DEPARTMENT OF AEROSPACE ENGINEERING

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UNIT IV - CRYOGENIC EQUIPMENT

Cryogenic Heat Exchangers

A heat exchanger is a device used to transfer heat between two or more fluids. The fluids can be single or two phase and, depending on the exchanger type, may be separated or in direct contact. Devices involving energy sources such as nuclear fuel pins or fired heaters are not normally regarded as heat exchangers although many of the principles involved in their design are the same.

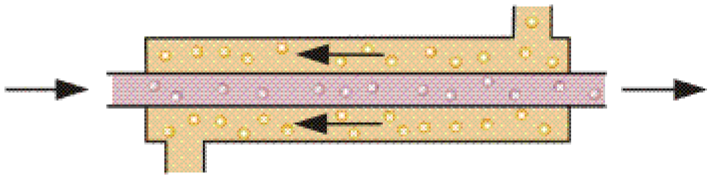
In order to discuss heat exchangers it is necessary to provide some form of categorization. There are two approaches that are normally taken. The first considers the flow configuration within the heat exchanger, while the second is based on the classification of equipment type primarily by construction. Both are considered here.

Classification of Heat Exchangers by Flow Configuration

There are four basic flow configurations:

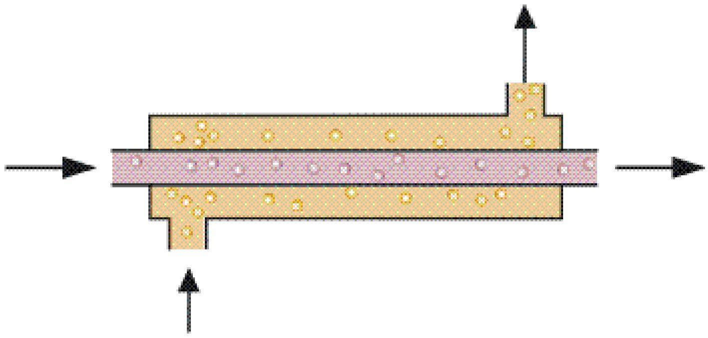
- Counter Flow
- Cocurrent Flow
- Crossflow
- Hybrids such as Cross Counterflow and Multi Pass Flow

An idealized counterflow exchanger in which the two fluids flow parallel to each other but in opposite directions. This type of flow arrangement allows the largest change in temperature of both fluids and is therefore most efficient (where efficiency is the amount of actual heat transferred compared with the theoretical maximum amount of heat that can be transferred).



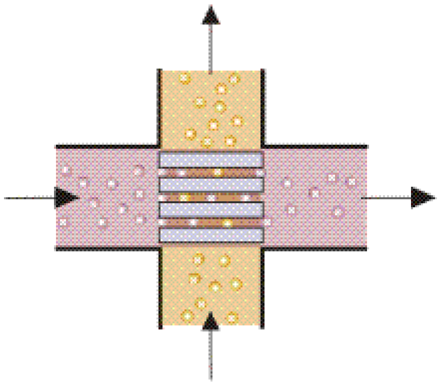
Countercurrent flow.

In cocurrent flow heat exchangers, the streams flow parallel to each other and in the same direction. This is less efficient than countercurrent flow but does provide more uniform wall temperatures.



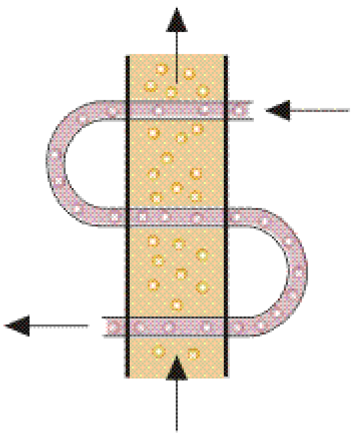
Cocurrent flow.

Crossflow heat exchangers are intermediate in efficiency between countercurrent flow and parallel flow exchangers. In these units, the streams flow at right angles to each other.



Crossflow.

In industrial heat exchangers, hybrids of the above flow types are often found. Examples of these are combined crossflow/counterflow heat exchangers and multi pass flow heat exchangers.



Cross/counter flow.

Classification of Heat Exchangers by Construction

In this section heat exchangers are classified mainly by their construction, Garland (1990). The first level of classification is to divide heat exchanger types into recuperative or regenerative. A *Recuperative Heat Exchanger* has separate flow paths for each fluid and fluids flow simultaneously through the exchanger exchanging heat across the wall separating the flow paths. A Regenerative Heat Exchanger has a single flow path, which the hot and cold fluids alternately pass through.

