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**Department of Energy
Fundamentals Handbook**

**MECHANICAL SCIENCE
Module 2
Heat Exchangers**

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TERMINAL OBJECTIVE

- 1.0 Without references, **DESCRIBE** the purpose, construction, and principles of operation for each major type of heat exchanger: parallel flow, counter flow, and cross flow.

ENABLING OBJECTIVES

- 1.1 **STATE** the two types of heat exchanger construction.
- 1.2 Provided with a drawing of a heat exchanger, **IDENTIFY** the following internal parts:
- a. Tubes
 - b. Tube sheet
 - c. Shell
 - d. Baffles
- 1.3 **DESCRIBE** hot and cold fluid flow in parallel flow, counter flow, and cross flow heat exchangers.
- 1.4 **DIFFERENTIATE** between the following types of heat exchangers:
- a. Single-pass versus multi-pass heat exchangers.
 - b. Regenerative versus non-regenerative heat exchangers.
- 1.5 **LIST** at least three applications of heat exchangers.
- 1.6 **STATE** the purpose of a condenser.
- 1.7 **DEFINE** the following terms:
- a. Hotwell
 - b. Condensate depression
- 1.8 **STATE** why condensers in large steam cycles are operated at a vacuum.

TYPES OF HEAT EXCHANGERS

In almost any nuclear, chemical, or mechanical system, heat must be transferred from one place to another or from one fluid to another. Heat exchangers are used to transfer heat from one fluid to another. A basic understanding of the mechanical components of a heat exchanger is important to understanding how they function and operate.

EO 1.1 STATE the two types of heat exchanger construction.

EO 1.2 Provided with a drawing of a heat exchanger, IDENTIFY the following internal parts:

- | | |
|----------------------|-------------------|
| a. Tubes | c. Shell |
| b. Tube sheet | d. Baffles |

EO 1.3 DESCRIBE hot and cold fluid flow in parallel flow, counter flow, and cross flow heat exchangers.

EO 1.4 DIFFERENTIATE between the following types of heat exchangers:

- | |
|--|
| a. Single-pass versus multi-pass heat exchangers |
| b. Regenerative versus non-regenerative heat exchangers |
-

Introduction

A heat exchanger is a component that allows the transfer of heat from one fluid (liquid or gas) to another fluid. Reasons for heat transfer include the following:

1. To heat a cooler fluid by means of a hotter fluid
2. To reduce the temperature of a hot fluid by means of a cooler fluid
3. To boil a liquid by means of a hotter fluid
4. To condense a gaseous fluid by means of a cooler fluid
5. To boil a liquid while condensing a hotter gaseous fluid

Regardless of the function the heat exchanger fulfills, in order to transfer heat the fluids involved must be at different temperatures and they must come into thermal contact. Heat can flow only from the hotter to the cooler fluid.

In a heat exchanger there is no direct contact between the two fluids. The heat is transferred from the hot fluid to the metal isolating the two fluids and then to the cooler fluid.

Types of Heat Exchanger Construction

Although heat exchangers come in every shape and size imaginable, the construction of most heat exchangers fall into one of two categories: tube and shell, or plate. As in all mechanical devices, each type has its advantages and disadvantages.

Tube and Shell

The most basic and the most common type of heat exchanger construction is the tube and shell, as shown in Figure 1. This type of heat exchanger consists of a set of *tubes* in a container called a *shell*. The fluid flowing inside the tubes is called the tube side fluid and the fluid flowing on the outside of the tubes is the shell side fluid. At the ends of the tubes, the tube side fluid is separated from the shell side fluid by the tube sheet(s). The tubes are rolled and press-fitted or welded into the tube sheet to provide a leak tight seal. In systems where the two fluids are at vastly different pressures, the higher pressure fluid is typically directed through the tubes and the lower pressure fluid is circulated on the shell side. This is due to economy, because the heat exchanger tubes can be made to withstand higher pressures than the shell of the heat exchanger for a much lower cost. The support plates shown on Figure 1 also act as baffles to direct the flow of fluid within the shell back and forth across the tubes.

