Chapter 3
Fundamentals of Energy Conversion

Abstract It is often taught in layman's terms that "energy may be neither created nor destroyed" and this brings into question the meaning of "energy conservation." Basic principles, such as energy conservation, stem from more general laws of Physics. The principles that govern the exchange and transformations of energy are succinctly examined in this chapter. The governing equations of energy conversion processes, or Laws of Thermodynamics, their corollaries and some of their applications to energy conversion processes are presented. A historical perspective is first given on the origins of modern energy conversion principles. The characteristics, significant variables/properties and types of Thermodynamic Systems are briefly explained. The two fundamental Laws of Thermodynamics (first and second) are postulated and the implications on the energy conversion processes are given succinctly. The operation of the simple gas and vapor power cycles is elucidated as well as several processes that are commonly used for the improvement of these cycles. Finally, the concept of exergy is introduced quantitatively and in detail. Based on exergy, several ways are presented on how this concept may be used to improve thermodynamic processes and cycles.

3.1 Origins of Thermodynamics and Historical Context

The development of the subject of Thermodynamics was the intellectual response to the technological advances that brought the Industrial Revolution in the mid eighteenth century. Following the invention of the steam engine that demonstrated the conversion of chemical energy through heat to mechanical power, the scientific and technical community of the nineteenth century developed the subject of Thermodynamics in order to understand and optimize the energy conversion processes and to better design heat engines.

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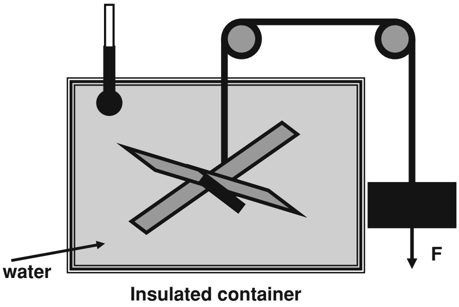
The concepts of work, heat and energy were not understood by scientists of the eighteenth century in the same way as they are today. Work was essentially motion and heat and motion were considered entirely different and, certainly, not equivalent. The seventeenth and eighteenth centuries are sometimes called the *Phlogiston Era* because the scientific community held the opinion that heat is not an energy form, but is a "weightless fluid." When this weightless fluid passed from one body to another it cooled the first and warmed the second. Thus, the direction of heat transfer or *heat flow* was established. In today's scientific and technical literature there are still reminders of the *Phlogiston Era*: Heat transfer is often described as *heat flow* and the potential of a substance to store thermal energy (internal energy or enthalpy) is called *specific heat capacity* (either at constant pressure or at constant volume) in analogy to the capacity of a vessel to hold a liquid.

Because of the preconception that heat is a weightless fluid, the establishment of the heat-work equivalency and the development of the First Law of Thermodynamics took a very torturous path. Benjamin Thomson was probably the first scientist to demonstrate experimentally the conversion of what we now call "work" to "heat," and, thus, establish the roots of what we now call *the first law of Thermodynamics.* An American who supported the British forces during the Revolutionary War, Colonel Thomson was forced to leave the United States and was hired by the Duke (later King) of Bavaria. He managed to excel in the service of the King of Bavaria during the early Napoleonic Wars and was awarded the title of Count Rumford of Munich. He devised a public demonstration for the production of a significant amount of heat by friction and demonstrated to the public the conversion of "motion" to heat: In 1799 he used friction belts and converted the power of four horses careening in a circular path to raise the temperature of water in a metallic vessel. He continued the experiment until the water boiled. Count Rumford's experiment is the first recorded instance when work or motion was converted to heat in a controlled experiment. However, he was considered a charlatan by the scientific community, because he performed his experiments in public, did not take any measurements and did not try to combine his empirical demonstrations with even a rudimentary analysis or property measurements. For this reason, his demonstrations were largely neglected by the mainstream scientists of the early nineteenth century.

The conversion of the chemical energy, stored in the food to motion (or, equivalently, to work) was documented by an Alsatian physician, Dr. Robert Meyer. While serving as a ship doctor in the tropics, Dr. Meyer observed that the blood of the European sailors had a brighter red color than that of the natives. He attributed this difference to higher amounts of hemoglobin produced by the organs of these sailors. The hemoglobin is the "food" of the muscles since it transfers oxygen to the muscles that produce motion and, thus, work and mechanical power. Based on his observations, in 1822, he promulgated the theory that the chemical energy in the food is converted to chemical compounds that flow in the blood, and, finally, produce the muscle power. In effect, he established the equivalency of chemical energy and the ability to produce work, which is considered now one of the cornerstones of the

Fig. 3.1 Schematic diagram of Joules experiment



modern theory of Thermodynamics. It is rather unfortunate, that the established scientific community of the early nineteenth century was stuck with the Phlogiston theory and vehemently rejected Dr. Meyer's ideas. This drove him to commit suicide.

Thomas Prescott Joule was a professor at the University of Manchester and a well known academician when he performed the definitive experiment that demonstrated the equivalency of work and heat, in 1848. The experimental apparatus he used is shown schematically in Fig. 3.1. A closed and well insulated vessel contains a constant mass of water with a thermometer and a paddle wheel is inside the vessel. The paddle wheel is driven by a mechanism, which is powered by a falling weight. The energy of the falling weight is dissipated by friction in the water. Joule demonstrated that the mechanical power generated by the falling weight caused an increase in the temperature of the water and, thus, the mechanical energy was converted into heat, which resulted in the increased temperature. Joule's meticulous experiment and accurate measurements not only established the equivalency of work and heat, but also helped calculate with high accuracy the conversion factor of 1 calorie being equal to 4.184 units of energy that are now called "Joule." Joule's experiment was definitive and brought an end to the Phlogiston era. Even though several scientists of the middle and late nineteenth century stuck to the idea of heat as a weightless fluid (Lord Kelvin was one of the late converters) the experimental evidence in support of the heat-work-energy equivalency became overwhelming and the statement of this equivalency resulted in the formulation of the First Law of Thermodynamics.

Sadi Carnot[1] is considered the discoverer of the Second Law of Thermodynamics, which is a central principle for the conversion of heat into work. In his short memoir "On the motive power of heat…" published in 1824, Carnot stipulated that there are limits to the conversion of a quantity of heat into work.

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[1] Sadi Carnot (1796–1832) was the fourth child of Lazare Carnot, a colleague and General of Napoleon, who was in charge of logistics during the early Napoleonic Wars and a member of the first Directorate. The father Carnot, a scientist in his own merit, contributed to the discipline of Mechanics and was often called "savant." Almost every city in the francophone world, including several in the United States, has a street or avenue named "Carnot," to honor Lazare Carnot (not Sadi). Other offspring of the same family became prominent statesmen in France.

His student, Clapeyron, wrote several commentaries on Sadi Carnot's work that emphasized the limitations of heat to work conversion. Later in the nineteenth century, Rudolf Clausius, William Thompson (Lord Kelvin) and Max Plank developed the several corollaries and implications of the 2nd Law on the property entropy and on the energy conversion processes. It must be noted that what is now called 2nd Law of Thermodynamics was formulated earlier and was more readily accepted than the 1st Law. The reasons for this acceptance are that the Law did not conflict with any pre-existing concepts and theories (e.g. heat is a weightless fluid) and that those who promulgated this principle (Carnot, Clapeyron and Clausius) were accomplished scientists, well known for their rigorous work, accurate measurements and came with excellent scientific credentials.

3.2 Fundamental Concepts of Thermodynamics

The concept of the *Thermodynamic system* (or simply *System*) is central to the understanding of the theory of Thermodynamics. The Thermodynamic System is enclosed by a *Boundary* and outside the boundary are the *Surroundings*. The latter is the part of the Universe that is affected by changes in the Thermodynamic System. Thermodynamic systems are *closed* or *open* Systems. The two types of systems are depicted in Fig. 3.2. Closed systems contain a fixed amount of molecules (and mass), while open systems have inlets and exits through which mass is allowed to flow. If the sums of the mass flow rates at the inlets and the exits are equal, the open system is at *steady state*. Otherwise it is *unsteady* or *transient*. Both closed and open systems receive or supply work and heat. In the case of closed systems we are usually interested in the total work and heat, $\dot{W}$ and $\dot{Q}$, while in the open systems we perform calculations based on the instantaneous rates of work and heat, $\dot{W}$ and $\dot{Q}$ as well as the mass flow rates that enter and leave the system.

The vast majority of energy conversion machinery is open systems: Pumps, boilers, turbines, compressors, nozzles and heat exchangers are all open systems. At typical operating conditions all these devices operate as open systems at steady state. Cylinders fitted with pistons are typical examples of closed systems.

