CL4001 HEAT TRANSFER OPERATIONS

MODULE

V

HEAT EXCHANGER

Lecture Notes:
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Heat Exchangers: Introduction and Basic Concepts

- A *heat exchanger* does exactly that -- exchanges heat between two streams, heating one and cooling the other. Levenspiel (1998) divides heat exchangers into three groups:

1. direct contact exchangers
2. recuperators
3. regenerators

- ***Direct contact*** **exchangers** are self-explanatory. The hot and cold streams are brought into direct contact (mixed) and heat is transferred. These are particularly common when one stream is solid or entrained with a solid (air dryers, etc.) or for vapor-liquid streams where only the liquid product is of value (spray dryers, cooling towers, etc.). Use of liquid-liquid systems is limited to immiscible pairs.
- A ***regenerating*** **exchanger** transfers heat in steps: first from the hot fluid to a storage medium and subsequently from the storage medium to the cold fluid. A sand tank or rotary slab may be used as the storage phase.

Heat Exchangers: Introduction and Basic Concepts

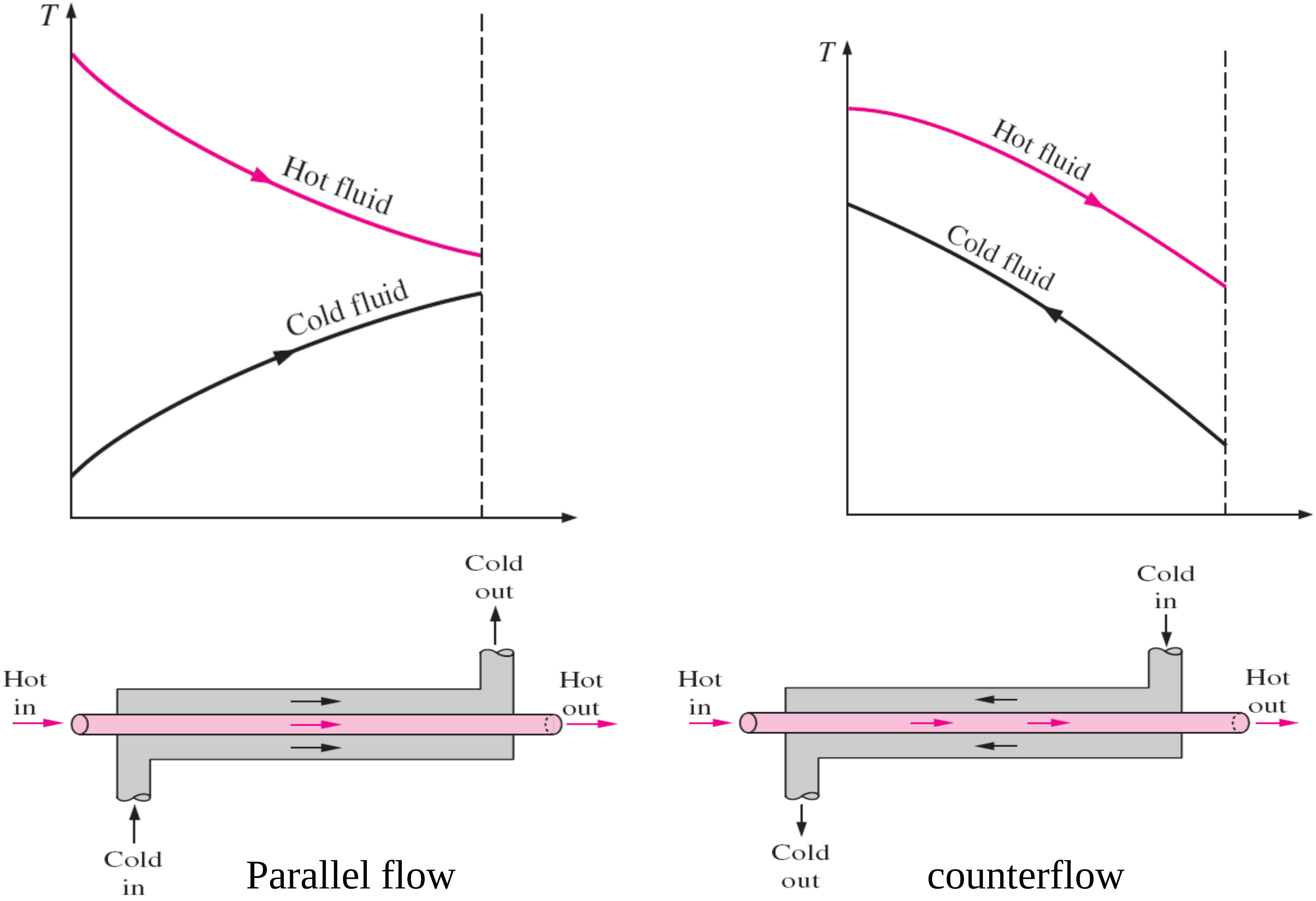
- In this class, we will primarily work with ***recuperating* exchangers**, since they are probably of the most industrial interest. In this arrangement, the hot and cold fluids are separated by a wall and heat is transferred by conduction through the wall. This class includes double pipe (hairpin), shell and tube, and compact (plate and frame, etc.) exchangers.

Flow patterns

- cocurrent (parallel)
- countercurrent
- cross flow (crosscurrent)

Double-pipe Heat Exchangers:

- Double-pipe heat exchanger: The simplest type of heat exchanger consists of two concentric pipes of different diameters, as shown in Figure , called the **double-pipe heat** exchanger.



Parallel flow

counterflow

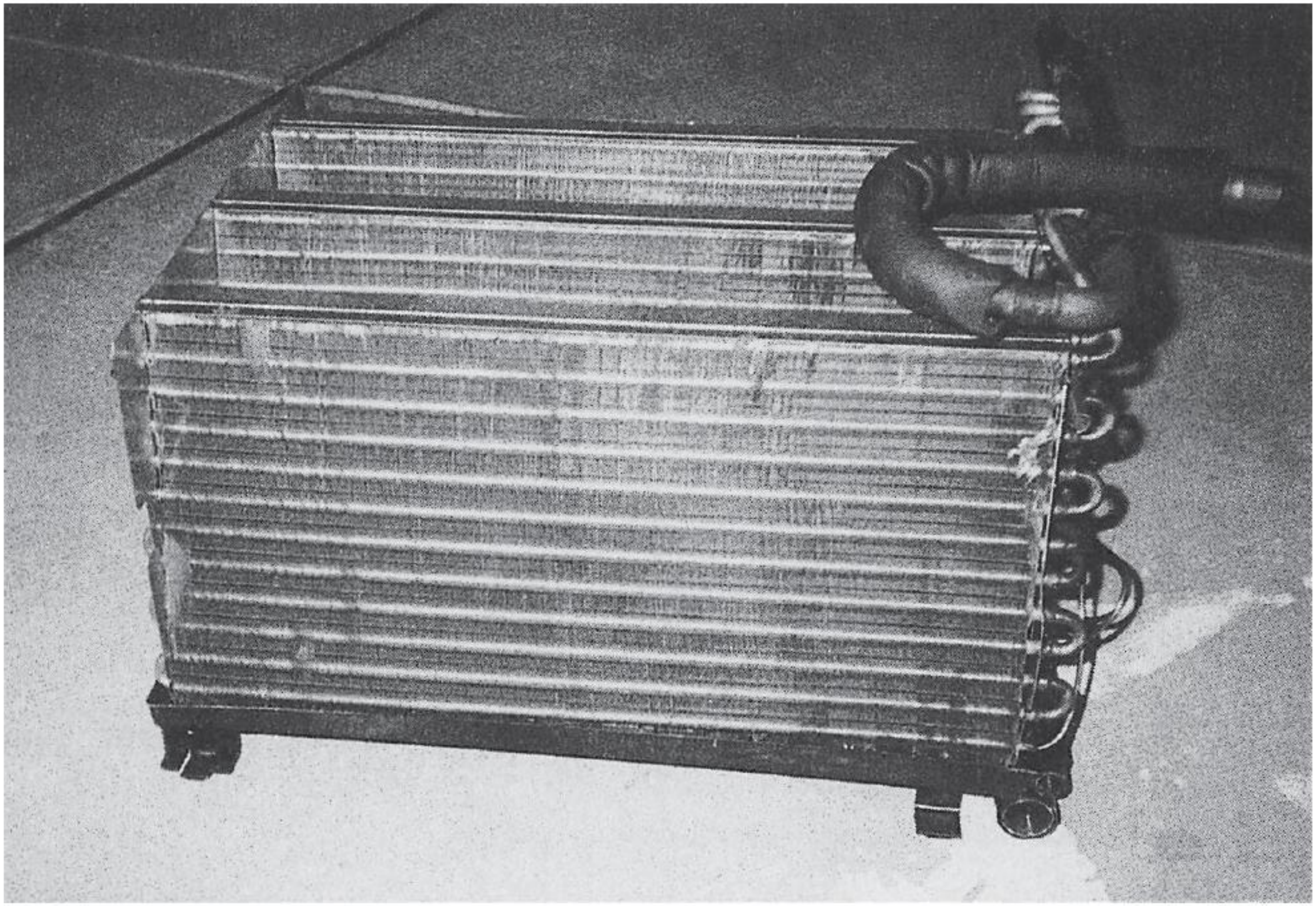
Compact Heat Exchangers:

