PDHonline Course K114 (2 PDH)

Basics of Industrial Heat Transfer

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COURSE CONTENT

Starting With the Base Equations

Any overall energy balance starts with the following equations:

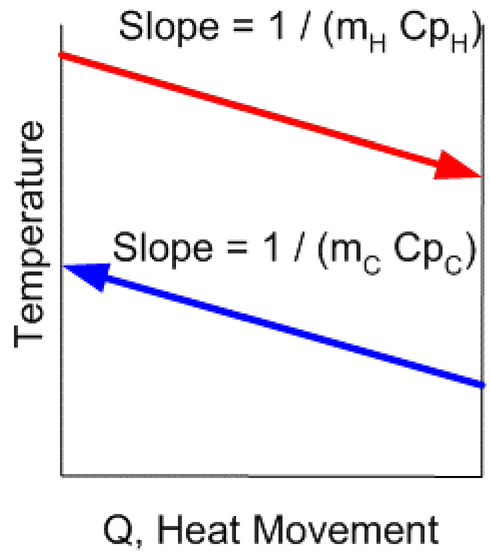
$$Q_H = m_H \ Cp_H \ (T_{inH} - T_{outH})$$
$$Q_C = m_C \ Cp_C \ (T_{outC} - T_{inC})$$

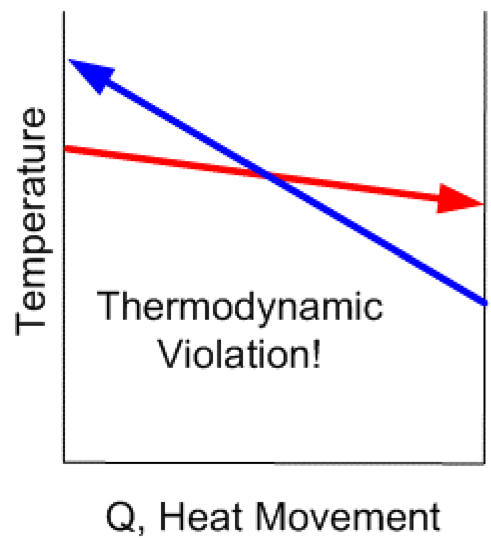
Where:

Q = heat transferred in thermal unit per time (Btu/h or kW)
M = mass flow rate
T = temperature
Cp = heat capacity or specific heat of fluid
Subscript "H" = hot fluid
Subscript "C" = cold fluid

In theory, the heat given up by the hot fluid is never exactly equal to the heat gained by the cold fluid due to environmental heat losses. In practice, however, they are generally assumed to be equal to simplify the calculations involved. Any environmental losses are generally minimized with insulation of equipment and piping.

When examining industrial systems, it is common practice to use a graphical form of these equations know as "T-Q diagrams" to enhance understanding and to make sure that the Second Law of Thermodynamics is not disobeyed. In other words, **heat can only move from a higher to a lower temperature fluid**. Here is how the generic diagram is constructed:





It's easy to see how viewing a particular heat transfer problem in this way is extremely valuable.

Now that's we've seen how heat moves from a hot fluid to a cold fluid, let's examine the third basic equation that is used to govern the equipment used for transferring heat.

The “Heat Exchanger Equation” takes the form:

$$Q = f\,U\,A\,\Delta T_{LM} = f\,U\,A\,(LMTD)$$

Where:

Q = heat transferred in thermal unit per time (Btu/h)
f = temperature correction factor
U = overall heat transfer coefficient (Btu/h ft^2 °F)
A = heat transfer area (ft^2)
LMTD = log mean temperature difference

These three (3) equations are the basis for virtually all heat exchanger design.

Examining the “Heat Exchanger Equation”

If we take a closer look at the heat exchanger equation, it’s worth noting some assumptions that are made in its derivation. First, the overall heat transfer coefficient and the specific heat (also called heat capacity) of the fluids are assumed to remain constant through the heat exchanger.