The *properties* of the Thermodynamic system are all the measurable variables associated with that system. Temperature, pressure, volume, enthalpy, entropy, electrical conductivity, viscosity are typical examples of Thermodynamic properties. When the properties of a System do not change with time, the system is considered to be in *Thermodynamic Equilibrium*. Thermodynamic properties of systems at equilibrium may be measured, calculated via *Equations of State*, or computed from *Thermodynamic Tables*. For homogeneous substances (substances that have only one molecular composition) two independent properties are sufficient for the determination of all the other properties. The *Equations of State* are algebraic equations that give one property in terms of two other measurable properties, as for example with the ideal gas equation of state, $Pv = RT$. When a simple equation may not be adequate for the accurate determination of properties,

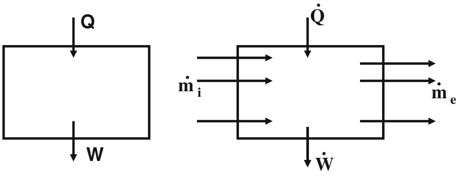


Fig. 3.2 Closed and open thermodynamic systems

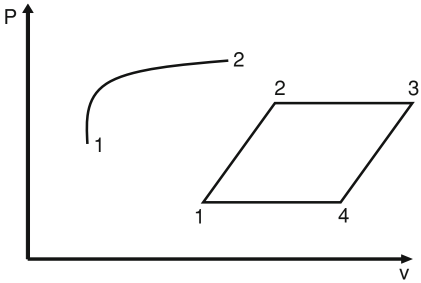


Fig. 3.3 A process, 1–2, and a cycle, 1–2–3–4, depicted on a P,v diagram

the latter are calculated by numerical computations and listed in Thermodynamic Tables. Such Tables for water/steam, refrigerants and several commonly used substances are routinely included in standard books of Thermodynamics.

The *State* is a fundamental concept of thermodynamics and is simply defined as the set of its properties. When the properties change, the state of the system changes and the system undergoes a *process*. The concept of the thermodynamic process is central to energy conversion. Processes take place within a finite amount of time. The system's properties change during a process as a response to the external changes imposed by the process. When the timescale of the change of the properties of the system is much lower than the characteristic time of the process, $\tau_{\text{system}} \ll \tau_{\text{process}}$, the system responds almost spontaneously to the imposed changes and the process is called *reversible*. Otherwise, the process is *irreversible*.

Processes are usually depicted in Thermodynamic diagrams, such as the pressure–volume (P,v) diagram, which is shown in Fig. 3.3. As a result of the details of a process the thermodynamic system may produce, absorb or reject work and heat. For example, a turbine produces work, a pump absorbs/consumes work, a boiler/burner produces heat by burning a fuel and a condenser rejects heat to the cooling system. Since the objective of the subject of Thermodynamics is the determination of the work and heat associated with processes that take place in a system, the understanding and good description of processes is of paramount importance. A combination of several processes, where the end point of the last process coincides with the starting point of the first, constitutes a *thermodynamic cycle* as depicted in Fig. 3.3. Thermodynamic cycles are routinely used for the production of electric power in thermal power plants as well as in engines that are used for propulsion and transportation (diesel, gasoline and jet engines). When the Thermodynamic cycles use an evaporating liquid/vapor fluid they are called *vapor cycles* and when they use a gas (ideal or real) they are called *gas cycles*.

3.3 Work, Heat and Energy

Work, heat and energy are considered three different forms of the layman's concept that is commonly referred to as *energy*. The three forms are measured by the same units, and each form may be transformed to one of the others. During these transformations the total *energy* is conserved.

3.3.1 Work

The concept of work is a primitive idea in the discipline of Mechanics and is associated with the concept of a force: A force performs work when its point of application moves. The amount of work done when the force moves by a distance described by the end points 1 and 2 is:

$$W_{12} = \int_1^2 \vec{F} \bullet d\vec{x}. \tag{3.1}$$

Work is a scalar and depends on the path followed between points 1 and 2. For a compressible substance enclosed in a cylinder that is fitted with a piston, this force is the external force acting on the piston. When the process 1-2 is reversible, the external force is equal to the product of the internal pressure and the area of the piston ($F_{ext} = PA$). Under these conditions, the last equation yields an expression of the work in terms of the two properties of the enclosed compressible substance, pressure, P, and volume, V:

$$W_{12} = \int_1^2 PdV. \tag{3.2}$$

A glance at Eq. (3.2) proves that the work depends on the process 1–2 and, therefore, it does not correspond to a potential function. The amount of work performed by a compressible substance, such as a gas or a vapor, during several commonly performed processes is given by one of the following expressions:

$$\begin{aligned}
&\textit{isobaric (constant pressure) process}: W_{12} = P(V_2 - V_1)\\
&\textit{isothermal (constant temperature) process, ideal gas}:\\
&W_{12} = mRTln(V_2/V_1) = mRTln(P_1/P_2)\\
&\textit{polytropic process } (PV^n = const): W_{12} = \frac{P_1V_1 - P_2V_2}{n-1} = m\frac{P_1v_1 - P_2v_2}{n-1}\\
&\textit{isochoric process (constant volume) process}: W_{12} = 0.
\end{aligned} \tag{3.3}$$

In the above expressions, m is the mass of the compressible substance that performs the work, R is the gas constant, $R = \tilde{R}/M$, and n is the *polytropic index*, a constant of the process, typically in the range 1–1.67.

3.3.2 Heat

Heat is transferred from an object at higher temperature to an object at a lower temperature. Thus, the prerequisite for the transfer of heat is a temperature difference, regardless of how low this difference may be. The transfer of heat takes place by one of the following transfer modes:

A. *Conduction*: Conduction occurs when a temperature gradient exists. The rate of heat conducted through an area A is given by the expression:

$$\dot{Q} = -kA\frac{dT}{dx}, \tag{3.4}$$

where k is the *thermal conductivity*, a property of the materials. The negative sign in the r.h.s of the last expression signifies that heat is transferred from the high-temperature part to the lower temperature part of the material.

B. *Convection*: Convection is caused by the motion of at least one fluid, which may pick or dissipate heat at a solid surface. *Forced convection* occurs when a fluid is pumped or blown by mechanical means with the purpose of causing heat to be transferred, as in the case of car radiators, where colder air is blown by the fan over a heat exchanger surface in order to cool the interior coolant. *Natural convection* occurs without mechanical forcing by the density difference, which is caused when a fluid's temperature changes. For example, an ice cube floating in a glass of warm water cools the water around it. Since the colder water around the ice cube has a higher density, it will sink into the glass. Thus, the colder ice cube creates a flow, which may be imperceptible to the naked eye, but nevertheless contributes significantly to the transfer of heat and to the melting of the ice cube. The rate of heat transferred by forced or natural convection from a solid object with an area A, which is at temperature T_H, to a fluid at temperature T_L is:

$$\dot{Q} = -hA(T_H - T_L) \tag{3.5}$$

where the coefficient h is the convective coefficient. This variable is a function of the flow conditions as well as of the properties of the fluid. The negative sign, again, signifies that the heat is transferred *from* the solid object at temperature T_H *to* the fluid at temperature T_L.

C. *Radiation*: Material contact is not necessary for the heat transfer by radiation. Radiation may pass through vacuum, fluids, and even some solids. The Sun heats the Earth by radiation to provide solar energy. Similarly, the Earth transfers heat to the rest of the Universe by radiation. Incoming radiation may be absorbed or reflected by an object, which emits radiation to all the other bodies around it by the same mechanism. The rate of total heat absorbed by radiation by an object at temperature T_L from another at temperature $\mathrm{T_H}$ is given by the expression:

$$\dot{Q} = \sigma A F_{HL} \varepsilon \left(T_H^4 - T_L^4 \right), \tag{3.6}$$

where σ is the Stefan-Boltzmann constant, $5.67*10^{-8}$ $\mathrm{W/m^2K^4}$; A is the surface area of the object at absolute temperature T_L; F_{HL} is a geometric factor that is related to the area the two bodies “see” through straight radiation rays; and ε is the emissivity of the surface of the same object, an empirical factor that characterizes surfaces.

3.3.3 Sign Convention

As it happens with the work performed during a process, the heat transfer also depends on the process and does not correspond to a potential function. The actual values of both the work and heat transfer are determined from the consideration and analysis of the underlying process. The scientific community has adopted a sign convention for the quantities of work and heat exchanged by a thermodynamic system for all processes, which is as follows:

- A quantity of work is positive when it is produced by a thermodynamic system and negative when it is absorbed by the system.
- A quantity of heat is positive when it enters the system and negative when it leaves the system.

Figure 3.4 illustrates schematically this scientific sign convention for the heat and work exchanged by a Thermodynamic system. The algebraic sign of the quantities of heat and work that enter or leave a Thermodynamic system are clearly shown in this figure.