- Another type of heat exchanger, which is specifically designed to realize a large heat transfer surface area per unit volume, is the **compact heat exchanger.** The ratio of the heat transfer surface area of a heat exchanger to its volume is called the *area density* β.
- A heat exchanger with $\beta > 700\ m^2/m^3$ (or 200 ft^2/ft^3) is classified as being compact. Examples of compact heat exchangers are car radiators ($\beta \sim 1000\ m^2/m^3$), glass ceramic gas turbine heat exchangers ($\beta \sim 6000\ m^2/m^3$), the regenerator of a Stirling engine ($\beta \sim$ 15,000 m2/m3), and the human lung ($\beta \sim$ 20,000 m^2/m^3). Compact heat exchangers enable us to achieve high heat transfer rates between two fluids in a small volume, and they are commonly used in applications with strict limitations on the weight and volume of heat exchangers (Fig.).

Compact Heat Exchangers:

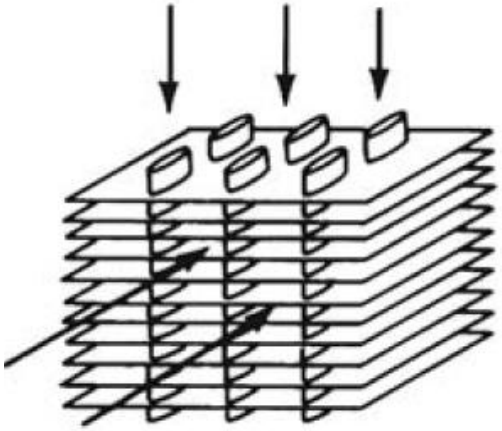
- The large surface area in compact heat exchangers is obtained by attaching closely spaced *thin plate or corrugated fins to the walls separating the two fluids*. Compact heat exchangers are commonly used in gas-to-gas and gas-toliquid (or liquid-to-gas) heat exchangers to counteract the low heat transfer coefficient associated with gas flow with increased surface area. In a car radiator, which is a water-to-air compact heat exchanger, for example, it is no surprise that fins are attached to the air side of the tube surface.
- In compact heat exchangers, the two fluids usually move *perpendicular to* each other, and such flow configuration is called **cross-flow. The cross-flow** is further classified as *unmixed and mixed flow, depending on the flow configuration*, as shown in Figure.

Compact Heat Exchangers:

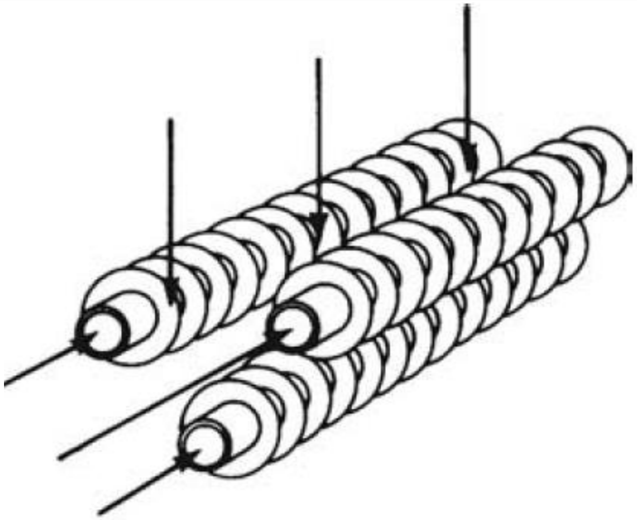


A gas-to-liquid compact heat exchanger for a residential air-conditioning system.

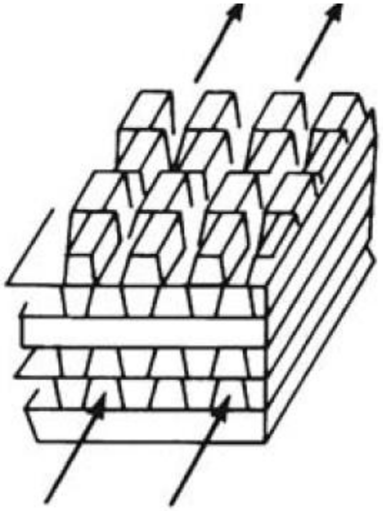
Compact Heat Exchangers:


(a)

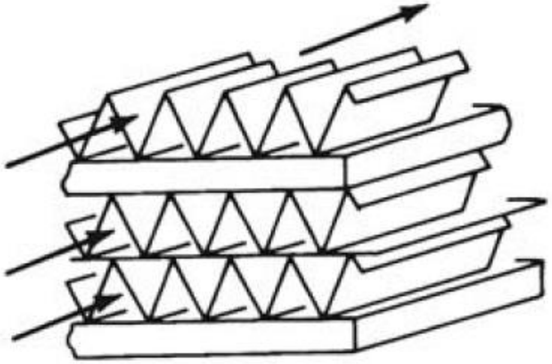
finned-tube exchanger with flat tubes


(b)

circular finned-tube array


(c)

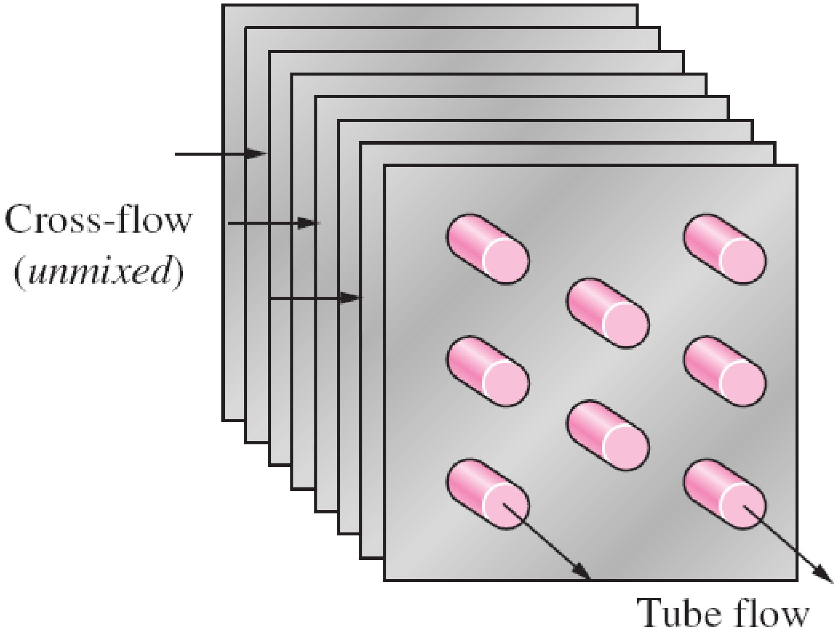
for gas-to-gas heat transfer


(d)

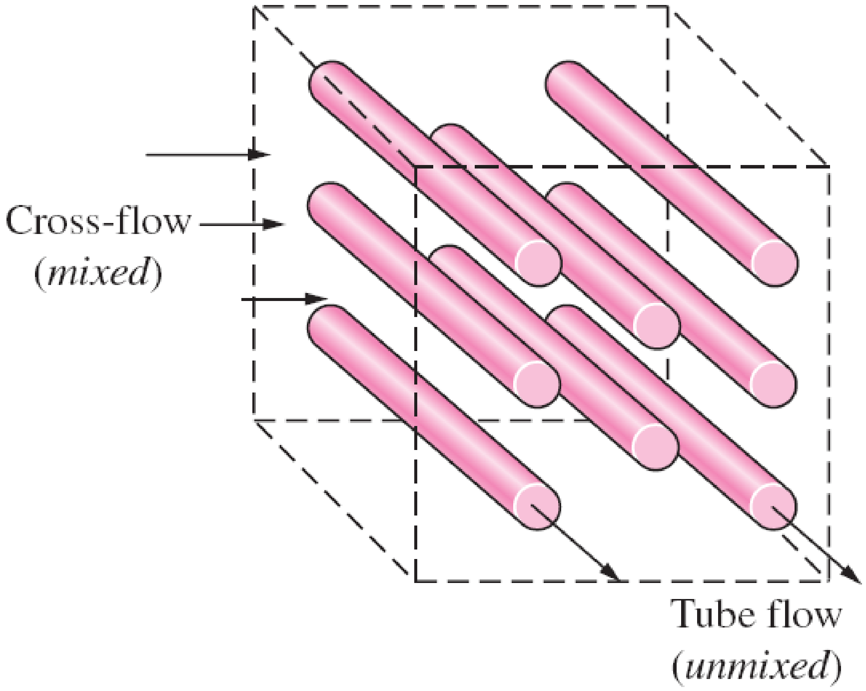
for gas-to-gas heat transfer

Compact Heat Exchangers:

In the cross-flow is said to be *unmixed* since the plate fins force the fluid to flow through a particular inter-fin spacing and prevent it from moving in the transverse direction (i.e., parallel to the tubes).