If we look at the change in the heat capacity of water, for example, over a reasonable temperature range, here is what we find:

Specific heat of water at 100 °F and atm. pressure = 0.9979 Btu / lb °F
Specific heat of water at 210 °F and atm. pressure = 1.0066 Btu / lb °F

So, we can see that this is a fairly reasonable assumption for water and it remains reasonable for most industrial fluids. The specific heat of a substance is defined as the amount of heat required to raise the temperature of one pound of the substance by a single degree Fahrenheit (other units can apply as well).

The overall heat transfer coefficient is a calculated variable based on the physical properties of the fluids involved in the heat transfer (hot and cold) as well as the geometry and type of heat exchanger to be used. We’ll examine this closer a little later.

The log mean temperature difference or LMTD is used to describe the average temperature difference throughout the exchanger. The difference between the temperatures of the fluids provides the "driving force" for the heat transfer to occur. The larger the temperature difference, the smaller the required heat exchanger and vice versa.

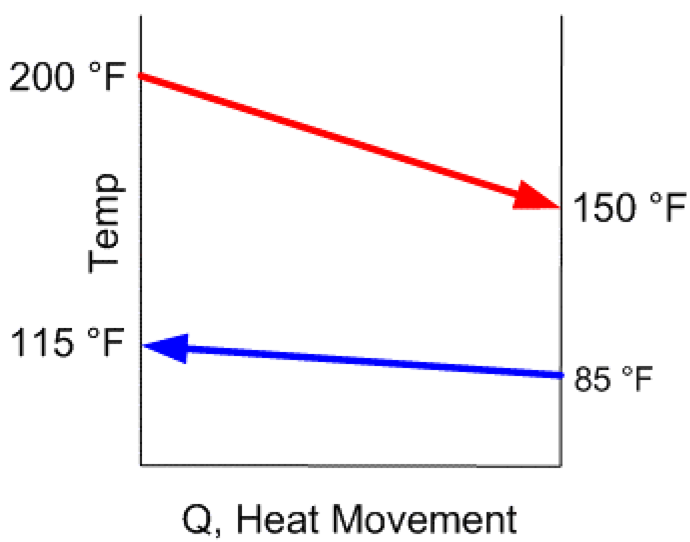
You'll notice from our T-Q diagram used to explain the equations:

$$Q_H = m_H \; Cp_H \; (T_{inH} - T_{outH})$$

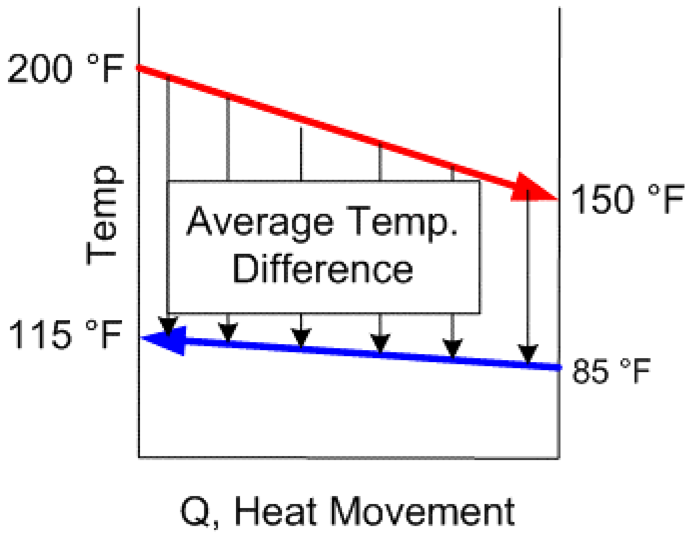
$$Q_C = m_C \; Cp_C \; (T_{outC} - T_{inC})$$

it appears that the temperature difference between the fluids remains almost constant throughout the heat exchanger. This is rarely the case. Let's look at a more practical example. Let's assume that a process stream containing water at 200 °F is to be cooled to 150 °F using cooling tower water available at 85 °F. It is common practice in industry to return cooling tower no higher than 120 °F. In other words, the cooling tower water flow must be such that its outlet temperature from the heat exchanger is less than 120 °F. The reason for this is that cooling tower water often contains treatment chemicals that can plate out onto heat transfer surfaces and cause severe fouling or degradation of the heat transfer rate at elevated temperatures.

