7.1 GENERAL ISSUES ON CYCLES, NOTATIONS

As shown by the examples of Chapter 6, in many practical applications, such as in steam power plants, the fluid undergoes a series of transformations that lead it to return in its original condition. This is called a cycle.

In some cases (internal combustion engines) exhaust gases are released into the atmosphere, so it is inappropriate to speak of a cycle. However, in a simplified approach to these processes, we can assume that the thermodynamic properties of the discharging fluid are the same as those of the incoming fluid, so that we can consider that the fluid flows through a partial cycle, the said open-cycle, which could be closed by a complementary dummy process, which then allows one to compare it to other closed cycles. By extension, we are used to talking of a cycle to describe the representation of the succession of changes undergone by thermodynamic fluids being involved in energy technologies.

7.1.1 MOTOR CYCLES

On Earth, the mechanical energy comes in two main forms:

- potential energy, mainly from the attraction of gravity, is that of a substance at rest in altitude: e.g. energy contained in water from a dam;
- kinetic energy is possessed by a moving substance: energy from wind, rivers etc.

Under these two forms available mechanical energy is far below the numerous needs of today’s human societies, which correspond to transport (23% of the French energy balance), generation of electricity or farm machinery and industrial drives etc.

Only since the mid-eighteenth century did man become capable, thanks to the discoveries of Watt and Papin, of transforming heat into mechanical energy. Since then, considerable progress has been made in the development of engines, and technological developments continue apace, because of scientific advances and environmental constraints that continue to become stricter.

To convert heat into mechanical energy, in almost all cycles used, the working fluid is successively compressed and heated, and finally expanded. If the cycle is open, the fluid is then discharged in the surroundings, if it is closed, it is cooled and then compressed again. The various engines that are used differ by:

- the type of thermodynamic cycle used;
- the nature of the working fluid flowing through them;
- the types of hot source and compression and expansion devices used.

Different typologies can thus be established. Generally, there are:

- compressible fluid engines, where the fluid remains in the state of gas or steam throughout the cycle. In this case, a compressor is of course necessary. Depending on circumstances, the heat source used is the boiler or combustion chamber of an open cycle if the technical fluid contains oxygen (usually air);
- condensable fluid engines, in which the fluid changes state: at the condenser outlet, it is a liquid which is compressed by a pump, then heated and converted into steam in a boiler, steam which is then expanded in a turbine or piston

engine. The compression work, proportional to the fluid specific volume, is much lower in these engines than in previous ones.

A distinction is also commonly made between:

- internal combustion engines, operating in an open cycle, where the heat source is a combustion chamber;
- external combustion engines, operating in a closed cycle, where the heat source is a boiler.

It is clear that these different categories overlap. For our part, we chose to present in Part 3 first the internal combustion engines: gas turbines and derivative engines (Chapter 2), gasoline engines and diesel engines (Chapter 3), then the external combustion engine: the Stirling engine (Chapter 4) and steam power plants (Chapters 6 and 7).

7.1.2 REFRIGERATION CYCLES

In a motor cycle, warmth is provided to produce mechanical energy. A refrigeration cycle operates in reverse: it receives mechanical energy which is used to raise the temperature level of the heat.

Three types of refrigeration cycles are commonly used:

- refrigeration cycles (Chapter 9);
- heat pump cycles (Chapter 10);
- mechanical vapor compression cycles (Chapter 10).

The first two differ only by the levels of operating temperature and the desired effect. In refrigeration cycles, we try to cool a cold chamber, while a heat pump is used for heating.

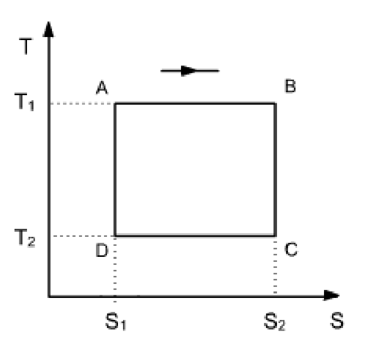

Figure 7.1.1: Carnot cycle

7.1.3 CARNOT CYCLE

Readers interested in a more detailed presentation of the Carnot cycle can refer to section 2.4.3 of this volume. It is known that the effectiveness of such a cycle is equal to $\eta = 1 - \frac{T_2}{T_1}$, if T_1 and T_2 are the temperatures of hot and cold sources (Figure 7.1.1).

This value corresponds to the maximum efficiency for a two-source machine, but the realization of a Carnot cycle presents many difficulties:

- firstly because in practice there must be some difference in temperature between the machine and the hot and cold sources during processes AB and CD;
- secondly because the realization of isothermal compression of CD or isothermal expansion AB poses many technological problems.

We have indeed seen (section 2.3.6 of this Part) that for various reasons one is generally led to use stationary devices to exchange heat, and adiabatic machines to achieve compression or expansion.

The actual motor cycles thus significantly differ from the Carnot cycle, isotherms AB and CD being most often replaced by isobars or isovolumes. However, attempts of course are made for expansion BC and compression AD to approach isentropic.