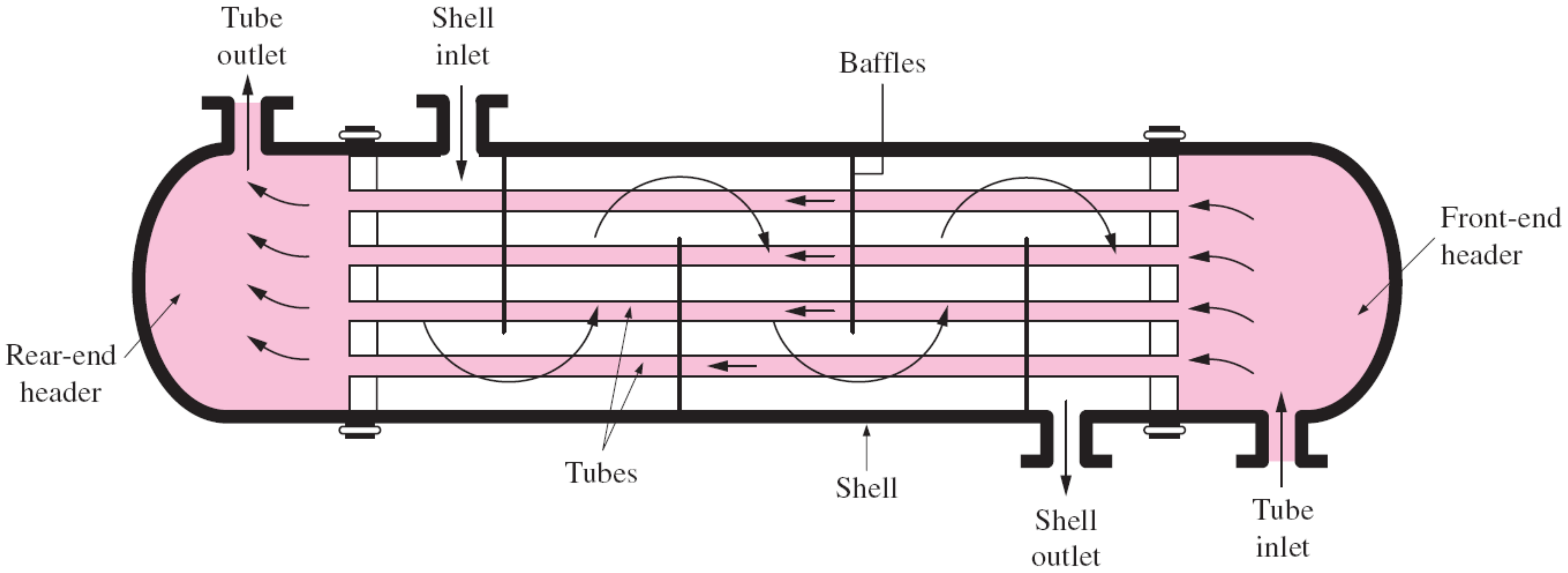


The cross-flow in *is said to be mixed since the fluid now is free* to move in the transverse direction. Both fluids are unmixed in a car radiator. The presence of mixing in the fluid can have a significant effect on the heat transfer characteristics of the heat exchanger.



Shell-and-Tube Heat Exchanger :

- The most common type of heat exchanger in industrial applications is the **shell-and-tube heat exchanger, shown in Figure. 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. Heat transfer takes place as one fluid flows inside the tubes while the other fluid flows outside the tubes through the shell.



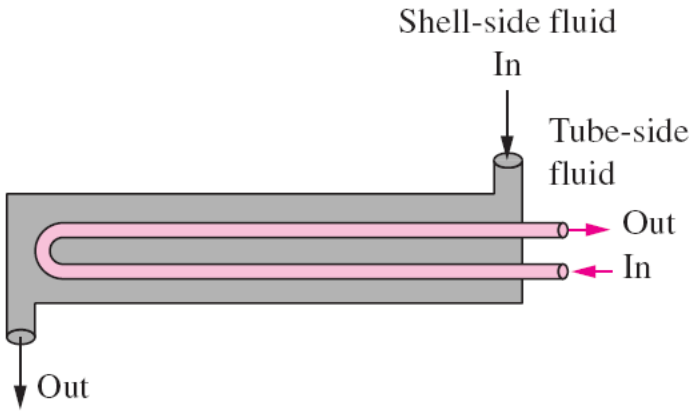
The schematic of a shell-and-tube heat exchanger (one-shell pass and one-tube pass).

Shell-and-Tube Heat Exchanger :

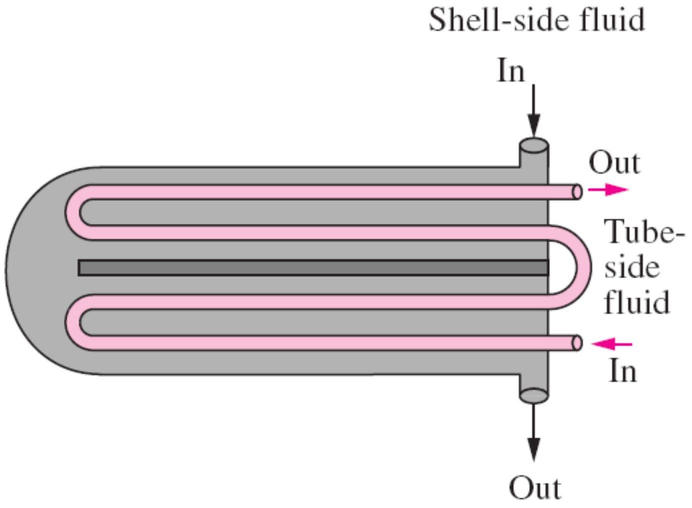
- *Baffles are commonly placed in the shell to force the* shell-side fluid to flow across the shell to enhance heat transfer and to maintain uniform spacing between the tubes.
- Despite their widespread use, shell-and- tube heat exchangers are not suitable for use in automotive and aircraft applications because of their relatively large size and weight. Note that the tubes in a shell-and-tube heat exchanger open to some large flow areas called *headers at both ends of the shell, where the tube-side fluid accumulates before* entering the tubes and after leaving them.

Shell-and-Tube Heat Exchanger :

- Shell-and-tube heat exchangers are further classified according to the number of shell and tube passes involved. Heat exchangers in which all the tubes make one U-turn in the shell, for example, are called *one-shell-pass and two-tube- passes heat exchangers*. *Likewise, a heat exchanger that involves two* passes in the shell and four passes in the tubes is called a *two-shell-passes and four-tube-passes heat exchanger (Fig.).*



