connected by equations that can only be determined if the environment is considered continuous and homogeneous, that is to say if these functions are sufficiently regular in the mathematical term. In particular, we will focus only on macroscopic quantities.

2.1.1 OPEN AND CLOSED SYSTEMS

A thermodynamic system means a quantity of matter isolated from its surroundings by a fictional or real boundary. This system is called closed if it does not exchange matter with the outside through its boundaries, otherwise it is called open. Note that this notion of system is not the same as the one we introduced above to characterize an energy technology as an assembly of components. There is a difficulty of vocabulary that we cannot avoid having regard to practice, but the context generally makes it not difficult to distinguish the two meanings of the term.
Beginners are often confused by the distinction between closed systems and open systems, the latter corresponding to a new concept for them, because during their undergraduate tuition they generally considered only closed systems (to avoid taking account the exchange of matter at boundaries).

In a diesel or gasoline engine, the valves are closed during compression, combustion and expansion, isolating from outside the mass of gas found between the piston, the jacket and head. The processes that take place inside the engine must be calculated in closed systems. In the case of a gas turbine, compressor, combustor and turbine, these are driven by a continuous flow of gas. At the entrance and exit of each of these components, matter is transferred. The changes must then be calculated in open systems.

There is a certain paradox in the fact that the calculations are generally easier to make for open systems than for closed systems, although these do not involve exchange of matter with the outside. The reason is that the pressure is usually given in the calculations in an open system, although it depends on many factors in a closed system.

For example, combustion in a gas turbine (open system) takes place at constant pressure, neglecting small pressure drops, whereas in a diesel or gasoline engine (closed system), the pressure varies greatly during the process, so it is preferable if one wants to stick to reality, to break it down into several stages: for example, first at constant volume and constant pressure, and finally constant temperature.

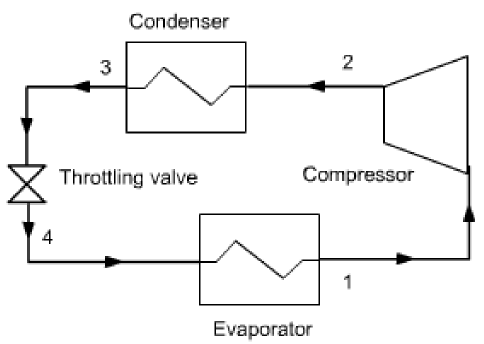

Figure 2.1.1: Compression refrigeration cycle

To complete complicating things, it is natural (but fatal) to confuse the concepts of open and closed systems in thermodynamic sense that we just introduced and its meaning when considering the whole cycle swept by the fluids in a thermal machine.

For example a refrigerator compression cycle is a closed cycle (Figure 2.1.1), otherwise the refrigerant would be lost to the atmosphere, which would be both costly and harmful to the environment, while each of its components taken separately (except optionally if the compressor is displacement type) is an open system, through which passes a steady-state flow of refrigerant.

The machine operates as a closed cycle involving several components, each working in open systems.

2.1.2 STATE OF A SYSTEM, INTENSIVE AND EXTENSIVE QUANTITIES

The notion of state of a system represents "the minimum information necessary to determine its future behavior". State variables (temperature, pressure. etc.) are all physical quantities (or thermodynamic properties) necessary and sufficient to fully characterize a system at a given moment. There are usually several sets that meet this definition, but note that speed is not a state variable, since its definition involves two successive times. We will see later that for a phase of unit mass, two quantities are sufficient to determine all the others. These results ensure the existence of equations relating each state variable to two of them independently: v = f (P, T)... We call such relationships equations of state, which are fundamental in practice.

Depending on the problem, the following pairs are generally retained: (pressure, volume), (pressure, temperature), (temperature, volume). A state function is a quantity whose value depends only on the state of the system, not its history.

A physical model involves variables representing the state of a system, which is *a priori* a function of time and position of the point considered. These quantities can be grouped into two broad classes:

intensive quantities such as pressure, temperature or specific enthalpy, which are independent of the amount of matter considered;

extensive quantities such as mass, enthalpy or entropy, which depend on the mass of the system.

An intensive quantity links the condition provided at a point of the medium to a reference condition at another point or another medium. For example, the temperature is defined relative to zero or to the triple point of water.

An extensive quantity is additive: if a system is composed of several phases, extensive quantities that characterize it are equal to the sum of those of its component phases. Mass or total enthalpy are extensive quantities.