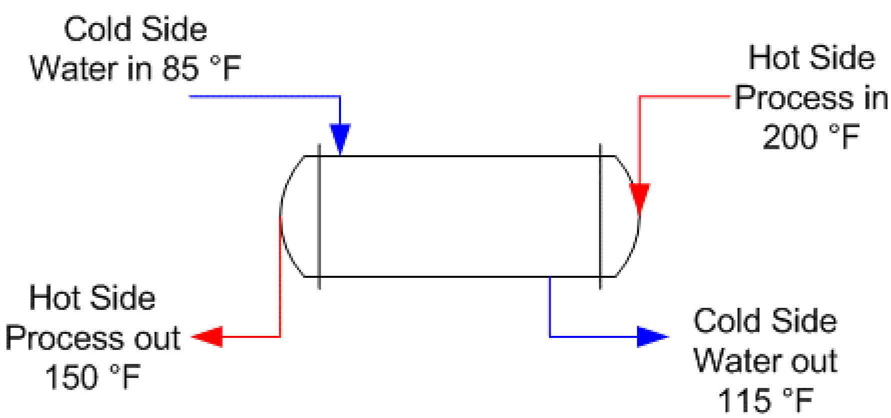
Here is what the T-Q diagram may look like for our example case:



You can see that the temperature difference between the two streams will vary widely. This is why the log mean temperature difference is used. Here is how the log mean temperature difference works:



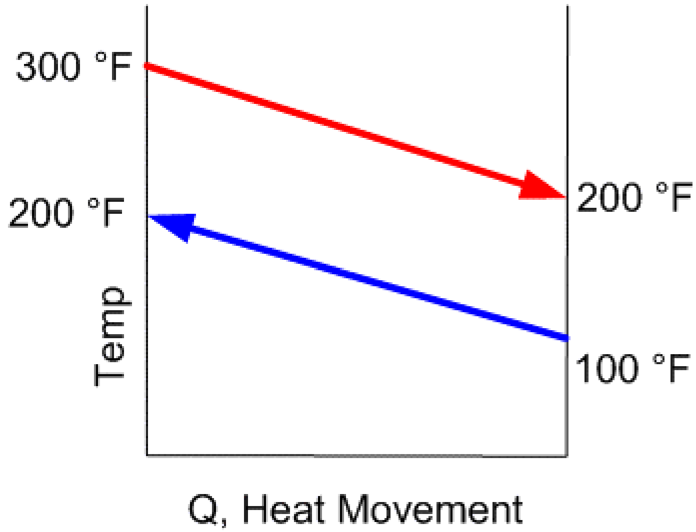
So, for a heat exchanger as described above, we calculate the LMTD as follows:



$$\Delta T_{LM} = \frac{(T_{Hin} - T_{Cout}) - (T_{Hout} - T_{Cin})}{LN\left(\frac{T_{Hin} - T_{Cout}}{T_{Hout} - T_{Cin}}\right)}$$

$$\Delta T_{LM} = \frac{(200 - 115) - (150 - 85)}{LN\left(\frac{200 - 115}{150 - 85}\right)} = 74.6°F$$

There can be special cases where the LMTD equation shown above is not applicable. Consider the case below.



If you tried apply the LMTD equation to this special case, you'd find that the result would be zero. In this case the LMTD is the same as the temperature difference on each "end" of the heat exchanger, or 100 °F.

