Heat Transfer: Heat Exchangers

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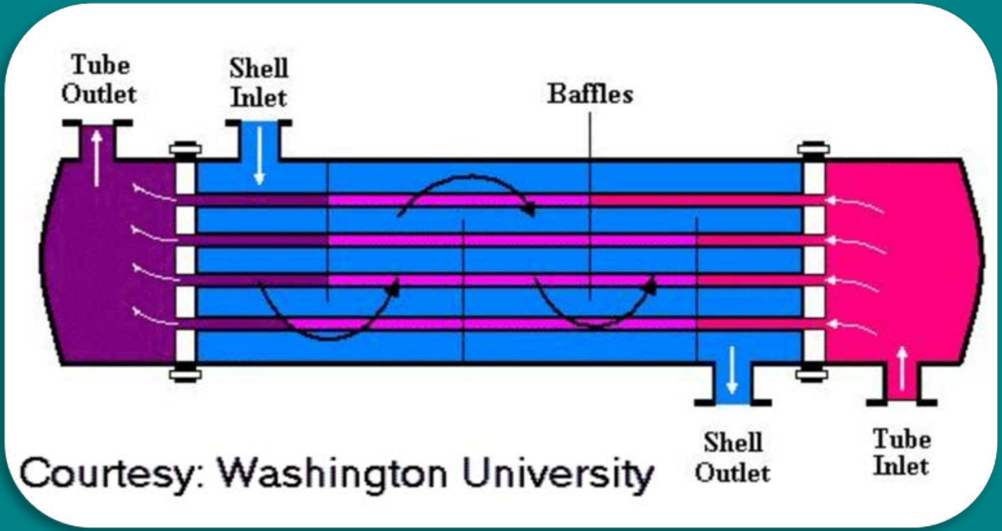
Definision of Heat Exchanger

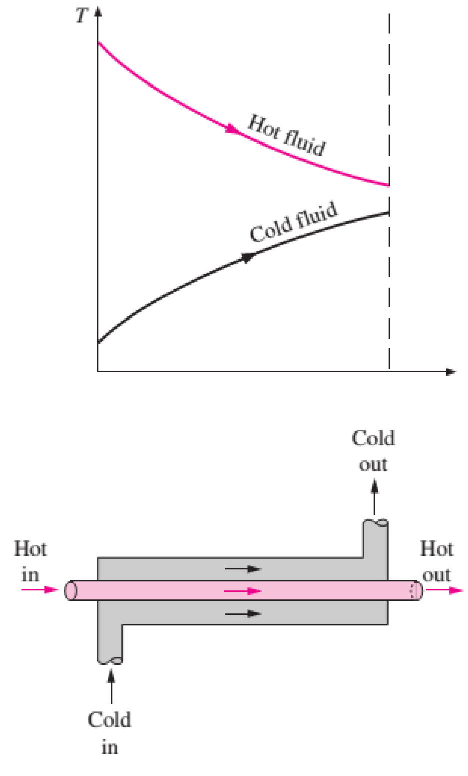


Devices that facilitate the exchange of heat between two fluids that are at different temperatures while keeping them from mixing with each other.

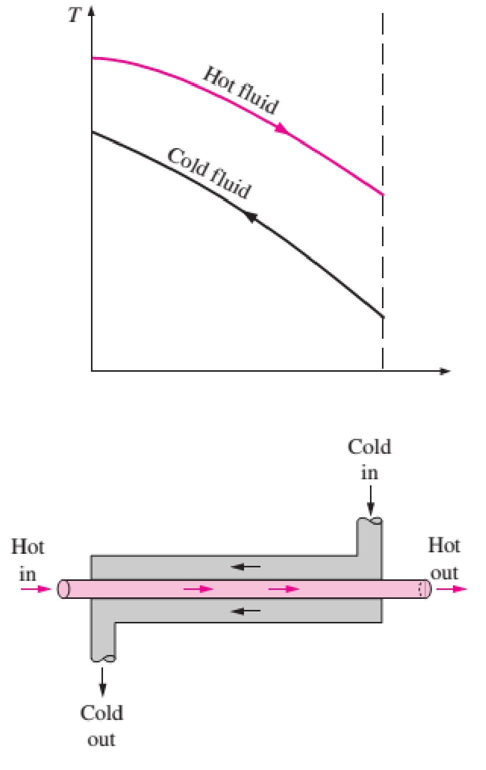
TYPES OF HEAT EXCHANGERS

1. Double-pipe heat exchanger

One fluid in a double-pipe heat exchanger flows through the smaller pipe while the other fluid flows through the annular space between the two pipes