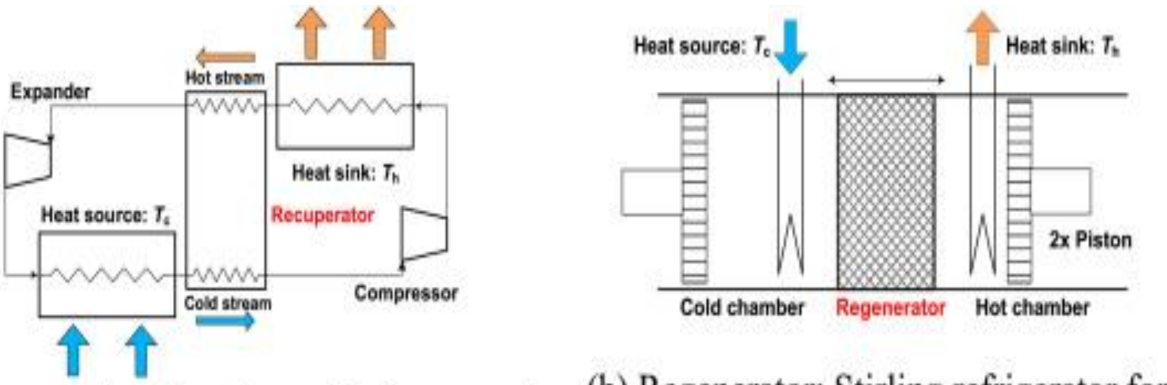
Regenerative heat exchangers

In a regenerative heat exchanger, the flow path normally consists of a matrix, which is heated when the hot fluid passes through it (this is known as the "hot blow"). This heat is then released to the cold fluid when this flows through the matrix (the "cold blow"). Regenerative Heat Exchangers are sometimes known as *Capacitive Heat Exchangers*. A good overview of regenerators is provided by Walker (1982).

Regenerators are mainly used in gas/gas heat recovery applications in power stations and other energy intensive industries. The two main types of regenerator are Static and Dynamic. Both types of regenerator are transient in operation and unless great care is taken in their design there is normally cross contamination of the hot and cold streams. However, the use of regenerators is likely to increase in the future as attempts are made to improve energy efficiency and recover more low grade heat. However, because regenerative heat exchangers tend to be used for specialist applications recuperative heat exchangers are more common.

Recuperative heat exchangers

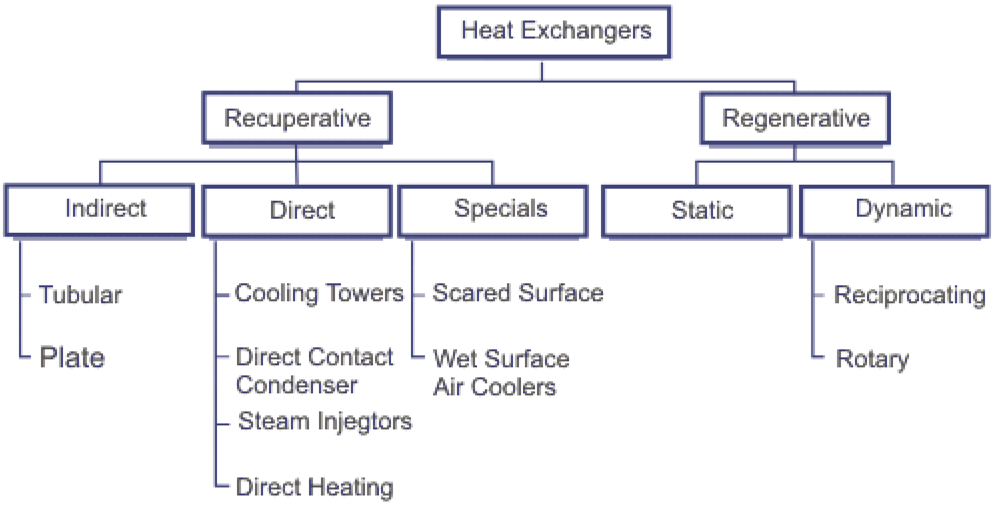
There are many types of recuperative exchangers, which can broadly be grouped into indirect contact, direct contact and specials. Indirect contact heat exchangers keep the fluids exchanging heat separate by the use of tubes or plates etc.. Direct contact exchangers do not separate the fluids exchanging heat and in fact rely on the fluids being in close contact.