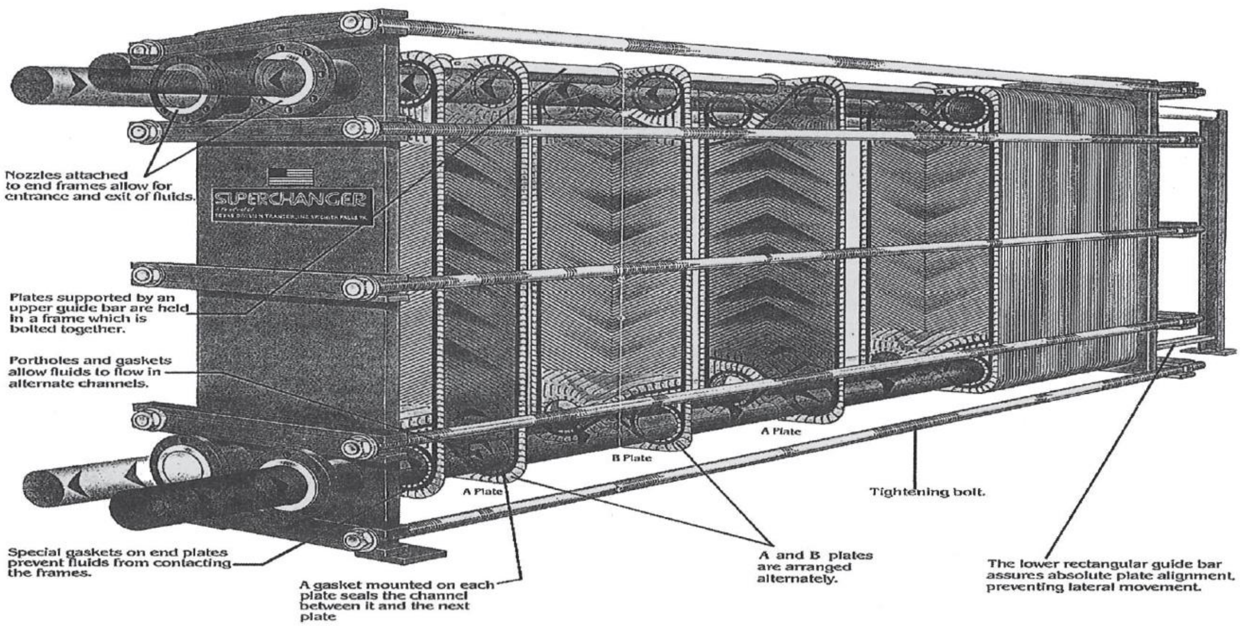
(*a*) One-shell pass and two-tube passes



Multi pass flow arrangements in shell-and- tube heat exchangers.

Plate and frame heat exchanger

- An innovative type of heat exchanger that has found widespread use is the **plate and frame (or just plate) heat exchanger, which consists of a series of** plates with corrugated flat flow passages (Fig. 13–6). The hot and cold fluids flow in alternate passages, and thus each cold fluid stream is surrounded by two hot fluid streams, resulting in very effective heat transfer. Also, plate heat exchangers can grow with increasing demand for heat transfer by simply mounting more plates. They are well suited for liquid-to-liquid heat exchange applications, provided that the hot and cold fluid streams are at about the same pressure.



Regenerative heat exchanger

- Another type of heat exchanger that involves the alternate passage of the hot and cold fluid streams through the same flow area is the **regenerative heat exchanger.** The *static-type regenerative heat exchanger is basically a porous* mass that has a large heat storage capacity, such as a ceramic wire mesh. Hot and cold fluids flow through this porous mass alternatively. Heat is transferred from the hot fluid to the matrix of the regenerator during the flow of the hot fluid, and from the matrix to the cold fluid during the flow of the cold fluid. Thus, the matrix serves as a temporary heat storage medium.
- The *dynamic-type regenerator involves a rotating drum and continuous flow* of the hot and cold fluid through different portions of the drum so that any portion of the drum passes periodically through the hot stream, storing heat, and then through the cold stream, rejecting this stored heat. Again the drum serves as the medium to transport the heat from the hot to the cold fluid stream.

Other heat exchangers

- Heat exchangers are often given specific names to reflect the specific application for which they are used. For example, a *condenser is a heat exchanger* in which one of the fluids is cooled and condenses as it flows through the heat exchanger. A *boiler is another heat exchanger in which one of the fluids absorbs* heat and vaporizes. A *space radiator is a heat exchanger that transfers* heat from the hot fluid to the surrounding space by radiation.

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* T_m *for use in the relation*

$$\dot{Q} = UA_s\,\Delta T_m.$$

- In order to develop a relation for the equivalent average temperature difference between the two fluids, consider the *parallel-flow double-pipe heat exchanger* shown in Figure below. Note that the temperature difference ΔT between the hot and cold fluids is large at the inlet of the heat exchanger but decreases exponentially toward the outlet. As you would expect, the temperature of the hot fluid decreases and the temperature of the cold fluid increases along the heat exchanger, but the temperature of the cold fluid can never exceed that of the hot fluid no matter how long the heat exchanger is.

Heat Exchanger Calculation

- But in a specified temperature range, it can be treated as a constant at some average value with little loss in accuracy. *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.

Heat Exchanger calculation:

- Heat exchangers are commonly used in practice, and an engineer often finds himself or herself in a position to *select a heat exchanger that will achieve a specified temperature change in a fluid stream of known mass flow rate, or to predict the outlet temperatures of the hot and cold fluid streams in a specified heat exchanger*.
- In upcoming sections, the two methods used in the analysis of heat exchangers will be discussed. Of these, the *log mean temperature difference (or LMTD)* method is best suited for the first task and the *effectiveness–NTU method for* the second task as just stated.
- Heat exchangers usually operate for long periods of time with no change in their operating conditions. Therefore, they can be modeled as *steady-flow devices*. As such, the mass flow rate of each fluid remains constant, and the fluid properties such as temperature and velocity at any inlet or outlet remain the same. Also, the fluid streams experience little or no change in their velocities and elevations, and thus the *kinetic and potential energy changes are negligible*. The *specific heat of a fluid, in general, changes with temperature*.

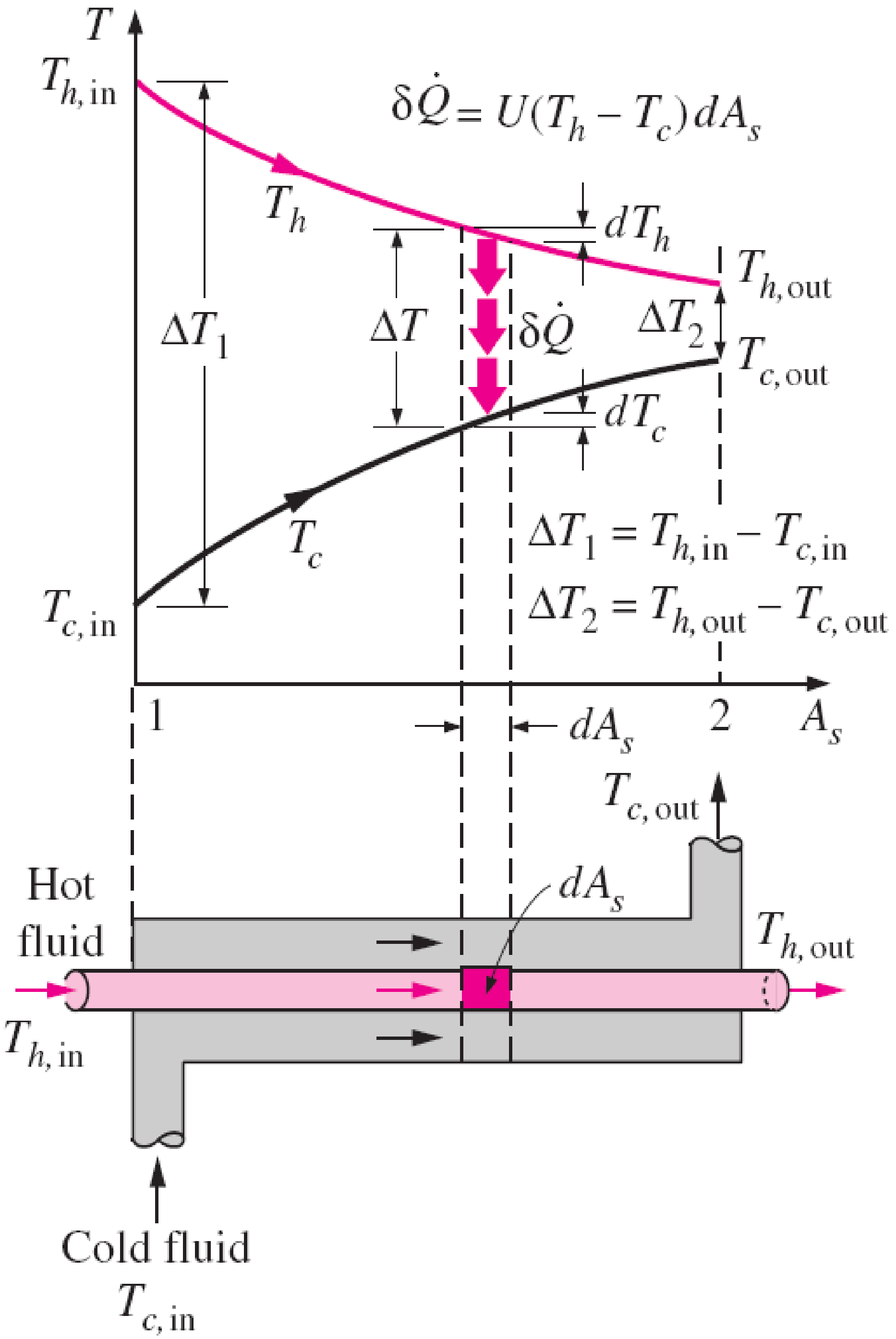
The log mean temperature difference method

