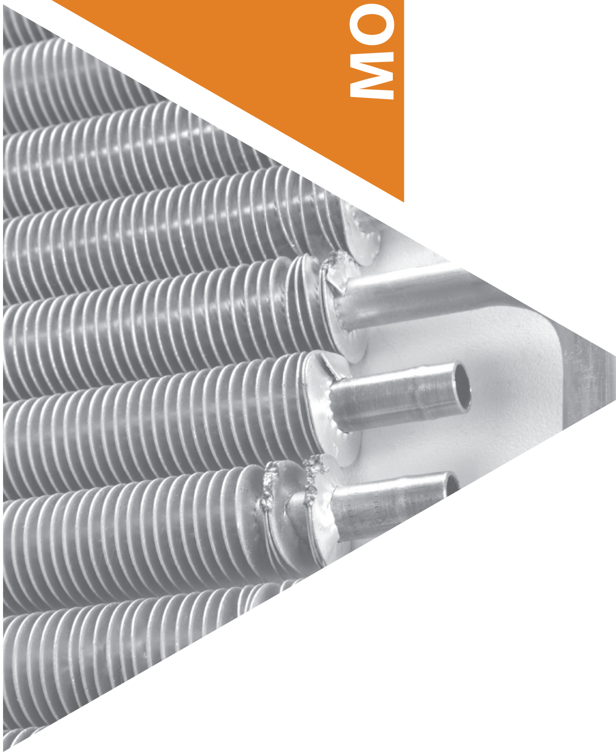
Heat exchanger devices



In this module, we will be covering the topic of **heat exchangers**, which have a fundamental role in several plant design applications; first, we will expand upon the general concepts, along with classification criteria, and them we will move to their dimensioning.

PREREQUISITES

- Knowing the definitions of the thermodynamic quantities, in particular those of temperature and heat
- Understanding combustion processes
- Understanding the mechanisms of heat transfer, in particular conduction and convection

OBJECTIVES

- Knowing and distinguishing between the different types of heat exchangers
- Knowing how to carry out the energy balance
- Knowing how to size the physical parameters of the exchanger
- Knowing how to represent the temperature distributions referring to different types of heat exchangers
- Knowing how to verify the choices related to a project

UNIT 12

Heat exchangers

12.1 General aspects and classification

Heat exchangers are *thermal devices whose function is allowing the mutual exchange of energy (in the form of heat) between two fluids moving through a surface that prevents them from mixing*. In fact, the exchange would not occur if the two fluids were in direct contact, since they could react. The heat flow is regulated by the laws which govern the conduction and convection heat transfer mechanisms through a solid surface, whose type, either *plates* (Figure 12.1) or *tubes* (Figure 12.2), strongly affects the flow exchanged per unit time.

Usually, in instantaneous production, the plate-type heat exchanger is used, while in accumulation production the tube exchanger is used.

The exchangers, depending on the type of fluid used, are named differently:

- **condensers**: they are those in which the exchange takes place between steam and cooling water;
- **kettles**: the exchange takes place between steam and boiling water.

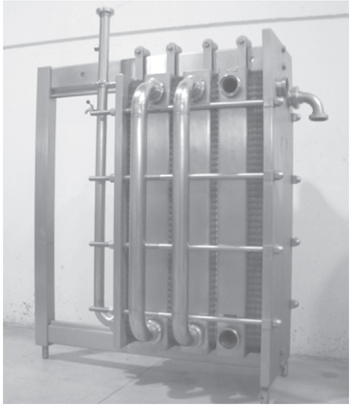


Figure 12.1

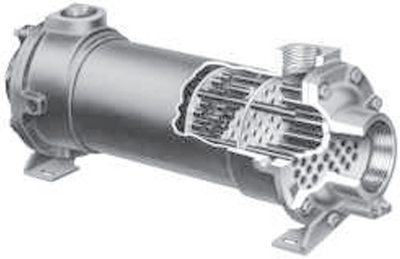
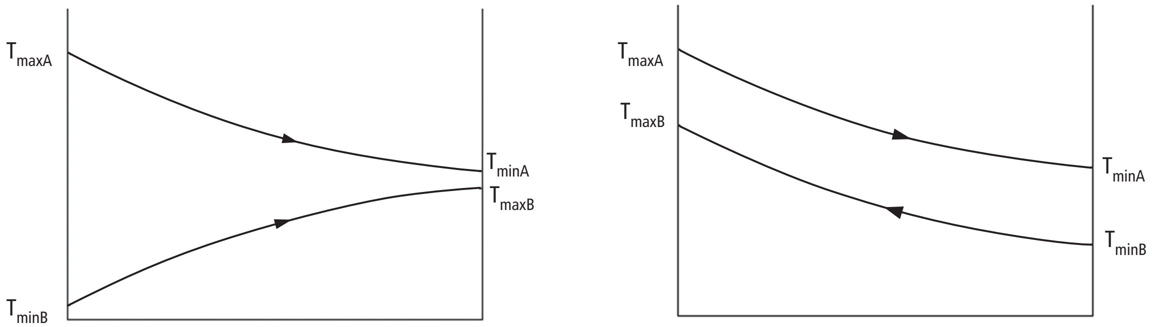


