide by \( \Delta x \) and take the limit as \( \Delta x \) goes to zero:

\[ \left( \frac{dQ_{m,\text{inner}}}{dx} \right) = \left( \frac{dQ_{m,\text{outer}}}{dx} \right) \]

\[ \equiv \frac{dQ_m}{dx} \]
The Simplest Heat Exchanger:  
Double-Pipe Heat exchanger - counter current

Result of inside balance:
\[ \frac{dQ_{\text{inner}}}{dx} = m\hat{c}_p \left( \frac{dT}{dx} \right) \]

Result of outside balance:
\[ -\frac{dQ_{\text{outer}}}{dx} = m\hat{T}' \left( \frac{dT'}{dx} \right) \]

Result of overall balance:
\[ \frac{dQ_{\text{inner}}}{dx} = \frac{dQ_{\text{outer}}}{dx} = \frac{dQ_{\text{in}}}{dx} = \frac{dQ_{\text{in}}}{dx} \]

Solve for temperature derivatives, and subtract:
\[ dQ_{\text{in}} \left( \frac{1}{m\hat{c}_p} - \frac{1}{m\hat{c}_p} \right) = \left( \frac{dT'}{dx} - \frac{dT}{dx} \right) = \frac{d(T' - T)}{dx} \]

This depends on \( T' - T \)

All the details of the algebra are here:
www.chem.mtu.edu/~fmorris/cm310/double_pipe.pdf

---

Analysis of double-pipe heat exchanger (continued)

Rate of change of heat transferred with respect to distance down the heat exchanger

Driving force for heat transfer

**Question:** How can we write \( \frac{dQ_{\text{in}}}{dx} \) in terms of \( T' - T \) ?

**Answer:** Define an “overall” heat transfer coefficient, \( U \)
Want to integrate to solve for $T' - T$, but this is a function of $T' - T$.

For the differential slice of the heat exchanger that we are considering (modeling our ideas on Newton's law of cooling),

$$\frac{dQ_{in}}{dA} = (?) (T' - T)$$

For the differential slice of the heat exchanger that we are considering (modeling our ideas on Newton's law of cooling),

$$dQ_{in} = (U) dA (T' - T) = U(2\pi R dx (T' - T))$$

We can write $\frac{dQ_{in}}{dx}$ in terms of $T' - T$ if we define an "overall" heat transfer coefficient, $U$.

This is the missing piece that we needed.
\[
\frac{d(T' - T)}{dx} = \frac{dQ_{in}}{dx} \left( \frac{1}{m'\hat{C}_p'} - \frac{1}{m\hat{C}_p} \right)
\]

\[
\frac{dQ_{in}}{dx} = 2\pi RU(T' - T)
\]

\[
\frac{d(T' - T)}{dx} = 2\pi RU \left( T' - T \right) \left( \frac{1}{\hat{C}_p' m'} - \frac{1}{\hat{C}_p m} \right)
\]

\[
\frac{d(T' - T)}{(T' - T)} = \left[ 2\pi RU \left( \frac{1}{\hat{C}_p' m'} - \frac{1}{\hat{C}_p m} \right) \right] dx
\]

\[
\Phi \equiv T' - T
\]

\[
\alpha_0 \equiv 2\pi RU \left( \frac{1}{\hat{C}_p' m'} - \frac{1}{\hat{C}_p m} \right)
\]  

(we'll assume \( U \) is constant)

\[
\frac{d\Phi}{\Phi} = \alpha_0 dx
\]

\[
\int \frac{d\Phi}{\Phi} = \alpha_0 \int dx
\]

\[
\ln\Phi = \alpha_0 x + \text{constant}
\]

\[
\Phi = \Phi_0 e^{\alpha_0 x}
\]

B.C.: \( x = 0, T - T' = T_1 - T_1' \)
Temperature profile in a double-pipe heat exchanger:

\[
\frac{T' - T}{T'_1 - T_1} = e^{\alpha_0 x} \quad \alpha_0 = 2\pi RU \left( \frac{1}{\hat{C}^{'\prime} m'} - \frac{1}{\hat{C}_p m} \right)
\]

\[
\frac{T'' - T}{T'_{1'} - T'_{1}} = e^{\alpha_0 L \left( \frac{x}{L} \right)} \quad \alpha_0 L = 2\pi RLU \left( \frac{1}{\hat{C}^{'\prime} m'} - \frac{1}{\hat{C}_p m} \right)
\]

Note that the temperature curves are not linear.
Temperature profile in a double-pipe heat exchanger:

\[
\frac{T' - T}{T'_1 - T'_0} = e^{\alpha_0 x}
\]

\[
\alpha_0 = 2\pi RU \left( \frac{1}{C'_p m'} - \frac{1}{C_p m} \right)
\]

Useful result, but what we **REALLY** want is an easy way to relate \( Q_{in, overall} \) to inlet and outlet temperatures.