(a) Recuperator: Brayton cycle for example (b) Regenerator: Stirling refrigerator for example

Heat Exchanger Types

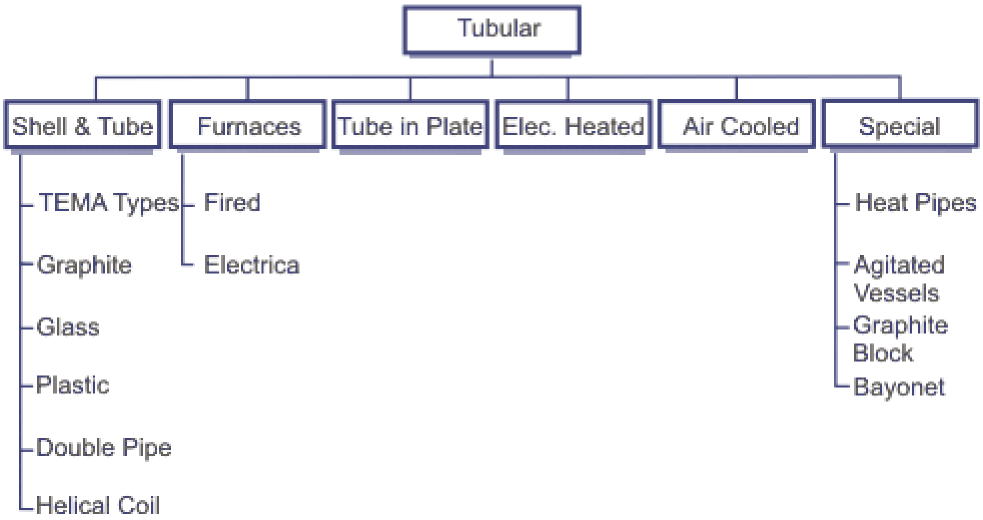
This section briefly describes some of the more common types of heat exchanger and is arranged according to the classification.



Heat exchanger classifications.

Indirect heat exchangers

In this type, the steams are separated by a wall, usually metal. Examples of these are tubular exchangers. Tubular heat exchangers are very popular due to the flexibility the designer has to allow for a wide range of pressures and temperatures. Tubular heat exchangers can be subdivided into a number of categories, of which the shell and tube exchanger is the most common.



Tubular exchanger classification.

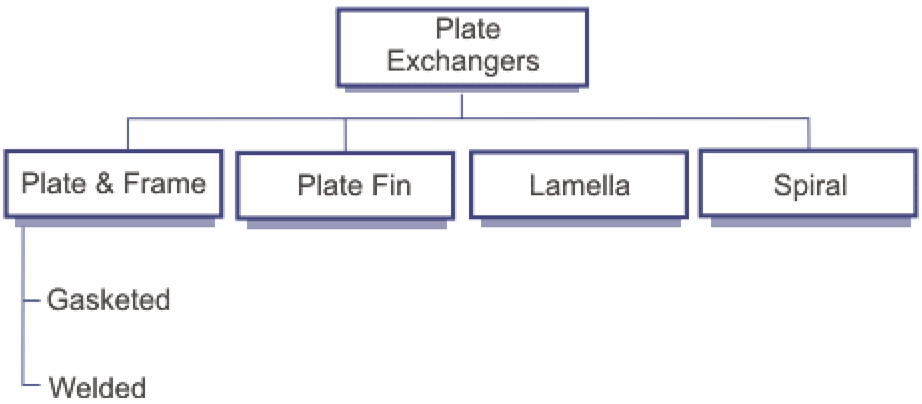
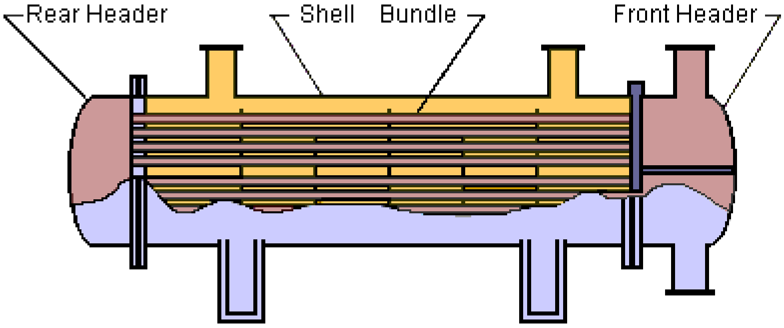


Plate exchanger classification.

A Shell and Tube Exchanger consists of a number of tubes mounted inside a cylindrical shell. Two fluids can exchange heat, one fluid flows over the outside of the tubes while the second fluid flows through the tubes. The fluids can be single or two phase and can flow in a parallel or a cross/counter flow arrangement. The shell and tube exchanger consists of four major parts:

- Front end–this is where the fluid enters the tubeside of the exchanger.
- Rear end–this is where the tubeside fluid leaves the exchanger or where it is returned to the front header in exchangers with multiple tubeside passes.
- Tube bundle–this comprises of the tubes, tube sheets, baffles and tie rods etc. to hold the bundle together.
- Shell—this contains the tube bundle.