Figure 12.2

In all other cases the generic name **exchangers** is used.

Relatively to the field of application, condensers are used in direct cycle systems (for the production of steam downstream of the turbine) or in reverse cycle plants (for the production of cold, downstream of the compressor), while kettles are used in the boilers of heating plants. The generic exchangers can be used in any other type of installation (in the form of *radiators*, *exchange batteries*, *preheaters*, *finned tubes*, *superheaters* etc.).



Concurrent **Countercurrent**

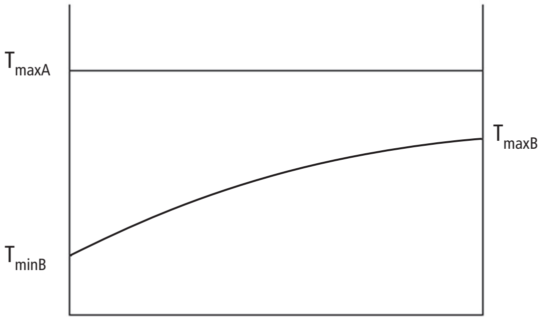


Figure 12.3 **Indifferent current**

Fluids can flow in different circuits in *concurrent*, *countercurrent,* or *indifferent currents*, as shown in Figure 12.3, where the temperature variation as a function of the length of the exchange in the various cases is shown.

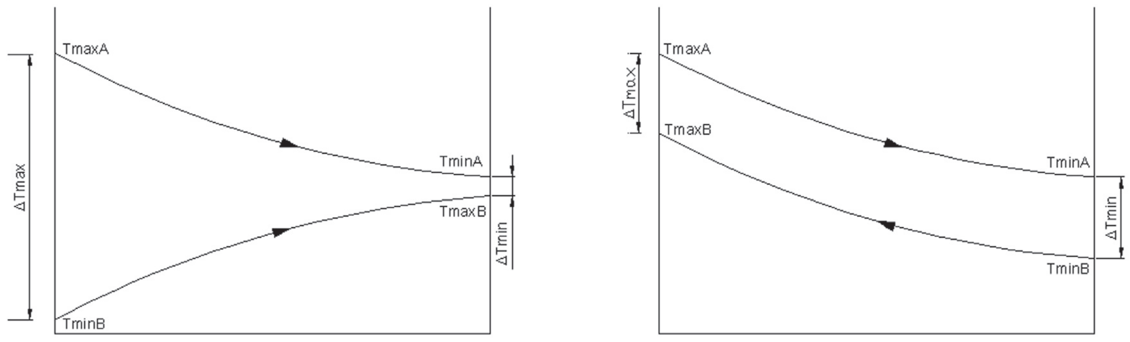
The exchange in **concurrent** occurs when the fluids are made to flow within the apparatus in the same direction, but this method has some drawbacks: the heating fluid must reach an end temperature which is always lower than that of the cooling fluid and, in addition to that, if the tubes are very long, the final portion of the appliance exchanges very little heat, due to a very small thermal jump ΔT. This entails a low quantity of thermal energy Q, and therefore a greater exchange surface; in other words, the efficiency of the apparatus is compromised. There are no such drawbacks if the exchange is in **countercurrent**, which occurs by making the fluids flow in opposite directions: the end temperature of the heating fluid can match and exceed that of the cooling fluid and, moreover, the value of the thermal jump remains high enough to make the energy exchange homogeneous throughout the length of the tubes of the apparatus.