At the exit: \( x = L, \ \ (T - T') = (T_2 - T'_2) \)

\[
\ln \left( \frac{T'_2 - T_2}{T'_1 - T_1} \right) = U \left( 2\pi RL \right) \left( \frac{1}{C'_p m'} - \frac{1}{C_p m} \right)
\]

The \( mC_p \) terms appear in the overall macroscopic energy balances. We can therefore rearrange this equation by replacing the \( mC_p \) terms with \( Q_{in} \):

\[
Q_{in} = mC_p (T_2 - T_1)
\]

\[
\Rightarrow \frac{1}{mC_p} = \frac{T_2 - T_1}{Q_{in}}
\]

\[
-Q_{in} = mC_p (T'_2 - T'_1)
\]

\[
\Rightarrow \frac{1}{mC_p} = \frac{(T'_2 - T'_1)}{Q_{in}}
\]

\[
Q_{in} = UA \frac{(T'_2 - T_2) - (T'_1 - T_1)}{\ln \left( \frac{T'_2 - T_2}{T'_1 - T_1} \right)}
\]

total heat transferred in exchanger

average temperature driving force
\[
Q = U(2\pi RL) \frac{(T'_{1} - T_{1}) - (T'_{2} - T_{2})}{A} \ln \left( \frac{T'_{1} - T_{1}}{T'_{2} - T_{2}} \right)
\]

\[
Q = UA\Delta T_{lm}
\]

\(\Delta T_{lm}\) is the correct average temperature to use for the overall heat-transfer coefficients in a double-pipe heat exchanger.

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Example: Heat Transfer in a Double-Pipe Heat Exchanger: Geankoplis 4th ed. 4.5-4

Water flowing at a rate of 13.85 kg/s is to be heated from 54.5 to 87.8°C in a double-pipe heat exchanger by 54,430 kg/h of hot gas flowing counterflow and entering at 427°C (\(\dot{Q}_{pm} = 1.005 \text{ kJ/kg K}\)).

The overall heat-transfer coefficient based on the outer surface is \(U_o = 69.1 \text{ W/m}^2\text{ K}\). Calculate the exit-gas temperature and the heat transfer area needed.
Summary:

Double-Pipe Heat Exchanger – the driving force for heat transfer changes along the length of the heat exchanger.

For example,

\[ T'_1 = 300^\circ C \]
\[ T'_2 = 430^\circ C \]
\[ \Delta T = (T'_1 - T'_2)_{x=x_0} = 340^\circ C \]
\[ \Delta T = (T'_1 - T'_2)_{x=x_1} = 250^\circ C \]

The correct average driving force for the whole exchanger is the log-mean temperature difference

\[ \Delta T_{lm} \]

Optimizing Heat Exchangers

double-pipe:

\[ Q = U A \Delta T_{lm} \]

To increase \( Q \) appreciably, we must increase \( A \), i.e. \( R_i \).

But:

- only small increases possible
- increasing \( R_i \) decreases \( h \)
1-1 Shell and Tube Heat Exchanger

(Same as double pipe H.E.)

1 shell
1 tube

1-2 Shell and Tube Heat Exchanger

Geankoplis 4th ed., p292

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Cross Baffles in Shell-and-Tube Heat Exchangers

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And other more complex arrangements:

2 shell
4 tube

For double-pipe heat exchanger:

$$Q = UA \Delta T_{lm}$$

For shell-and-tube heat exchangers:

$$Q = UA \left[ \Delta T_{lm} \left( F_T \right) \right] \equiv \Delta T_m$$

calculated correction factor (obtain from experimentally determined charts)
correct mean temperature difference for shell-and-tube heat exchangers
**Heat Exchanger Design**

To calculate $Q$, we need both inlet and outlet temperatures:

$$Q = UA \Delta T_m = UA (F_T \Delta T_{lm})$$

Where $F_T = 1 - \frac{T_{hi} - T_{ho}}{T_{ci} - T_{co}}$.

What if the outlet temperatures are unknown? i.e., the design/spec problem.
Water flowing at a rate of $0.723 \text{ kg/s}$ enters the inside of a countercurrent, double-pipe heat exchanger at $300.\text{K}$ and is heated by an oil stream that enters at $385 \text{ K}$ at a rate of $3.2 \text{ kg/s}$. The heat capacity of the oil is $1.89 \text{ kJ/kgK}$, and the average heat capacity of the water of the temperature range of interest is $4.192 \text{ kJ/kgK}$. The overall heat-transfer coefficient of the exchanger is $300. \text{ W/m}^2\text{K}$, and the area for heat transfer is $15.4 \text{ m}^2$. What is the total amount of heat transferred?