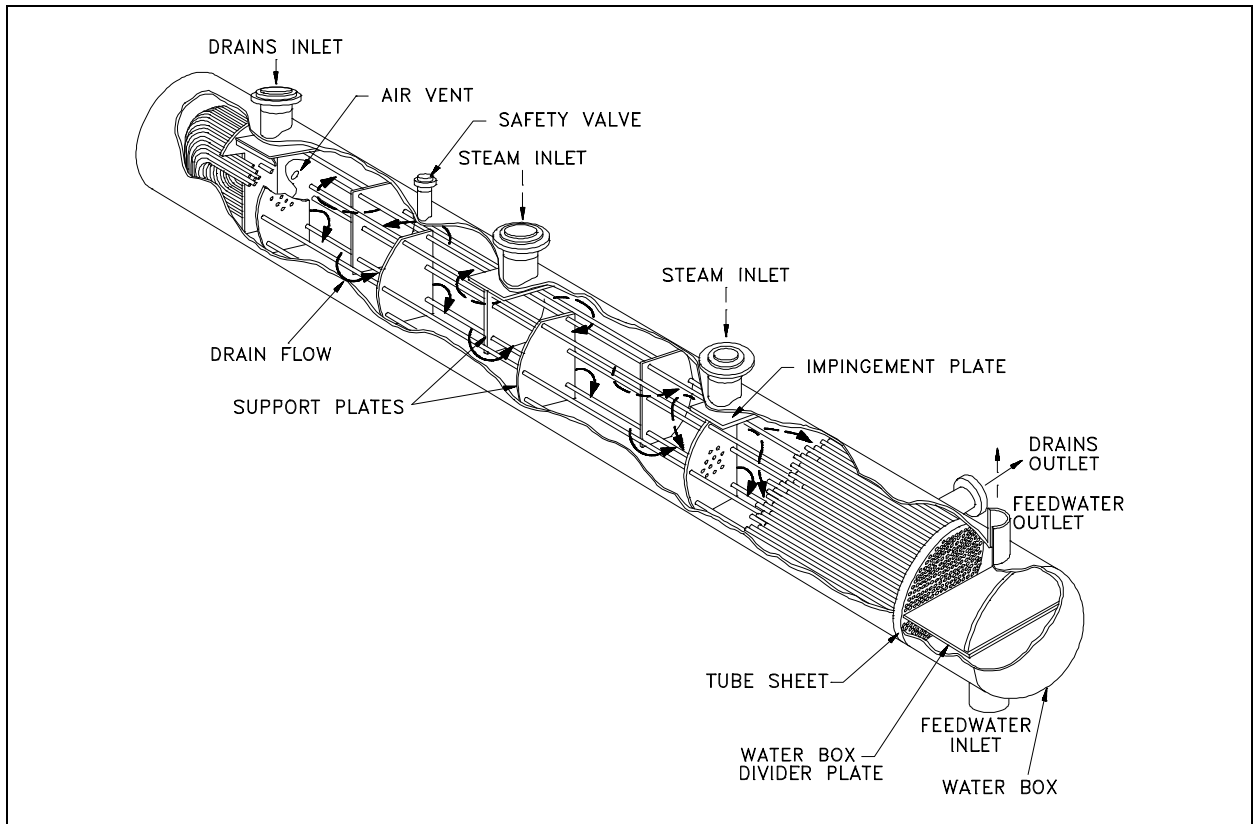


Figure 1 Tube and Shell Heat Exchanger

Plate

A plate type heat exchanger, as illustrated in Figure 2, consists of plates instead of tubes to separate the hot and cold fluids. The hot and cold fluids alternate between each of the plates. Baffles direct the flow of fluid between plates. Because each of the plates has a very large surface area, the plates provide each of the fluids with an extremely large heat transfer area. Therefore a plate type heat exchanger, as compared to a similarly sized tube and shell heat exchanger, is capable of transferring much more heat. This is due to the larger area the plates provide over tubes. Due to the high heat transfer efficiency of the plates, plate type heat exchangers are usually very small when compared to a tube and shell type heat exchanger with the same heat transfer capacity. Plate type heat exchangers are not widely used because of the inability to reliably seal the large gaskets between each of the plates. Because of this problem, plate type heat exchangers have only been used in small, low pressure applications such as on oil coolers for engines. However, new improvements in gasket design and overall heat exchanger design have allowed some large scale applications of the plate type heat exchanger. As older facilities are upgraded or newly designed facilities are built, large plate type heat exchangers are replacing tube and shell heat exchangers and becoming more common.

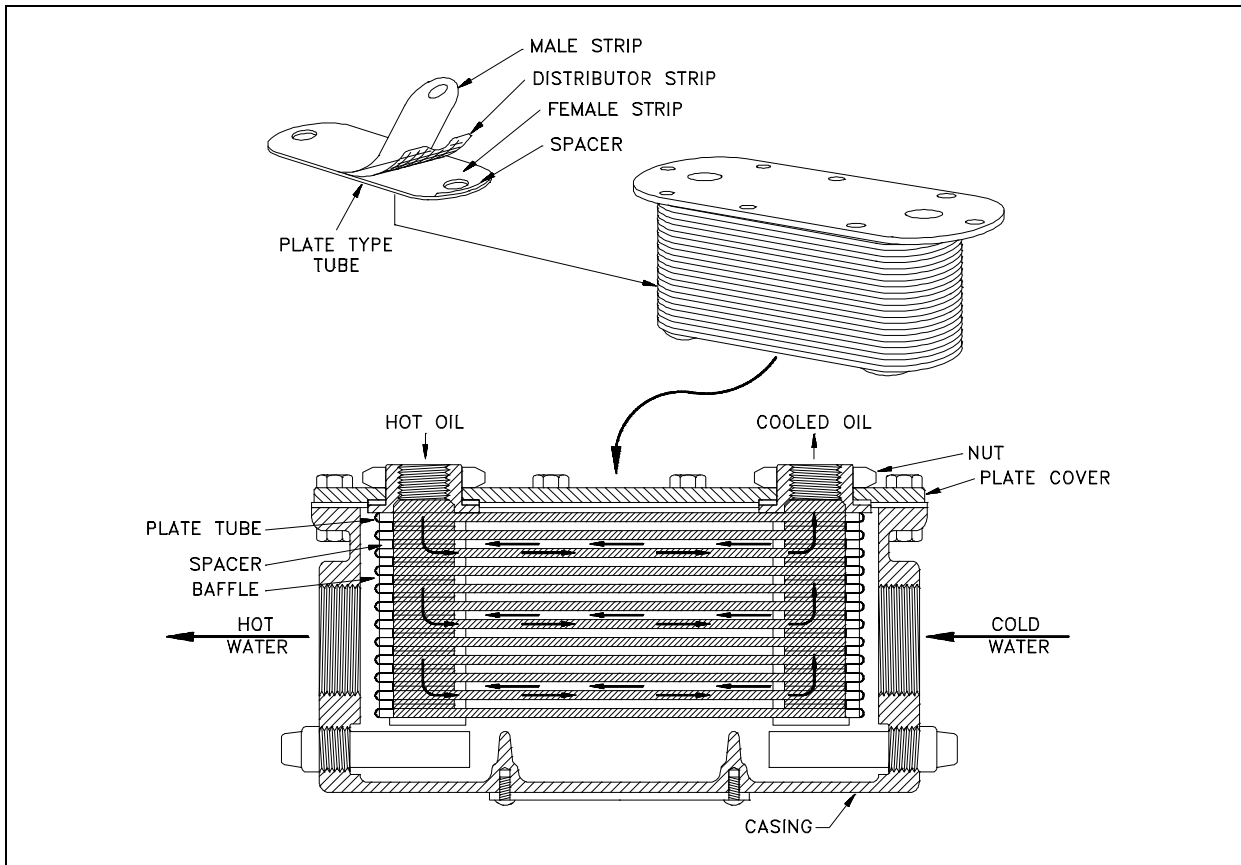


Figure 2 Plate Heat Exchanger

Types of Heat Exchangers

Because heat exchangers come in so many shapes, sizes, makes, and models, they are categorized according to common characteristics. One common characteristic that can be used to categorize them is the direction of flow the two fluids have relative to each other. The three categories are parallel flow, counter flow and cross flow.

Parallel flow, as illustrated in Figure 3, exists when both the tube side fluid and the shell side fluid flow in the same direction. In this case, the two fluids enter the heat exchanger from the same end with a large temperature difference. As the fluids transfer heat, hotter to cooler, the temperatures of the two fluids approach each other. Note that the hottest cold-fluid temperature is always less than the coldest hot-fluid temperature.