3.4 The First Law of Thermodynamics: Energy Balance

The First Law of Thermodynamics is one of the fundamental and most general principles of science. It defines what is commonly referred to as the *energy conservation principle.* There are several formulations of the First Law, which are pertinent to the various types of systems and processes used. All formulations may be summarized by the general expression of energy conservation: *energy is neither created nor destroyed. It may only be transformed from one form to another.*

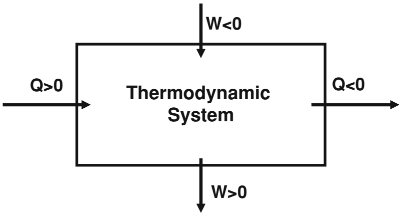


Fig. 3.4 Scientific convention for the algebraic signs of work and heat

3.4.1 Closed Systems

For a closed Thermodynamic system, the energy balance is best given in terms of a process leading from state 1 to state 2 and may be stated as follows: The heat entering a closed system minus the work produced by this system during a process 1–2 is equal to the difference of the total energy of the system between these two states. This energy conservation law is depicted schematically in Fig. 3.5. In symbolic form we may write:

$$Q_{12} - W_{12} = E_2 - E_1, \tag{3.7}$$

where the total energy of the system E is defined as the sum of the internal energy, U, the potential energy, mgz, the kinetic energy, 1/2 mV^2, and any other forms of energy the system may possess, and which may be described by potential functions as for example, electric charge energy, magnetic energy, surface tension energy, elastic energy, etc. Thus:

$$E_2 - E_1 = (U_2 - U_1) + \frac{1}{2}m\left(V_2^2 - V_1^2\right) + mg(z_2 - z_1) + \ldots \tag{3.8}$$

It must be noted that the symbol V (in italic) denotes the velocity, while the symbol V denotes the volume and v the specific volume. For most terrestrial thermal systems, the internal energy difference is typically very large and by far exceeds the changes in kinetic, potential and any other form of energy the system may possess. For example, when 10 kg of water boil to produce steam the internal energy change is 20,880,000 J. The same mass of water would gain approximately 1,000 J if it were raised to a height of 100 m; or 50,000 J if it were accelerated from rest to 100 m/s (or 360 km/hr or 225 mph). For this reason, one may approximate Eq. (3.8) in terms of the internal energy and the specific internal energy, u, as follows:

$$Q_{12} - W_{12} = U_2 - U_1 = m(u_2 - u_1), \tag{3.9}$$

The specific internal energy difference $u_2 - u_1$ is typically obtained from thermodynamic tables or by using a closure equation with the specific heat capacity at constant volume, e.g. $u_2 - u_1 = c_v(T_2 - T_1)$. Most of the engineering thermodynamics textbooks include thermodynamic tables as well as the numerical values for the specific heats for commonly used materials, such as steam, gases,

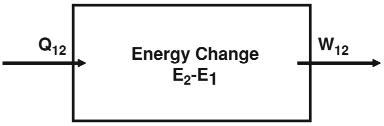


Fig. 3.5 The first law of thermodynamics as an energy balance

refrigerants and several hydrocarbons. Alternatively, one may obtain these properties from software.

The first part of Eq. (3.9) simply states that, for a closed system undergoing a process 1–2, the energy entering the system in the form of heat minus the energy exiting the system in the form of work is equal to the total energy change of the system.

3.4.2 Cyclic Systems

Thermodynamic systems undergoing a series of processes that constitute a cycle, as in Fig. 3.3 are commonly used for the production of power in thermal power plants, and in most of the engines used in the transportation industry. Let us visualize a thermodynamic system undergoing a series of n processes, 1–2, 2–3, 3–4, …, n − 1, where the last process, n − 1, ends at the initial state of the system. One may write the first law of thermodynamics (Eq. 3.1) for each one of the n processes and add the resulting n equations to obtain the following expression:

$$\begin{aligned} Q_{12} - W_{12} + Q_{23} - W_{23} + \cdots + Q_{n1} - W_{n1} &= \\ U_2 - U_1 + U_3 - U_2 + \cdots + U_1 - U_n &= 0. \end{aligned} \tag{3.10}$$

A glance at Eq. (3.10) proves that the left hand side represents the difference of the net heat entering the system and the net work produced by system during the cycle 1-2-3.…n-1. The r.h.s of this equation is equal to zero. Therefore, Eq. (3.10) may be written more succinctly as follows:

$$Q_{net} = W_{net}, \tag{3.11}$$

or, the net amount of heat that enters a cyclic thermodynamic engine is equal to the net amount of work performed by this engine. This is another expression of the law of conservation of energy as applied to cyclic systems.

Example 3.1: 0.1 kg of air, enclosed in a cylinder is compressed by a piston during a polytropic process from 1 bar, 300 K to 7 bar. The polytropic index during this process is n = 1.3. Determine the work performed and the heat transfer during this process.

Solution: The air enclosed in the piston-cylinder assembly constitutes a closed system. Under these conditions, air may be approximated as an ideal gas, with a gas constant $R = 0.287$ kJ/kg K and $c_v = 0.719$ kJ/kg K.

Step 1—*determine the properties of the air at states* 1 *and* 2: From the ideal gas equation, $Pv = RT$, $v_1 = 0.861$ m^3/kg and from the polytropic relationship, which applies to the entire process including both states 1 and 2 one obtains: $P_1 v_1^{1.3} = P_2 v_2^{1.3}$. This yields $v_2 = 0.193$ m^3/kg and applying again the ideal gas equation $Pv = RT$ for state 2, $T_2 = 470.7$ K.
Step 2—*determine the amount of work*: Substitute in the third part of Eq. (3.3) for the polytropic process 1–2, the values for these properties to obtain: $W_{12} = -16.3$ kJ. The negative sign signifies that the system receives work (or the piston does work to the gas).
*Step*3—*determine the amount of heat*: From Eq. (3.9) $Q_{12} = W_{12} + m(u_2\text{-}u_1)$ and since air is an ideal gas $(u_2\text{-}u_1) = c_v(T_2\ \text{-}T_1)$. Therefore, $Q_{12} = W_{12} + m\ c_v\ (T_2 - T_1)$ and upon substitution, $Q_{12} = -4.05$ kJ. The negative sign signifies that the system (air) transfers heat to the surroundings.

3.4.3 Open Systems

Mass flow rates cross the boundaries of open systems, which typically have several inlets and exits. At the same time, a net rate of heat enters the system and a net rate of work, that is power, is produced by the system. The conservation equations for the open systems are described in terms of rates, which are typically denoted by a dot (.) above the symbol of the corresponding variable. The laws of mass and energy conservation apply to open systems. For the typical open system depicted in Fig. 3.2 the mass conservation law may be written as follows:

$$\frac{dm}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e, \tag{3.12}$$

where *i* denotes the inlets and *e* the exits of the system. The last equation may be interpreted as: the rate of increase of the mass in the open system (or the rate of mass accumulation) is equal to the difference of the mass flow rates that enter the system minus the mass flow rates that exit the system. When an open system operates at steady state, there is no accumulation of mass. Thus, for open systems at steady state the mass conservation equation stipulates that the sum of the mass flow rates entering the open system equals to the sum of the mass flow rates that exit the system. For simple, steady-state open systems with only one entrance and one exit, such as pumps, compressors, turbines, nozzles, etc., the mass conservation equation simplifies to the following expression:

$$\dot{m}_i = \dot{m}_e = \dot{m}. \tag{3.13}$$

For the development of the energy conservation equation, one should take into account that the effluent masses, which enter and exit an open system, perform a certain amount of work (called *the atmospheric* or *boundary work*) by flowing against the pertinent pressures at the inlets and outlets, which are denoted as P_i and

P_e. This work is incorporated as an addition to the property of internal energy u, which produces a similar property, the enthalpy: $h = u + Pv$. At steady state, the energy conservation law for an open system may be written in terms of the thermal and mechanical power exchanges by the system as follows:

$$\dot{Q} - \dot{W} = \sum_e \dot{m}_e h_e^o - \sum_i \dot{m}_i h_i^o, \tag{3.14}$$

where the property of specific total enthalpy, h^o (that is total enthalpy per unit mass) incorporates the specific enthalpy, h, as well as all the other potential forms of energy that are present in the specific total energy, e, or

$$\dot{Q} - \dot{W} = \sum_e \dot{m}_e \left(h_e + \frac{1}{2} V_e^2 + gz_e + \right) \ldots - \sum_i \dot{m}_i \left(h_i + \frac{1}{2} V_i^2 + gz_i + \ldots \right). \tag{3.15}$$

Since the *atmospheric* or *boundary work* has been taken into account in the property of enthalpy, the power, W, that appears in the above two expressions pertains only to the *useful power* that the system produces or absorbs. The useful power is power that may be used for the fulfillment of a task or a process. Of the systems that are routinely used in the power production industry, only pumps, compressors and turbines produce or consume useful power. For all the other open systems $\dot{W} = 0$.

For typical thermal systems, and as in the case of the closed systems that resulted in Eq. (3.9), the enthalpy changes are by far more significant than the changes in the other forms of energy. Hence, for typical open systems, such as pumps, turbines, compressors, heat exchangers, etc. the first law of thermodynamics at steady state may be simply written as:

$$\dot{Q} - \dot{W} = \sum_e \dot{m}_e h_e - \sum_i \dot{m}_i h_i. \tag{3.16}$$

For open thermodynamic systems at steady state with a single inlet and a single outlet, such as pumps, most turbines and compressors, Eq. (3.16) simplifies to the following:

$$\dot{Q} - \dot{W} = \dot{m}(h_e - h_i). \tag{3.17}$$

It must be noted that the first law of thermodynamics is applicable to open systems with chemical changes, such as burners and combustors. When chemical reactions are involved, a useful quantity is the heat of the reaction, or heat of combustion, which is expressed as enthalpy change per kg of the fuel, Δh, or as enthalpy change per kmol of the fuel, $\Delta\tilde{h}$. This enthalpy change is often called the *heating value* of the fuel. Burners and combustors do not produce or consume power. Hence, $\dot{W} = 0$ and the first law of thermodynamics may be used in the following simplified form to calculate the rate of heat released in the open system (combustor, boiler, burner, etc.) where a chemical reaction takes place:

$$\dot{Q} = \dot{m}\Delta h = \dot{n}\Delta\tilde{h}. \tag{3.18}$$

Nozzles and diffusers are the most commonly used thermodynamic systems in the power industry, where kinetic energy changes are significant enough to be accounted for in the energy balance equation. Both diffusers and nozzles do not consume or produce useful work (as mentioned above only pumps, turbines and compressors do so). Because fluids move very fast through these devises, the fluid properties are not influenced significantly by the, relatively slow, rate of heat transfer. Processes in nozzles and diffusers are usually approximated as adiabatic processes and, hence, it is assumed that the heat transfer during these processes is zero. Thus, for nozzles and diffusers, which always have one inlet and one outlet, one may simplify Eq. (3.15) to obtain:

$$V_e^2 - V_i^2 = \sqrt{2(h_i - h_e)} \tag{3.19}$$

In the numerical implementation of the last equation, care must be taken to use the appropriate units. For example, in the S.I. one must use J/kg for the specific enthalpy in order to calculate the velocity in m/s. Since, in most thermodynamic expressions, the specific enthalpy is given in units of kJ/kg, one must multiply the values obtained from the tables by the factor 1,000 J/kJ. Other conversion factors also apply in the English System of units.