Example Problem: How will this heat exchanger perform?

You try.
Example Problem:
How will this heat exchanger perform?

To calculate unknown outlet temperatures:

Procedure:
1. Guess $Q$
2. Calculate outlet temperatures
3. Calculate $\Delta T_{lm}$
4. Calculate $Q$
5. Compare, adjust, repeat

<table>
<thead>
<tr>
<th>Procedure</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</thead>
<tbody>
<tr>
<td>$U$</td>
<td>0.3 W/m²K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>15.4 m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_1$</td>
<td>300 K</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$T_{prime, 2}$</td>
<td>388 K</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$m_{water}$</td>
<td>0.22 kg/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$cp_{water}$</td>
<td>4.192 kJ/kgK</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m'_{oil}$</td>
<td>3.2 kg/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$cp_{oil}$</td>
<td>1.89 kJ/kgK</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_2$</td>
<td></td>
<td>333 K</td>
<td>366 K</td>
<td>349 K</td>
</tr>
<tr>
<td>$T_{prime, 1}$</td>
<td></td>
<td>332 K</td>
<td>352 K</td>
<td>360 K</td>
</tr>
<tr>
<td>$\Delta T_{lm}$</td>
<td></td>
<td>68 K</td>
<td>52 K</td>
<td>60 K</td>
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<tr>
<td>$Q_{new}$</td>
<td>276.5 kW</td>
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<tr>
<td>$Q_{new}$</td>
<td>151.4 kW</td>
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<tr>
<td>$Q_{new}$</td>
<td>216.1 kW</td>
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<table>
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<td>$Q$</td>
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<td>$T_2$</td>
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<td>178.1 kW</td>
</tr>
<tr>
<td>$Q_{new}$</td>
<td>179.9 kW</td>
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Example Problem:
How will this heat exchanger perform?

<p>| | | | |</p>
<table>
<thead>
<tr>
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<th></th>
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</thead>
<tbody>
<tr>
<td>U</td>
<td>0.3 <strong>[W/m²K]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>15.4 <strong>[m²]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_{\text{prime}_1})</td>
<td>385 <strong>[K]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(m_{\text{water}})</td>
<td>0.723 <strong>[kg/s]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(m_{\text{oil}})</td>
<td>3.2 <strong>[kg/s]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c_p_{\text{water}})</td>
<td>4.192 <strong>[kJ/kgK]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c_p_{\text{oil}})</td>
<td>1.89 <strong>[kJ/kgK]</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This procedure can be sped up considerably by the use of the concept of Heat-Exchanger Effectiveness, \(\epsilon\).

2013HeatExchEffecExample.xlsx

**Heat Exchanger Effectiveness**

Consider a counter-current double-pipe heat exchanger:

\[ T_{co} \]
\[ T_{hi} \]
\[ T_{ho} \]
\[ T_{ci} \]
\[ T_{prime}\]

distance along the exchanger

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Energy balance cold side:

\[ Q_{in,cold} = Q = (mC_p)_{cold}(T_{co} - T_{ci}) \]

Energy balance hot side:

\[ Q_{in,hot} = -Q = (mC_p)_{hot}(T_{ho} - T_{hi}) \]

Equate:

\[ \frac{(mC_p)_{hot}}{(mC_p)_{cold}} = \frac{(T_{co} - T_{ci})}{(T_{ho} - T_{hi})} = \frac{\Delta T_c}{\Delta T_h} \]

Case 1:

\[
\begin{cases}
    (mC_p)_{hot} > (mC_p)_{cold} \\
    \Delta T_c > \Delta T_h
\end{cases}
\]

We want to compare the amount of heat transferred in this case to the amount of heat transferred in a PERFECT heat exchanger.
If the heat exchanger were perfect, \( T_{hi} = T_{co} \) (no heat left un-transferred)

**Cold Side:**

\[
Q_{A=\infty} = (m\hat{C}_p)_{cold} (T_{co} - T_{ci})
\]

This temperature difference only depends on inlet temperatures.