(a) Parallel flow



(b) Counter flow

TYPES OF HEAT EXCHANGERS

2. Compact heat exchanger

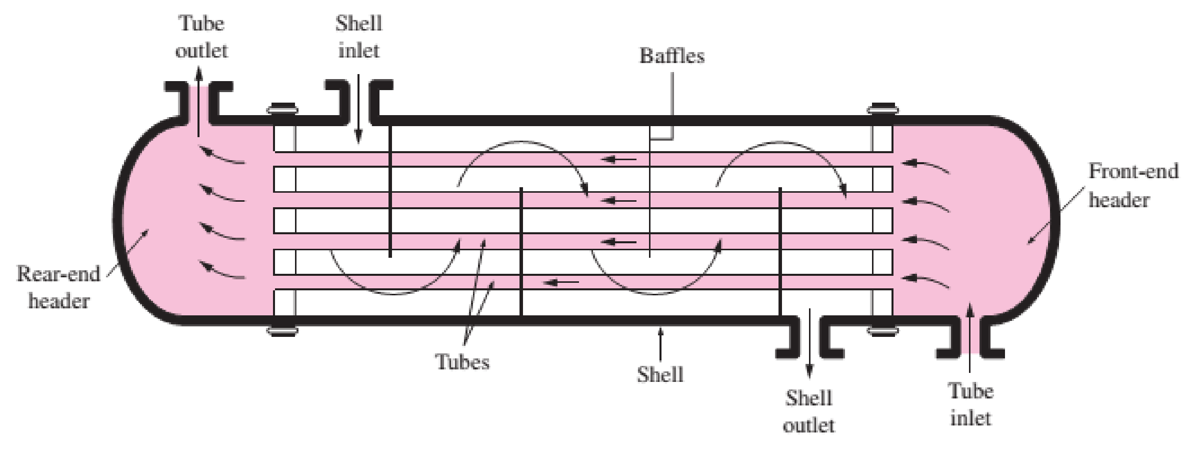
A heat exchanger with $\beta < 700m^2/m^3$ is classified as compact heat exchanger. Where β is the ratio of the heat transfer surface area of a heat exchanger to its volume. This type enable us to achieve high heat transfer rates between two fluids.

TYPES OF HEAT EXCHANGERS

3. Shell and tube heat exchanger

Shell and tube heat exchangers contain a large number of tubes (sometimes several hundred) packed in a shell with their axes parallel to that of the shell. This type is the most common type of heat exchanger in industrial applications.

TYPES OF HEAT EXCHANGERS

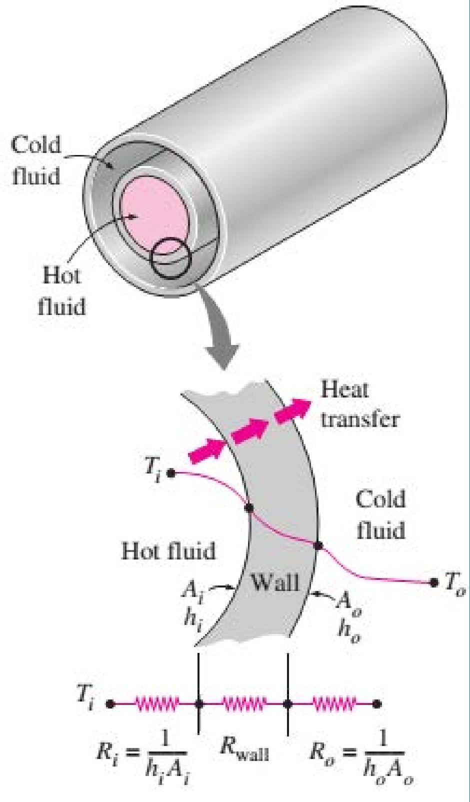


Heat transfer takes place as one fluid flows inside the tubes while the other fluidflows outside the tubes through the shell. Baffles are commonly placed in the shell to force the shell-side fluid to flow across the shell to enhance heat transfer and to maintain uniform spacing between the tubes.

THE OVERALL HEAT TRANSFER COEFFICIENT

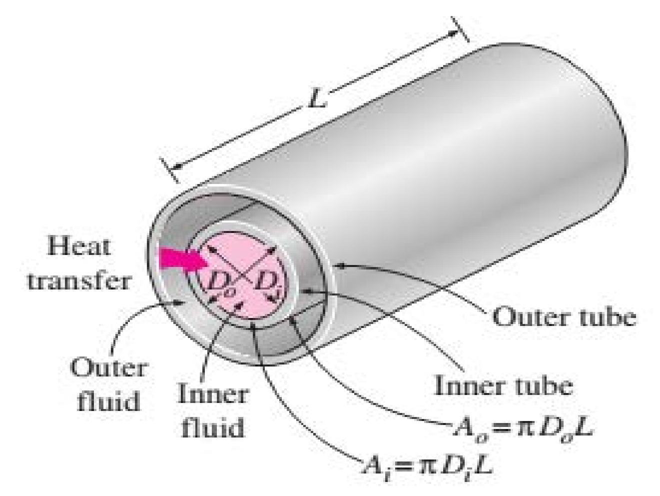
Heat is first transferred from the hot fluid to the wall by convection, through the wall by conduction, and from the wall to the cold fluid again by convection. Any radiation effects are usually included in the convection heat transfer coefficients. The thermal resistance network associated with this heat transfer process involves two convection and one conduction resistances, as shown in the picture.