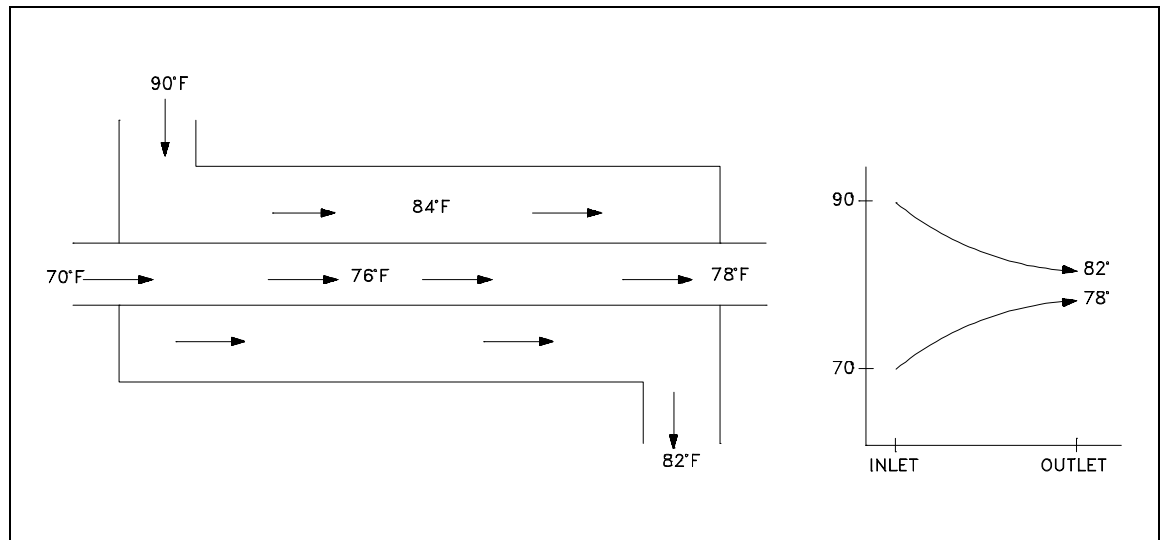


Figure 3 Parallel Flow Heat Exchanger

Counter flow, as illustrated in Figure 4, exists when the two fluids flow in opposite directions. Each of the fluids enters the heat exchanger at opposite ends. Because the cooler fluid exits the counter flow heat exchanger at the end where the hot fluid enters the heat exchanger, the cooler fluid will approach the inlet temperature of the hot fluid. Counter flow heat exchangers are the most efficient of the three types. In contrast to the parallel flow heat exchanger, the counter flow heat exchanger can have the hottest cold-fluid temperature greater than the coldest hot-fluid temperature.

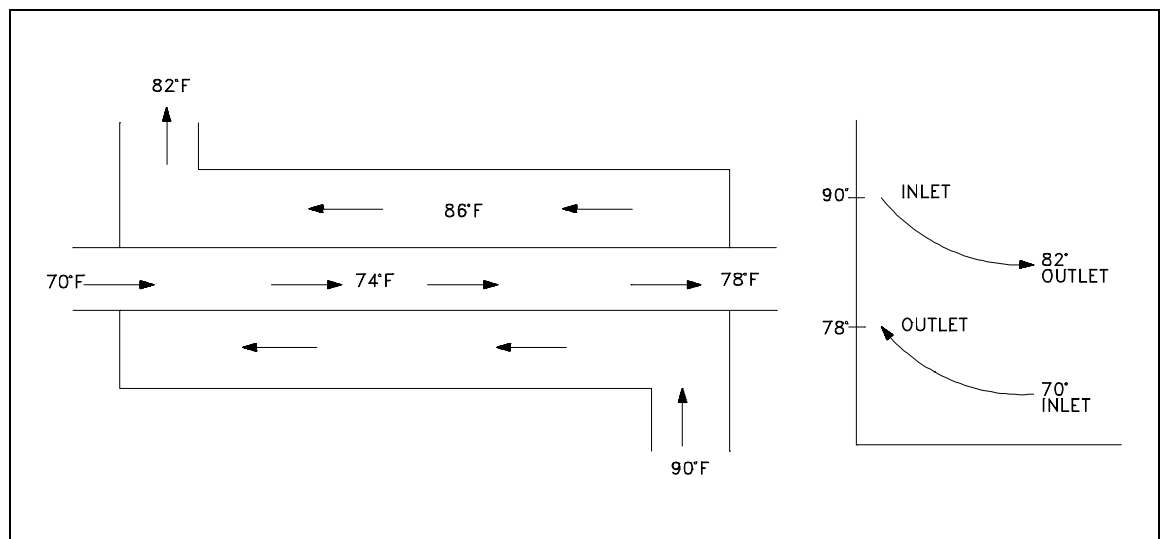


Figure 4 Counter Flow Heat Exchange

Cross flow, as illustrated in Figure 5, exists when one fluid flows perpendicular to the second fluid; that is, one fluid flows through tubes and the second fluid passes around the tubes at 90° angle. Cross flow heat exchangers are usually found in applications where one of the fluids changes state (2-phase flow). An example is a steam system's condenser, in which the steam exiting the turbine enters the condenser shell side, and the cool water flowing in the tubes absorbs the heat from the steam, condensing it into water. Large volumes of vapor may be condensed using this type of heat exchanger flow.