Given the different directions of the fluids and the different variations of temperature between input and output, in practice reference is made to a mean temperature jump that involves all four values; this temperature drop is defined as *the mean of the differences between the values of the temperature curves calculated over the entire length of the pipe*. The logarithmic mean temperature difference is given by:

$$\Delta T_m = \frac{\Delta T_{Max} - \Delta T_{min}}{\ln\left(\dfrac{\Delta T_{Max}}{\Delta T_{min}}\right)} \tag{12.1}$$

There are two theories concerning the determination of ΔT_{Max} and ΔT_{min}. According to the first one, ΔT_{Max} is to be interpreted as the difference between the highest and the lowest temperature between the four in discussion, that is, between the temperature of the hot fluid and that of the cold fluid, both in input, while ΔT_{min} is the difference between the other two remaining temperatures, that of both fluids in output, considering Δ always positive. According to this theory, the movement of the fluids is irrelevant for the purposes of calculating ΔT_m. The second theory considers ΔT_{Max} the temperature difference between the two fluids measured on one side of the heat exchanger (the left part of the graph of Figure 12.4), while ΔT_{min} is the difference between the temperatures of the two fluids measured on the other side of the heat exchanger (the right part of the graph of Figure 12.4). From this theory, with which we do agree, it can be deduced that, for the purposes of calculating ΔT_m, the path of the fluids is of critical importance.

Obviously, if the curves are equidistant in such a way that the gap is maintained constant for the whole length, mathematically the value ΔT_m given by (12.1) is zero, but the value to be considered for the dimensioning of the apparatus is the constant ΔT_m which coincides with both ΔT_{Max} and ΔT_{min}.



Concurrent

Countercurrent

Figure 12.4

12.2 Dimensioning of the heat exchanger

The dimensioning of a heat exchanger implies the knowledge of certain parameters such as, for example, the input and output temperatures of one of the two fluids and mass flow rate, from which we can derive, by means of the energy balance equation for open systems, the quantity of energy possessed by a fluid and then the heat that can be exchanged:

$$Q = mc\,(T_{\text{max}} - T_{\text{min}}) \qquad (12.2)$$

where:

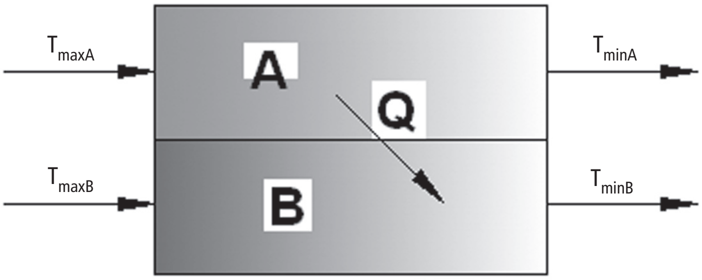
- Q = thermal energy;
- c = specific heat capacity;
- T_{max} = the higher temperature between input and output;
- T_{min} = the lower temperature between input and output.

Consider a hot fluid, referred to as A, and a cold one, referred to as B. Within a heat exchanger, the energy balance is given by:

$$Q = m_A c_A \,(T_{\text{maxA}} - T_{\text{minA}}) = m_B c_B \,(T_{\text{maxB}} - T_{\text{minB}}) \qquad (12.3)$$

The hot fluid yields heat, cooling down, and the cold fluid absorbs the same amount of heat as it heats up. The process occurs as shown in Figure 12.5.

Figure 12.5



Once calculated, by means of the equation of the **energy balance**, the amount of heat that a fluid may yield and/or absorb, proceed to measure the exchange surface.

The relationship between the thermal energy and the exchange surface is given by (12.4):

$$Q = k\,S\,\Delta T_m \qquad (12.4)$$

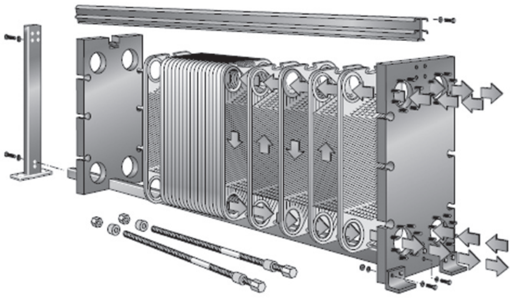
where:

- Q = thermal energy;
- k = global heat transfer coefficient;
- S = heat exchange surface;
- ΔT_m = logarithmic mean temperature difference.

As a preliminary reference value, it is possible to consider the global heat transfer coefficient k equal to about 900 W (m^2 °C)$^{-1}$. For more indicative values, see Tables 12.1 and 12.2.