- the outer surface of the heat exchanger assume 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

$$\delta\dot{Q} = -\dot{m}_h C_{ph}\, dT_h$$

and

$$\delta\dot{Q} = \dot{m}_c C_{pc}\, dT_c$$



The log mean temperature difference method

- That is, the rate of heat loss from the hot fluid at any section of a heat exchanger is equal to the rate of heat gain by the cold fluid in that section. The temperature change of the hot fluid is a *negative quantity, and so a negative sign is added to above Eq. to make the heat transfer rate* a positive quantity. Solving the equations above for dT_h *and* dT_c *gives*

$$dT_h = -\frac{\delta \dot{Q}}{\dot{m}_h C_{ph}}$$

and

$$\delta \dot{Q} = \dot{m}_c C_{pc}\, dT_c$$

therefore

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

The log mean temperature difference method

- The rate of heat transfer in the differential section of the heat exchanger can also be expressed as

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

And

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

By integration

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

The log mean temperature difference method

- Over all heat transfer equation:

$$\dot{Q} = UA_s \, \Delta T_{\text{lm}}$$

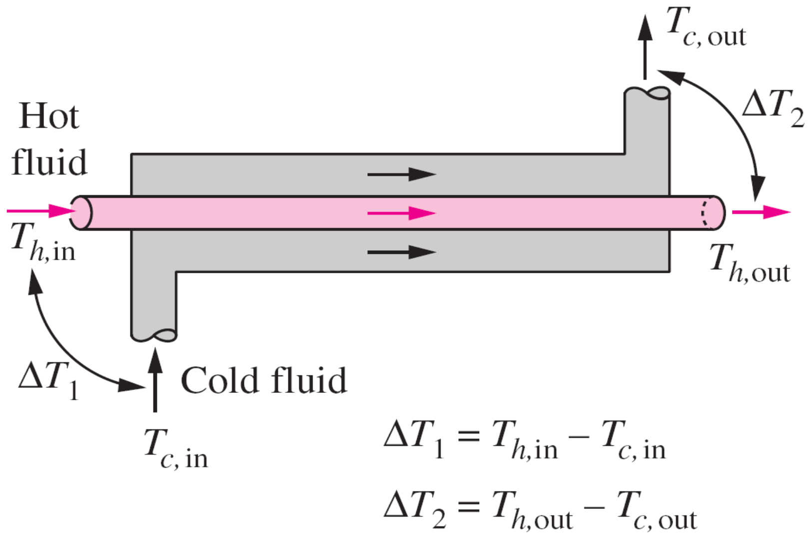
Where log mean temperature difference is as follows:

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

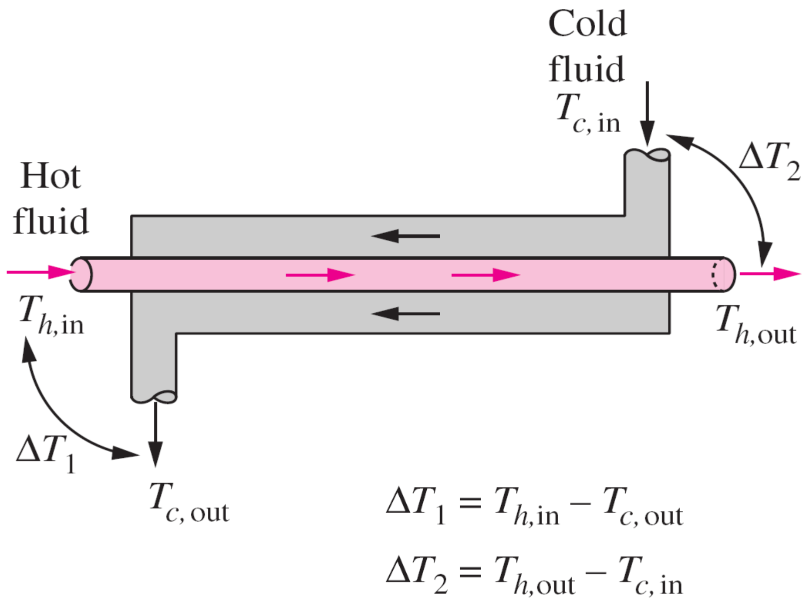
Here ΔT_1 *and* ΔT_2 *represent the temperature difference between the two fluids* at the two ends (inlet and outlet) of the heat exchanger. It makes no difference which end of the heat exchanger is designated as the *inlet or the outlet* (Fig.).

The log mean temperature difference method

The temperature difference between the two fluids decreases from ΔT_1 *at* the inlet to ΔT_2 *at the outlet. Thus, it is tempting to use the arithmetic mean* temperature ΔTam = *$(\Delta T_1 + \Delta T_2)/2$ as the average temperature difference. The* logarithmic mean temperature difference ΔT_{lm} *is obtained by tracing the actual* temperature profile of the fluids along the heat exchanger and is an *exact* representation of the *average temperature difference between the hot and* cold fluids. It truly reflects the exponential decay of the local temperature difference.



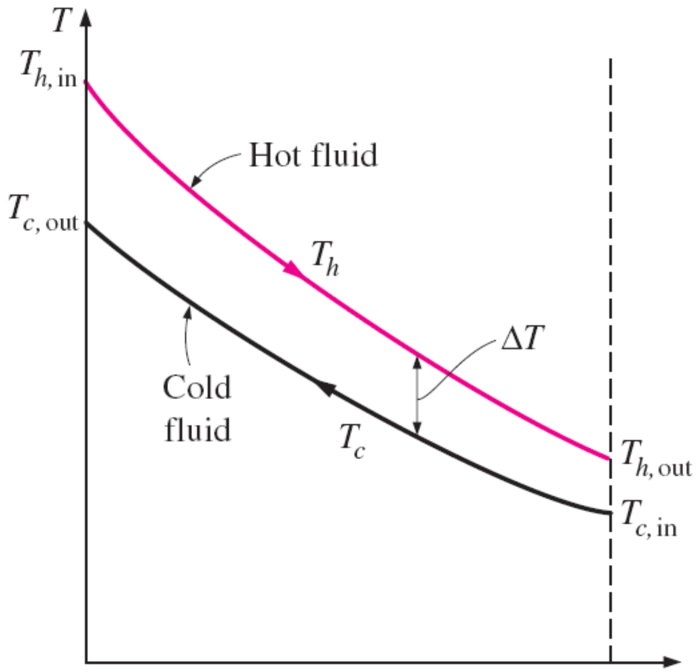
(*a*) Parallel-flow heat exchangers

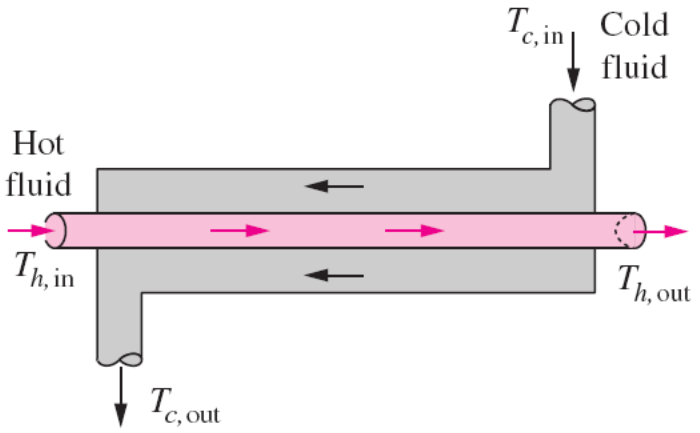


(*b*) Counter-flow heat exchangers

LMTD method for counter flow Heat Exchanger

- The variation of temperatures of hot and cold fluids in a counter-flow heat exchanger is given in Figure. Note that the hot and cold fluids enter the heat exchanger from opposite ends, and the outlet temperature of the *cold fluid in this case may exceed the outlet temperature of the hot fluid. In the limiting* case, the cold fluid will be heated to the inlet temperature of the hot fluid. However, the outlet temperature of the cold fluid can *never exceed the inlet* temperature of the hot fluid, since this would be a violation of the second law of thermodynamics.