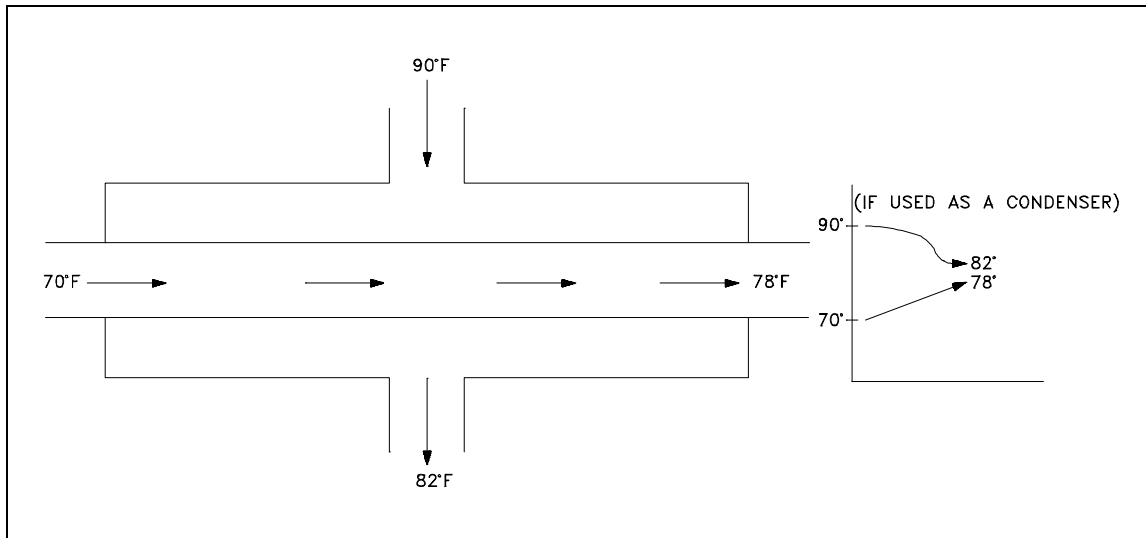


Figure 5 Cross Flow Heat Exchanger

Comparison of the Types of Heat Exchangers

Each of the three types of heat exchangers has advantages and disadvantages. But of the three, the counter flow heat exchanger design is the most efficient when comparing heat transfer rate per unit surface area. The efficiency of a counter flow heat exchanger is due to the fact that the average ΔT (difference in temperature) between the two fluids over the length of the heat exchanger is maximized, as shown in Figure 4. Therefore the log mean temperature for a counter flow heat exchanger is larger than the log mean temperature for a similar parallel or cross flow heat exchanger. (See the Thermodynamics, Heat Transfer, and Fluid Flow Fundamentals Handbook for a review of log mean temperature). This can be seen by comparing the graphs in Figure 3, Figure 4, and Figure 5. The following exercise demonstrates how the higher log mean temperature of the counter flow heat exchanger results in a larger heat transfer rate. The log mean temperature for a heat exchanger is calculated using the following equation.

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln \frac{\Delta T_2}{\Delta T_1}} \quad (2-1)$$

Heat transfer in a heat exchanger is by conduction and convection. The rate of heat transfer, "Q", in a heat exchanger is calculated using the following equation.

$$\dot{Q} = U_o A_o \Delta T_{lm} \quad (2-2)$$

Where:

\dot{Q} = Heat transfer rate (BTU/hr)

U_o = Overall heat transfer coefficient (BTU/hr-ft²-°F)

A_o = Cross sectional heat transfer area (ft²)

ΔT_{lm} = Log mean temperature difference (°F)

Consider the following example of a heat exchanger operated under identical conditions as a counter flow and then a parallel flow heat exchanger.

T_1 = represents the hot fluid temperature

T_{1in} = 200°F

T_{1out} = 145°F

U_o = 70 BTU/hr-ft²-°F

A_o = 75ft²

T_2 = represents the cold fluid temperature

T_{2in} = 80°F

T_{2out} = 120°F

$$\text{Counter flow } \Delta T_{lm} = \frac{(200-120^\circ\text{F}) - (145-80^\circ\text{F})}{\ln \frac{(200-120^\circ\text{F})}{(145-80^\circ\text{F})}} = 72^\circ\text{F}$$

$$\text{Parallel flow } \Delta T_{\text{lm}} = \frac{(200-80^{\circ}\text{F}) - (145-120^{\circ}\text{F})}{\ln \frac{(200-80^{\circ}\text{F})}{(145-120^{\circ}\text{F})}} = 61^{\circ}\text{F}$$

Inserting the above values into heat transfer Equation (2-2) for the counter flow heat exchanger yields the following result.

$$\dot{Q} = \left(70 \frac{\text{BTU}}{\text{hr-ft}^2\text{-}^{\circ}\text{F}}\right) (75\text{ft}^2) (72^{\circ}\text{F})$$

$$\dot{Q} = 3.8 \times 10^5 \frac{\text{BTU}}{\text{hr}}$$

Inserting the above values into the heat transfer Equation (2-2) for parallel flow heat exchanger yields the following result.

$$\dot{Q} = \left(70 \frac{\text{BTU}}{\text{hr-ft}^2\text{-}^{\circ}\text{F}}\right) (75\text{ft}^2) (61^{\circ}\text{F})$$

$$\dot{Q} = 3.2 \times 10^5 \frac{\text{BTU}}{\text{hr}}$$

The results demonstrate that given the same operating conditions, operating the same heat exchanger in a counter flow manner will result in a greater heat transfer rate than operating in parallel flow.

In actuality, most large heat exchangers are not purely parallel flow, counter flow, or cross flow; they are usually a combination of the two or all three types of heat exchangers. This is due to the fact that actual heat exchangers are more complex than the simple components shown in the idealized figures used above to depict each type of heat exchanger. The reason for the combination of the various types is to maximize the efficiency of the heat exchanger within the restrictions placed on the design. That is, size, cost, weight, required efficiency, type of fluids, operating pressures, and temperatures, all help determine the complexity of a specific heat exchanger.

One method that combines the characteristics of two or more heat exchangers and improves the performance of a heat exchanger is to have the two fluids pass each other several times within a single heat exchanger. When a heat exchanger's fluids pass each other more than once, a heat exchanger is called a *multi-pass heat exchanger*. If the fluids pass each other only once, the heat exchanger is called a *single-pass heat exchanger*. See Figure 6 for an example of both types. Commonly, the multi-pass heat exchanger reverses the flow in the tubes by use of one or more sets of "U" bends in the tubes. The "U" bends allow the fluid to flow back and forth across the length of the heat exchanger. A second method to achieve multiple passes is to insert baffles on the shell side of the heat exchanger. These direct the shell side fluid back and forth across the tubes to achieve the multi-pass effect.