Example 3.2: A small steam turbine admits 5 kg/s of steam at 10 bar, 360°C and exhausts saturated steam at 45°C. The turbine transfers 8.5 kW of heat to the surroundings. Determine the power produced by the turbine.

Solution: The turbine is an open thermodynamic system with a single inlet and a single outlet operating at steady state. The working fluid is steam.

Step 1—*determine the properties at the entrance and exit*: From the Steam Tables, $h_i = 3{,}178.9$ kJ/kg and $h_e = 2{,}583.2$ kJ/kg.

Step 2—*determine the power:* The algebraic value of the rate of heat is −8.5 kW, because heat leaves this open system. Using Eq. (3.17), $\dot{W} = \dot{Q} + \dot{m}\left(h_i - h_e\right)$, and substituting the enthalpy and mass flow rate values one obtains: $\dot{W} = 2,970\text{kW}$. The positive value signifies that power is produced by the turbine.

One observes in this example that the rate of heat loss is a very small fraction of the power produced by the turbine. This is typical of turbines and, for this reason, the typical turbine operation is often approximated as adiabatic $(\dot{Q} = 0)$.

Example 3.3: An adiabatic engine compresses 6 kg/s of helium from 1 bar, 300 K to 8 bar. During this process the temperature of helium rises to 753 K. Determine the power consumed by the compressor.

Solution: The compressor is an open system with a single inlet and outlet. Since it is also adiabatic, the rate of heat is 0. Helium is an ideal gas with $c_P = 2.5$ kJ/kg K.

Step 1—*Determine the enthalpy difference:* Because helium is an ideal gas, the change of the enthalpy of helium may be obtained from the temperature difference and the specific heat at constant pressure: $h_2 - h_1 = c_p(T_2 - T_1)$.

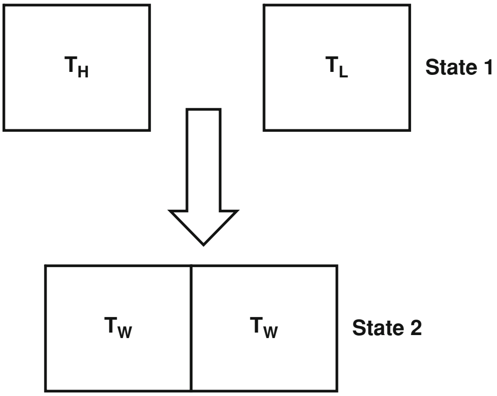
Step 2—determine the power: From Eq. (3.17) with $\dot{Q} = 0 : \dot{W} = \dot{m}c_P(T_i - T_e)$. Hence, $\dot{W} = -6,795\text{kW}$. The negative sign signifies that power is consumed by the compressor. Compressors usually get power (are driven) from electric motors.
Example 3.4: A nozzle admits 0.7 kg/s of steam at 5 bar, 400°C with a velocity 46 m/s and exhausts at 3 bar and 360°C. The rate of heat transfer from the nozzle is measured as 0.9 kW. Determine the exit velocity of the steam.
Solution: The nozzle is an open system with a single inlet and a single outlet. Nozzles do not produce or absorb power and, hence, $\dot{W} = 0$. The rate of heat output is negative, that is, $\dot{Q} = -0.9\text{kW}$.
Step 1*—determine the properties at the entrance and exit:* From Steam Tables we obtain: $h_i = 3{,}271.9$ kJ/kg and $h_e = 3{,}192.2$ kJ/kg.
Step 2—determine the exit velocity using the First Law: Using Eq. (3.15), which includes velocities, with one inlet and one outlet, one obtains the expression:
$V_e = \sqrt{2(h_i - h_e) + 2\dot{Q}/\dot{m} + V_i^2}$. Upon substitution of all the variables and conversion of the units from kJ/kg to J/kg—the square root of J/kg is equivalent to m/s—one obtains: $V_e = 399.6$ m/s.

It must be noted that the finite rate of heat transfer only makes a marginal difference in the final answer of this problem. If one neglects the heat transfer and assumes that the nozzle operates adiabatically, Eq. 3.19 yields: $V_e = 401.9$ m/s. The difference between the two values of the exit velocity is less than 0.5%.

3.5 The Second Law of Thermodynamics

It has always been observed that all natural processes have a directionality, that is they only proceed in one way: if left unsupported, an apple will always fall down and will not rise, a billiards ball will finally stop at a position on the table, fluids will flow from a higher pressure to a lower pressure and heat will be transferred from a hotter to a colder body. When these processes end, it is not possible to reverse them *spontaneously,* that is without spending work for the reversal. For example, if we allow two bodies one at high temperature, T_H, and the other at lower temperature, T_L, to come to thermal equilibrium, finally they will both assume a common temperature T_W, which is between the two original temperatures, $T_L < T_W < T_H$, as it is depicted in Fig. 3.6. During this process, from state 1 to state 2, the total internal energy that was originally contained in the two bodies, has been conserved, that is the total energy at state 1 is equal to the total energy at state 2. Now, if we wish to restore the two bodies to their original temperatures, T_H and T_L, we will soon find out that this cannot be done without the use of a refrigeration devise, which consumes work. Hence, despite of the fact that the energy of state 2 is equal to that of state 1, the process 2–1 is impossible without the addition of work. Similarly, if we wish to restore the apple that has fallen from a higher level 1 to a lower level 2, we must also perform work by lifting it back to its original level.

Fig. 3.6 The heat transfer process 1–2 that brought the two bodies to thermal equilibrium may not be reversed without the expense of work



The Second Law of Thermodynamics explains the directionality of all natural processes, by defining the property *entropy*, which increases in all natural processes undergone by all adiabatic systems. The Second Law may be expressed more generally by the following two simple statements:

1. There is a property of every system, entropy, which is defined as:

$$dS = \frac{dQ^O}{T} \Rightarrow S_2 - S_1 = \int_1^2 \frac{dQ^O}{T}. \tag{3.20}$$

2. For all natural process 1–2 occurring in adiabatic systems, that is systems with zero heat transfer to their surroundings:

$$S_2 - S_1 > 0. \tag{3.21}$$

The superscript “0” in the differential of heat denotes that this integral must be calculated during a *reversible* process. Although such processes are idealized processes, according to standard procedures of the theory of Thermodynamics, one may express the differential dQ^0 in terms of the system’s properties (e.g. for a system containing a compressible substance $dQ^0 = dU + PdV$) and then carry the integration process using only the system’s properties. The inequality (>) sign in Eq. (3.21) points out to the directionality of the natural processes: Any thermodynamic system is part of a (usually greater) adiabatic system. All thermodynamic systems that undergo processes would always proceed to a direction where the entropy of the adiabatic system increases. Since the Universe as a whole is considered to be adiabatic, the Second Law is sometimes expressed by the statement: *the entropy of the Universe tends to a maximum.*[2]

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[2] This statement is often attributed to Rudolf Clausius who also coined the term “entropy”.

Regarding the last inequality, it must be noted that there is not an, *a priory* established limit on how low or high the entropy change may be or should be. Processes where the entropy change is low and approaches zero are usually idealized as processes of constant entropy or *isentropic processes.* In all the other processes, the change in entropy is significant, e.g. in isothermal or isobaric processes.

3.5.1 Implications of the Second Law on Energy Conversion Systems and Processes

The most important implication of the Second Law on the subject of energy conversion is that work may not be produced spontaneously by a cyclic engine, when this engine receives heat from a single heat reservoir.[3] As a consequence of the Second Law, a cyclic engine—most power plants, gas turbines, jet and car engines are all cyclic engines—must be in contact with another heat reservoir where it rejects heat. Figure 3.7 shows a schematic diagram of the operation of the cyclic engines. During a cycle, the engine receives heat Q_H, rejects heat Q_L, and produces net work, $W = Q_H - Q_L$. Typically, the heat is rejected in the atmosphere (gas turbines, jet and car engine exhausts) or the hydrosphere (large steam power plants) and contributes to the *thermal pollution.*

A second consequence of the Second Law is that the thermal efficiency of such a cyclic engine may not exceed the *Carnot efficiency*, η_C:

$$\eta = \frac{W}{Q_H} \leq 1 - \frac{T_H}{T_L} = \eta_C. \tag{3.22}$$

Typical thermal efficiencies of fossil fuel thermal power cycles are close to 40% and typical efficiencies of nuclear power cycles are close to 33%. This implies that a coal power plant, which produces 400 MW of electric power, must use approximately 1,000 MW of heat and rejects 600 MW of heat, usually to a river or a lake. For a typical nuclear power plant that produces close to 1,000 MW of electric power, the heat produced in the reactor is close to 3,000 MW and the amount of heat rejected is 2,000 MW. It is apparent, that the most important consequence of the Second Law of Thermodynamics is that, even though heat may be readily converted to work or power, it is only a fraction of the heat that is actually converted in today's thermal engines. The rest of this form of energy must be rejected to the environment as low temperature heat and becomes the *waste heat*.