A Brief Word on Flow Direction

Notice that up to this point, the two fluids considered in a heat exchanger have been moving in opposite directions to one another. This is known as counter-current flow. This is the predominantly preferred flow direction because it results in higher temperature difference driving forces within the heat exchanger, thus minimizing the heat transfer area required.

The other flow configuration, where the fluids flow in the same direction, is called co-current flow. Co-current flow, while it is rarely used, does have the advantage of lowering the heat exchanger wall temperature on the hot side fluid. This can be useful for temperature sensitive fluids or as a means of minimizing deposits that are temperature sensitive.

The Temperature Correction Factor, f

The temperature correction factor, f, is used to correct the log mean temperature difference for heat exchangers than lack truly counter-current flow. Many different heat transfer technologies lack truly counter-current flow patterns as a result of their inherent mechanical design. Generally, the value for f should be between 0.75 of 0.97. There are cases when this value can be taken as one, but only if the flow in the exchanger is purely counter-current. There are countless charts available to look up the temperature correction factor for a given configuration.

The Overall Heat Transfer Coefficient

The overall heat transfer coefficient describes the rate of heat transfer in the heat exchanger. Generically, it is described by the following equation:

$$\frac{1}{U} = \frac{1}{h_H} + \frac{\Delta x}{k} + \frac{1}{h_C} + R_f$$

Where:

U = overall heat transfer coefficient (Btu / h ft^2 °F)
h_H = hot side heat transfer coefficient
h_C = cold side heat transfer coefficient
Delta x = exchanger wall thickness
k = exchanger wall material thermal conductivity
R_f = fouling coefficient (h ft^2 °F / Btu)

The equation for the overall heat transfer coefficient is often reduced to the following:

$$\frac{1}{U} = \frac{1}{h_H} + \frac{1}{h_C} + R_f$$

because the term Delta x / k seldom has any significant impact on the overall U-value.

The overall heat transfer coefficient can either be calculated, looked up in reference materials for a given duty, estimated from past plant experience, or supplied by a heat exchanger vendor.

Brief Overview of Heat Exchanger Types

In the chemical processing industry, there are numerous types of heat exchanger devices. The types of exchangers can be classified by the duty that they perform, surface compactness, construction features, flow arrangements, and others. In general, a heat exchanger can fall into one of these processing categories:

No Phase Change
Liquid to Liquid heat transfer
Liquid to Gas heat transfer
Gas to Gas heat transfer

Phase Change
Condensing a vapor with a liquid or gas service fluid
Vaporizing a liquid with a liquid, gas, or condensing fluid

Heat exchangers can also be broken down into the following two types of mechanical geometries:

Shell and Tube Heat Exchangers
Compact and Extended Surface Heat Exchangers

Approximately 70-80% of the heat exchanger market is dominated by the shell and tube type heat exchanger. It is largely favored due to its long performance history, relative simplicity, and its wide temperature and pressure design ranges. We will explore this technology in further detail later.

The second category mentioned, compact and extended surface heat exchangers, play a smaller role in the chemical processing industry. Some of the available technologies that fit into this category are the plate and frame heat exchanger, finned tube heat exchangers, spiral heat exchangers, fin-fan heat exchangers, and many others.

Compact Heat Exchanger Technologies

The plate exchanger, shown below in Figure 1, consists of corrugated plates assembled into a frame. The hot fluid flows in one direction in alternating channels while the cold fluid flows in true countercurrent flow in the opposite alternating channels. The fluids are directed into their proper channels either by a rubber gasket or a weld depending on the type of exchanger chosen.

Traditionally, plate and frame exchangers have been used almost exclusively for liquid to liquid heat transfer. Today, many variations of the plate technology have proven useful in applications where a phase change occurs as well. This includes condensing duties as well as vaporization duties. Plate heat exchangers are best known for having overall heat transfer coefficients (U-values) in excess of 3-5 times the U-value in a shell and tube designed for the same service.

