4.1 COMPRESSIONS

In this chapter we will mainly deal with compressors, which can be grouped into two broad classes: displacement compressors and dynamic compressors. The most common are the displacement compressors, in which the fluid is trapped in a closed volume which is gradually reduced to achieve compression. Dynamic compressors use a different principle: the compression is achieved by converting into pressure the kinetic energy communicated to the fluid by moving blades.

Compressors are used for many industrial applications: refrigeration, air conditioning, transportation of natural gas etc. A special mention must be made of air compressors, used as a source of power for public and building works as well as in factories, pneumatic tools having many benefits.

In this section, having established the theoretical basis of compression, valid for all types of compressors, we will consider initially the displacement compressors (reciprocating and screw), then in a second stage dynamic compressors (centrifugal and axial) and pumps and fans. A comparison between different types of compressors is finally presented.

The fundamentals you have to make sure you understand are: isentropic, polytropic compression, adiabatic, isentropic or polytropic efficiency, polytropic exponent (4.1.3) and volumetric efficiency (4.2.1.3).

4.1.1 THERMODYNAMICS OF COMPRESSION

Compressing a fluid is to raise it from the suction pressure P_a to the discharge pressure P_r (above P_a). The process involves some work, called "compression".
The fluid initial state "a" before compression is known: pressure P_a, temperature T_a and specific volume v_a. However, of state "r" after compression, only the discharge pressure P_r is determined. The final temperature depends on heat exchanges with the outside. It is the same for all functions referred to the "r" thermodynamic state, including the compression work.
Assuming the process (a-r) is known, the compression work τ is given by (2.3.6) which is written here:

$$h_r - h_a + \Delta K = \tau + Q_a^r \tag{4.1.1}$$

Assuming that the fluid velocities are low, which is legitimate if we consider state in the discharge tank, we get:

$$\tau = h_r - h_a - Q_a^r \tag{4.1.2}$$

4.1.2 REFERENCE COMPRESSION

Compressors are compact machines, through which pass a gaseous fluid that stays there very briefly. Exchange surfaces are reduced and heat exchange coefficients are low. As a result, generally heat transfer between the working fluid and the outside is negligible compared to the compression work: the reference compression is therefore an adiabatic compression. If it is reversible, it is an isentropic.
A second type of compression is of interest, at least in theory: it is the isothermal compression, which would be realized if we were able to cool the working fluid, which receives heat because of compression, so that its temperature remains constant.

The advantage of such a compression is that it would minimize the work required. Although generally not feasible in practice as we have seen, it may be advantageous to cool the fluid between two compression stages when you need to achieve a multi-stage compression. The process that is then performed approaches an isotherm and is called para-isothermal.

4.1.2.1 Reversible isothermal compression

Knowing the equation of state, it is easy to calculate τ_i by integration:

$\delta\tau_i = vdP$

For example, for an ideal gas: $Pv = rT$, and $\delta\tau_i = r\,T\,\frac{dP}{P}$

As $T = T_a$ is constant:

$$\tau_i = r\,T_a \ln\left(\frac{P_r}{P_a}\right) = P_a v_a \ln\left(\frac{P_r}{P_a}\right) \qquad (4.1.3)$$

4.1.2.2 Reversible adiabatic compression

The second law gives s = Const., and, in the entropy chart, the process is represented by a vertical segment (a-s) (Figure 4.1.1). The corresponding work is called isentropic or sometimes adiabatic work. We denote it by τ_s.

Relationship (4.1.2) gives here:

$$\tau_s = h_s - h_a \qquad (4.1.4)$$

For perfect gases whose heat capacity is independent of temperature, the isentropic process law reads:

$$Pv^{\gamma} = \text{Const or } v_r = v_a \left(\frac{P_r}{P_a}\right)^{-1/\gamma}$$

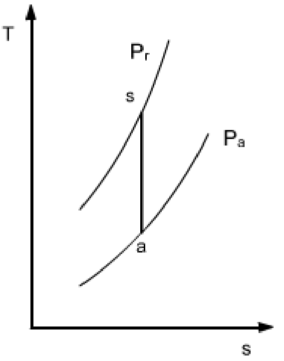

Figure 4.1.1: Isentropic compression

The integration of the vdP term gives the expression of the isentropic work:

$$\tau_s = \frac{\gamma}{\gamma-1} P_a v_a \left[\left(\frac{P_r}{P_a}\right)^{(\gamma-1)/\gamma} - 1\right] \qquad (4.1.5)$$

Given the equation of state and relations between r and the heat capacity, the above equality can be written as:

$$\tau_s = c_p\,T_a \left[\left(\frac{P_r}{P_a}\right)^{(\gamma-1)/\gamma} - 1\right] \qquad (4.1.6)$$

For ideal or real gases integration of vdP term is not so simple. The calculation must be done by solving the equations of state. In all cases, we know the pressure and suction temperature, which determine the entropy and enthalpy at the suction. So we know the discharge pressure and entropy, thereby determining the temperature and corresponding enthalpy. Work τ is deduced by (4.1.4).