The subscripts i and o represent the inner and outer surfaces of the inner tube



THE OVERALL HEAT TRANSFER COEFFICIENT

For a double-pipe heat exchanger, we have $A_i = \pi D_i \mathrm{L}$ and $A_o = \pi D_o \mathrm{L}$, and the thermal resistance of the tube wall is: $R_{wall} = \frac{\ln(\frac{D_o}{D_i})}{2\pi k L}$, k is the thermal conductivity of the wall material



Then the total thermal resistance becomes:

$$R = R_{total} = R_i + R_{wall} + R_o = \frac{1}{h_i A_i} + \frac{\ln(\frac{D_o}{D_i})}{2\pi k L} + \frac{1}{h_o A_o}$$

THE OVERALL HEAT TRANSFER COEFFICIENT

The rate of heat transfer between the two fluids is:

$\dot{Q} = \frac{\Delta T}{R} = UA\Delta T = U_i A_i \Delta T = U_o A_o \Delta T$, U is the overall heat transfer coefficient (W/m^2 .℃)

Canceling ΔT, the equation becomes:

$$\frac{1}{UA_s} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = R = \frac{1}{h_i A_i} + \frac{\ln(\frac{D_o}{D_i})}{2\pi k L} + \frac{1}{h_o A_o}$$

If the wall thickness of the tube is small and the thermal conductivity of the tube material is high, the thermal resistance of the tube is negligible ($R_{wall} \approx 0$) and the inner and outer surfaces of the tube are almost identical ($A_i \approx A_o \approx A_s$). Then Equation for the overall heat transfer coefficient simplifies to:

$$\frac{1}{U} \approx \frac{1}{h_i} + \frac{1}{h_o}$$

THE OVERALL HEAT TRANSFER COEFFICIENT

Fouling is the accumulation of unwanted material on solid surfaces of heat exchanger. The layer of deposits represents additional resistance to heat transfer and causes the rate of heat transfer in a heat exchanger to decrease. The net effect of these accumulations on heat transfer is represented by a fouling factor (R_f). So, the overall heat transfer coefficient with the effect of fouling is:

$$\frac{1}{UA_s} = \frac{1}{U_iA_i} = \frac{1}{U_oA_o} = R = \frac{1}{h_iA_i} + \frac{R_{f,i}}{A_i} + \frac{\ln(\frac{D_o}{D_i})}{2\pi kL} + \frac{1}{h_oA_o} + \frac{R_{f,o}}{A_o}$$

GEO CAP

ANALYSIS OF HEAT EXCHANGERS

Axial heat conduction along the tube is usually insignificant and can be considered negligible. Finally, the outer surface of the heat exchanger is assumed to be perfectly insulated, so that there is no heat loss to the surrounding medium, and any heat transfer occurs between the two fluids only. Under these assumptions, the first law of thermodynamics requires that the rate of heat transfer from the hot fluid be equal to the rate of heat transfer to the cold one:

$$\dot{Q} = \dot{m}_c C_{pc}(T_{c,\,out} - T_{c,in}) \text{ and } \dot{Q} = \dot{m}_h C_{ph}(T_{h,\,in} - T_{h,\,out})$$

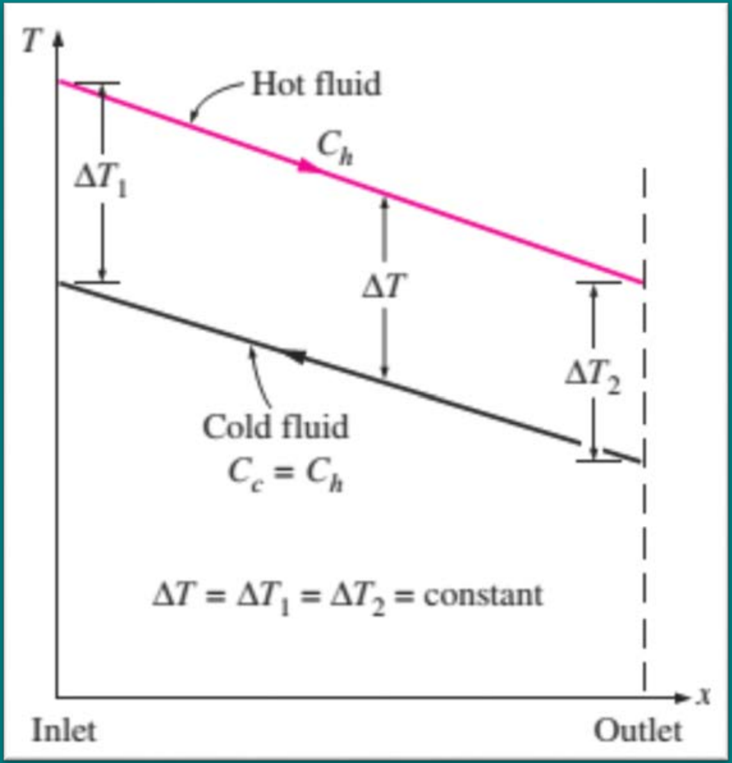
Since heat capacity is : $C_c = \dot{m}_c C_{pc}$ and $C_h = \dot{m}_h C_{ph}$

So, the heat transfer rate in a heat exchanger can also be expressed as

$$\dot{Q} = C_c(T_{c,\,out} - T_{c,in}) \text{ and } \dot{Q} = C_h(T_{h,\,in} - T_{h,\,out})$$