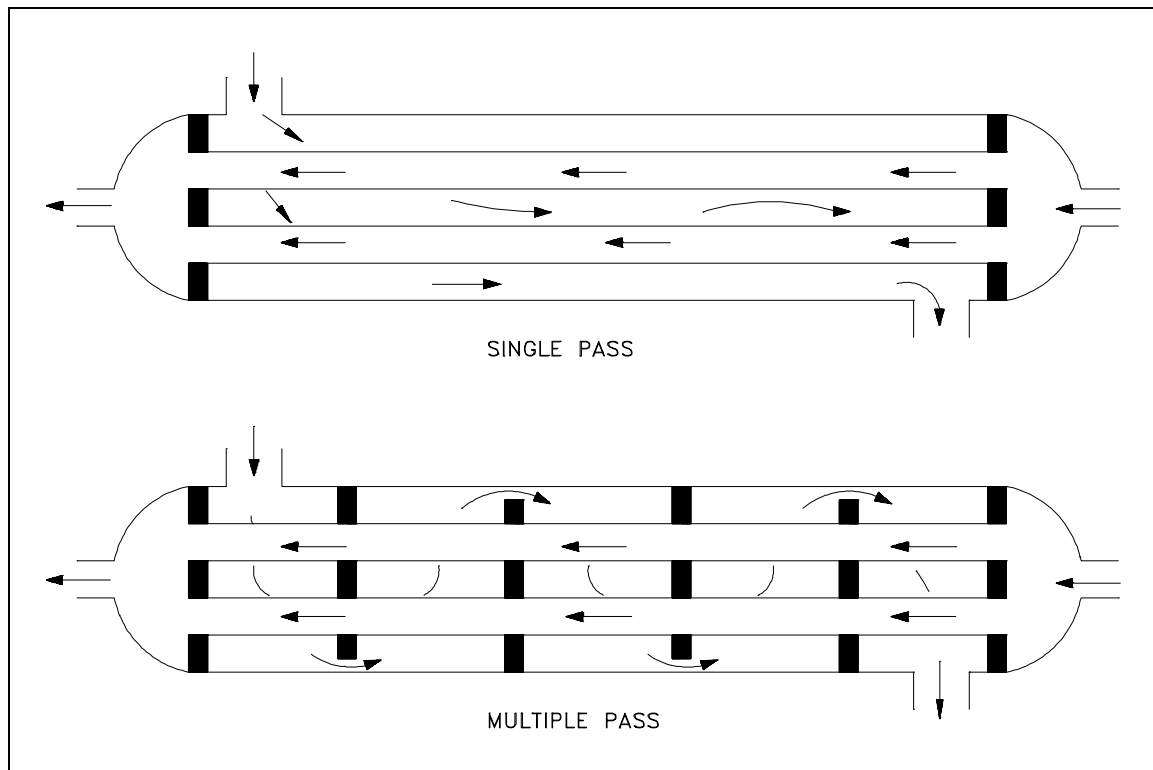


Figure 6 Single and Multi-Pass Heat Exchangers

Heat exchangers are also classified by their function in a particular system. One common classification is regenerative or nonregenerative. A *regenerative* heat exchanger is one in which the same fluid is both the cooling fluid and the cooled fluid, as illustrated in Figure 7. That is, the hot fluid leaving a system gives up its heat to "regenerate" or heat up the fluid returning to the system. Regenerative heat exchangers are usually found in high temperature systems where a portion of the system's fluid is removed from the main process, and then returned. Because the fluid removed from the main process contains energy (heat), the heat from the fluid leaving the main system is used to reheat (regenerate) the returning fluid instead of being rejected to an external cooling medium to improve efficiency. It is important to remember that the term regenerative/nonregenerative only refers to "how" a heat exchanger functions in a system, and does not indicate any single type (tube and shell, plate, parallel flow, counter flow, etc.).

In a *nonregenerative* heat exchanger, as illustrated in Figure 7, the hot fluid is cooled by fluid from a separate system and the energy (heat) removed is not returned to the system.

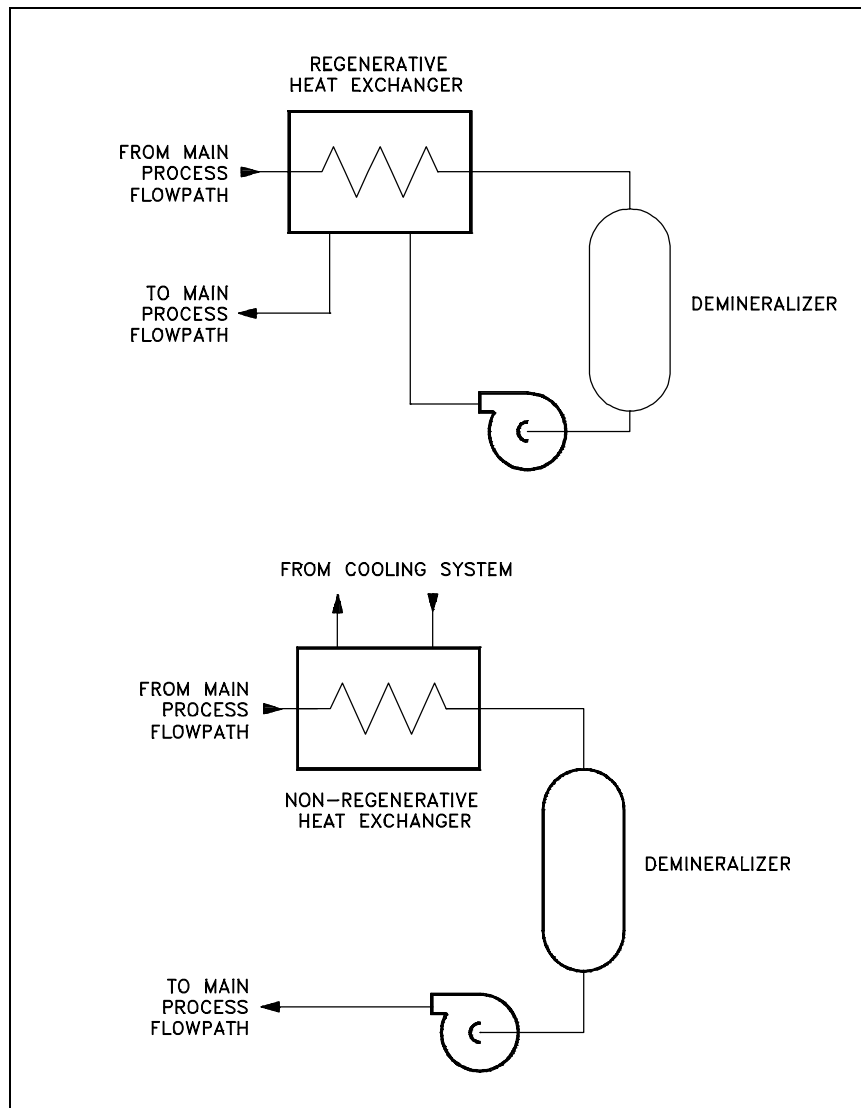


Figure 7 Regenerative and Non-Regenerative Heat Exchangers

Summary

The important information from this chapter is summarized below.