LMTD method for counter flow Heat Exchanger

- For specified inlet and outlet temperatures, the log mean temperature difference for a *counter-flow heat exchanger is always greater than that for a* parallel-flow heat exchanger. That is, $T_{lm,CF} > T_{lm,\ PF}$, *and thus a smaller* surface area (and thus a smaller heat exchanger) is needed to achieve a specified heat transfer rate in a counter-flow heat exchanger. Therefore, it is common practice to use counter-flow arrangements in heat exchangers.
- In a counter-flow heat exchanger, the temperature difference between the hot and the cold fluids will remain constant along the heat exchanger when the *heat capacity rates of the two fluids are equal (that is,* ΔT = *constant* when $C_h = C_c$ *or* $m_h C_{ph} = m_c C_{pc}$*). Then we have* $\Delta T_1 = \Delta T_2$*, and the last log* mean temperature difference relation gives $\Delta T_{lm} = 0/0$, *which is indeterminate*. It can be shown by the application of l'Hôpital's rule that in this case we have $\Delta T_{lm} = \Delta T_1 = \Delta T_2$*, as expected.*
- A *condenser or a boiler can be considered to be either a parallel- or counterflow* heat exchanger since both approaches give the same result.

Correction Factor for Multipass and Cross-Flow Heat Exchangers:

- The log mean temperature difference ΔT_{lm} *relation developed earlier is limited* to parallel-flow and counter-flow heat exchangers only. Similar relations are also developed for *cross-flow and multi pass shell-and-tube heat exchangers*, but the resulting expressions are too complicated because of the complex flow conditions.
- In such cases, it is convenient to relate the equivalent temperature difference to the log mean temperature difference relation for the counter-flow case as

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

- F is the correlation factor, which depends on the *geometry of the heat* exchanger and the inlet and outlet temperatures of the hot and cold fluid streams.

Correction Factor for Multi pass and Cross-Flow Heat Exchangers:

- The correction factor is less than unity for a cross-flow and multi pass shell-and- tube heat exchanger. That is, $F \leq 1$. *The limiting value of F = 1 corresponds* to the counter-flow heat exchanger. Thus, the correction factor *F for a* heat exchanger is *a measure of deviation of the* ΔT_{lm} *from the corresponding values for the counter-flow case.*
- The correction factor *F for common cross-flow and shell-and-tube heat exchanger* configurations is given by two temperature ratios *P and R defined as*

$$P = \frac{t_2 - t_1}{T_1 - t_1}$$

and

$$R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{(\dot{m}C_p)_{\text{tube side}}}{(\dot{m}C_p)_{\text{shell side}}}$$

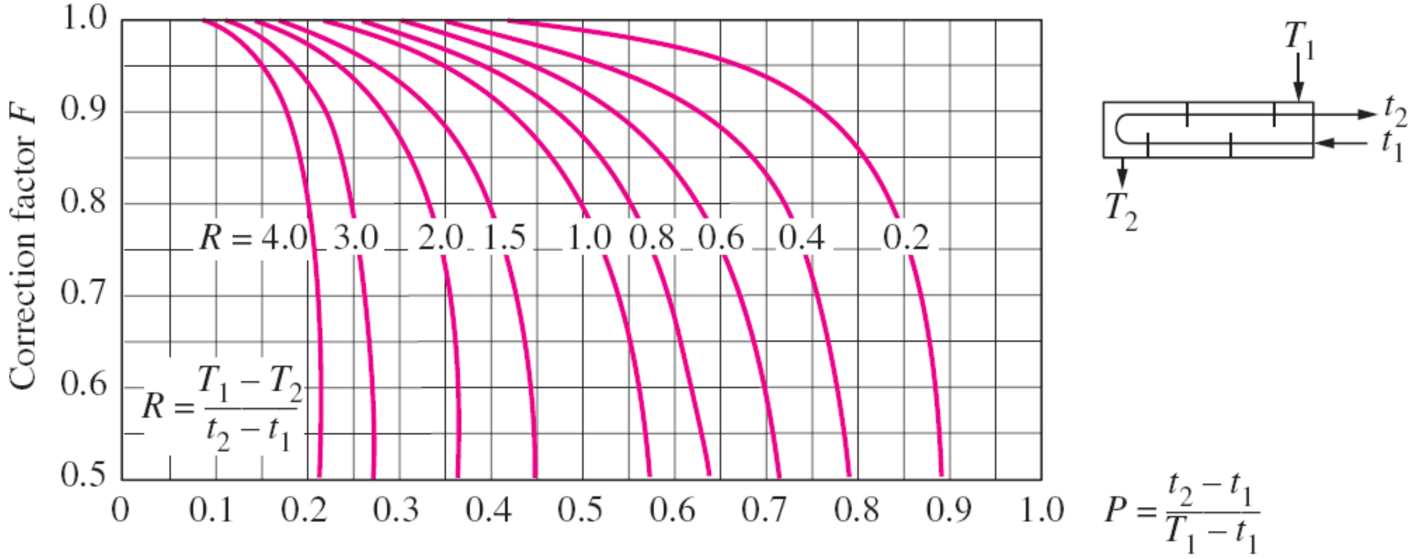
- where the subscripts 1 and 2 represent the *inlet and outlet, respectively. Note* that for a shell-and-tube heat exchanger, *T and t represent the shell- and tube-side temperatures, respectively, as shown in the correction factor* charts.

Correction Factor for Multi pass and Cross-Flow Heat Exchangers:

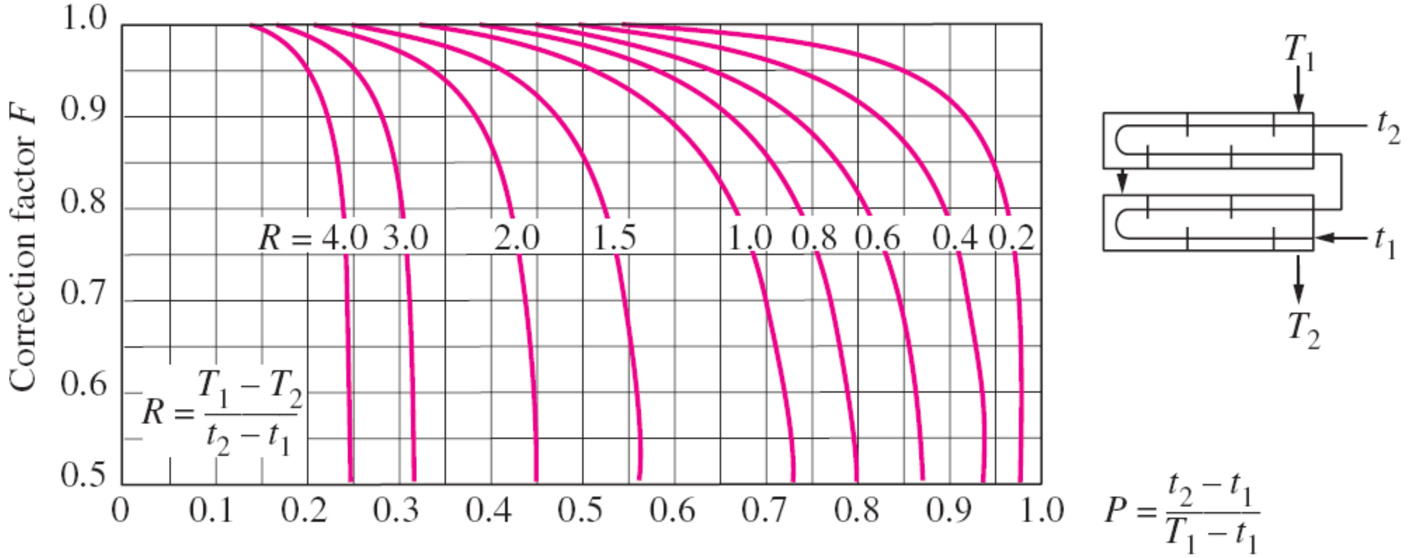
- The value of P *ranges from 0 to 1. The value of* R, *on the other* hand, ranges from 0 to infinity, with $R = 0$ *corresponding to the phase-change* (condensation or boiling) on the shell-side and $R \to \infty$ *to phase-change on the* tube side. The correction factor is $F = 1$ *for both of these limiting cases*. Therefore, the correction factor for a *condenser or boiler is* $F = 1$, *regardless* of the configuration of the heat exchanger.