In addition to the cycle thermal efficiencies, we also define *component efficiencies*, for turbines, compressors and pumps. The component efficiencies are

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[3] This statement is attributed to Lord Kelvin and Max Plank.

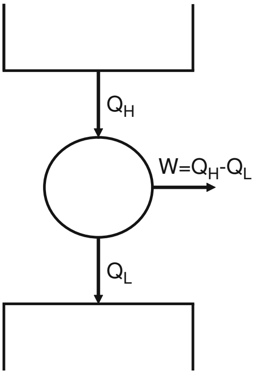

Fig. 3.7 The operation of a cyclic engine connected to two heat reservoirs

defined as ratios of the actual work, W_{act}, produced by the component and the isentropic work, W_s, which is achieved during the isentropic operation of the component. The component efficiencies are defined in a way that their numerical values are between 0 and 1 and are often given in percentages. For turbines, compressors and pumps these component efficiencies are respectively defined as follows:

$$\eta_T = \frac{W_{act}}{W_s}, \quad \eta_C = \frac{W_s}{W_{act}}, \quad \eta_P = \frac{W_s}{W_{act}}. \tag{3.23}$$

Typical turbine efficiencies are in the range 75–88%; compressor efficiencies are in the range 70–85%; and pump efficiencies in the range 70–80%. In practice, the component efficiency charts are supplied by the manufacturers of the equipment. In typical calculations, an engineer first calculates the isentropic work, W_s, from the theory of Thermodynamics using the First and Second Laws and then calculates the actual work, W_{act}, using the pertinent expression of Eq. (3.23).

3.6 Thermal Power Plants

The vast majority of the currently used thermal power plants utilize two main types of cycles: vapor and gas cycles. A succinct description of the essential components of these types of cycles will follow. Practical methods and processes for the improvement of the thermal efficiency of the cycles will also be discussed. For a more detailed description of the cycles one is encouraged to read a book on Engineering Thermodynamics, such as the one by Moran and Shapiro [1].

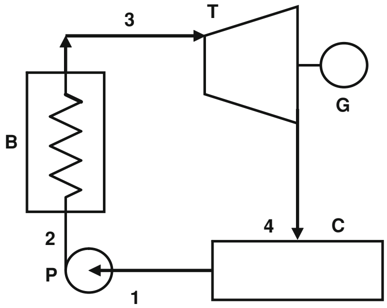

Fig. 3.8 Schematic diagram of the principal components used in a vapor power cycle

3.6.1 Vapor Power Cycles: The Rankine Cycle

The *Rankine cycle* is the most commonly used vapor power cycle. The working fluid of this cycle is usually water. The basic components of a typical Rankine cycle power plant are depicted schematically in Fig. 3.8 and the thermodynamic processes that comprise this cycle are depicted in Fig. 3.9a, b on the temperature-entropy and pressure–volume diagrams respectively:

1. Process 1–2 is the pressurization of the water effluent from the condenser. A pump (P) carries out this process, which is almost isentropic. Typical inlet conditions at state 1 for water are 0.06 to 0.10 kPa (6% to 10% of atmospheric pressure). The outlet conditions of the pump at state 2 vary from a few MPa to 30 MPa for supercritical cycles. A small amount of power, typically 1–2% of that produced by the turbine, is required for the operation of the pump. Since there is a small amount of power involved in process 1–2, the temperature of the pressurized water at state 2 is almost the same as that at state 1 ($T_2 \approx T_1$).
2. The boiler/superheater (B) receives the pressurized water at state 2 and, by imparting a significant amount of heat to the cycle, produces steam at high pressure and high temperature at state 3. The boiler is the high temperature reservoir for the cycle. The heating process 2–3 is considered to be isobaric (constant pressure).
3. The steam enters the turbine (T), or a system of turbines in large power plants and provides the motive power for its rotation and the simultaneous production of electricity in the generator (G). The pressure and temperature of the steam are reduced significantly in the turbine and the steam is exhausted in the condenser at the very low pressure range of 0.06–0.10 kPa and at low temperatures in the range of 40–50°C. The steam expansion process in the turbine, 3–4, is almost isentropic.
4. The function of the condenser (C) is to receive the steam from the turbine and condense it to liquid water. The condenser is a heat exchanger, where the steam from the cycle is condensed by warming up large quantities of *cooling water*. Heat is rejected at this part of the cycle to the cooling water and, finally, to the environment. The condensation process, 4–1, is considered to be isobaric.

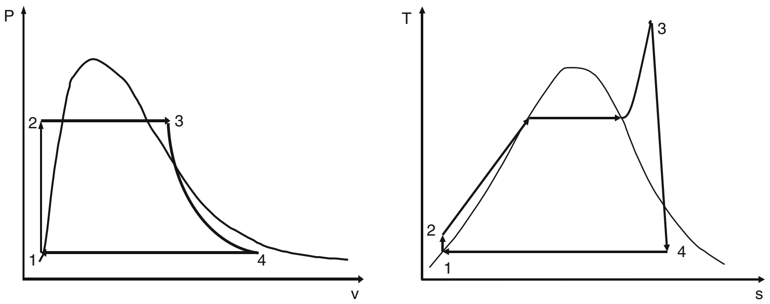

Fig. 3.9 **a** and **b.** A simple Rankine cycle depicted on the P–v and T-s diagrams

It must be pointed out that the condensation is not a necessary operation for the production of power and that the early power plants and locomotives operated without condensers by exhausting steam to the atmosphere. The condenser represents a significant improvement for the vapor cycle because, by reducing the steam pressure to sub-atmospheric values, it almost doubles the amount of power produced, thus, significantly improving the efficiency of the vapor cycle.

If the mass flow rate of water in the cycle is denoted by $\dot{m}$ then the amount of power consumed by the pump is: $\dot{m}(h_2 - h_1)$, the amount of heat power produced by the boiler/superheater is: $\dot{m}(h_3 - h_2)$, the amount of power produced by the turbine is $\dot{m}(h_3 - h_4)$, and the amount of heat rejected by the condenser via the cooling water to the environment is $\dot{m}(h_4 - h_1)$. The net electric power, which is produced by this plant in the generator, is: $\dot{m}(h_{3.}h_4) - \dot{m}(h_2 - h_1)$. Finally, the thermal efficiency of the power plant is defined as:

$$\eta_t = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}. \tag{3.24}$$

The enthalpy and other properties of the water and steam at the states 1–2–3–4 may be obtained from *steam tables* that are standard appendices of books on Engineering Thermodynamics. It must be also noted that the definition of the thermal efficiency of a cycle does not emanate from any of the Laws of Thermodynamics and that it is merely a benefit to cost ratio: the benefit is the power produced, which represents the revenue for the power plant operator. The cost is the heat addition to the cycle, which typically comes from a fuel that represents cost.

As with any benefit-to-cost ratio, engineers strive to improve the thermal efficiency of the power plants.[4] One may improve the efficiency of Rankine cycles by adopting several of the following processes:

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[4] If the heat to the cycle is "free," as for example in the case of solar thermal power plants, one has to think carefully what the "thermal efficiency improvements" would mean for the operation of such a power plant.

1. Increase the upper cycle temperature, by superheating the steam in the boiler/superheater to higher temperatures. There is a limit to this process, the *metallurgical limit*, where the temperatures are too high for the turbine materials to handle and fracture may occur. With the materials used at present, this limit is approximately 600°C.
2. Increase the upper pressure P_3. Again the materials used in the superheater and the turbines impose a limit, which is typically 35 MPa (350 atm).
3. Reduce the lower temperature and pressure of the cycle. This is limited by the temperature of the cooling environment, where finally all the heat must be rejected. When water is available, from a river or a lake, the temperature of the water is the limit temperature. Because water is colder than the ambient air, most of the modern power plants are close to lakes or rivers.
4. Use a reheat process: steam is partly expanded in the turbine to a lower pressure and is then directed back to the superheater, where it receives more heat and its temperature is increased to approximately T_3. This reheating process may be repeated 2–3 times and is facilitated considerably if the pressure P_3 is very high, as for example in supercritical cycles.
5. Use the *regeneration* or *bleeding* process: For this efficiency improvement process a fraction of the steam (10–20%) is extracted from the turbine at moderately high temperature. This part of the steam is used to heat up the water effluent of the pump at state 2 in a heat exchanger, which is called the *feedwater heater (FWH)*. This process may also be repeated 2–3 times by extracting steam at 2–3 points from the turbine. The effect of regeneration is to use heat at a lower temperature from the expanding steam in order to heat up the water at the lower temperatures of the cycle. In this case, high temperature heat is saved by not being used in the lower temperatures of the cycle.

Practical vapor cycles that utilize the above methods have upper cycle temperatures close to 560°C and may reach thermal efficiencies in the range 42–46%.