Note that by multiplying the phase mass by certain intensive quantities such as mass, enthalpy or entropy, extensive quantities are obtained as enthalpy or entropy.

Recall that a control volume is a region of space with real or fictitious boundaries, thus defining the system of interest (thermodynamic in this case). An example of a control volume is given in Figure 2.3.1. It is bounded by the walls of the fixed and mobile machine M and two immaterial geometric surfaces named A_1 and A_2 at the initial instant t_0, and B_1 and B_2 at t_0 + dt.

In the example in Figure 2.3.1, the control volume is considered a closed system, which is followed in its movement over time, from A_1 to B_1 and A_2 to B_2. In other cases, the control volumes can define open systems. The masses they isolate may then vary depending on mass flow rates crossing their boundaries.

In general, the component models we use are established by writing the laws of continuity and conservation of extensive variables: mass, energy, entropy etc., balance sheets being established for well-chosen control volumes.

Conservation laws are written in the general form:

$$\left\{\begin{array}{l}\text{accumulation}\\ \text{in the control}\\ \text{volume}\end{array}\right\} = \left\{\begin{array}{l}\text{inward transport}\\ \text{by the}\\ \text{surface}\end{array}\right\} - \left\{\begin{array}{l}\text{outward transport}\\ \text{by the}\\ \text{surface}\end{array}\right\}$$

$$+ \left\{\begin{array}{l}\text{transfer}\\ \text{through}\\ \text{the surface}\end{array}\right\} + \left\{\begin{array}{l}\text{generation}\\ \text{in the}\\ \text{volume}\end{array}\right\} - \left\{\begin{array}{l}\text{consumption}\\ \text{in the}\\ \text{volume}\end{array}\right\} \qquad (2.1.1)$$

For the conservative quantities, such as mass, internal energy and enthalpy, the last two terms in the equation vanish. For non-conservative quantities, such as entropy or the number of moles of chemical species in reaction, it may be necessary to introduce one or the other.

Building a model is to translate that expression into a set of semantic equations and set the initial and boundary conditions.

2.1.3 PHASE, PURE SUBSTANCES, MIXTURES

A phase is a continuous medium having the following three properties:

it is homogeneous (which implies a uniform temperature);

speed in each point is zero in a suitable reference frame;

it is subject to no external force at distance (uniform pressure).
As is known, matter exists in three phases: solid, liquid and gas. A thermodynamic system may consist of a single pure substance, or have several. In the latter case, the mixture is characterized by its molar or mass composition. Each of the components of the mixture may be present in one or more phases. If the components and their phases are uniformly distributed throughout the volume defined by the system boundaries, the mixture is homogeneous, otherwise it is heterogeneous. The properties of a mixture depend obviously on its homogeneity.

The concept of phase plays a very important role in practice, because we always assume in what follows that any physical system is decomposed into a set of phases.

2.1.4 EQUILIBRIUM, REVERSIBLE PROCESS

A phase is said to be in static equilibrium, or simply in equilibrium, if:

pressure and temperature are uniform in space;

all state variables are constant over time.

We call a reversible process between two equilibrium states 1 and 2 a fictitious process which has the following two properties:

it is slow enough at all points of view (speed, heat and matter transfer etc.) so it can be likened to a continuous state of equilibrium;

it is the common boundary of two families of real processes, one of which leads from 1 to 2, and the other from 2 to 1.

A process is said to be irreversible in the following two cases:

the reverse process is not feasible without substantial modification of equipment (mixing, combustion etc.);

it contains a cause of irreversibility of the friction or viscosity type.

2.1.5 TEMPERATURE

The concept of temperature can be introduced in several different ways. We content ourselves here with the operational definition given by F. Fer (1970), which is based on two propositions:

- we know how to construct a thermometer device, of which all physical properties are, under well defined operating conditions, function of a single variable called temperature;
- we know how to get a physical system such that when a thermometer is immersed in it, its indication remains constant over time and independent of its orientation and its place.

It is said the temperature of the medium is equal to that of the thermometer and that the medium is in thermal equilibrium.

It is possible to link this presentation with the axiomatic definitions of the temperature deduced for example from the second principle. A rigorous and comprehensive presentation of this notion, however, is beyond the limits we have set for this book. Furthermore this introduction is quite intuitive and its practical use does not generally pose a particular problem.