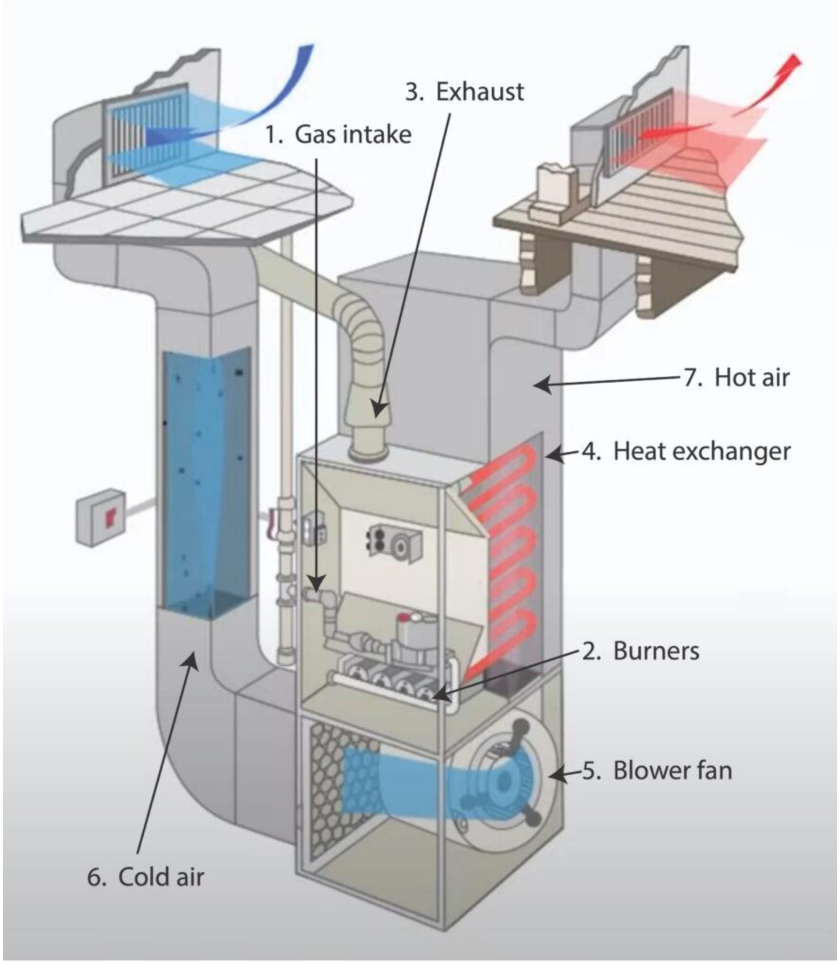
Shell and tube exchanger.

The popularity of shell and tube exchangers has resulted in a standard being developed for their designation and use. This is the Tubular Exchanger Manufactures Association (TEMA) Standard. In general shell and tube exchangers are made of metal but for specialist applications (e.g., involving strong acids of pharmaceuticals) other materials such as graphite, plastic and glass may be used. It is also normal for the tubes to be straight but in some cryogenic applications helical or *Hampson coils* are used. A simple form of the shell and tube exchanger is the Double Pipe Exchanger. This exchanger consists of a one or more tubes contained within a larger pipe. In its most complex form there is little difference between a multi tube double pipe and a shell and tube exchanger. However, double pipe exchangers tend to be modular in construction and so several units can be bolted together to achieve the required duty. The book by E.A.D. Saunders [Saunders (1988)] provides a good overview of tubular exchangers.

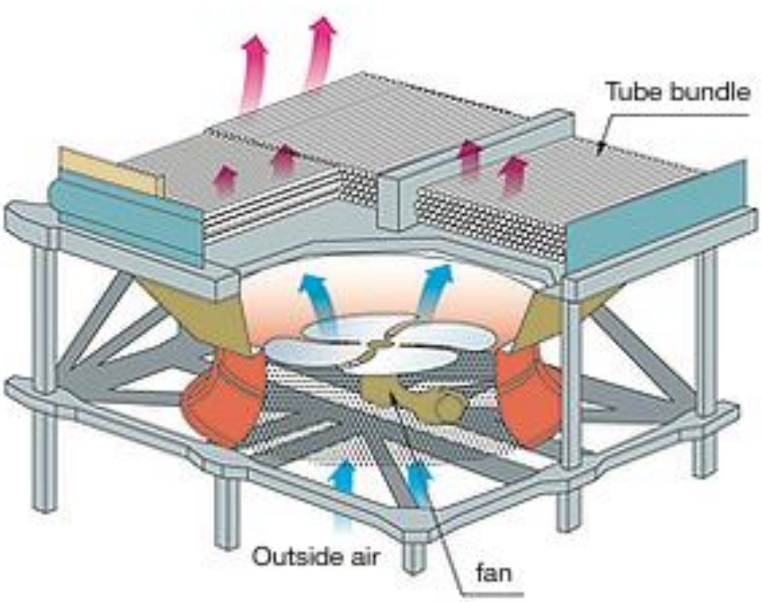
Other types of tubular exchanger include:

Furnaces—the process fluid passes through the furnace in straight or helically wound tubes and the heating is either by burners or electric heaters.

