

### CHAPTER

# 2

## BASIC PRINCIPLES OF ENERGY CONVERSION

A large number of energy conversion processes take place in nature. Man is capable of performing a number of additional energy conversion processes by means of various devices invented during the history of man. Such devices may be classified according to the type of construction used, according to the underlying physical or chemical principle, or according to the forms of energy appearing before and after the action of the device. In this chapter, a survey of conversion methods, which may be suitable for the conversion of renewable energy flows or stored energy, will be given. A discussion of general conversion principles will be made below, followed by an outline of engineering design details for specific energy conversion devices, ordered according to the energy form being converted and the energy form obtained. The collection is necessarily incomplete and involves judgment about the importance of various devices.

### 2.1 Conversion between energy forms

For a number of energy forms, Table 2.1 lists some examples of energy conversion processes or devices currently in use or contemplated, organised according to the energy form emerging after the conversion. In several cases more than one energy form will emerge as a result of the action of the device, e.g. heat in addition to one of the other energy forms listed. Many devices also perform a number of energy conversion steps, rather than the single ones given in the table. A power plant, for example, may perform the conversion process chain between energy forms: chemical  $\rightarrow$  heat  $\rightarrow$  mechanical  $\rightarrow$  electrical. Diagonal transformations are also possible, such as conversion of mechanical energy into mechanical energy (potential energy of elevated fluid  $\rightarrow$  kinetic energy of flowing fluid  $\rightarrow$  rotational energy of

turbine) or of heat into heat at a lower temperature (convection, conduction). The second law of thermodynamics forbids a process in which the only change is that heat is transferred from a lower to a higher temperature. Such transfer can be established if at the same time some high-quality energy is degraded, e.g. by a heat pump (which is listed as a converter of electrical into heat energy in Table 2.1, but is discussed further in Chapter 6).

<i>Initial energy form</i>	<i>Converted energy form</i>				
	<i>Chemical</i>	<i>Radiant</i>	<i>Electrical</i>	<i>Mechanical</i>	<i>Heat</i>
<i>Nuclear</i>					Reactor
<i>Chemical</i>			Fuel cell, battery discharge		Burner, boiler
<i>Radiant</i>	Photolysis		Photovoltaic cell		Absorber
<i>Electrical</i>	Electrolysis, battery charging	Lamp, laser		Electric motor	Resistance, heat pump
<i>Mechanical</i>			Electric generator, MHD	Turbines	Friction, churning
<i>Heat</i>			Thermionic & thermoelectric generators	Thermodynamic engines	Convector, radiator, heat pipe

Table 2.1. Examples of energy conversion processes listed according to the initial energy form and one particular converted energy form (the one primarily wanted).

The efficiency with which a given conversion process can be carried out, i.e. the ratio between the output of the desired energy form and the energy input, depends on the physical and chemical laws governing the process. For the heat engines, which convert heat into work or vice versa, the description of thermodynamic theory may be used in order to avoid the complication of a microscopic description on the molecular level (which is, of course, possible, e.g. on the basis of statistical assumptions). According to thermodynamic theory (again the “second law”), no heat engine can have an efficiency higher than that of a reversible Carnot process, which is depicted in Fig. 2.1, in terms of different sets of thermodynamic state variables,