Plate exchangers can be especially attractive when more expensive materials of construction are required. The significantly higher U-value results in far less area for a given application, thus a lower purchased and installed cost due to its relatively small size. The higher U-values are gained by inducing extremely high wall shear on the plate surface. The best way to think of a plate heat exchanger is that it is essentially a static mixer that happens to transfer heat very well. The plate exchanger, by virtue of its high wall shear stress also minimizes fouling very well.

Typical plate thicknesses range from 0.40 mm to 0.60 mm and passage channel openings can range from 1.5 mm up to 11.0 mm depending on the application and required design pressure (the larger the opening, the lower the design pressure available). These small passages also restrict the size of solids that can be successfully passed through the exchanger.

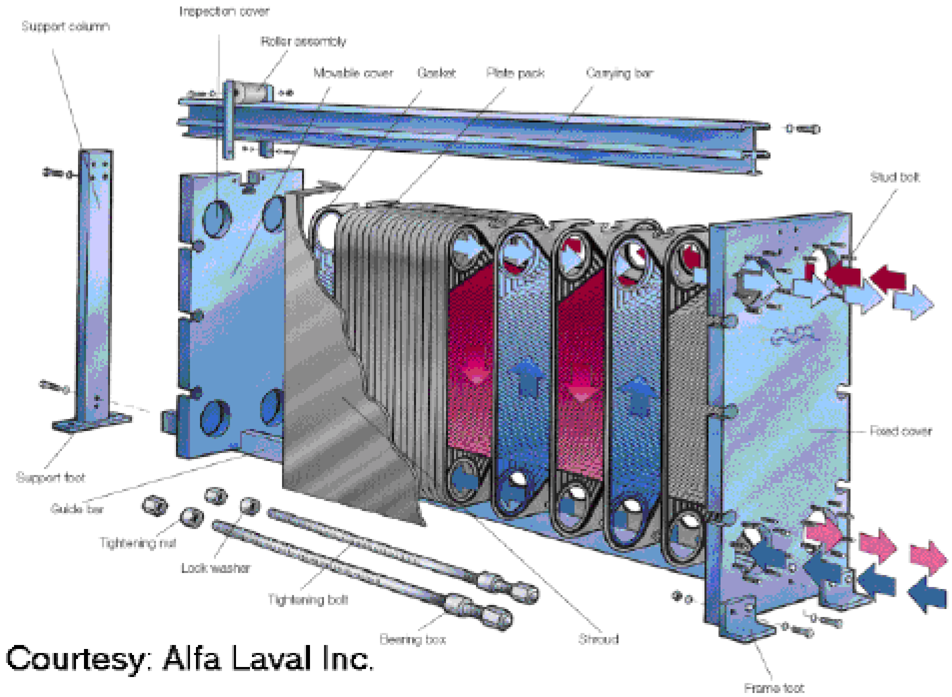
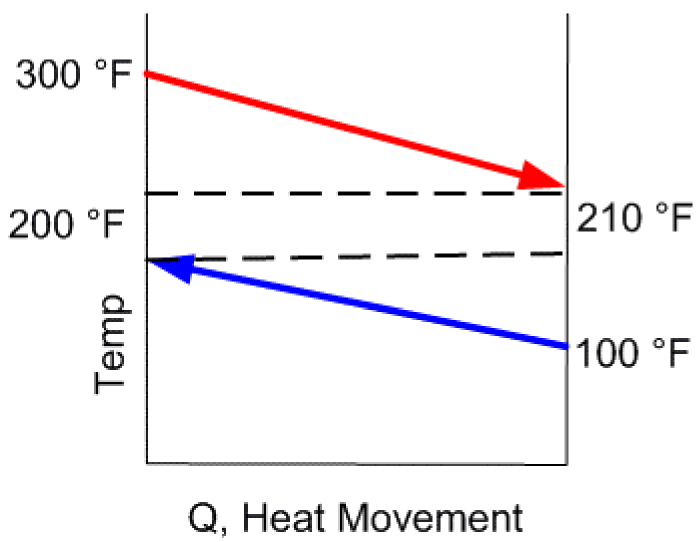