7.1.4 REGENERATION CYCLES

We can imagine cycles where the isentropic compression AD and expansion BC are replaced by other processes, each of them being deduced from the other by a translation in the entropy diagram (Figure 7.1.2). This is called regeneration.

In these circumstances, it is theoretically possible to make all the internal and external heat exchanges at constant temperature, and the ideal cycle with regeneration reaches the same efficiency as that of the Carnot.

In practice, the internal heat exchange is of course not at constant temperature, and we introduce the notion of regenerator effectiveness to characterize performance.

Examples of regeneration motor cycles are given in Part 3 (gas turbine section 2.1.5.1, Stirling cycle Chapter 4, reheat steam cycle section 6.1.2).

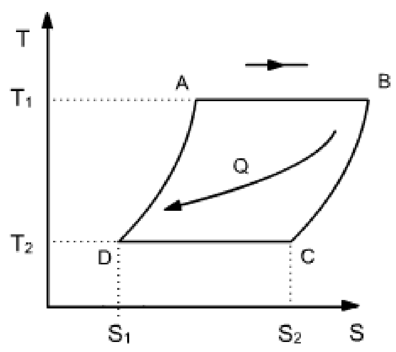

Figure 7.1.2: Regenerative cycle

7.1.5 THEORETICAL AND REAL CYCLES

What essentially distinguishes cycles, are firstly the states (gaseous or liquid) in which the working fluid is likely to be, and secondly the nature of the changes it undergoes.

The study of heat engines allows, from the theoretical thermodynamic cycle analysis, to include all the constraints that one faces when trying to convert heat into mechanical or electric power, or vice versa mechanical energy in heating or cooling.

In practice, as we shall see, many technological difficulties arise, and real cycles often deviate significantly from the theoretical cycles we can calculate. The study of a particular machine thus depends heavily on the technical devices, especially mechanical and thermal, which are involved, and we will try in what follows to take into account these peculiarities as far as possible.

The presentation of theoretical cycles still is of great interest because they represent the thermodynamic reference, and determine the limits it is possible to achieve in terms of efficiency, for example. The study of cycles can thus effectively guide the engineer in his approach to improving engines.

7.1.6 NOTIONS OF EFFICIENCY AND EFFECTIVENESS

It may be helpful at this stage to specify what is meant by the notion of efficiency or effectiveness, although we have already used it several times.

In the general case, it is quite intuitive: for a heat engine aiming at converting heat into mechanical power, it is the ratio of the power output to the heat supplied to the machine: $\eta = \frac{\tau}{Q}$.

Difficulties arise because the terms "power output" or "heat supplied to the machine" may not have a single meaning.

Heat supplied

The hot source provides some heat energy Q_0, determined by fuel flow rate and combustion conditions. We have seen that, even assuming complete combustion, the heat received depends on the enthalpy of condensation of water recovered. Generally, Q_0 is calculated relative to the lower heating value (LHV) of the fuel, which amounts to slightly underestimating its potential. When combustion is incomplete, things can get considerably complicated, as we showed in section 4.6.

Now suppose Q_0 is determined. In general, some of that heat escapes from the hot source, and is not transferred to the working fluid. These are losses by convection, conduction and radiation from the boiler or the combustion chamber, potential losses from flue gases etc. These losses can be characterized by a boiler efficiency η_{ch} equal to the ratio of fluid supplied Q_1 to Q_0.

Power output

The net power τ produced by the machine is by definition equal to the difference between the power delivered τ_d, and the internal power consumption τ_c, with agreement to positively express their values. If they are calculated algebraically it is equal to their sum.

τ_d is equal to the sum of the powers provided by the different shafts of the expansion devices, and τ_c to the total power consumed in the shafts of compression devices.

We call thermodynamic efficiency, or internal efficiency η_i, the ratio of power produced τ to Q_1.

Power τ does not correspond entirely to that which is delivered by the engine because auxiliary equipment is necessary so that the whole system can work. Their role is to supply fuel to the engine, to provide lubrication and cooling etc.

In addition, a number of internal frictions must be overcome. One generally groups together as mechanical losses of all these levies on the available power, which drops accordingly. They be represented by a mechanical efficiency η_m, the total efficiency being equal to the product of the latter by the internal efficiency defined above: $\eta = \eta_i \cdot \eta_m$.

In more general terms, when dealing with relatively complex cycles, one is led to adopt a broader definition of efficiency or effectiveness: it is the ratio of the useful energy effect to the purchased energy put in.

$$\eta = \frac{\text{useful energy effect}}{\text{purchased energy}}$$

This way of working is similar to that used in Thermoptim (section 3.3.1). It has the advantage of remaining valid in all cases for both motor cycles and refrigeration cycles. In the latter case, we no longer talk of efficiency but rather of COP coefficient of performance (see sections 9.3 and 10.1 of Part 3).

Note that some purists prefer to reserve the term efficiency for the Carnot efficiency, and recommend the use of effectiveness in other cases. We have not, however, given the wide use of the efficiency word in industry.