$$(P, V) = (\text{pressure, volume}),$$

$$(T, S) = (\text{absolute temperature, entropy}),$$

and

$$(H, S) = (\text{enthalpy, entropy}).$$

## 2. BASIC PRINCIPLES OF ENERGY CONVERSION

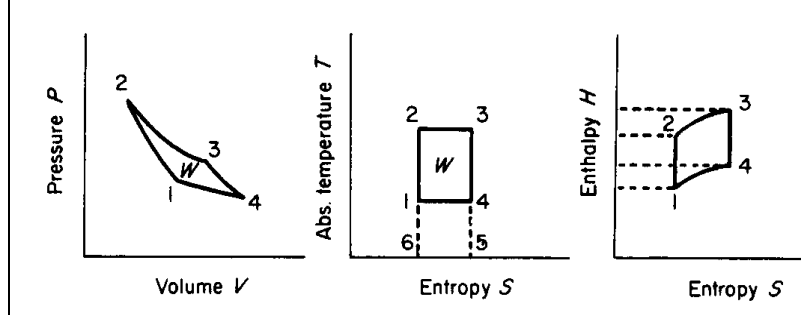


Figure 2.1. The cyclic Carnot process in different representations. Traversing the cycle in the direction  $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$  leads to the conversion of a certain amount of heat into work (see text for details).

The change of the entropy  $S$  during a process (e.g. an energy conversion process), which brings the system from a state 1 to a state 2, is defined by

$$\Delta S = \int_{T_1}^{T_2} T^{-1} dQ, \quad (2.1)$$

where the integral is over successive infinitesimal and reversible process steps (not necessarily related to the real process, which may not be reversible), during which an amount of heat  $dQ$  is transferred from a reservoir of temperature  $T$  to the system. The imagined reservoirs may not exist in the real process, but the initial and final states of the system must have well-defined temperatures  $T_1$  and  $T_2$  in order for (2.1) to be applicable. The entropy may contain an arbitrary common constant fixed by the third law of thermodynamics (Nernst's law), which states that  $S$  may be taken as zero at zero absolute temperature ( $T = 0$ ).

The enthalpy  $H$  is defined by

$$H = U + PV,$$

in terms of  $P$ ,  $V$  and the internal energy  $U$  of the system. According to the first law of thermodynamics,  $U$  is a state variable given by

$$\Delta U = \int dQ + \int dW, \quad (2.2)$$

in terms of the amounts of heat and work added to the system [ $Q$  and  $W$  are not state variables, and the individual integrals in (2.2) depend on the paths of integration]. The equation (2.2) determines  $U$  up to an arbitrary constant, the zero point of the energy scale. Using the definition (2.1),

$$dQ = T dS$$

and

$$dW = -P dV,$$

both of which are valid only for reversible processes. The following relations are found among the differentials:

$$\begin{aligned} dU &= T dS - P dV, \\ dH &= T dS + V dP. \end{aligned} \quad (2.3)$$

These relations are often assumed to have general validity.

If chemical reactions occur in the system, additional terms  $\mu_i dn_i$  should be added on the right-hand side of both relations (2.3), in terms of the chemical potentials  $\mu_i$  (see e.g. Maron and Prutton, 1959).

For a cyclic process such as the one shown in Fig. 2.1,  $\int dU = 0$  upon returning to the initial locus in one of the diagrams, and thus according to (2.3)  $\int T dS = \int P dV$ . This means that the area enclosed by the path of the cyclic process in either the  $(P, V)$  or the  $(T, S)$  diagram equals the work  $-W$  performed by the system during one cycle (in the direction of increasing numbers on Fig. 2.1).

The amount of heat added to the system during the isothermal process 2-3 is  $\Delta Q_{23} = T(S_3 - S_2)$ , if the constant temperature is denoted  $T$ . The heat added in the other isothermal process, 4-1, at a temperature  $T_{ref}$  is  $\Delta Q_{41} = -T_{ref}(S_3 - S_2)$ . It follows from the  $(T, S)$  diagram that  $\Delta Q_{23} + \Delta Q_{41} = -W$ . The efficiency by which the Carnot process converts heat available at temperature  $T$  into work, when a reference temperature of  $T_{ref}$  is available, is then

$$\eta = \frac{-W}{\Delta Q_{23}} = \frac{T - T_{ref}}{T}. \quad (2.4)$$

The Carnot cycle (Fig. 2.1) consists of four steps: 1-2, adiabatic compression (no heat exchange with the surroundings, i.e.  $dQ = 0$  and  $dS = 0$ ); 2-3, heat drawn reversibly from the surroundings at constant temperature (the amount of heat transfer  $\Delta Q_{23}$  is given by the area enclosed by the path 2-3-5-6-2 in the  $(T, S)$ -diagram); 3-4, adiabatic expansion; and 4-1, heat given away to the surroundings by a reversible process at constant temperature [ $|\Delta Q_{41}|$  equal to the area of the path 4-5-6-1-4 in the  $(T, S)$ -diagram].