4.1.3 ACTUAL COMPRESSIONS

4.1.3.1 Actual adiabatic

We have already established in section 2.4.2 the equations to be used when the compression, still adiabatic, is no longer reversible. Irreversibilities (friction, impact etc.) cause an entropy generation and, in the entropy chart (Figure 4.1.2), adiabatic compression is represented by a real curve (a-r) located to the right of the theoretical vertical (a-s). The temperature at the end of the compression is greater than that which would result in a reversible adiabatic compression.

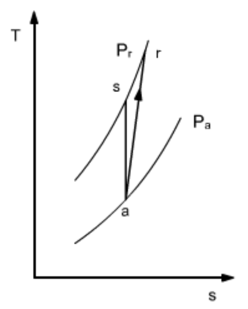

Figure 4.1.2: Real compression

Formula (4.1.2) follows directly from the first law, which does not involve any assumptions about the reversibility of the processes. The one that interests us being adiabatic Q = 0, we get:

$$\tau = h_r - h_a$$

It is clearly greater than the isentropic work τ_s.

If the gas can be regarded as perfect:

$$\tau = c_p\,(T_r - T_a)$$

Isentropic efficiency, or adiabatic efficiency, is defined as the ratio of isentropic work to real work:

$$\eta_s = \frac{\tau_s}{\tau} = \frac{h_s - h_a}{h_r - h_a} \tag{4.1.7}$$

This efficiency measures the imperfection of the process from the reversible adiabatic. It is important to note that the adiabatic efficiency η_s is thus the main characteristic of an irreversible adiabatic process, but its determination also presents the greatest difficulties.

When the machine considered is conventional, that is to say, has no major innovations as compared to machines made and tested, we take as a provisional value the one which results from testing these machines. Where no such data are available, or if they are not satisfactory, the preliminary evaluation of η_s is always very difficult. It is the result of the detailed study of losses and is only possible if one has numerous basic experimental data. The problem thus posed (calculation of losses, leaks, wall friction etc.) falls within the field of experimental fluid mechanics, not thermodynamics.

4.1.3.2 Polytropic adiabatic compression

Note that knowing the isentropic efficiency η_s provides no guidance on the law followed by the fluid during an irreversible compression, so that we cannot integrate the vdP term. To do so, we must make additional assumptions. One of the most common assumptions leads to the widely used concept of a polytropic process, which may cover slightly different definitions according to the authors. For some it is an irreversible process, while for others it is inherently reversible. We begin by presenting the first way of seeing things, which is justified for adiabatic compression, then we will show how the second is well suited to the study of nonadiabatic compressions. In addition, we will discuss this concept with two approaches often given as equivalent, whereas they are strictly so for perfect gas only, that is to say, for gases following to law Pv = rT, and whose specific heat capacity is constant (see 2.6.2.1).

4.1.3.2.1 Differential approach of the polytropic

The assumption that we make here is to consider that the irreversibilities are uniformly distributed throughout the compression, which is to assume that during any infinitesimal process stage, the isentropic efficiency keeps a constant value, equal by definition to the polytropic efficiency η_p (Figure 4.1.3).

For multi-stage machines, this efficiency has a clear physical meaning: it is the basic stage efficiency.

An infinitely small compression leads to state functions variations dP, dT, dh and ds.

The process being adiabatic, the actual work $\delta\tau$ is equal to dh, while the reversible work is $\delta\tau_s = vdP$.

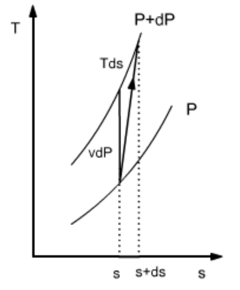

Figure 4.1.3: Elementary compression

By definition: $\eta_p = \dfrac{\delta\tau_s}{\delta\tau}$

The assumption η_p constant thus results in the differential equation:

$$\eta_p = \frac{vdP}{vdP+Tds} = \frac{dh - Tds}{dh} = \text{Const}$$

which can be written in different equivalent forms, such as:

$$\frac{Tds}{dh} = 1 - \eta_p = \text{Const} \quad \text{or} \quad \frac{1-\eta_p}{\eta_p}\, vdP - T\,ds = 0 \qquad (4.1.8)$$

Note that all these equations express the existence of a proportionality between the enthalpy change of the fluid and the work or the heat dissipated by the irreversibilities.

4.1.3.2.2 Integral approach of the polytropic

The assumption that we make here is to apply the law followed by the fluid between the compressor inlet and outlet, which is of type:

$$Pv^k = \text{Const} \qquad (4.1.9)$$

k is called the polytropic coefficient of the process.

One of the great interests of the polytropic concept lies in the simplicity of equation (4.1.9), which generalizes that of isentropic Pv^γ = Const. By varying k, it generates a large number of elementary thermodynamic processes:

$k = 0$	P = Const	isobaric
$k = 1$	$P\,v$ = Const	isotherm for an ideal gas
$k = \gamma$	Pv^γ = Const	isentropic for a perfect gas
$k = \infty$	v = Const	isovolume (isochoric)