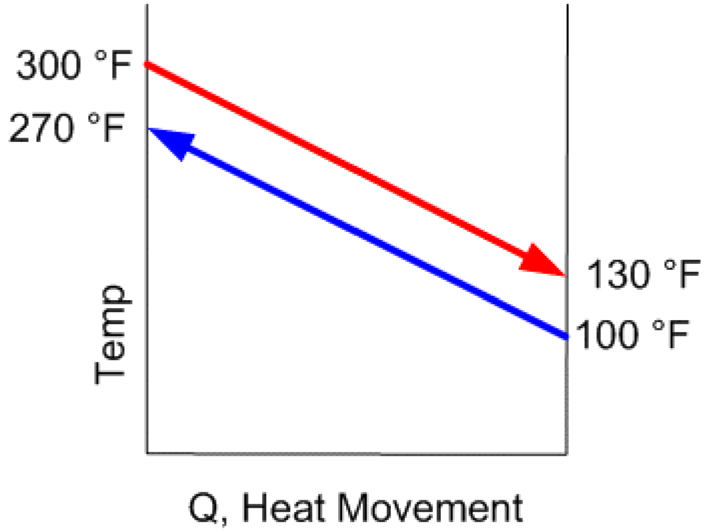
Figure 1. Plate Exchanger

Perhaps the biggest advantage of the plate and frame heat exchanger, and a situation where it is most often used, is when the heat transfer application calls for the cold side fluid to exit the exchanger at a temperature significantly higher than the hot side fluid exit temperature. This situation is best explained with another set of T-Q diagrams:



Duty 1

Duty 1 shown above is easily accomplished in a single and tube heat exchanger.



Duty 2

Duty 2 shows a severe "temperature cross" or the cold side fluid exiting higher than the hot side fluid. This would require several shell and tube exchangers in series due to the lack of purely counter-current flow. On the other hand, this duty is easily accomplished in a single plate and frame heat exchanger.

Finned tube heat exchangers are commonly used to transfer heat between a gas and liquid. The tubes used in these units are equipped with fins that extend outward from the tubes as shown below in Figure 2.

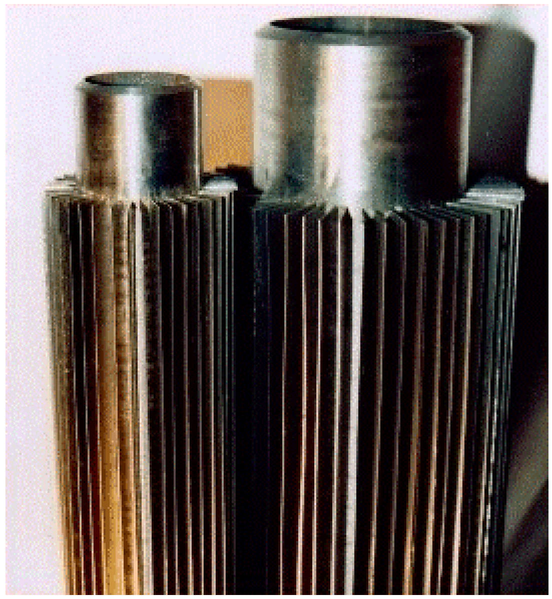


Figure 2. Finned Tube Heat Exchanger

The fins on the tubes allow for a much larger surface area to be packed into a small volume. This is especially important when transferring heat to or from a gas as gasses have extremely low heat transfer coefficients (meaning that large amounts of area are required).

Fin-fan heat exchangers are designed to use air to cool process fluids. Think of them as a giant radiator. The process fluid is passed through the coils and a fan helps pull air over the outside surface to promote cooling. These units again must provide a very large surface area to make up for the poor heat transfer of the air. See below in Figure 3.