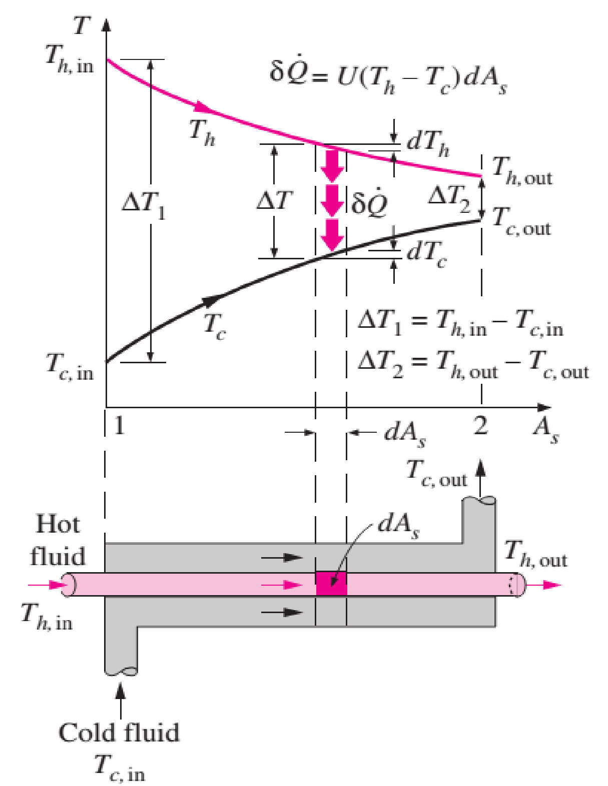
ANALYSIS OF HEAT EXCHANGERS

The heat transfer rate in a heat exchanger is equal to the heat capacity rate of either fluid multiplied by the temperature change of that fluid. The only time the temperature rise of a cold fluid is equal to the temperature drop of the hot fluid is when the heat capacity rates of the two fluids are equal to each other



THE LOG MEAN TEMPERATURE DIFFERENCE METHOD

The temperature difference between the hot and cold fluids varies along the heat exchanger, and it is convenient to have a mean temperature difference ΔT_m for use in the relation $\dot{Q} = \mathrm{U}A_s\Delta T_m$. In order to develop a relation for the temperature, consider the parallel-flow double-pipe heat exchanger shown in picture.



THE LOG MEAN TEMPERATURE DIFFERENCE METHOD

Assuming the outer surface of the heat exchanger to be well insulated so that any heat transfer occurs between the two fluids, and disregarding any changes in kinetic and potential energy, an energy balance on each fluid in a differential section of the heat exchanger can be expressed as:

$$\delta\dot{Q} = -\dot{m}_h C_{ph} dT_h \text{ and } \delta\dot{Q} = \dot{m}_c C_{pc} dT_c$$

Taking the difference between dT_h and dT_c, we get:

$$dT_h - dT_c = d(T_h - T_c) = -\delta\dot{Q}\left(\frac{1}{\dot{m}_h C_{ph}} + \frac{1}{\dot{m}_c C_{pc}}\right)$$

The rate of heat transfer can be expressed as:

$$\delta\dot{Q} = \mathrm{U}(T_h - T_c)dA_s$$

THE LOG MEAN TEMPERATURE DIFFERENCE METHOD

Substitusing the rate of heat transfer into $dT_h - dT_c$, we get:

$$\frac{d(T_h - T_c)}{T_h - T_c} = -U\, dA_s\left(\frac{1}{\dot{m}_h C_{ph}} + \frac{1}{\dot{m}_c C_{pc}}\right)$$

Integrating from the inlet of the heat exchanger to its outlet,we obtain:

$$\ln\frac{T_{h,out} - T_{c,out}}{T_{h,in} - T_{c,in}} = -UA\left(\frac{1}{\dot{m}_h C_{ph}} + \frac{1}{\dot{m}_c C_{pc}}\right)$$

Finally, by solving $\dot{m}_h C_{ph}$ and $\dot{m}_c C_{pc}$, we get:

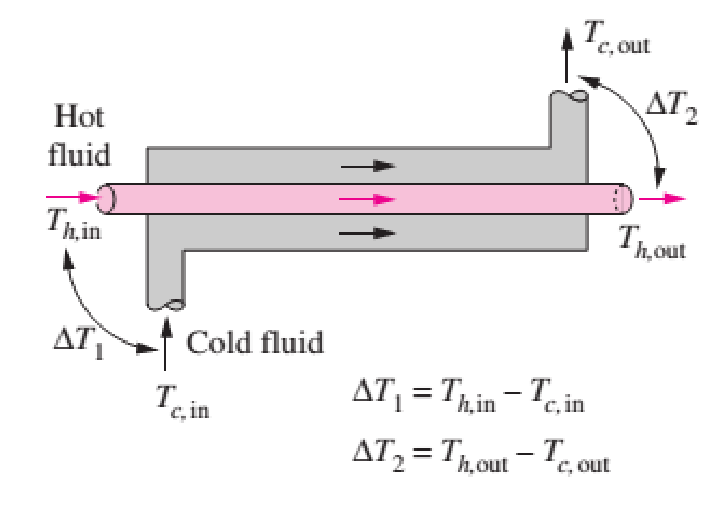
$$\dot{Q} = \mathrm{U}A_s \Delta T_{lm}$$

Where ΔT_{lm} is the log mean temperature difference

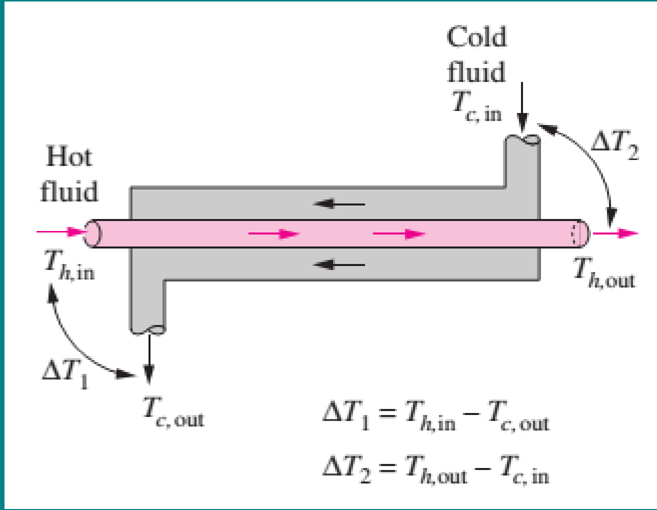
$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})}$$