- Tubes in plate—these are mainly found in heat recovery and air conditioning applications. The tubes are normally mounted in some form of duct and the plates act as supports and provide extra surface area in the form of fins.
- Electrically heated–in this case the fluid normally flows over the outside of electrically heated tubes, (see Joule Heating).



Air Cooled Heat Exchangers consist of bundle of tubes, a fan system and supporting structure. The tubes can have various type of fins in order to provide additional surface area on the air side. Air is either sucked up through the tubes by a fan mounted above the bundle (induced draught) or blown through the tubes by a fan mounted under the bundle (forced draught). They tend to be used in locations where there are problems in obtaining an adequate supply of cooling water.



Heat Pipes, Agitated Vessels and Graphite Block Exchangers can be regarded as tubular or could be placed under Recuperative "Specials". A heat pipe consists of a pipe, a wick material and a working fluid. The working fluid absorbs heat, evaporates and passes to the other end of the heat pipe were it condenses and releases heat. The fluid then returns by capillary action to the hot end of the heat pipe to re-evaporate. Agitated vessels are mainly used to heat viscous fluids. They consist of a vessel with tubes on the inside and an agitator such as a propeller or a helical ribbon impeller. The tubes carry the hot fluid and the agitator is introduced to ensure uniform heating of the cold fluid. Carbon block exchangers are normally used when corrosive fluids need to be heated or cooled. They consist of solid blocks of carbon which have holes drilled in them for the fluids to pass through. The blocks are then bolted together with headers to form the heat exchanger.

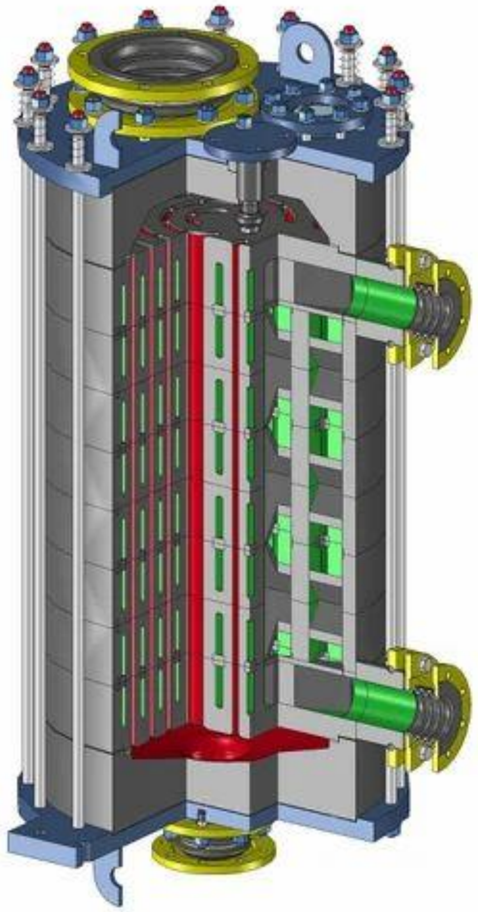


Plate heat exchangers separate the fluids exchanging heat by the means of plates. These normally have enhanced surfaces such as fins or embossing and are either bolted together, brazed or welded. Plate heat exchangers are mainly found in the cryogenic and food processing industries. However, because of their high surface area to volume ratio, low inventory of fluids and their ability to handle more than two steams, they are also starting to be used in the chemical industry.

Plate and Frame Heat Exchangers consist of two rectangular end members which hold together a number of embossed rectangular plates with holes on the corner for the fluids to pass through. Each of the plates is separated by a gasket which seals the plates and arranges the flow of fluids between the plates. This type of exchanger is widely used in the food industry because it can easily be taken apart to clean. If leakage to the environment is a concern it is possible to weld two plate together to ensure that the fluid flowing between the welded plates can not leak. However, as there are still some gaskets present it is still possible for leakage to occur. Brazed plate heat exchangers avoid the possibility of leakage by brazing all the plates together and then welding on the inlet and outlet ports.