The  $(H, S)$ -diagram is an example of a representation in which energy differences can be read directly on the ordinate, rather than being represented by an area.

It requires long periods of time to perform the steps involved in the Carnot cycle in a way that approaches reversibility. As time is important for man (the goal of the energy conversion process being power rather than just an amount of energy), irreversible processes are deliberately introduced into

## 2. BASIC PRINCIPLES OF ENERGY CONVERSION

the thermodynamic cycles of actual conversion devices. The thermodynamics of irreversible processes are described below using a practical approximation, which will be referred to in several of the examples to follow. Readers without special interest in the thermodynamic description may go lightly over the formulae (unless such readers are up for an exam!).

### 2.2 Irreversible thermodynamics

The degree of irreversibility is measured in terms of the rate of energy dissipation,

$$D = T \, dS/dt, \quad (2.5)$$

where  $dS/dt$  is the entropy production of the system while held at the constant temperature  $T$  (i.e.  $T$  may be thought of as the temperature of a large heat reservoir, with which the system is in contact). In order to describe the nature of the dissipation process, the concept of free energy may be introduced (cf. E.G. Callen, 1960).

The free energy of a system,  $G$ , is defined as the maximum work that can be drawn from the system under conditions where the exchange of work is the only interaction between the system and its surroundings. A system of this kind is said to be in thermodynamic equilibrium if its free energy is zero.

Consider now a system divided into two subsystems, a small one with extensive variables (i.e. variables proportional to the size of the system)  $U$ ,  $S$ ,  $V$ , etc. and a large one with intensive variables  $T_{ref}$ ,  $P_{ref}$  etc., which is initially in thermodynamic equilibrium. The terms “small system” and “large system” are meant to imply that the intensive variables of the large system (but not its extensive variables  $U_{ref}$ ,  $S_{ref}$  etc.) can be regarded as constant, regardless of the processes by which the entire system approaches equilibrium.

This implies that the intensive variables of the small system, which may not even be defined during the process, approach those of the large system when the combined system approaches equilibrium. The free energy, or maximum work, is found by considering a reversible process between the initial state and the equilibrium. It equals the difference between the initial internal energy,  $U_{init} = U + U_{ref}$ , and the final internal energy,  $U_{eq}$ , or it may be written (all in terms of initial state variables) as

$$G = U - T_{ref} S + P_{ref} V, \quad (2.6)$$

plus terms of the form  $\sum \mu_{i,ref} n_i$  if chemical reactions are involved, and similar generalisations in case of e.g. electromagnetic interactions.

If the entire system is closed, it develops spontaneously towards equilibrium through internal, irreversible processes, with a rate of free energy change

$$\frac{dG}{dt} = \frac{d}{dt}(U_{init} - U_{eq}(t)) = \left( \frac{\partial}{\partial S(t)} U_{eq}(t) \right) \frac{dS(t)}{dt},$$

assuming that the entropy is the only variable.  $S(t)$  is the entropy at time  $t$  of the entire system, and  $U_{eq}(t)$  is the internal energy that would be possessed by a hypothetical equilibrium state defined by the actual state variables at time  $t$ , that is  $S(t)$  etc. For any of these equilibrium states,  $\partial U_{eq}(t)/\partial S(t)$  equals  $T_{ref}$  according to (2.3), and by comparison with (2.5) it is seen that the rate of dissipation can be identified with the loss of free energy, as well as with the increase in entropy,