Types of Heat Exchangers Summary

- There are two methods of constructing heat exchangers: plate type and tube type.
- Parallel flow - the hot fluid and the coolant flow in the same direction.
- Counter flow - The hot fluid and the coolant flow in opposite directions.
- Cross flow - the hot fluid and the coolant flow at 90° angles (perpendicular) to each other.
- The four heat exchanger parts identified were:
 - Tubes
 - Tube Sheet
 - Shell
 - Baffles
- Single-pass heat exchangers have fluids that pass each other only once.
- Multi-pass heat exchangers have fluids that pass each other more than once through the use of U tubes and baffles.
- Regenerative heat exchangers use the same fluid for heating and cooling.
- Non-regenerative heat exchangers use separate fluids for heating and cooling.

HEAT EXCHANGER APPLICATIONS

This chapter describes some specific applications of heat exchangers.

EO 1.5 **LIST at least three applications of heat exchangers.**

EO 1.6 **STATE the purpose of a condenser.**

EO 1.7 **DEFINE the following terms:**

- a. **Hotwell**
- b. **Condensate depression**

EO 1.8 **STATE why condensers in large steam cycles are operated at a vacuum.**

Introduction

Heat exchangers are found in most chemical or mechanical systems. They serve as the system's means of gaining or rejecting heat. Some of the more common applications are found in heating, ventilation and air conditioning (HVAC) systems, radiators on internal combustion engines, boilers, condensers, and as preheaters or coolers in fluid systems. This chapter will review some specific heat exchanger applications. The intent is to provide several specific examples of how each heat exchanger functions in the system, not to cover every possible application.

Preheater

In large steam systems, or in any process requiring high temperatures, the input fluid is usually preheated in stages, instead of trying to heat it in one step from ambient to the final temperature. Preheating in stages increases the plant's efficiency and minimizes thermal shock stress to components, as compared to injecting ambient temperature liquid into a boiler or other device that operates at high temperatures. In the case of a steam system, a portion of the process steam is tapped off and used as a heat source to reheat the feedwater in preheater stages. Figure 8 is an example of the construction and internals of a U-tube feedwater heat exchanger found in a large power generation facility in a preheater stage. As the steam enters the heat exchanger and flows over and around the tubes, it transfers its thermal energy and is condensed. Note that the steam enters from the top into the shell side of the heat exchanger, where it not only transfers sensible heat (temperature change) but also gives up its latent heat of vaporization (condenses steam into water). The condensed steam then exits as a liquid at the bottom of the heat exchanger. The feedwater enters the heat exchanger on the bottom right end and flows into the tubes. Note that most of these tubes will be below the fluid level on the shell side.

This means the feedwater is exposed to the condensed steam first and then travels through the tubes and back around to the top right end of the heat exchanger. After making the 180° bend, the partially heated feedwater is then subjected to the hotter steam entering the shell side.

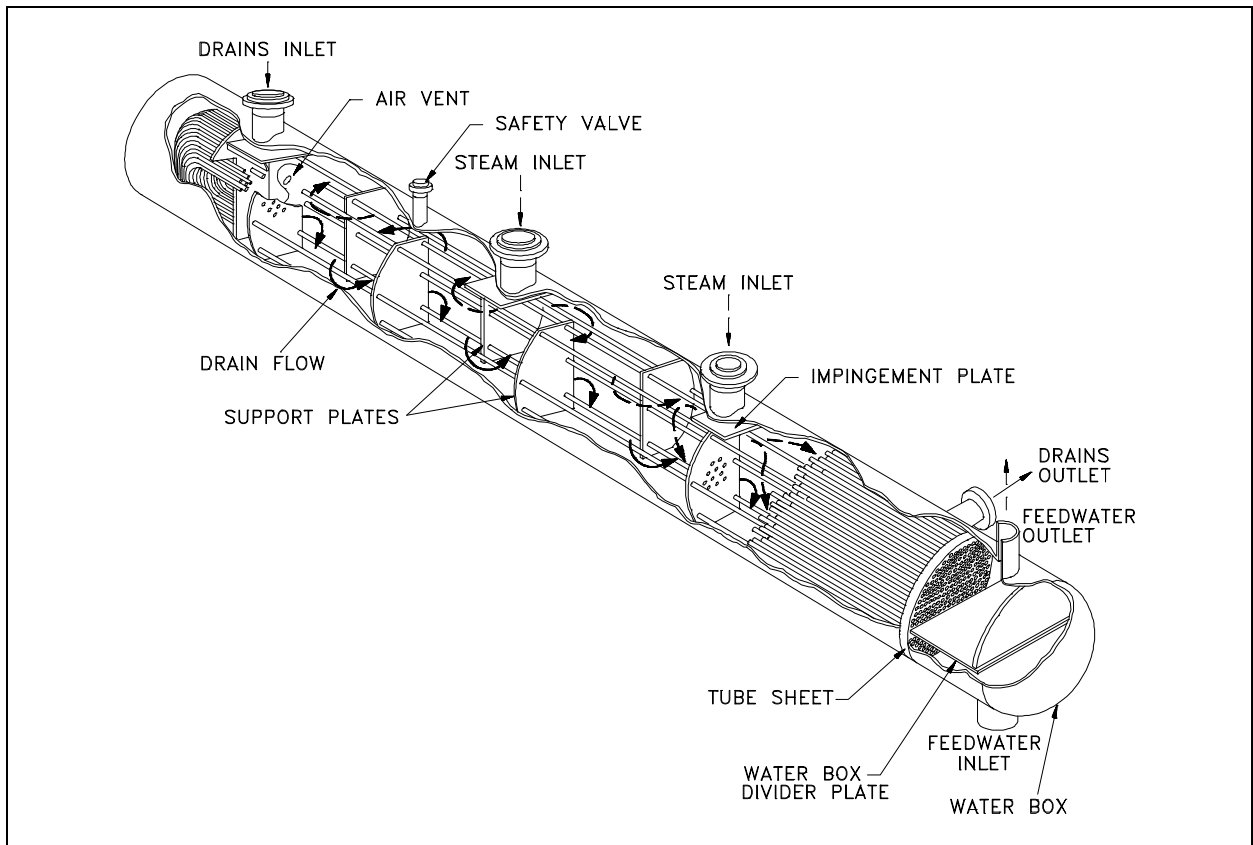


Figure 8 U-tube Feedwater Heat Exchanger

The feedwater is further heated by the hot steam and then exits the heat exchanger. In this type of heat exchanger, the shell side fluid level is very important in determining the efficiency of the heat exchanger, as the shell side fluid level determines the number of tubes exposed to the hot steam.