THE LOG MEAN TEMPERATURE DIFFERENCE METHOD

Parallel-Flow



Counter-Flow



THE LOG MEAN TEMPERATURE DIFFERENCE METHOD

Multipass and Cross-Flow Heat Exchangers

For this type of heat exchanger, we use correction factor F, which depends on the geometry of the heat exchanger and the inlet and outlet temperatures of the hot and cold fluid streams.

$$\Delta T_{lm} = F \Delta T_{lm,CF}$$

where $\Delta T_{lm,CF}$ is the log mean temperature difference for counter flow

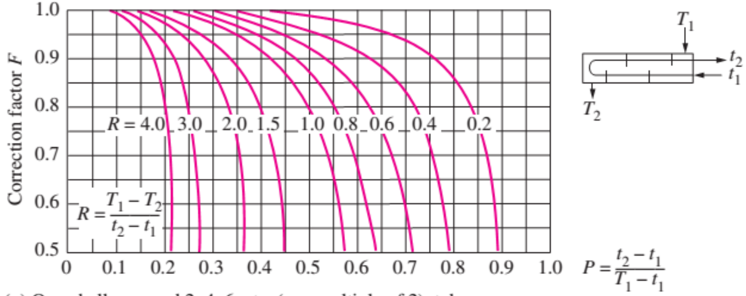
The correction factor F for common cross-flow and shell-and-tube heat exchanger configurations depend on P and R, where

$P = \frac{t_2 - t_1}{T_1 - t_1}$ and $R = \frac{T_1 - T_2}{t_2 - t_1}$, the subscripts 1 and 2 represent the inlet and outlet

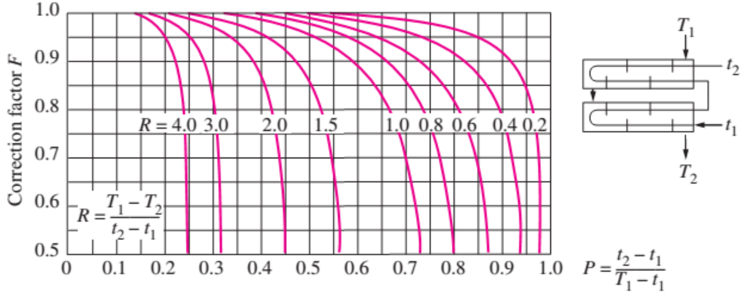
THE LOG MEAN TEMPERATURE DIFFERENCE METHOD

Multipass and Cross-Flow Heat Exchangers

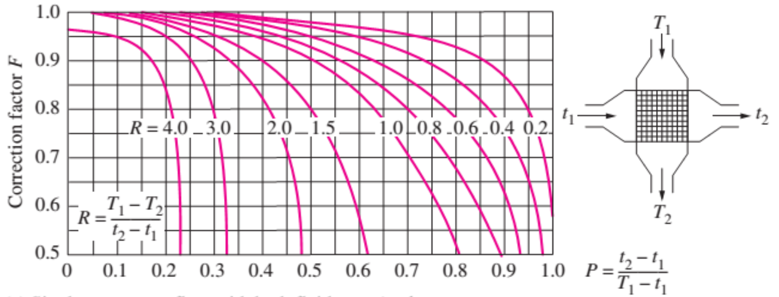
Correction factor F charts for common shell-and-tube and cross-flow heat exchangers (from Bowman, Mueller, and Nagle, Ref. 2)



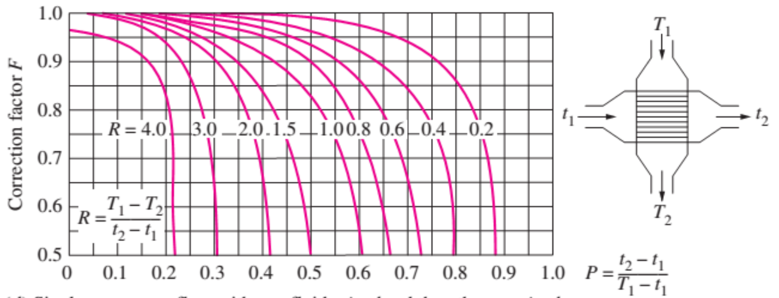
(*a*) One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes



(*b*) Two-shell passes and 4, 8, 12, etc. (any multiple of 4), tube passes



(*c*) Single-pass cross-flow with both fluids *unmixed*



(*d*) Single-pass cross-flow with one fluid *mixed* and the other *unmixed*

THE EFFECTIVENESS–NTU METHOD

Heat transfer effectiveness ε, defined as:

$$\varepsilon = \frac{\dot{Q}}{Q_{max}} = \frac{Actual\ heat\ transfer\ rate}{Maximum\ possible\ heat\ transfer\ rate}$$

The actual heat transfer rate can be determined from an energy balance on the hot or cold fluids:

$$\dot{Q} = C_c\left(T_{c,out} - T_{c,in}\right) = C_h\left(T_{h,in} - T_{h,out}\right)$$