$$D = -dG/dt = T_{ref} dS(t)/dt. \quad (2.7)$$

For systems met in practice, there will often be constraints preventing the system from reaching the absolute equilibrium state of zero free energy. For instance, the small system considered above may be separated from the large one by walls keeping the volume  $V$  constant. In such cases the available free energy (i.e. the maximum amount of useful work that can be extracted) becomes the absolute amount of free energy, (2.6), minus the free energy of the relative equilibrium, which the combined system can be made to approach in the presence of the constraint. If the extensive variables in the constrained equilibrium state are denoted  $U^0$ ,  $S^0$ ,  $V^0$ , etc., then the available free energy becomes

$$\Delta G = (U - U^0) - T_{ref}(S - S^0) + P_{ref}(V - V^0), \quad (2.8)$$

eventually with the additions involving chemical potentials. In the form (2.6) or (2.8),  $G$  is called the Gibbs potential. If the small system is constrained by walls, so that the volume cannot be changed, the free energy reduces to the Helmholtz potential  $U - TS$ , and if the small system is constrained so that it is incapable of exchanging heat, the free energy reduces to the enthalpy  $H$ . The corresponding forms of (2.8) give the maximum work that can be obtained from a thermodynamic system with the given constraints.

A description of the course of an actual process as a function of time requires knowledge of "equations of motion" for the extensive variables, i.e. equations that relate the currents such as

$$\begin{aligned} J_s &= dS/dt \text{ (entropy flow rate) or } J_Q = dQ/dt \text{ (heat flow rate),} \\ J_m &= dm/dt \text{ (mass flow rate) or } J_\theta = d\theta/dt \text{ (angular velocity),} \\ J_q &= dq/dt = I \text{ (charge flow rate or electrical current), etc.} \end{aligned} \quad (2.9)$$

## 2. BASIC PRINCIPLES OF ENERGY CONVERSION

to the (generalised) forces of the system. As a first approximation, the relation between the currents and the forces may be taken as linear (Onsager, 1931),

$$J_i = \sum_j L_{ij} F_j. \quad (2.10)$$

The direction of each flow component is  $J_i / F_i$ . The arbitrariness in choosing the generalised forces is reduced by requiring, as did Onsager, that the dissipation be given by

$$D = -dG/dt = \sum_i J_i \cdot F_i. \quad (2.11)$$

Examples of the linear relationships (2.10) are Ohm's law, stating that the electric current  $J_q$  is proportional to the gradient of the electric potential ( $F_q \propto \text{grad } \phi$ ), and Fourier's law for heat conduction or diffusion, stating that the heat flow rate  $E^{\text{ens}} = J_Q$  is proportional to the gradient of the temperature.

Considering the isothermal expansion process required in the Carnot cycle (Fig. 2.1), heat must be flowing to the system at a rate  $J_Q = dQ/dt$ , with  $J_Q = LF_Q$  according to (2.10) in its simplest form. Using (2.11), the energy dissipation takes the form

$$D = T dS/dt = J_Q F_Q = L^{-1} J_Q^2.$$

For a finite time  $\Delta t$ , the entropy increase becomes

$$\Delta S = (dS/dt) \Delta t = (LT)^{-1} J_Q^2 \Delta t = (LT\Delta t)^{-1} (\Delta Q)^2,$$

so that in order to transfer a finite amount of heat  $\Delta Q$ , the product  $\Delta S \Delta t$  must equal the quantity  $(LT)^{-1} (\Delta Q)^2$ . In order that the process approaches reversibility, as the ideal Carnot cycle should,  $\Delta S$  must approach zero, which is seen to imply that  $\Delta t$  approaches infinity. This qualifies the statement made in the beginning of this subsection that, in order to go through a thermodynamic engine cycle in a finite time, one has to give up reversibility and accept a finite amount of energy dissipation and an efficiency that is smaller than the ideal one (2.4).