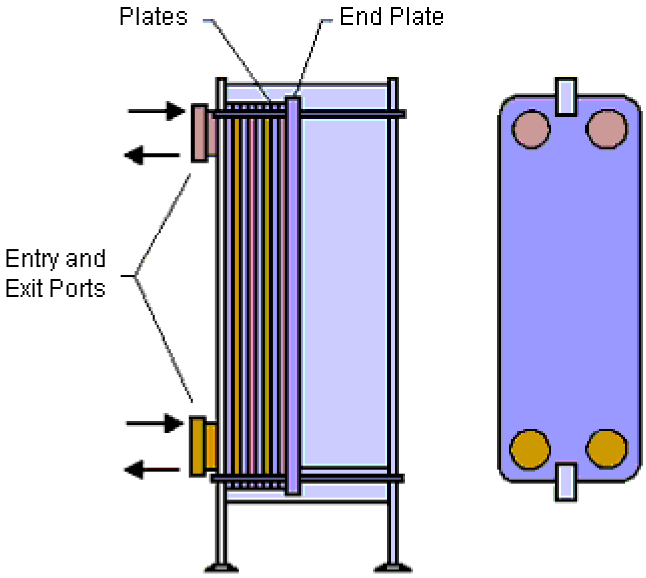
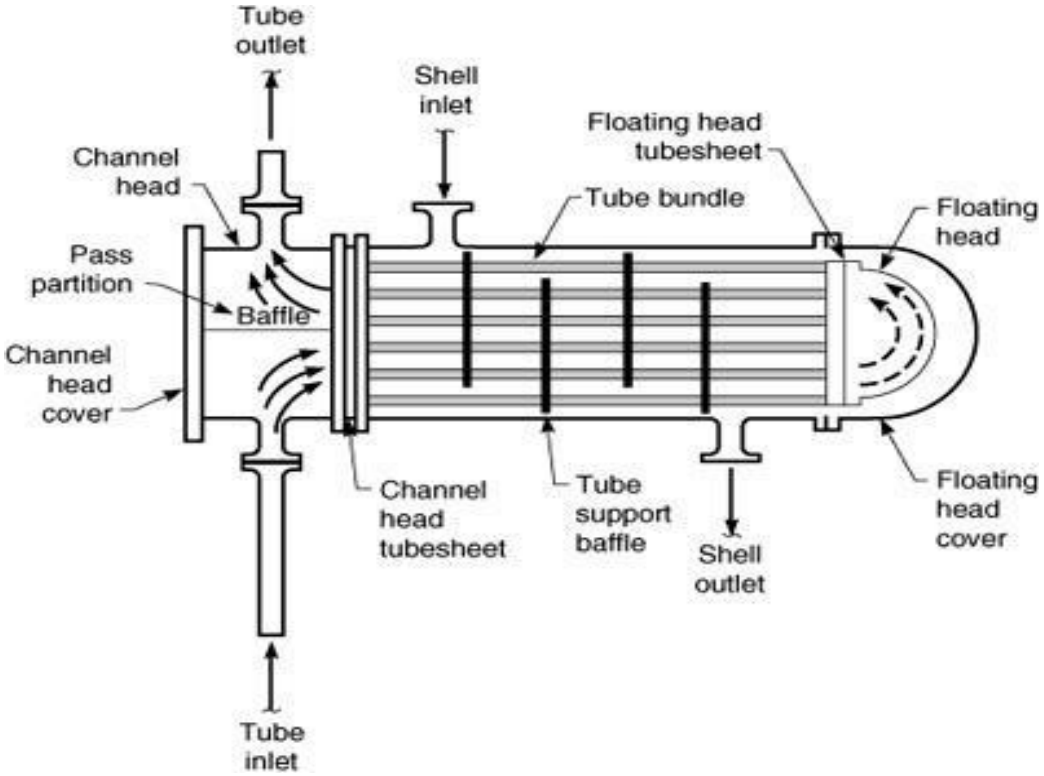


Plate and frame exchanger.

Plate Fin Exchangers consist of fins or spacers sandwiched between parallel plates. The fins can be arranged so as to allow any combination of crossflow or parallel flow between adjacent plates. It is also possible to pass up to 12 fluid streams through a single exchanger by careful arrangement of headers. They are normally made of aluminum or stainless steel and brazed together. Their main use is in gas liquefaction due to their ability to operate with close temperature approaches.

Lamella heat exchangers are similar in some respects to a shell and tube. Rectangular tubes with rounded corners are stacked close together to form a bundle, which is placed inside a shell. One fluid passes through the tubes while the fluid flows in parallel through the gaps between the tubes. They tend to be used in the pulp and paper industry where larger flow passages are required.

Spiral plate exchangers are formed by winding two flat parallel plates together to form a coil. The ends are then sealed with gaskets or are welded. They are mainly used with viscous, heavily fouling fluids or fluids containing particles or fibres.