Figure 3. Finned-Fan Heat Exchanger

Shell and Tube Heat Exchanger Technologies

Shell and tube heat exchangers are known as the work-horse of the chemical process industry when it comes to transferring heat. These devices are available in a wide range of configurations as defined by the Tubular Exchanger Manufacturers Association (TEMA, www.tema.org). In essence, a shell and tube exchanger is a pressure vessel with many tubes inside of it. One process fluids flows through the tubes of the exchanger while the other flows outside of the tubes within the shell. The tube side and shell side fluids are separated by a tube sheet.

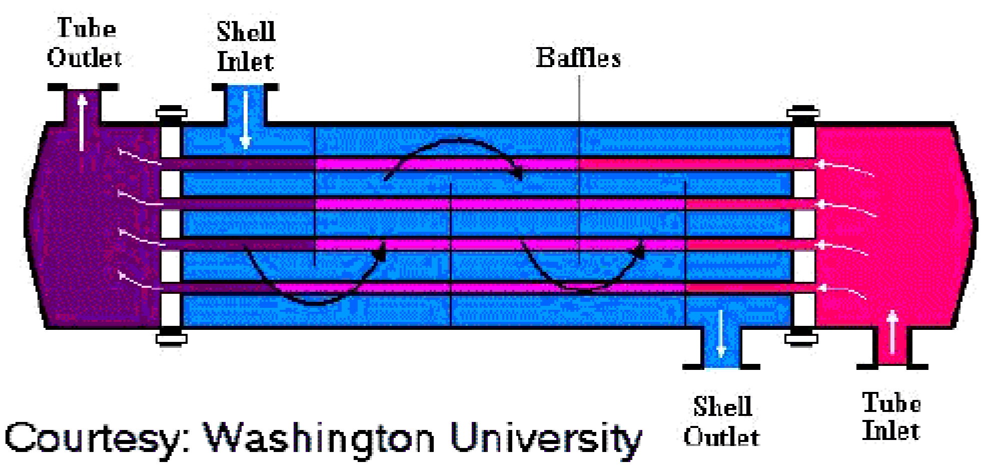
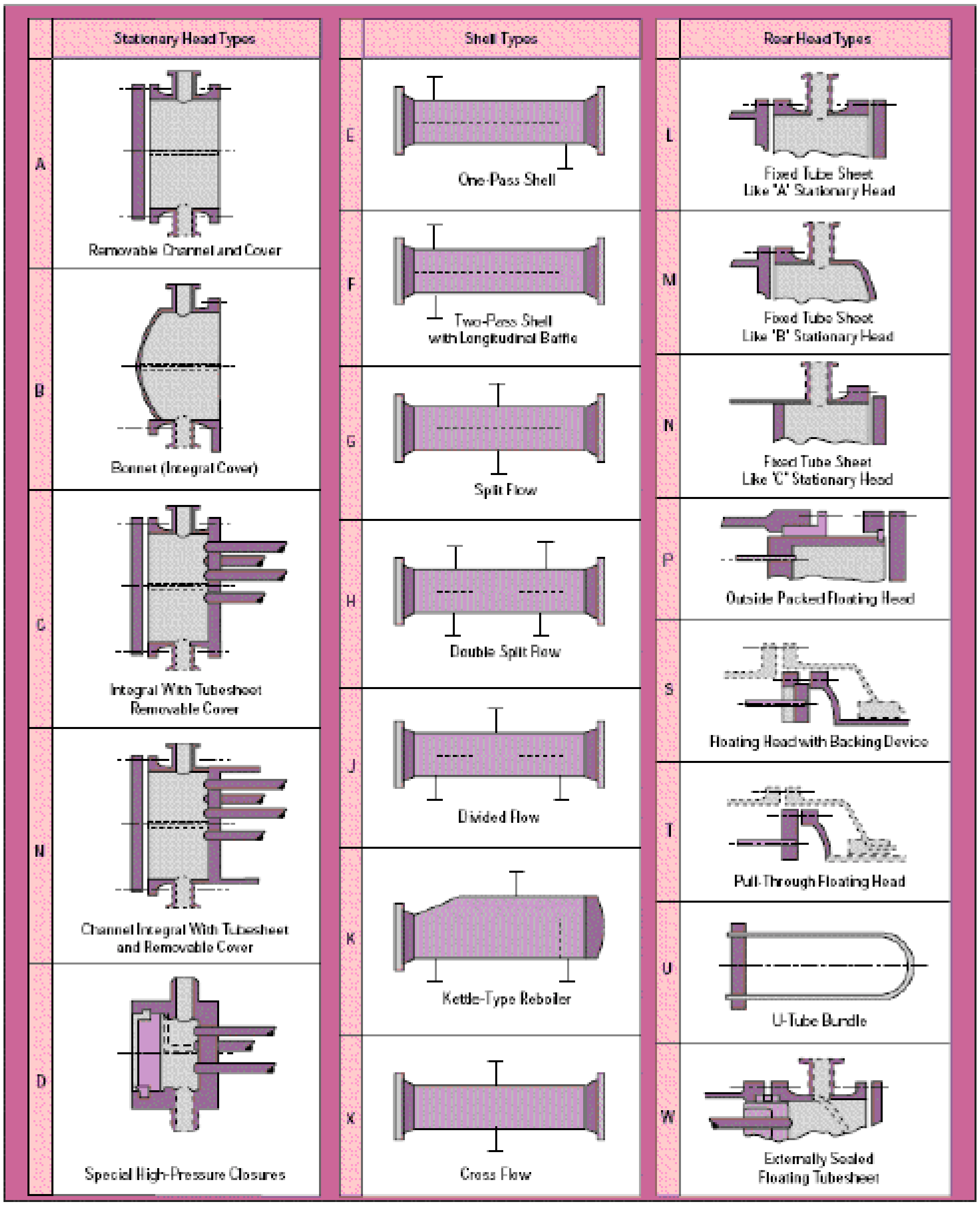