### 2.3 Efficiency of an energy conversion device

A schematic picture of an energy conversion device is shown in Fig. 2.2, sufficiently general to cover most types of converters in practical use (Angström, 1976; Osterle, 1964). There is a mass flow into the device and another one out from it, as well as an incoming and outgoing heat flow. The work output may be in the form of electric or rotating shaft power.

It may be assumed that the converter is in a steady state, implying that the incoming and outgoing mass flows are identical and that the entropy of

the device itself is constant, that is, that all entropy created is being carried away by the outgoing flows.

From the first law of thermodynamics, the power extracted,  $E$ , equals the net energy input,

$$E = J_{Q,in} - J_{Q,out} + J_m (w_{in} - w_{out}). \quad (2.12)$$

The magnitude of the currents is given by (2.9), and their conventional signs may be inferred from Fig. 2.2. The specific energy content of the incoming mass flow,  $w_{in}$ , and of the outgoing mass flow,  $w_{out}$ , are the sums of potential energy, kinetic energy and enthalpy. The significance of the enthalpy to represent the thermodynamic energy of a stationary flow is established by Bernoulli's theorem (Pippard, 1966). It states that for a stationary flow, if heat conduction can be neglected, the enthalpy is constant along a streamline. For the uniform mass flows assumed for the device in Fig. 2.2, the specific enthalpy,  $h$ , thus becomes a property of the flow, in analogy with the kinetic energy of motion and, for example, the geopotential energy,

$$w = w^{pot} + w^{kin} + h. \quad (2.13)$$

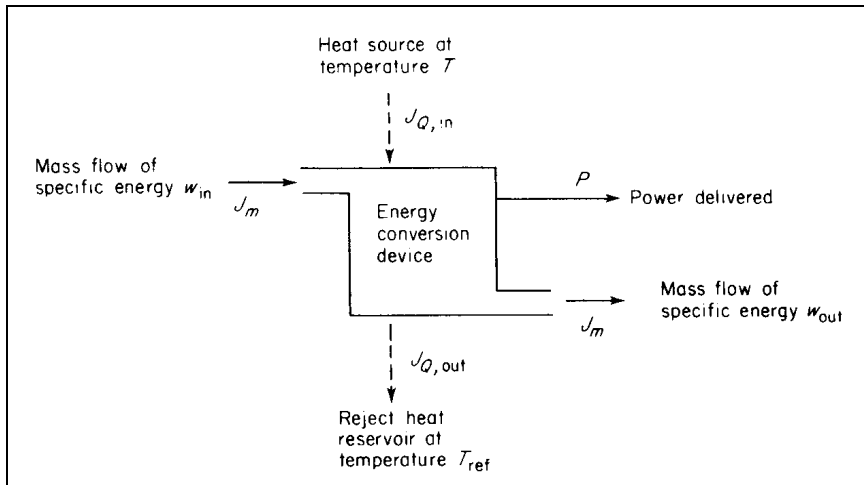


Figure 2.2. Schematic picture of an energy conversion device with a steady-state mass flow. The sign convention is different from the one used in (2.2), where all fluxes into the system were taken as positive.

The power output may be written

$$E = -J_\theta \cdot F_\theta - J_q \cdot F_q, \quad (2.14)$$

with the magnitude of currents given by (2.9) and the generalised forces given by