Direct contact

This category of heat exchanger does not use a heat transfer surface, because of this, it is often cheaper than indirect heat exchangers. However, to use a direct contact heat exchanger with two fluids they must be immiscible or if a single fluid is to be used it must undergo a phase change. (See Direct Contact Heat Transfer.)

The most easily recognizable form of direct contact heat exchanger is the natural draught Cooling Tower found at many power stations. These units comprise of a large approximately cylindrical shell (usually over 100 m in height) and packing at the bottom to increase surface area. The water to be cooled is sprayed onto the packing from above while air flows in through the bottom of the packing and up through the tower by natural buoyancy. The main problem with this and other types of direct contact cooling tower is the continuous need to make up the cooling water supply due to evaporation.

Direct contact condensers are sometimes used instead of tubular condensers because of their low capital and maintenance costs. There are many variations of direct contact condenser. In its simplest form a coolant is sprayed from the top of a vessel over vapor entering at the side of the vessel. The condensate and coolant are then collected at the bottom. The high surface area achieved by the spray ensures they are quite efficient heat exchangers.

Steam injection is used for heating fluids in tanks or in pipelines. The steam promotes heat transfer by the turbulence created by injection and transfers heat by condensing. Normally no attempt is made to collect the condensate.

Direct heating is mainly used in dryers where a wet solid is dried by passing it through a hot air stream. Another form of direct heating is Submerged Combustion. This was developed mainly for the concentration and crystallization of corrosive solutions. The fluid is evaporated by the flame and exhaust gases being aimed down into the fluid which is held in some form of tank.

Specials

The wet surface air cooler is similar in some respects to an air cooled heat exchanger. However, in this type of unit water is sprayed over the tubes and a fan sucks air and the water down over the tube bundle. The whole system is enclosed and the warm damp air is normally vented to atmosphere.

Scraped Surface Exchangers consist of a jacketed vessel which the fluid passes through and a rotating scraper which continuously removes deposit from the inside walls of the vessel. These units are used in the food and pharmaceutical industry in process where deposits form on the heated walls of the jacketed vessel.

Static Regenerators

Static regenerators or fixed bed regenerators have no moving parts except for valves. In this case the hot gas passes through the matrix for a fixed time period at the end of which a reversal occurs, the hot gas is shut off and the cold gas passes through the matrix. The main problem with this type of unit is that both the hot and cold flow are intermittent. To overcome this and have continuous operation at least two static regenerators are required or a rotary regenerator could be used.

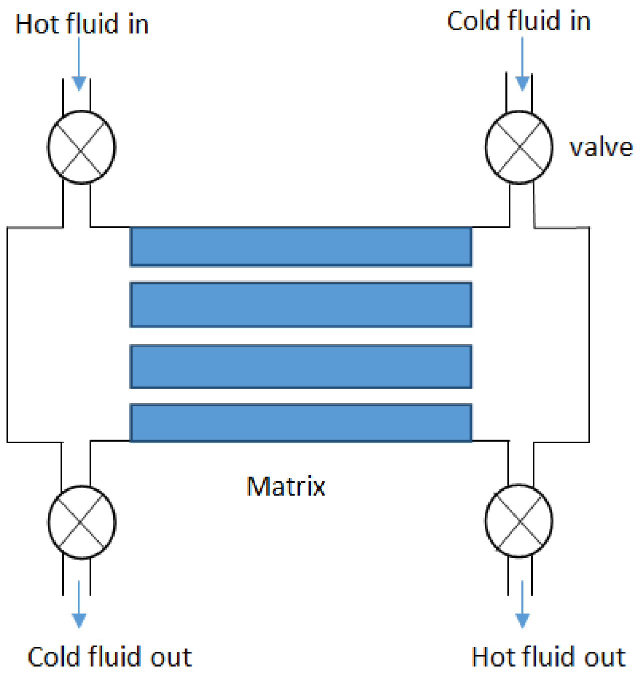
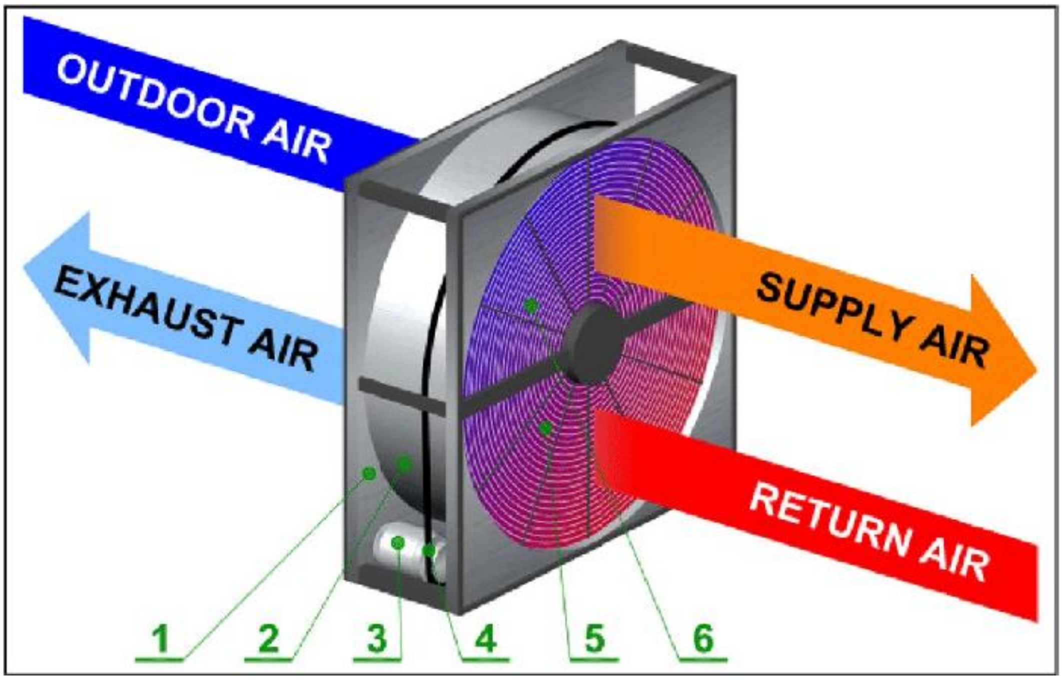