The maximum possible heat transfer rate in a heat exchanger is:

$$\dot{Q}_{max} = C_{min}\Delta T_{max} = C_{min}\left(T_{h,in} - T_{c,in}\right)$$

Once the effectiveness of the heat exchanger is known, the actual heat transfer rate Q can be determined from:

$$\dot{Q} = \varepsilon\dot{Q}_{max} = \varepsilon C_{min}\left(T_{h,in} - T_{c,in}\right)$$

THE EFFECTIVENESS–NTU METHOD

For parallel flow, effectiveness defined as:

$$\varepsilon_{parallel\ flow} = \frac{1 - exp\left[-\frac{UA_s}{C_{min}}\left(1 + \frac{C_{min}}{C_{max}}\right)\right]}{1 + \frac{C_{min}}{C_{max}}}$$

Effectiveness relations of the heat exchangers typically involve the dimensionless group UA_s/C_{min}. This quantity is called the number of transfer units NTU and is expressed as:

$$NTU = \frac{UA_s}{C_{min}} = \frac{UA_s}{(\dot{m}C_p)_{min}}$$

It is also convenient to define another dimensionless quantity called the capacity ratio c as:

$$c = \frac{C_{min}}{C_{max}}$$

effectiveness of a heat exchanger is a function of the number of transfer units NTU and the capacity ratio c: $\varepsilon = function(UA_s/C_{min}, C_{min}/C_{max}) = function\ (NTU, c)$

THE EFFECTIVENESS–NTU METHOD

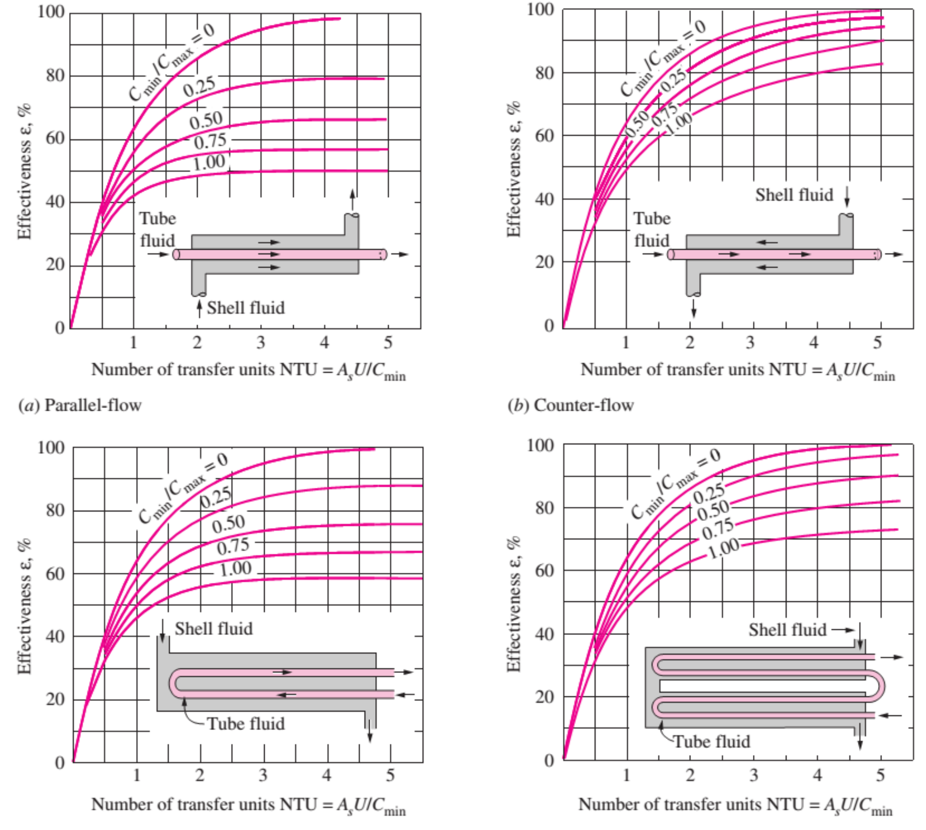
Effectiveness relations of heat exchangers table

Effectiveness relations for heat exchangers: NTU $= UA_s/C_{min}$ and $c = C_{min}/C_{max} = (\dot{m}C_p)_{min}/(\dot{m}C_p)_{max}$ (Kays and London, Ref. 5.)

Heat exchanger type	Effectiveness relation
1 *Double pipe:*	
Parallel-flow	$\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1 + c)]}{1 + c}$
Counter-flow	$\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1 - c)]}{1 - c\exp[-\text{NTU}(1 - c)]}$
2 *Shell and tube:*	
One-shell pass 2, 4, . . . tube passes	$\varepsilon = 2\left\{1 + c + \sqrt{1 + c^2}\,\dfrac{1 + \exp[-\text{NTU}\sqrt{1 + c^2}]}{1 - \exp[-\text{NTU}\sqrt{1 + c^2}]}\right\}^{-1}$
3 *Cross-flow (single-pass)*	
Both fluids unmixed	$\varepsilon = 1 - \exp\left\{\dfrac{\text{NTU}^{0.22}}{c}[\exp(-c\ \text{NTU}^{0.78}) - 1]\right\}$
C_{max} mixed, C_{min} unmixed	$\varepsilon = \dfrac{1}{c}(1 - \exp\{1 - c[1 - \exp(-\text{NTU})]\})$
C_{min} mixed, C_{max} unmixed	$\varepsilon = 1 - \exp\left\{-\dfrac{1}{c}[1 - \exp(-c\ \text{NTU})]\right\}$
4 *All heat exchangers with $c = 0$*	$\varepsilon = 1 - \exp(-\text{NTU})$