Radiator

Commonly, heat exchangers are thought of as liquid-to-liquid devices only. But a heat exchanger is any device that transfers heat from one fluid to another. Some of a facility's equipment depend on air-to-liquid heat exchangers. The most familiar example of an air-to-liquid heat exchanger is a car radiator. The coolant flowing in the engine picks up heat from the engine block and carries it to the radiator. From the radiator, the hot coolant flows into the tube side of the radiator (heat exchanger). The relatively cool air flowing over the outside of the tubes picks up the heat, reducing the temperature of the coolant.

Because air is such a poor conductor of heat, the heat transfer area between the metal of the radiator and the air must be maximized. This is done by using fins on the outside of the tubes. The fins improve the efficiency of a heat exchanger and are commonly found on most liquid-to-air heat exchangers and in some high efficiency liquid-to-liquid heat exchangers.

Air Conditioner Evaporator and Condenser

All air conditioning systems contain at least two heat exchangers, usually called the evaporator and the condenser. In either case, evaporator or condenser, the refrigerant flows into the heat exchanger and transfers heat, either gaining or releasing it to the cooling medium. Commonly, the cooling medium is air or water. In the case of the condenser, the hot, high pressure refrigerant gas must be condensed to a subcooled liquid.

The condenser accomplishes this by cooling the gas, transferring its heat to either air or water. The cooled gas then condenses into a liquid. In the evaporator, the subcooled refrigerant flows into the heat exchanger, but the heat flow is reversed, with the relatively cool refrigerant absorbing heat from the hotter air flowing on the outside of the tubes. This cools the air and boils the refrigerant.

Large Steam System Condensers

The steam condenser, shown in Figure 9, is a major component of the steam cycle in power generation facilities. It is a closed space into which the steam exits the turbine and is forced to give up its latent heat of vaporization. It is a necessary component of the steam cycle for two reasons. One, it converts the used steam back into water for return to the steam generator or boiler as feedwater. This lowers the operational cost of the plant by allowing the clean and treated condensate to be reused, and it is far easier to pump a liquid than steam. Two, it increases the cycle's efficiency by allowing the cycle to operate with the largest possible delta-T and delta-P between the source (boiler) and the heat sink (condenser).

Because condensation is taking place, the term latent heat of condensation is used instead of latent heat of vaporization. The steam's latent heat of condensation is passed to the water flowing through the tubes of the condenser.

After the steam condenses, the saturated liquid continues to transfer heat to the cooling water as it falls to the bottom of the condenser, or *hotwell*. This is called subcooling, and a certain amount is desirable. A few degrees subcooling prevents condensate pump cavitation. The difference between the saturation temperature for the existing condenser vacuum and the temperature of the condensate is termed *condensate depression*. This is expressed as a number of degrees condensate depression or degrees subcooled. Excessive condensate depression decreases the operating efficiency of the plant because the subcooled condensate must be reheated in the boiler, which in turn requires more heat from the reactor, fossil fuel, or other heat source.

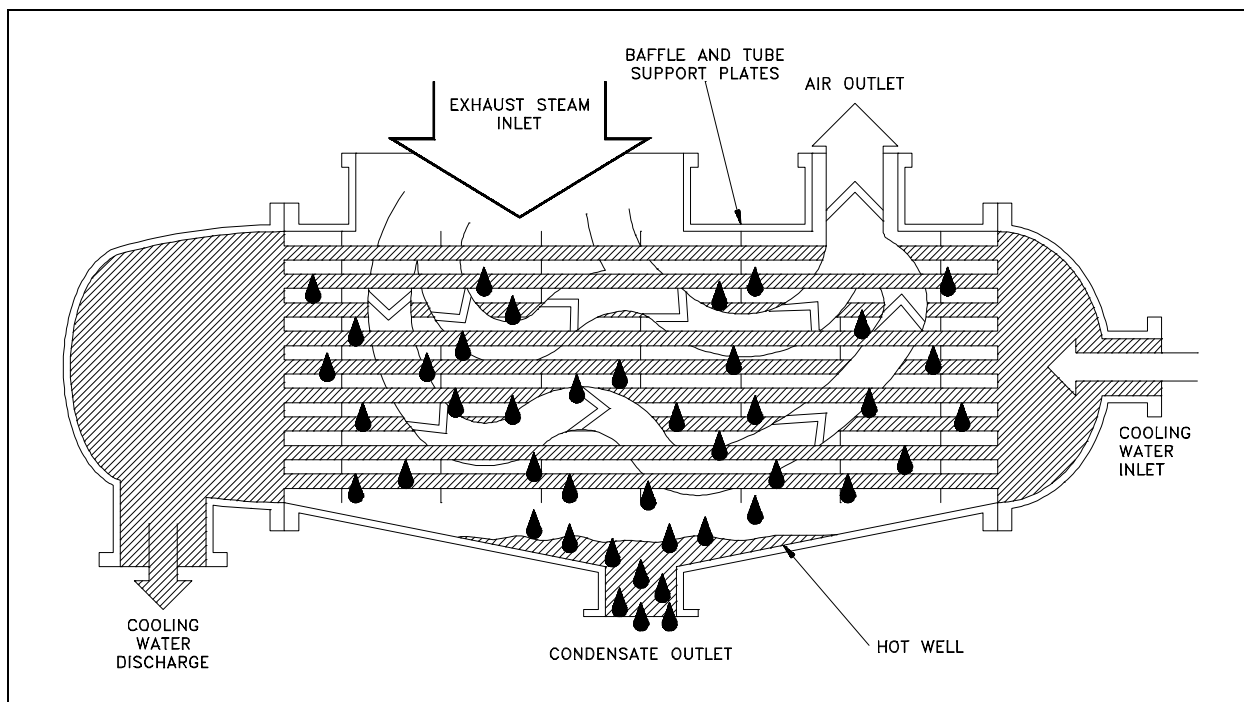


Figure 9 Single-Pass Condenser

There are different condenser designs, but the most common, at least in the large power generation facilities, is the straight-through, single-pass condenser illustrated Figure 9. This condenser design provides cooling water flow through straight tubes from the inlet water box on one end, to the outlet water box on the other end. The cooling water flows once through the condenser and is termed a single pass. The separation between the water box areas and the steam condensing area is accomplished by a tube sheet to which the cooling water tubes are attached. The cooling water tubes are supported within the condenser by the tube support sheets. Condensers normally have a series of baffles that redirect the steam to minimize direct impingement on the cooling water tubes. The bottom area of the condenser is the hotwell, as shown in Figure 9. This is where the condensate collects and the condensate pump takes its suction. If noncondensable gasses are allowed to build up in the condenser, vacuum will decrease and the saturation temperature at which the steam will condense increases.