3.6.2 Gas Cycles: The Brayton Cycle

Gas cycles typically use air as the working fluid. However, advanced gas cycles that are used in some nuclear reactors have used carbon dioxide or helium. The arrangement of the components in a typical gas cycle is shown in Fig. 3.10. The processes that constitute this cycle may be enumerated as follows:

1. Air at ambient temperature and pressure, at state 1, enters a compressor where its pressure and temperature rise to state 2. Typical pressures at the exit of the compressor are 10–20 atm. Because a gas is compressed during this process, the compressor consumes a significant amount of power, typically one third of

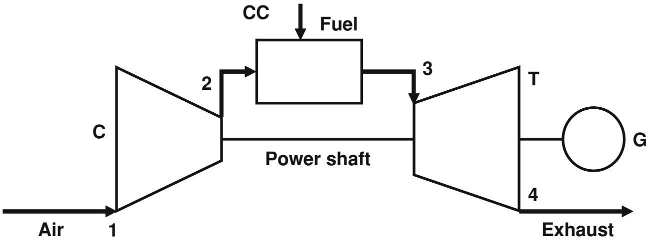

Fig. 3.10 Schematic diagram of the components used in a gas power cycle

the total power produced by the cycle. For this reason, the compressor is usually coupled mechanically and driven directly by the turbine.

2. The compressed air enters the burner or combustion chamber (CC). Fuel (typically natural gas or liquid hydrocarbons) is also introduced in this devise, where it burns by combining with the oxygen in the air. The combustion results in the significant elevation of the temperature of the remaining air and the combustion products. Temperatures at the exhaust of the combustion chamber (state 3) may reach as high as 2,000°C.
3. This high-temperature mixture is introduced to the gas turbine (T) where the air and the products of the combustion expand to atmospheric pressure and then are exhausted to the atmosphere at state 4. A generator (G), which is coupled to the turbine, produces electric power. The latter is equal to the difference of the power produced by the turbine minus the power consumed by the compressor.

Strictly speaking, the gas cycle is not a cycle *per se* because the turbine exhaust is at different state and composition from the compressor input. However, this series of processes is always treated as a cycle, because the input to the compressor is always air at ambient temperature and the rest of the atmosphere may be thought of as an enormous reservoir of mass and heat, which receives the hotter output of the turbine, cools and purifies it to the ambient temperature and composition and, finally, allows it to be fed to the compressor at the same, ambient pressure, temperature and composition. The temperature-entropy and pressure–volume diagram of this virtual cycle are depicted in Fig. 3.11a, b respectively. The thermal efficiency of the gas cycle is defined in the same way as in the vapor cycles and may be expressed as follows in terms of the states depicted in these two diagrams:

$$\eta_t = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}. \tag{3.25}$$

The enthalpy and other properties of the air at the states 1–2–3–4 may be found in *air tables* that are standard appendices of a book on Thermodynamics [1]. Alternatively, the enthalpy differences may be expressed in terms of a specific heat

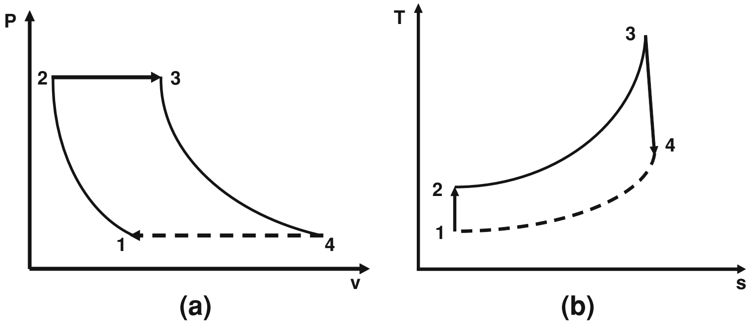

Fig. 3.11 **a** and **b.** A simple Brayton cycle depicted in a P–v and a T-s diagram

and the corresponding temperature differences. The efficiency of gas cycles may be improved by using the following processes:

1. Use a reheat process, similar to the vapor cycle: The gas expands in the first turbine to lower pressure and then is introduced to the combustion chamber, or a second combustion chamber, where more fuel burns. The temperature of the gas increases again to a value close to T_3. The gas is then directed to another turbine where it produces more power.
2. The temperature at the last turbine exhaust is rather high, typically at 400–500°C. This is oftentimes higher than the temperature, T_2, at the exit of the compressor. In such cases one may use a *regenerator*, which is a heat exchanger that heats up the compressor output by using the turbine exhaust mixture.
3. Use of intercoolers: the power requirement of the compression process is significantly lower if the compression is closer to isothermal than to isentropic. In this case, a single large compressor is replaced by a series of smaller compressors that operate in series. At the exit of each compressor, air is cooled to almost ambient temperature and is further pressurized in the next compressor. Intercooling in compression processes and its benefits in improving the efficiency of gas cycles are further explained in Sect. 13.2.2 and depicted in Fig. 13.1, which shows the use of intercoolers with a series of three compressors.
4. Use of a bottoming vapor cycle: The high-temperature gases that exhaust at the turbine may be used in a heat exchanger to generate steam (or another vapor) at high pressure, which in turn may produce power using another turbine-condenser-pump combination. The heat supplied to this cycle is the *waste heat* of the turbine and is virtually free of any cost because it comes from gases that would have been otherwise exhausted to the atmosphere. The additional power produced enhances significantly the thermal efficiency of the original gas cycle, which may reach values close to 50%.

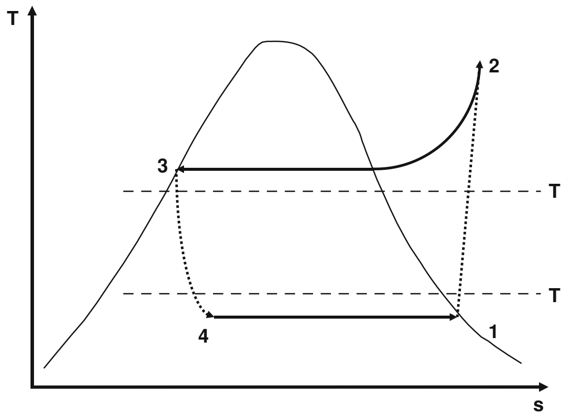

Fig. 3.12 Thermodynamic diagram of the operation of the heat pump/refrigeration/air-conditioning cycle

3.6.3 Refrigeration and Heat Pump Cycles

In principle, a reversed power generation cycle would absorb heat from a colder heat reservoir and will dissipate another amount of heat to a higher temperature reservoir. Depending on its use, such a reversed cycle is called a *refrigeration cycle* or a *heat pump cycle*. The former is used as an air-conditioning cycle too. The thermodynamic diagram in the T,s coordinates of a typical refrigeration cycle, which is a slightly modified, reversed Rankine cycle, is shown in Fig. 3.12. The four processes of the refrigeration cycle are as follows:

1. A compressor raises the pressure of the working fluid from state 1 to 2. The compressor consumes electric work, which is work given to the cycle and has a negative algebraic sign. Both the temperature and pressure of the fluid that exits the compressor are significantly high.
2. The refrigerant fluid is then passed through the condenser and undergoes the process 2–3. During this process the fluid dissipates heat to a heat sink at a higher temperature T_H. In a heat pump operation, the heat sink is the interior of a building. In a refrigeration operation the heat sink is the coils at the back of the refrigerator, which always feel warmer to the touch. In an air-conditioning cycle, the heat sink is the outside atmospheric air.
3. Process 3–4 is caused by an expansion valve and produces a mixture of liquid and vapor at significantly lower temperature ($T_1 = T_4$). The valve is insulated and the process is considered isenthalpic ($h_3 = h_4$).
4. After this stage, the refrigerant fluid passes through the evaporator and undergoes the process 4–1. Because the temperature of the fluid at this stage is very low, the fluid absorbs heat from the lower temperature source at T_L, and exits the evaporator at the original state 1. In an air-conditioning cycle, the lower temperature heat source, at temperature T_L, is the air in the interior of the building. In a refrigeration cycle this is the interior of the refrigerator.

In a heat pump the low temperature reservoir is the atmospheric air. The corresponding higher temperature reservoir, at temperature T_H, in all three cases is the outside air, the room where the refrigerator is located (e.g. the kitchen) and the interior of the building, respectively. It must be noted that the main difference between a reversed Rankine cycle and a refrigeration cycle is that process 3–4 of the refrigeration cycle does not produce work. This happens because the actual work that may be produced from the liquid refrigerant at state 3 is too low to justify the capital expense of an expander/turbine. The simple expansion valve that is used for the process 3–4 is by far cheaper and fulfills the task to lower the temperature of the refrigerant fluid at state 4.

The principal function of the heat pump cycle is to remove heat, Q_L, from a colder heat source and dissipate a significantly higher quantity of heat, Q_H, to a hotter environment. The addition of work, W, which emanates from electric power via a motor, is essential to the cycle and makes possible this heat transfer process. In the common household refrigerator, this cycle removes heat from the colder interior of the refrigerator and dissipates a higher quantity of heat to the coils in the back of the refrigerator. The energy conservation principle—the first law of Thermodynamics—applies to the transfers of heat and of work in the heat pump/refrigeration cycle and may be written as follows:

$$Q_H = Q_L + W. \tag{3.26}$$

Depending on the function of the cycle, two benefit-to-cost ratios, the coefficients of performance (c.o.p.) have been defined for the heat pump and the refrigeration cycles. The c.o.p. is the ratio of the units of heat removed by the refrigerator (or added by the heat pump) to the electric work that must be spent for the operation of the cycle. Thus, the coefficients of performance of a heat pump cycle, β_{hp}, and a refrigerator or an air conditioning cycle, β_r, are defined as follows:

$$\beta_{hp} = \frac{Q_H}{W} \quad \textit{and} \quad \beta_r = \frac{Q_L}{W}. \tag{3.27}$$

It is the absolute and not the algebraic values of the heat and work that are used in the calculation of the c.o.p.'s. The heat removed or added and the coefficients of performance of the cycles depend on the cycle temperatures and pressures. In general, the lower the difference between the condenser and the evaporator temperatures, T_1 and T_3 are (or correspondingly the pressures P_1 and P_3) the higher the coefficient of performance of the cycle will be. Thus, an air-conditioner would have a lower coefficient of performance during the hotter summer days, when heat is rejected to a higher temperature environment. Also, a heat pump has a lower coefficient of performance during the coldest days of the winter, when heat must be removed from a very cold environment.