If the device is of the *plate* type, the surface calculated by the inversion of (12.4) is the definitive one, except for a 8-10% increase to take into account any possible passive zones of the exchanger, due to sediments, deposits or other, especially when using industrial water.

Figure 12.6



If the device is of the *tube* type, the exchange is carried out by means of a high number of tubes, whose diameter and length can vary and influence the dimensioning phase. In this case, the surface calculated by the inversion of (12.4) is the total surface of all the tubes of the device; the surface of each cylindrical tube is given by the product of its circumference and the length of the tube itself, so the number n of tubes is given by:

$$n = \frac{S}{2\pi r_m l}$$

where:

- r_m = mean radius of the tube;
- l = length of the tube;
- S = heat exchange surface.

Table 12.1 • Practical values of global heat transfer coefficients ***k*** in W (m² °C)⁻¹

Device	**Fluids**	***k***
CALDAIE		
Boiler	*Hot fluid*: fumes at 1200 °C, average speed 10-15 m s^{-1} *Cold fluid*: water at 200 °C, average speed 1-1,5 m s^{-1}	30-60
Evaporator	*Hot fluid*: fumes at 1200 °C, average speed 10-15 m s^{-1} *Cold fluid*: saturated steam at 200 °C, average speed 10 m s^{-1}	40-80
Superheater	*Hot fluid*: fumes at 1200 °C, average speed 10-20 m s^{-1} *Cold fluid*: superheated steam at 200-300 °C, average speed 10-20 m s^{-1}	40-80
CONDENSER	*Hot fluid*: condensing steam, average speed 10-20 m s^{-1} *Cold fluid*: water, average speed 0,2-1 m s^{-1}	1000-2000
RADIATOR (HEATING)	*Hot fluid*: water at 80°C, average speed 1 m s^{-1} *Cold fluid*: ambient air, average speed 0,2-0,3 m s^{-1}	5-12

Table 12.2 • Typical values of global heat transfer coefficients ***k*** in W (m² °C)⁻¹

Fluid combination	***k***
Water/water	850-1700
Water/oil	110-350
Gas/gas	10-40
Steam condenser (water in the tubes)	1000-6000
Ammonia condenser (water in the tubes)	1000-6000
Alcohol condenser (water in the tubes)	250-700
Steam / thick combustible oil	56-170
Finned tube heat exchanger (water in the tubes, cross-flow air)	25-50

In this case, too, the surface to be used is increased by 8-10%, while for the length and diameter of the tubes refer to the commercial values in use.

Once determined the exchange surface and the number of tubes (only in the case of a tube heat exchanger), it is necessary to check the validity of the design choices by controlling the speed of the fluids, in fact the value of k estimated in the preliminary dimensioning is valid if the speed of the fluids is not less than certain values. In addition to that, choosing unsuitable r_m and l values will lead to speed values out of range. In these cases, it is necessary to adjust the speed values or to make more suitable choices or fixing the system by setting up longitudinal and/or transverse partitions within the heat exchangers, as shown in Figures 12.7 and 12.8.

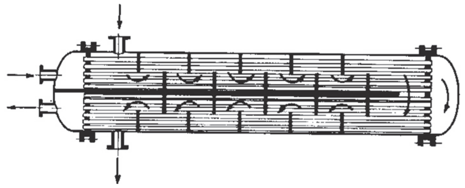


Figure 12.7

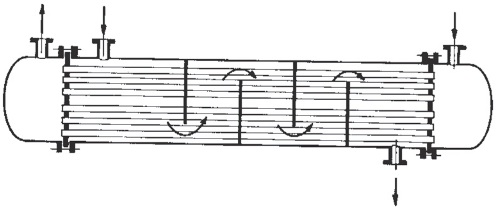


Figure 12.8

The speed control is carried out by using the **continuity equation** formula (12.5) of the fluids:

$$\dot{m} = Av \tag{12.5}$$

where:

- $\dot{m}$ = mass flow rate of water;
- A = inner section of the tube;
- v = speed of the fluid.

12.3 Condensers

Condensers are worth mentioning, especially because of their widespread usage in both heating plants and air conditioning systems, and in steam generating plants.

The purpose of the condenser is to create and environment for the turbine exhaust and retrieve the condensation water.

The advantage of recovering water is mainly obtained with surface condensers, and is useful when there is only little water available.

Since at the and of the expansion phase the pressure in the turbine is relatively low, the condensers operate with absolute pressures normally ranging between 0.05 and 0.03 bar.

They are classified as follows:

- *jet condensers*;
- *surface condensers*.