Non-condensable gasses also blanket the tubes of the condenser, thus reducing the heat transfer surface area of the condenser. This surface area can also be reduced if the condensate level is allowed to rise over the lower tubes of the condenser. A reduction in the heat transfer surface has the same effect as a reduction in cooling water flow. If the condenser is operating near its design capacity, a reduction in the effective surface area results in difficulty maintaining condenser vacuum.

The temperature and flow rate of the cooling water through the condenser controls the temperature of the condensate. This in turn controls the saturation pressure (vacuum) of the condenser.

To prevent the condensate level from rising to the lower tubes of the condenser, a hotwell level control system may be employed. Varying the flow of the condensate pumps is one method used to accomplish hotwell level control. A level sensing network controls the condensate pump speed or pump discharge flow control valve position. Another method employs an overflow system that spills water from the hotwell when a high level is reached.

Condenser vacuum should be maintained as close to 29 inches Hg as practical. This allows maximum expansion of the steam, and therefore, the maximum work. If the condenser were perfectly air-tight (no air or noncondensable gasses present in the exhaust steam), it would be necessary only to condense the steam and remove the condensate to create and maintain a vacuum. The sudden reduction in steam volume, as it condenses, would maintain the vacuum. Pumping the water from the condenser as fast as it is formed would maintain the vacuum. It is, however, impossible to prevent the entrance of air and other noncondensable gasses into the condenser. In addition, some method must exist to initially cause a vacuum to exist in the condenser. This necessitates the use of an air ejector or vacuum pump to establish and help maintain condenser vacuum.

Air ejectors are essentially jet pumps or eductors, as illustrated in Figure 10. In operation, the jet pump has two types of fluids. They are the high pressure fluid that flows through the nozzle, and the fluid being pumped which flows around the nozzle into the throat of the diffuser. The high velocity fluid enters the diffuser where its molecules strike other molecules. These molecules are in turn carried along with the high velocity fluid out of the diffuser creating a low pressure area around the mouth of the nozzle. This process is called entrainment. The low pressure area will draw more fluid from around the nozzle into the throat of the diffuser. As the fluid moves down the diffuser, the increasing area converts the velocity back to pressure. Use of steam at a pressure between 200 psi and 300 psi as the high pressure fluid enables a single-stage air ejector to draw a vacuum of about 26 inches Hg.

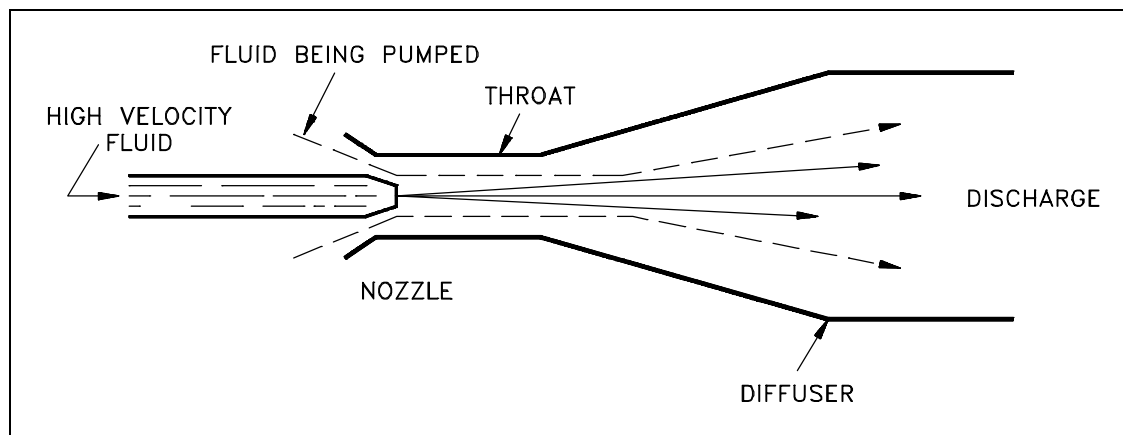


Figure 10 Jet Pump

Normally, air ejectors consist of two suction stages. The first stage suction is located on top of the condenser, while the second stage suction comes from the diffuser of the first stage. The exhaust steam from the second stage must be condensed. This is normally accomplished by an air ejector condenser that is cooled by condensate. The air ejector condenser also preheats the condensate returning to the boiler. Two-stage air ejectors are capable of drawing vacuums to 29 inches Hg.

A vacuum pump may be any type of motor-driven air compressor. Its suction is attached to the condenser, and it discharges to the atmosphere. A common type uses rotating vanes in an elliptical housing. Single-stage, rotary-vane units are used for vacuums to 28 inches Hg. Two stage units can draw vacuums to 29.7 inches Hg. The vacuum pump has an advantage over the air ejector in that it requires no source of steam for its operation. They are normally used as the initial source of vacuum for condenser start-up.

Summary

The important information from this chapter is summarized below.

Heat Exchanger Applications Summary

- Heat exchangers are often used in the following applications.
 - Preheater
 - Radiator
 - Air conditioning evaporator and condenser
 - Steam condenser
- The purpose of a condenser is to remove the latent heat of vaporization, condensing the vapor into a liquid.
- Heat exchangers condense the steam vapor into a liquid for return to the boiler.
- The cycle's efficiency is increased by ensuring the maximum ΔT between the source and the heat sink.
- The hotwell is the area at the bottom of the condenser where the condensed steam is collected to be pumped back into the system feedwater.
- Condensate depression is the amount the condensate in a condenser is cooled below saturation (degrees subcooled).
- Condensers operate at a vacuum to ensure the temperature (and thus the pressure) of the steam is as low as possible. This maximizes the ΔT and ΔP between the source and the heat sink, ensuring the highest cycle efficiency possible.