THE EFFECTIVENESS–NTU METHOD

The effectivenesses of some common types of heat exchangers are also plotted in graphics



(a) Parallel-flow

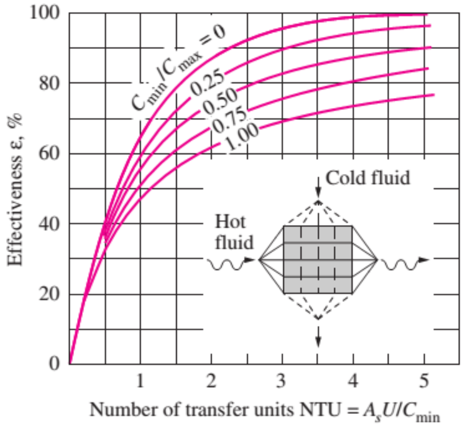
(b) Counter-flow

(c) One-shell pass and 2, 4, 6, … tube passes

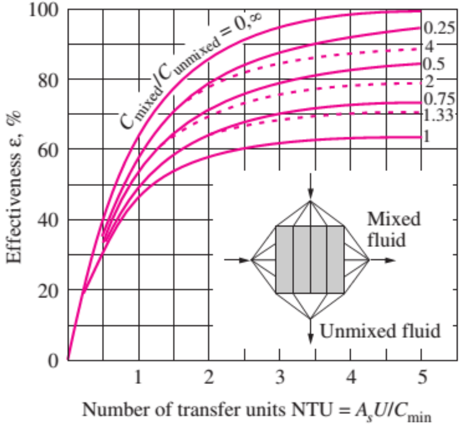
(d) Two-shell passes and 4, 8, 12, … tube passes

THE EFFECTIVENESS–NTU METHOD

The effectivenesses of some common types of heat exchangers are also plotted in graphics



(e) Cross-flow with both fluids unmixed



(f) Cross-flow with one fluid mixed and the other unmixed

THE EFFECTIVENESS–NTU METHOD

NTU relations for heat exchangers table

NTU relations for heat exchangers $\text{NTU} = UA_s/C_{min}$ and $c = C_{min}/C_{max} = (\dot{m}C_p)_{min}/(\dot{m}C_p)_{max}$ (Kays and London, Ref. 5.)

Heat exchanger type	NTU relation
1 *Double-pipe:* Parallel-flow	$\text{NTU} = -\dfrac{\ln[1-\varepsilon(1+c)]}{1+c}$
Counter-flow	$\text{NTU} = \dfrac{1}{c-1}\ln\left(\dfrac{\varepsilon-1}{\varepsilon c-1}\right)$
2 *Shell and tube:* One-shell pass 2, 4, . . . tube passes	$\text{NTU} = -\dfrac{1}{\sqrt{1+c^2}}\ln\left(\dfrac{2/\varepsilon-1-c-\sqrt{1+c^2}}{2/\varepsilon-1-c+\sqrt{1+c^2}}\right)$
3 *Cross-flow (single-pass)* C_{max} mixed, C_{min} unmixed	$\text{NTU} = -\ln\left[1+\dfrac{\ln(1-\varepsilon c)}{c}\right]$
C_{min} mixed, C_{max} unmixed	$\text{NTU} = -\dfrac{\ln[c\ln(1-\varepsilon)+1]}{c}$
4 *All heat exchangers with $c = 0$*	$\text{NTU} = -\ln(1-\varepsilon)$

SELECTION OF HEAT EXCHANGERS

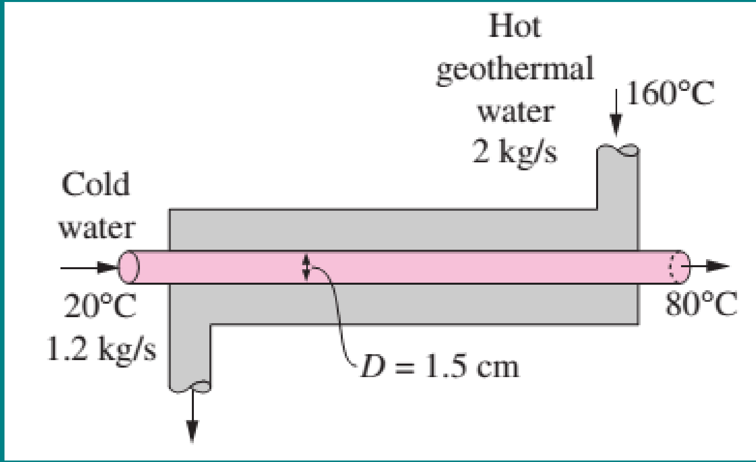
Engineers in industry often find themselves in a position to select heat exchangers to accomplish certain heat transfer tasks. Here is the considerations of selecting the heat exchanger

1. Heat Transfer Rate
2. Cost
3. Pumping Power
4. Size and Weight
5. Type
6. Materials
7. etc.

EXAMPLE

Heating Water in a Counter-Flow Heat Exchanger

A counter-flow double-pipe heat exchanger is to heat water from 20℃ to 80℃ at a rate of 1.2 kg/s. The heating is to be accomplished by geothermal water available at 160 ℃ at a mass flow rate of 2 kg/s. The inner tube is thin-walled and has a diameter of 1.5 cm. If the overall heat transfer coefficient of the heat exchanger is 640 W/m^2.℃, determine the length of the heat exchanger required to achieve the desired heating.