Distance along the exchanger

---

**Heat Exchanger Effectiveness, \( \varepsilon \):**

\[
\varepsilon \equiv \frac{Q}{Q_{A=\infty}}
\]

\[
\Rightarrow Q = \varepsilon (mC_p)_{cold} (T_{hi} - T_{ci})
\]

cold fluid = minimum fluid

If \( \varepsilon \) is known, we can calculate \( Q \) without iterations.
Case 2:
\[
\begin{cases}
(mC_p)_\text{hot} < (mC_p)_\text{cold} \\
\Delta T_c < \Delta T_h
\end{cases}
\]
\(\frac{(mC_p)_\text{hot}}{(mC_p)_\text{cold}} = \frac{\Delta T_{\text{cold}}}{\Delta T_{\text{hot}}} \)

hot fluid = minimum fluid

If the heat exchanger were perfect, \(T_{ho} = T_{ci}\) (no heat left un-transferred)

\(Q_{A=\infty} = -(m\dot{C}_p)_\text{hot}(T_{ho} - T_{hi})\)

The same temperature difference as before (inlets)

\(Q_{A=\infty} = (m\dot{C}_p)_\text{hot}(T_{hi} - T_{ci})\)
Heat Exchanger Effectiveness

\[ \varepsilon \equiv \frac{Q}{Q_{A=\infty}} \]

\[ \Rightarrow Q = \varepsilon (mC_p)_\text{hot} (T_{hi} - T_{ci}) \]

hot fluid = minimum fluid

in general,

\[ Q = \varepsilon (mC_p)_\text{min} (T_{hi} - T_{ci}) \]

if \( \varepsilon \) is known, we can calculate \( Q \) without iterations

**But where do we get \( \varepsilon \)?**

The same equations we use in the trial-and-error solution can be combined algebraically to give \( \varepsilon \) as a function of \( (mC_p)_\text{min}, (mC_p)_\text{max} \).

counter-current flow:

\[
\varepsilon = \frac{1 - e^{-\frac{UA}{(mC_p)_\text{min}} \left(1 - \frac{(mC_p)_\text{min}}{(mC_p)_\text{max}}\right)}}{1 - \frac{(mC_p)_\text{min}}{(mC_p)_\text{max}} e^{-\frac{UA}{(mC_p)_\text{min}} \left(1 - \frac{(mC_p)_\text{min}}{(mC_p)_\text{min}}\right)}}
\]

This relation is plotted in Geankoplis, as is the relation for co-current flow.
Heat Exchanger Effectiveness for Double-pipe or 1-1 Shell-and-Tube Heat Exchangers

**counter-current**

<table>
<thead>
<tr>
<th>$\frac{C_{\text{min}}}{C_{\text{max}}} = 0$</th>
<th>0.20</th>
<th>0.50</th>
<th>0.75</th>
<th>1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.20</td>
<td>0.40</td>
<td>0.60</td>
<td>0.80</td>
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</table>

**co-current**

<table>
<thead>
<tr>
<th>$\frac{C_{\text{min}}}{C_{\text{max}}} = 0$</th>
<th>0.20</th>
<th>0.50</th>
<th>0.75</th>
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<td>0.20</td>
<td>0.40</td>
<td>0.60</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Note: Geankoplis' $C_{\text{min}} = (mC_p)_{\text{min}}$

---

Example Problem:
How will this heat exchanger perform?

Water flowing at a rate of 0.723 kg/s enters the inside of a countercurrent, double-pipe heat exchanger at 300 K and is heated by an oil stream that enters at 385 K at a rate of 3.2 kg/s. The heat capacity of the oil is 1.89 kJ/kgK, and the average heat capacity of the water of the temperature range of interest is 4.192 kJ/kgK. The overall heat-transfer coefficient of the exchanger is 380 W/m²K, and the area for heat transfer is 15.4 m². What is the total amount of heat transferred?

You try.
Heat Exchanger Fouling

- material deposits on hot surfaces
- rust, impurities
- strong effect when boiling occurs

heat transfer resistances

\[
U_{i \text{oro}} = \frac{1}{\frac{1}{R_i} + \frac{1}{R_o} + \frac{1}{h_iR_i} + \frac{1}{h_oR_o} + \frac{1}{h_dR_d} + \frac{1}{kR_i} \ln \left( \frac{R_o}{R_i} \right)} - \frac{1}{R_{i \text{oro}}}
\]

scale adds an additional resistance to heat transfer

add effect of fouling

\[
U_{i \text{oro}} = \frac{1}{\frac{1}{R_i} + \frac{1}{R_o} + \frac{1}{h_iR_i} + \frac{1}{h_oR_o} + \frac{1}{h_dR_d} + \frac{1}{kR_i} \ln \left( \frac{R_o}{R_i} \right) + \frac{1}{h_{do}R_{do}} + \frac{1}{h_{oi}R_{oi}}}
\]

see Perry's Handbook, or Geankoplis 4th ed. Table 4.9-1, page 300 for values of \(h_d\)
Heat Exchanger Fouling

Next:
- Heat transfer with phase change
- Evaporators
- Radiation
- DONE

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