Correction Factor for Multi pass and Cross-Flow Heat Exchangers:

- Correction factor *F charts* for common shell-and-tube and cross-flow heat exchangers



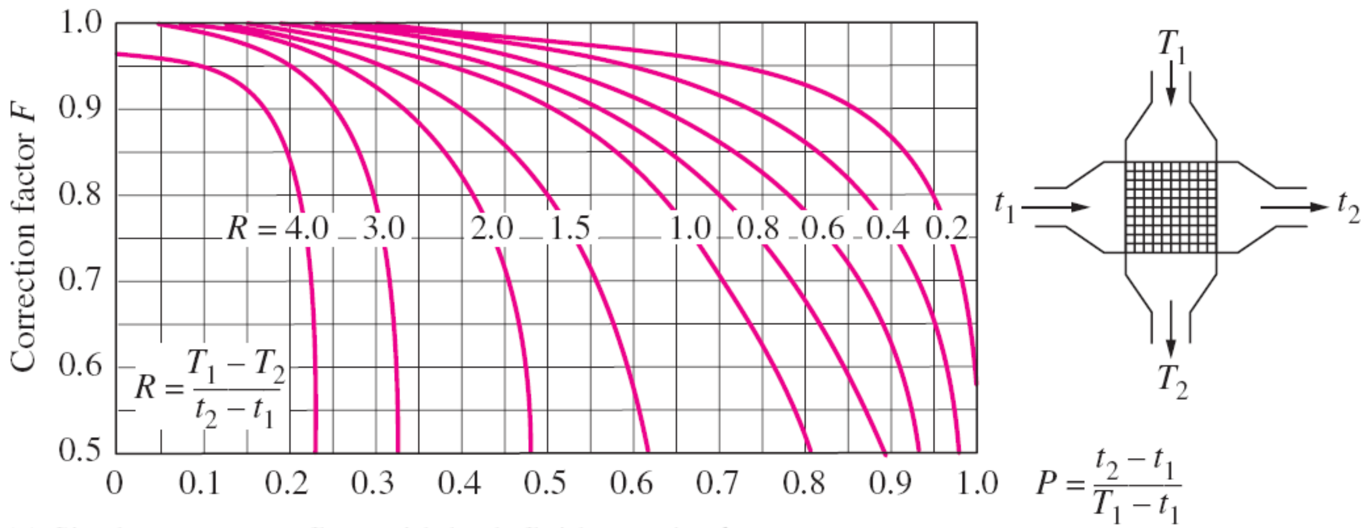
(*a*) One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes



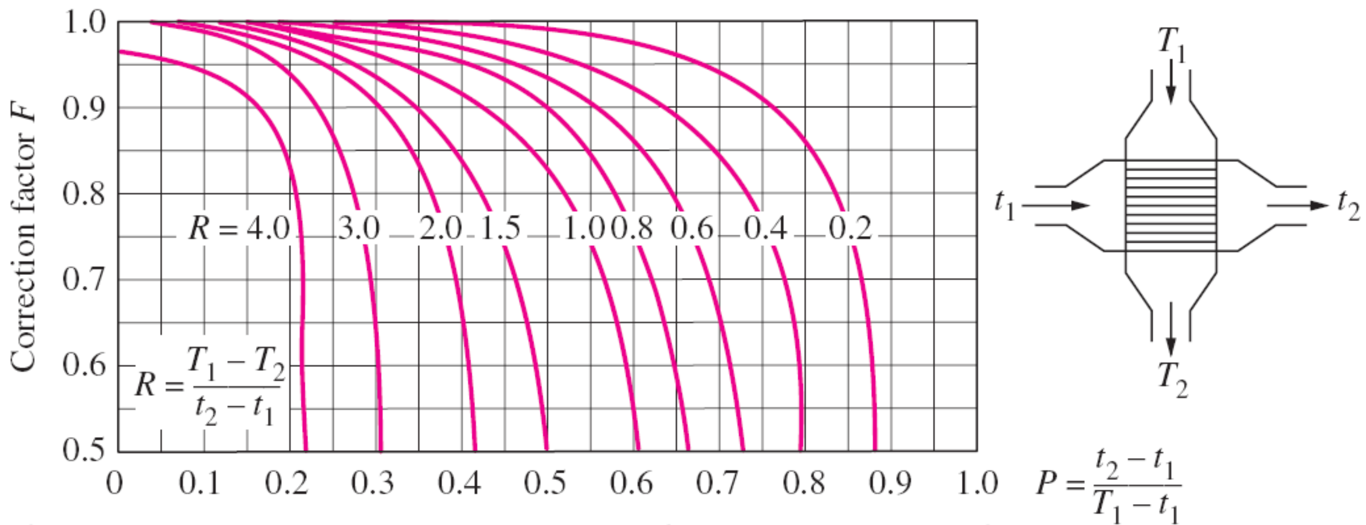
(*b*) Two-shell passes and 4, 8, 12, etc. (any multiple of 4), tube passes

Correction Factor for Multi pass and Cross-Flow Heat Exchangers:

- Correction factor *F charts* for common shell-and-tube and cross-flow heat exchangers



(*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 for Heat Exchanger

- The LMTD method is very suitable for determining the *size* of a heat exchanger to realize prescribed outlet temperatures when the mass flow rates and the inlet and outlet temperatures of the hot and cold fluids are specified.

- The LMTD procedure would require tedious iterations, and thus it is not practical. In an attempt to eliminate the iterations from the solution of such problems, Kays and London came up with a method in 1955 called the **effectiveness–NTU method, which greatly simplified heat exchanger analysis.**
- This method is based on a dimensionless parameter called the **heat transfer effectiveness ε, defined as**

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

The effectiveness–NTU method for Heat Exchanger

- The *actual heat transfer rate in a heat exchanger can be determined from an* energy balance on the hot or cold fluids and can be expressed as

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

- where $C_c = \dot{m}_c C_{pc}$ and $C_h = \dot{m}_c C_{ph}$ are the heat capacity rates of the cold and the hot fluids, respectively.
- To determine the maximum possible heat transfer rate in a heat exchanger, we first recognize that the *maximum temperature difference in a heat exchanger* is the difference between the *inlet temperatures of the hot and cold* fluids. That is,

$$\Delta T_{\max} = T_{h,\text{ in}} - T_{c,\text{ in}}$$

The effectiveness–NTU method for Heat Exchanger

- The heat transfer in a heat exchanger will reach its maximum value when (1) the cold fluid is heated to the inlet temperature of the hot fluid or (2) the hot fluid is cooled to the inlet temperature of the cold fluid. These two limiting conditions will not be reached simultaneously unless the heat capacity rates of the hot and cold fluids are identical (i.e., $C_c = C_h$). *When* $C_c \neq C_h$, which is usually the case, the fluid with the *smaller heat capacity rate will experience* a larger temperature change, and thus it will be the first to experience the maximum temperature, at which point the heat transfer will come to a halt. Therefore, the maximum possible heat transfer rate in a heat exchanger is

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

where C_{min} is the smaller of $C_h = \dot{m}_h C_{ph}$ and $C_c = \dot{m}_c C_{pc}$.

The effectiveness–NTU method for Heat Exchanger

- The determination of $\dot{Q}_{\max}$ requires the availability of the *inlet temperature* of the hot and cold fluids and their *mass flow rates, which are usually specified*. Then, once the effectiveness of the heat exchanger is known, the actual heat transfer rate $\dot{Q}$ can be determined from
- Therefore, the effectiveness of a heat exchanger enables us to determine the heat transfer rate without knowing the *outlet temperatures of the fluids.*
- The effectiveness of a heat exchanger depends on the *geometry of the heat* exchanger as well as the *flow arrangement. Therefore, different types of heat* exchangers have different effectiveness relations. Below we illustrate the development of the effectiveness relation for the double-pipe *parallel-flow* heat exchanger.
- for a parallel-flow heat exchanger can be rearranged as

$$\ln \frac{T_{h,\,\mathrm{out}} - T_{c,\,\mathrm{out}}}{T_{h,\,\mathrm{in}} - T_{c,\,\mathrm{in}}} = -\frac{UA_s}{C_c}\left(1 + \frac{C_c}{C_h}\right)$$

- and

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

The effectiveness–NTU method for Heat Exchanger

- Substituting this relation into the above Eq. after adding and subtracting T_c, *in gives*

$$\ln \frac{T_{h,\text{ in}} - T_{c,\text{ in}} + T_{c,\text{ in}} - T_{c,\text{ out}} - \dfrac{C_c}{C_h}(T_{c,\text{ out}} - T_{c,\text{ in}})}{T_{h,\text{ in}} - T_{c,\text{ in}}} = -\frac{UA_s}{C_c}\left(1 + \frac{C_c}{C_h}\right)$$