3.7 Exergy: Availability

The concept of the *Carnot efficiency* is very useful in giving us a quantitative measure of the maximum efficiency when a given quantity of heat, *Q*, is to be converted to work. However, quantities of heat at high temperatures are not found in nature. Heat is normally released in burners and boilers from the consumption of fossil or nuclear fuels. Instead what is abundantly found are *natural energy resources*, such as fossil fuels, nuclear fuels, geothermal fluids, incident solar radiation, wind power, etc. Therefore, one may ask the question, "what is the maximum amount of work, one may obtain from a given quantity of an energy resource?" Clearly, the *Carnot efficiency* does not give an answer to this question, because the conversion of the energy resource to heat always involves thermodynamic irreversibilities and the subsequent conversion of this quantity of heat to work does not necessarily yield the maximum amount of work the original resource may provide. In such cases, one may use the concept of *exergy* or *availability,* which gives a quantitative measure of the maximum amount of work one may obtain from an energy resource.

One may make the following observations regarding the processes of the conversion of energy resources to work or power:

1. All energy conversion processes occur in the environment—the atmosphere and the hydrosphere—which act as reservoirs of mass, heat and work, that is, they may absorb or provide very large quantities of mass, heat and work without their state changing significantly.
2. Energy conversion processes are possible, because there are natural substances, the *energy resources,* which are not in thermodynamic equilibrium with the atmosphere. For example, coal is not in equilibrium with the atmosphere. Coal will come to equilibrium with the atmosphere when it combines with oxygen and forms carbon dioxide.
3. The maximum work is extracted from an *energy resource*, when, through several processes, the materials of the resource are brought in thermodynamic equilibrium with the environment. This is called the *dead state* of the resource.

Hence, one may conclude that the maximum work from a *energy resource* will depend on the following:

1. The type of the resource.
2. The thermodynamic characteristics of the environment, which include temperature, pressure and chemical composition.
3. The interaction allowed between the resource and the environment.
4. The rate of dissipation or irreversibilities in all the conversion processes.

Therefore, the maximum work that may be obtained from an energy resource may not be described by a single formula, such as the one of the *Carnot efficiency.*

One may obtain such formulae, which are applicable to specific resources by using the First and Second Laws of Thermodynamics in combination. This type of analysis leads to the thermodynamic concept of exergy. The following are some examples of the use of the exergy concept to three types of natural energy resources.

3.7.1 Geothermal Energy Resources

Geothermal reservoirs supply power plants with geothermal fluid, which is in the one of the following three conditions:

1. Superheated steam (e.g. the Geysers in California and Lardarelo in Italy).
2. Mixture of steam and water (e.g. Warakei in New Zealand).
3. Geopressured liquid water at high temperature (e.g. Port Aransas, Texas).

The geothermal power plant is an open thermodynamic system that receives a certain mass flow rate of the geothermal resource$\dot{m}$, at high temperature, T, pressure, P, specific enthalpy, h, and specific entropy, s. The plant operates in the atmosphere, which is at temperature T_0 and pressure P_0, and discharges the geothermal fluid as an effluent at temperature T_e, pressure P_e, specific enthalpy, h_e and specific entropy s_e. Therefore one may write the two laws of thermodynamics for this open system as follows:

$$\dot{Q} - \dot{W} = \dot{m}(h_e - h), \tag{3.28}$$

and

$$\dot{m}(s_e - s) - \frac{\dot{Q}}{T_0} = \dot{\Theta} > 0. \tag{3.29}$$

The 2nd Law inequality of Eq. (3.21) has been converted to an equation (Eq. 3.29) by introducing the rate of entropy generation, $\dot{\Theta}$, which is always a positive quantity ($\dot{\Theta} > 0$). Substituting the rate of heat from the second expression to the first, one may obtain the following expression for the power produced by the geothermal power plant:

$$\dot{W} = \dot{m}[(h - T_0 s) - (h_e - T_0 s_e)] - T_0\dot{\Theta}. \tag{3.30}$$

It is now apparent that the power plant will deliver maximum work and power under the following two conditions:

1. The rate of entropy generation,$\dot{\Theta}$, is minimized to a value close to zero.
2. The state of the effluents, e, is the same as the state of the environment, at temperature T_0 and pressure P_0, as implied by observation 3, in the previous

Table 3.1 Specific work produced, in kJ/kg, by several types of geothermal resources

Steam at 280°C, 15 atm	955
Saturated steam at 220°C	929
50% water and 50% steam at 220°C	552
Saturated liquid water at 200°C	158
Saturated liquid water at 160°C	97
Geopressured liquid water at 140°C, 25 atm	73

section. At this state the specific enthalpy and entropy of the effluents will be denoted as h_O and s_O [2].

Hence, the maximum rate of work, or power, one may obtain from the geothermal resource is:

$$\dot{W}_{\max} = \dot{m}[(h - T_0 s) - (h_0 - T_0 s_0)] = \dot{m}(e - e_0). \tag{3.31}$$

In the last expression, the quantity $e = h\text{-}T_O s$, is the *exergy* of the geothermal resource. It is apparent that the exergy of a resource utilized by an open system is a function of the thermodynamic state of the resource as well as of the state of the environment, where the energy conversion processes occur. In the case of geothermal resources, the maximum amount of specific work obtained by the geothermal fluid may be easily calculated from the properties of this fluid. Table 3.1 provides values of the specific work for several states of geothermal fluid, which is assumed to be water. For the calculations, the environmental temperature, T_0, is 298 K (25°C). It is observed in this table that, resources with significant amount of vapor (steam) would provide much higher amount of work than liquid water resources. Also, that the amount of specific work diminishes significantly when the temperature of the resource is relatively low.

It must be noted that, for vapor–liquid systems, such as steam-water, the numerical value obtained for the exergy at the dead state is very close to zero, that is $e_O \approx 0$, which implies:

$$\mathrm{W}_{\max} \approx \dot{\mathrm{m}}\mathrm{e} \tag{3.32}$$

3.7.2 Fossil-Fuel Resources

Fossil fuels may provide heat and work because they are not in chemical equilibrium with the atmosphere. An equilibrium state is reached when fossil fuels combine with the oxygen of the atmosphere and produce carbon dioxide and water. Figure 3.13 is a schematic diagram of the conversion of the hydrocarbon octane (C_8H_{18}) supplied to an engine at a mole flow rate $\dot{n}$ to produce power.

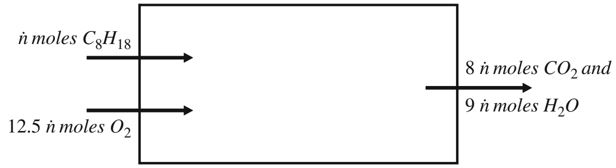

Fig. 3.13 Schematic diagram of the work production process from the chemical reaction of octane oxidation

Since fossil fuels undergo chemical reactions, the mole flow rates and properties of the reactants, denoted by the subscript *R*, and of the products, denoted by the subscript *P*, are used in the derivation of the maximum power that may be produced. The energy conversion process occurs in an open thermodynamic system. One may write the laws of Thermodynamics and the power delivered by the engine as follows:

$$\dot{Q} - \dot{W} = \sum_P \dot{n}_P h_P - \sum_R \dot{n}_R h_R, \tag{3.33}$$

and

$$\sum_P \dot{n}_P s_P - \sum_R \dot{n}_R s_R - \frac{\dot{Q}}{T_0} = \dot{\Theta} > 0. \tag{3.34}$$

After combining the last two expressions by eliminating the rate of heat, one obtains the following expression for the power produced by the engine that utilizes the fossil fuel:

$$\dot{W} = \left[\sum_R \dot{n}_R(h_R - T_0 s_R) - \sum_P \dot{n}_P(h_P - T_0 s_P)\right] - T_0\dot{\Theta} \tag{3.35}$$

The maximum power will be produced by the engine when:

1. The internal irreversibilities are minimized to the point where the rate of entropy production is zero, and
2. When the products are exhausted and reach equilibrium with the atmosphere, that is, at temperature T_0 and pressure P_0.

Under these conditions of maximum power production, the terms in the square bracket may be written in terms of the *Gibbs free energy* of the reaction, ΔG, and the molar flow rate of the fuel, $\dot{n}_F$:

$$\dot{W}_{\max} = -\dot{n}_F \Delta G. \tag{3.36}$$

If the reaction takes place at atmospheric pressure, as most reactions do, the Gibbs free energy at atmospheric pressure, ΔG^0, should be used. From the last expression one may deduce that the maximum amount of specific work per kmol, which may be obtained from a fossil fuel at atmospheric pressure, is:

$$\tilde{w}_{\max} = -\Delta G^0 \text{in units of kJ/kmol or Btu/lbmol} \tag{3.37}$$

The *Gibbs free energy* of the reaction is a thermodynamic property for all reactions and may be found in standard thermodynamic or chemical tables. The superscript, *0*, denotes that this function is evaluated at the atmospheric pressure and temperature. One may easily observe that there are many similarities between Eqs. 3.35 and 3.31 and that the specific exergy of a fossil fuel may be defined as $e_F = h_F - T_0 s_F$.