Fig:7

Rotary regenerator

In a rotary regenerator cylindrical shaped packing rotates about the axis of a cylinder between a pair of gas seals. Hot and cold gas flows simultaneously through ducting on either side of the gas seals and through the rotating packing. (See Regenerative Heat Exchangers.)



Heat recovery section with a rotary heat exchanger: 1-metal housing, 2-rotor, 3-electric motor, 4-drive belt, 5-return air side, 6-supply air side

Thermal Analysis

The thermal analysis of any heat exchanger involves the solution of the basic heat transfer equation.

$$d\dot{Q} = \alpha(T_h - T_c)\,dA \qquad (1)$$

This equation calculates the amount of heat $d\dot{Q}$ transferred through the area dA, where T_h and T_c are the local temperatures of the hot and cold fluids, α is the local heat transfer coefficient and dA is the local incremental area on which α is based. For a flat wall

$$\alpha_w = \delta_w / \lambda_w \qquad (2)$$

where δ_w is the wall thickness and λ_w its thermal conductivity.

For single phase flow past the wall α for each of the streams is a function of Re and Pr. When condensing or boiling is taking place α may also be a function of the temperature difference. Once the heat transfer coefficient for each stream and the wall are known the overall heat transfer coefficient U is then given by

$$1/U = 1/\alpha_h + r_w + 1/\alpha_c \qquad (3)$$

where the wall resistance r_w is given by $1/\alpha_w$. The total rate of heat transfer between the hot and cold fluids is then given by

$$\dot{Q}_T = UA_T(T_h - T_c) \quad (4)$$

This equation is for constant temperatures and heat transfer coefficients. In most heat exchangers this is not the case and so a different form of the equation is used

$$\dot{Q}_T = UA_T\Delta T_M \quad (5)$$

where $\dot{Q}_T$ is the total heat load, U is the mean overall heat transfer coefficient and ΔT_M the mean temperature difference. The calculation of ΔT_M and the removal of the constant heat transfer coefficient assumption is described in Mean Temperature Difference.

Calculation of U and ΔT_M requires information on the exchanger type, the geometry (e.g., the size of the passages in a plate or the diameter of a tube), flow orientation, pure countercurrent flow or crossflow, etc. The total duty $\dot{Q}_T$ can then be calculated using an assumed value of AT and compared with the required duty. Changes to the assumed geometry can then be made and U, ΔT_M and $\dot{Q}_T$ recalculated to eventually iterate to a solution where $\dot{Q}_T$ is equal to the required duty. However, in performing the thermal analysis a check should also be made at each iteration that the allowable pressure drop is not exceeded. Computer programs such as TASC from HTFS (Heat Transfer and Fluid Flow Service) perform these calculations automatically and optimize the design.

Mechanical Considerations

All heat exchangers types have to undergo some form of mechanical design. Any exchanger that operates at above atmospheric pressure should be designed according to the locally specified *pressure vessel design code* such as ASME VIII (American Society of Mechanical Engineers) or BS 5500 (British Standard). These codes specify the requirements for a pressure vessel, but they do not deal with any specific features of a particular heat exchanger type. In some cases specialist standards exist for certain types of heat exchanger. Two of these are listed below, but in general individual manufacturers define their own standards.