Or

$$\ln\left[1 - \left(1 + \frac{C_c}{C_h}\right)\frac{T_{c,\text{ out}} - T_{c,\text{ in}}}{T_{h,\text{ in}} - T_{c,\text{ in}}}\right] = -\frac{UA_s}{C_c}\left(1 + \frac{C_c}{C_h}\right)$$

From definition effectiveness is

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} = \frac{C_c(T_{c,\text{ out}} - T_{c,\text{ in}})}{C_{\min}(T_{h,\text{ in}} - T_{c,\text{ in}})} \longrightarrow \frac{T_{c,\text{ out}} - T_{c,\text{ in}}}{T_{h,\text{ in}} - T_{c,\text{ in}}} = \varepsilon\frac{C_{\min}}{C_c}$$

Therefore for parallel flow

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

The effectiveness–NTU method for Heat Exchanger

- Taking either C_c *or* C_h *to be* C_{min} *(both approaches give the same result), the* relation above can be expressed more conveniently as

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

- Again C_{min} *is the smaller heat capacity ratio and* C_{max} *is the larger one, and it* makes no difference whether C_{min} *belongs to the hot or cold fluid.*
- 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**

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

The effectiveness–NTU method for Heat Exchanger

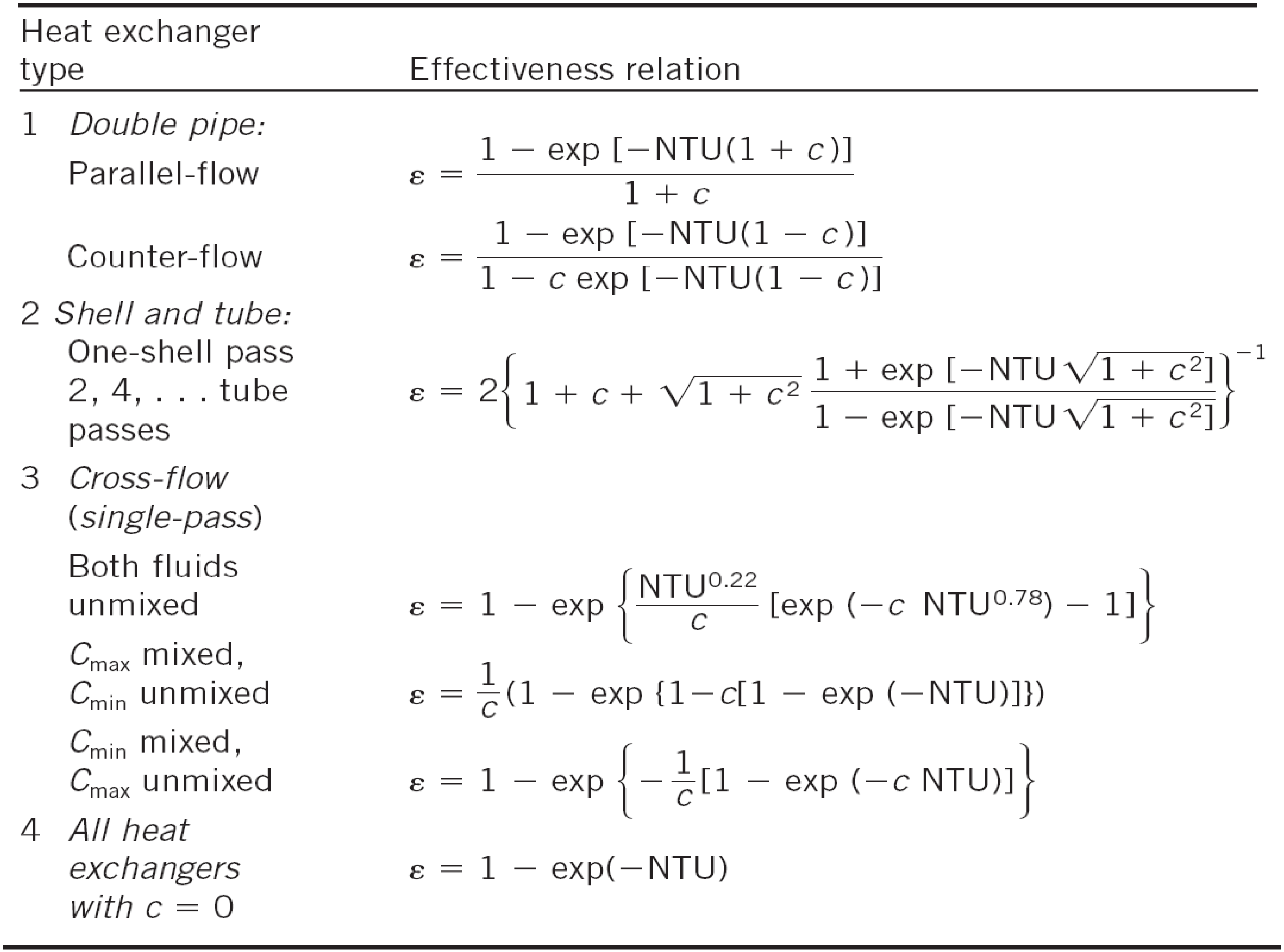
- where *U is the overall heat transfer coefficient and* A_s *is the heat transfer surface* area of the heat exchanger. Note that NTU is proportional to A_s . *Therefore, for* specified values of *U and* C_{min}*, the value of NTU is a measure of the heat transfer surface area* A_s *. Thus, the larger the NTU, the larger the heat exchanger.*
- In heat exchanger analysis, it is also convenient to define another dimensionless quantity called the **capacity ratio *c as***

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

- ***and***

$$\varepsilon = \text{function}\,(UA_s/C_{\min},\, C_{\min}/C_{\max}) = \text{function}\,(\text{NTU},\, c)$$

Effectiveness relations for heat exchangers:



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

NTU relations for heat exchangers

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

- An engineer going through catalogs of heat exchanger manufacturers will be overwhelmed by the type and number of readily available off-the-shelf heat exchangers. The proper selection depends on several factors.

1. **Heat Transfer Rate:** This is the most important quantity in the selection of a heat exchanger. A heat exchanger should be capable of transferring heat at the specified rate in order to achieve the desired temperature change of the fluid at the specified mass flow rate.
2. **Cost:** Budgetary limitations usually play an important role in the selection of heat exchangers, except for some specialized cases where "money is no object." An off-the-shelf heat exchanger has a definite cost advantage over those made to order. However, in some cases, none of the existing heat exchangers will do, and it may be necessary to undertake the expensive and time-consuming task of designing and manufacturing a heat exchanger from scratch to suit the needs. This is often the case when the heat exchanger is an integral part of the overall device to be manufactured.

Selection of Heat Exchangers

3. **Pumping Power:** In a heat exchanger, both fluids are usually forced to flow by pumps or fans that consume electrical power. The annual cost of electricity associated with the operation of the pumps and fans can be determined from

$$\text{Operating cost} = (\text{Pumping power, kW}) \times (\text{Hours of operation, h}) \times (\text{Price of electricity, \$/kWh})$$

4. **Size and Weight:** Normally, the *smaller and the lighter the heat exchanger, the better it is. This* is especially the case in the *automotive and aerospace industries, where size* and weight requirements are most stringent. Also, a larger heat exchanger normally carries a higher price tag. The space available for the heat exchanger in some cases limits the length of the tubes that can be used.

5. **Type:** The type of heat exchanger to be selected depends primarily on the type of *fluids involved, the size and weight limitations, and the presence of any phase change* processes. For example, a heat exchanger is suitable to cool a liquid by a gas if the surface area on the gas side is many times that on the liquid side. On the other hand, a plate or shell-and-tube heat exchanger is very suitable for cooling a liquid by another liquid.

Selection of Heat Exchangers

6. **Materials:** The materials used in the construction of the heat exchanger may be an important consideration in the selection of heat exchangers. For example, the thermal and structural *stress effects need not be considered at pressures below* 15 atm or temperatures below 150°C. But these effects are major considerations above 70 atm or 550°C and seriously limit the acceptable materials of the heat exchanger. A temperature difference of 50°C or more between the tubes and the shell will probably pose *differential thermal expansion problems and needs to be* considered. In the case of corrosive fluids, we may have to select expensive *corrosion-resistant materials such as stainless steel or even titanium if we are* not willing to replace low-cost heat exchangers frequently.

7. **Other Considerations:** There are other considerations in the selection of heat exchangers, depend on the application. For example, being *leak-tight is an important consideration when toxic or expensive fluids are involved.* Ease of servicing, low maintenance cost, and safety and reliability are some other important considerations in the selection process. Quietness is one of the primary considerations in the selection of liquid-to-air heat exchangers used in heating and air-conditioning applications.