## 2. BASIC PRINCIPLES OF ENERGY CONVERSION

$$\begin{aligned} F_\theta &= \int \mathbf{r} \times d\mathbf{F}_{\text{mech}}(\mathbf{r}) & (\text{torque}), \\ F_q &= -\text{grad}(\phi) & (\text{electric field}) \end{aligned} \quad (2.15)$$

corresponding to a mechanical torque and an electric potential gradient. The rate of entropy creation, i.e. the rate of entropy increase in the surroundings of the conversion device (as mentioned, the entropy inside the device is constant in the steady-state model), is

$$dS/dt = (T_{\text{ref}})^{-1} J_{Q,\text{out}} - T^{-1} J_{Q,\text{in}} + J_m (s_{m,\text{out}} - s_{m,\text{in}}),$$

where  $s_{m,\text{in}}$  is the specific entropy of the mass (fluid, gas, etc.) flowing into the device, and  $s_{m,\text{out}}$  is the specific entropy of the outgoing mass flow.  $J_{Q,\text{out}}$  may be eliminated by use of (2.12), and the rate of dissipation obtained from (2.7),

$$\begin{aligned} D &= T_{\text{ref}} dS/dt = \\ &= J_{Q,\text{in}} (1 - T_{\text{ref}}/T) + J_m (w_{\text{in}} - w_{\text{out}} - T_{\text{ref}} (s_{m,\text{in}} - s_{m,\text{out}})) - E = \max(E) - E. \end{aligned} \quad (2.16)$$

The maximum possible work (obtained for  $dS/dt = 0$ ) is seen to consist of a Carnot term (closed cycle, i.e. no external flows) plus a term proportional to the mass flow. The dissipation (2.16) is brought in the Onsager form (2.11),

$$D = J_{Q,\text{in}} F_{Q,\text{in}} + J_m F_m + J_\theta \cdot F_\theta + J_q \cdot F_q, \quad (2.17)$$

by defining generalised forces

$$\begin{aligned} F_{Q,\text{in}} &= 1 - T_{\text{ref}}/T, \\ F_m &= w_{\text{in}} - w_{\text{out}} - T_{\text{ref}} (s_{m,\text{in}} - s_{m,\text{out}}) \end{aligned} \quad (2.18)$$

in addition to those of (2.15).

The efficiency with which the heat and mass flow into the device is converted to power is, in analogy to (2.4),

$$\eta = \frac{E}{J_{Q,\text{in}} + J_m w_{\text{in}}}, \quad (2.19)$$

where the expression (2.16) may be inserted for  $E$ . This efficiency is sometimes referred to as the “first law” efficiency, because it only deals with the amounts of energy input and output in the desired form and not with the “quality” of the energy input related to that of the energy output.

In order to include reference to the energy quality, in the sense of the second law of thermodynamics, account must be taken of the changes in entropy taking place in connection with the heat and mass flows through the conversion device. This is accomplished by the “second law” efficiency, which for power-generating devices is defined by

$$\eta^{(2.law)} = \frac{E}{\max(E)} = -\frac{\mathbf{J}_\theta \cdot \mathbf{F}_\theta + \mathbf{J}_q \cdot \mathbf{F}_q}{J_{Q,in} F_{Q,in} + J_m F_m}, \quad (2.20)$$

where the second expression is valid specifically for the device considered in Fig. 2.2, while the first expression is of general applicability, when  $\max(E)$  is taken as the maximum rate of work extraction permitted by the second law of thermodynamics. It should be noted that  $\max(E)$  depends not only on the system and the controlled energy inputs, but also on the state of the surroundings.

Conversion devices for which the desired energy form is not work may be treated in a way analogous to the example in Fig. 2.2. In the form (2.17), no distinction is made between input and output of the different energy forms. Taking, for example, electrical power as input (sign change), output may be obtained in the form of heat or in the form of a mass stream. The efficiency expressions (2.19) and (2.20) must be altered, placing the actual input terms in the denominator and the actual output terms in the numerator. If the desired output energy form is denoted  $W$ , the second law efficiency can be written in the general form

$$\eta^{(2.law)} = W / \max(W). \quad (2.21)$$

For conversion processes based on principles other than those considered in the thermodynamic description of phenomena, alternative efficiencies could be defined by (2.21), with  $\max(W)$  calculated under consideration of the non-thermodynamic types of constraints. In such cases, the name “second law efficiency” would have to be modified.