EXAMPLE

Heating Water in a Counter-Flow Heat Exchanger

Assumptions: 1. Steady operating conditions exist. **2.** The heat exchanger is well insulated. **3.** Changes in the kinetic and potential energies of fluid streams are negligible. **4.** There is no fouling. 5. Fluid properties are constant.

Properties: We take the specific heats of water and geothermal fluid to be 4.18 and 4.31 $kJ/kg\ .\ ℃$

Analysis: The rate of heat transfer in the heat exchanger can be determined from:

$$\dot{Q} = [\dot{m}C_P(T_{out} - T_{in})]_{water} = (1.2\ kg/s)(4.18\ kJ/kg\ .\ ℃)\ (80 - 20)℃ = 301\ \mathrm{kW}$$

EXAMPLE

Heating Water in a Counter-Flow Heat Exchanger

Analysis: The outlet temperature of the geothermal water

$$\dot{Q} = [\dot{m}C_P(T_{out} - T_{in})]_{geothermal} \longrightarrow T_{out} = T_{in} - \frac{\dot{Q}}{\dot{m}C_P}$$

$$= 160℃ - \frac{301\ \text{kW}}{(2\ kg/s)(4.31\ kJ/kg\ .\ ℃)}$$

$$= 125℃$$

The logarithmic mean temperature difference

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{(T_{h,in} - T_{c,out})}{T_{h,out} - T_{c,in}}\right)}$$

$$= \frac{(160 - 80)℃ - (125 - 20)℃}{\ln\left(\frac{160 - 80}{125 - 20}\right)} = 92℃$$

EXAMPLE

Heating Water in a Counter-Flow Heat Exchanger

Analysis: The surface area of the heat exchanger is determined to be

$$\dot{Q} = \mathrm{U}A_s\Delta T_{lm} \longrightarrow A_s = \frac{\dot{Q}}{U\Delta T_{lm}} = \frac{301000\,W}{(640\,W/m^2\,.\,℃)(91℃)} = 5.11\,m^2$$

The length of the tube must be

$$A_s = \pi DL \longrightarrow L = \frac{A_s}{\pi D} = \frac{5.11\,m^2}{\pi(0.015\,m)} = 108\,m$$

Discussion: The inner tube of this counter-flow heat exchanger (and thus the heat exchanger itself) needs to be over 100 m long to achieve the desired heat transfer, which is impractical. we need to use a plate heat exchanger or a multipass shell-and-tube heat exchanger with multiple passes of tube bundles.

EXAMPLE

Heating Water in a Counter-Flow Heat Exchanger

Repeat the example which was solved with the LMTD method, using the effectiveness–NTU method.

Assumptions: The same assumptions are utilized.

Analysis: Determine the heat capacity rates of the hot and cold fluids and identify the smaller one

$$C_h = \dot{m}_h C_{ph} = (2\ kg/s)(4.31\ kJ/kg\ .\ °C) = 8.62\ kW/°C$$

$$C_c = \dot{m}_c C_{pc} = (1.2\ kg/s)(4.18\ kJ/kg\ .\ °C) = 5.02\ kW/°C$$

Therefore,

$$C_{min} = C_c = 5.02\ kW/°C \quad \text{and} \quad c = C_{min}/C_{max} = 5.02/8.62 = 0.583$$

The maximum heat transfer rate

$$\dot{Q}_{max} = C_{min}(T_{h,in} - T_{c,in}) = (5.02\ kW/°C)\ (160 - 20)\ °C = 702.8\ kW$$

EXAMPLE

Heating Water in a Counter-Flow Heat Exchanger

Analysis: The actual rate of heat transfer in the heat exchanger

$$\dot{Q} = [\dot{m}C_p(T_{out} - T_{in})]_{water} = (1.2\ kg/s)(4.18\ kJ/kg\ .\ ℃)(80 - 20)℃$$
$$= 301.0\ \mathrm{kW}$$

The effectiveness of the heat exchanger

$$\varepsilon = \frac{\dot{Q}}{Q_{max}} = \frac{301.0}{702.8} = 0.428$$

The NTU of this **counter-flow heat exchanger** (from table)

$$NTU = \frac{1}{c-1} ln\left(\frac{\varepsilon-1}{\varepsilon c-1}\right) = \frac{1}{0.583-1} ln\left(\frac{0.428\ \ -1}{(0.428)(0.583)-1}\right) = 0.651$$

Theat transfer surface area

$$NTU = \frac{UA_s}{C_{min}} \longrightarrow A_s = \frac{NTU\ C_{min}}{U} = \frac{(0.651)(5.02\ kW/\ ℃)}{(640\ W/m^2.\ ℃)} = 5.11m^2$$

EXAMPLE

Heating Water in a Counter-Flow Heat Exchanger

Analysis: Then the length of the tube must be

$$A_s = \pi D L \longrightarrow L = \frac{A_s}{\pi D} = \frac{5.11\ m^2}{\pi(0.015\ m)} = 108\ m$$

Discussion: We obtained the same result with the effectiveness–NTU method in a systematic and straightforward manner.