Jet condensers

In jet condensers, steam condensates by means of direct contact between the steam (at a high temperature) and the cooling water (at a low temperature). The direct contact, result of the mixing between the two fluids, prevents water recovery.

From the technical standpoint, they are cylindrical receptacles containing a series of alternating circular or ring-shaped plates; water is always poured in from above and descends, due to gravity, on the lower plates, the steam entering the condensers tends to fill the cylinder, and in the meantime it transfers to water, with which it comes into contact, its heat, condensing.

Depending on how steam is fed into the device (from above or below), and therefore its path relatively to the water, jet condensers can be, respectively, **in concurrent** (Figure 12.9) or **countercurrent** (Figure 12.10).

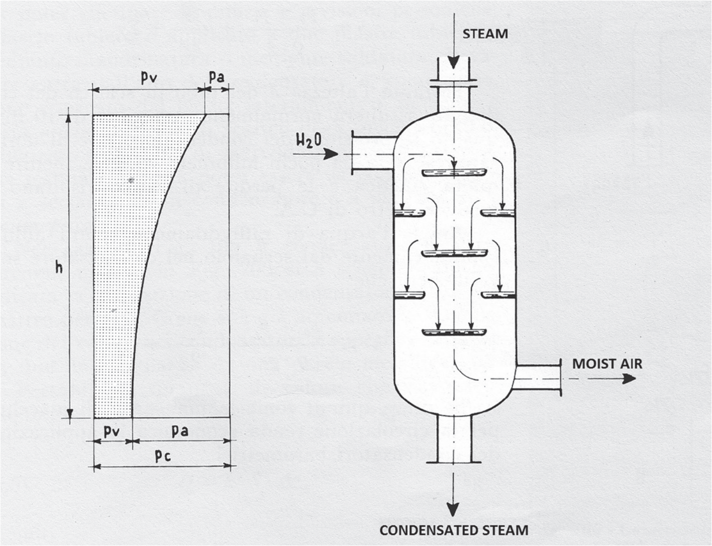


Figure 12.9

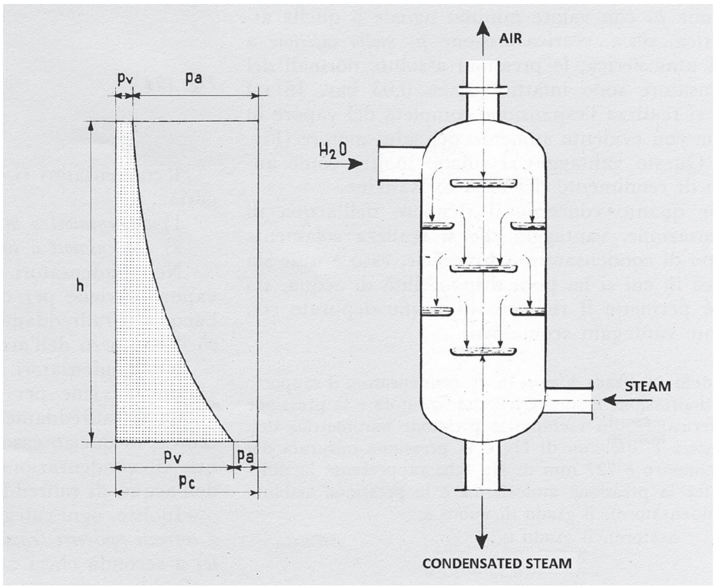


Figure 12.10

In the first ones, the condensate produced by the mixture of steam and water is extracted from the bottom, as well as the moist air that is an uncondensable element. This technical solution, despite all the disadvantages of concurrent exchangers, has the advantage of being an easily implemented technique, since it is sufficient to apply it directly at the turbine exhaust without the need for additional pipes.

In countercurrent jet condensers, the water flowing downwards meets the rising steam; the steam that, mixing with the water, condensates, is collected, like in the previous case, from below, while the uncondensable elements, in the form of moist air, are removed from the top of the condenser. Unlike the concurrent jet condensers, the steam pressure, which is usually higher than that of the water, is higher in the lower part of the condenser (as highlighted in Figures 12.9 and 12.10), and this makes it easier to install the extraction pump in an optimal position, since the highest point is also the coldest one, with the reduction of size.

Surface condensers

For this type of condensers (Figure 12.11), what was said relatively to generic surface heat exchangers still applies. They are to be dimensioned using the same criteria listed in paragraph 12.2.

Figure 12.11