Figure 4. Shell and Tube Heat Exchanger

The shell and tube type is usually indicated as a three (3) letter code from the TEMA specifications shown below:



Source:
CHEMICAL ENGINEERING PROGRESS • FEBRUARY 1998

Figure 5. Shell and Tube Types

The shell side of a shell and tube exchanger usually contains baffles as shown above in Figure 5 to direct the shell side flow around the tubes to enhance heat transfer. As you can see, shell and tube exchangers can be configured for liquid-liquid, gas-liquid, condensing, or vaporizing heat transfer.

The tubes can be a different material than shell and the shell can either be cladded or of solid construction. It's impossible to go over all of the mechanical details of the shell and tube here, but this should provide you with a general overview of the construction. There are numerous other sources of information freely available on these types of units.

The tubes and shell can be designed for a variety of design temperatures and pressures.

The thermal design of shell and tube heat exchangers is often performed by vendors. The process engineer generally completes a TEMA specification sheet and submits it to vendors for bids. If you're interested in more details on the thermal design aspects of shell and tube heat exchangers, you can visit Wolverine Engineering's website at:

http://www.wlv.com/products/databook/databook.pdf

This online design manual is extremely well done and is a valuable, freely available resource.

There are well documented sources of estimated overall heat transfer coefficients and fouling factors that can be specified. Fouling factors are historic safety factors that allow for the over sizing of a shell and tube in anticipation of eventual surface build-up that will form a resistance to heat transfer. Remember, the overall heat transfer coefficient of a new heat exchanger will slowly degrade over time until it "levels off" to what is known as the "service U-value". This is the actual rate of a heat transfer that the unit will achieve on a nominal basis. The combination of a well selected U-value and a fouling factor should ensure a good shell and tube design. Typical U-values for various services and fouling factors can be found on the internet or in various text references.

Links are provided within this course to download two MS Excel spreadsheets which you can use to specify heat transfer equipment. There is a version which uses U.S. Customary units as well as a version which employs SI units.