In a strict sense, the theoretical maximum amount of work one may extract from a chemical substance is slightly higher than the amount indicated in the last two equations. For example for Eq. (3.37) the maximum theoretical work may be given by the expression:

$$\tilde{w}_{\max} = -\Delta G^0 - \tilde{R}T_0 \ln \frac{\prod_p x_p^{v_p}}{\prod_r x_r^{v_r}}, \tag{3.38}$$

where the operator Π denotes the algebraic product of the variables; x is the mole fraction of a chemical compound; v is the stoichiometric coefficient of the compound; and the subscripts p and r refer to the products and reactants of the pertinent chemical reaction. However, the last term may only be practically harnessed if semi-permeable membranes were available that would allow the reversible expansion of the reactants and products into the atmosphere. Because this technology is not available, it is best to use Eqs. (3.36) or (3.37) as expressions for the maximum work from fossil fuels and other chemical compounds.

3.7.3 Radiation: The Sun as Energy Resource

Contrary to popular thinking, not all of the solar radiation energy may be converted to work. The energy flux (in W/m^2) emitted by a source at temperature T_H is equal to: σT_H^4, where σ is the Stefan-Boltzmann constant. By combining the first and second Laws of Thermodynamics and substituting the appropriate expressions for the specific energy and entropy of radiation, one may obtain the following expression for the exergy flux of radiation energy emanating from a source at temperature T_H and utilized in an environment at temperature T_0.

$$E = \frac{\sigma}{3}\left(3T_H^4 - 4T_H^3 T_0 + T_0^4\right). \tag{3.39}$$

The units of this expression are power per unit area (e.g. W/m^2). In the case of solar energy, the temperature of the source of radiation, the Sun, is at approximately 5,900 K, while the temperature of the receiving object is that of the Earth, approximately 300 K. When these numbers are substituted in the last equation, it is concluded that approximately 93.5% of the amount of incident solar energy may be converted to work. It is of interest that, if one considers the Sun and the Earth as the two temperature reservoirs of a cycle connected by a cyclic thermodynamic engine, the maximum efficiency of this giant cyclic engine would be determined from Eq. (3.22) to be 95%.

3.7.4 Second Law Efficiency: Utilization Factor

The thermal efficiencies defined in Eqs. (3.22) and (3.23) are based on the thermal energy that could have been extracted from the heat source. Because heat is an integral part and is defined by the First Law of Thermodynamics, these efficiencies are often referred to as first law efficiencies. Essentially, the first law efficiency defines how much of the available heat in the energy resource is converted into work. It is apparent that the available heat from a resource is not the best indicator of the work that may be extracted from a particular resource and that the exergy of the resource is a better measure of the work that may be extracted from it. For this reason, for energy conversion processes and systems another figure of merit, which is based on the concept of exergy is defined as follows:

$$\eta_u = \frac{W}{m(e - e_0)} \quad or \quad \eta_u = \frac{\dot{W}}{\dot{m}(e - e_0)}. \tag{3.40}$$

This figure of merit is called *second law efficiency* or *utilization factor*. The second law efficiency is, essentially, the ratio of the actual work produced in an energy conversion process or energy cycle to the maximum possible work. Since it is based on the maximum work that *could* have been extracted from the energy resource, the second law efficiency gives a better indication as to the specific way the energy resource is utilized. A low numerical value for the second law efficiency indicates that the method of energy utilization is not optimum and that the energy conversion process or cycle would benefit from improvements. On the contrary, a high value of the second law efficiency would indicate that the process or cycle is near optimum and that any improvements would only result in marginal gains of the total work or power produced.

Problems

Thermodynamic tables are needed for problems marked with an asterisk (*).

1*. A cylinder fitted with a piston contains 2 kg of liquid water and 1 kg of steam at equilibrium at 0.2 MPa.

   a) What is the equilibrium temperature of the mixture?
   b) Heat is added at constant pressure until all the water has evaporated. Show the process carefully in a P – v diagram.

   c) Determine the amount of heat added and the change in the volume of the system.

2. Ammonia at temperature $T_1 = 27.0°C$ and pressure 0.1 MPa (atmospheric pressure) flows into an apparatus where it is heated by an electric resistance of 100 ohm at a volumetric rate of 0.000041 m^3/s. When a current of 0.050 A (Ampere) flows through the resistance, the exit temperature of ammonia is 31.1°C.

   a) What are the specific heat capacities, c_p and c_v for ammonia?
   b) Note: Ammonia at ambient conditions may be considered to be an ideal gas and the power supplied by an electric heater is equal to I^2R.

3. Helium enters an isentropic nozzle at 3 MPa, 350°C with a negligible velocity and exits at 1.6 MPa. The mass flow rate is 0.5 kg/s. Calculate:

   a) The exit temperature.
   b) The velocity of the gas at the exit of the nozzle.
   c) The area at the exit of the nozzle.
      You may assume that helium is an ideal gas with constant specific heats, $M = 4$ kg/kmol, $k = 1.67$ and $c_p = 5.2$ kJ/kg.

4*. Steam at 2 MPa and 450° C enters an isentropic nozzle with a velocity of 10 m/s and exits at 1.5 MPa. The mass flow rate is 0.2 kg/s. Calculate:

   a) The exit temperature.
   b) The velocity of the steam at the exit of the nozzle.
   c) The area at the exit of the nozzle.

5*. A steam turbine admits 50 kg/s of steam at 10 MPa and 450°C. The turbine operates with an isentropic efficiency of 85% and exhausts at 0.08 MPa. Determine

a) The specific work of the turbine in kJ/kg.
b) The total power produced by the turbine in kW.

6*. For the operation of the turbine in problem 5 determine the amount of cooling water needed at the condenser, in kg/s, if the water is supplied from and returned to a river. The temperature difference of the supply and return water is 3°C and the specific heat of liquid water is constant and equal to 4.184 kJ/kg K. Note that the condenser receives the effluent of the turbine and exhausts it as saturated liquid water.

7. Steam Rankine cycle with superheat: The turbine entrance pressure is 15 bar and the temperature is 400°C. The condenser pressure is 0.08 bar. The mass flow rate is 850 kg/min. The turbine efficiency is 82% and the pump efficiency 75%. Calculate:

   a) The thermal efficiency of the cycle.
   b) The total power produced in MW.
   c) Suggest three ways to improve the efficiency of this cycle.

8*. Steam enters the turbine of a power plant operating with a Rankine cycle at 500°C and 100 bar. The turbine exhausts to a condenser at 0.08 bar. If the isentropic efficiency of the turbine is 84% and that of the pump is 75%, calculate:

   a) The thermal efficiency of the cycle.
   b) Suggest three ways to improve the efficiency of this cycle.

9. Air in a Brayton cycle enters the turbine at 1.8 MPa and 1200°C. The compressor entrance conditions are 0.1 MPa and 20°C. The isentropic efficiency of the turbine is 83% and that of the compressor 78%. Calculate:

   a) The thermal efficiency of the cycle.
   b) The back work ratio.
   c) Suggest three ways to improve the efficiency of this cycle.

10*. Propose a simple Rankine cycle that would utilize as a source of heat the exhaust gas from the turbine of problem 9. Determine the amount of additional work this bottoming cycle may produce and the efficiency of the combined cycle.

11. The exhaust gases of a gas turbine, are used in a well insulated regenerator (heat exchanger) to raise steam at 2 bar, which is subsequently fed to a steam turbine in order to produce additional power. The air enters the regenerator at 758 K and exits at 350 K. The mass flow rate of the air is 3.2 kg/s. Water at 45°C and 2 bar enters the regenerator and exits as saturated steam at the same pressure. Determine:

   a) The mass flow rate of the water.
   b) The rate of entropy production in the regenerator in kJ/s.

12. A small residential water heater uses methane gas (CH_4) as its fuel. The heater uses 92 m^3 of water annually and raises its temperature from an average 18–50°C. The density and specific heat capacity of water is 1,000 kg/m^3 and 4.18 kJ/kg K. Determine:

   a) The amount of energy consumed by this water heater.
   b) The amount of methane used annually and the amount of CO_2 released in the atmosphere from this heater if the heater burns methane. The heating value of methane is 50,020 kJ/kg.

13*. The cooling system of a power plant uses lake water. The mass flow rate of the plant cycle is 1,050 kg/min. Wet steam with quality 92% at 0.01 MPa (0.1 bar) enters the condenser of the power plant and saturated liquid water at the same pressure exits the condenser. The cooling water of the lake enters the condenser at 18°C and exits at 20.8°C. For this range of temperatures you may assume that the liquid water is incompressible and its specific heat is constant and equal to 4.18 kJ/kgK. Determine the mass flow rate of the water that is needed to cool this plant.

14*. Determine the exergy of saturated liquid water and saturated steam at the following temperatures: 100, 150, 200, 250, 300 and 350°C.

From the above values what can you conclude about the potential of steam and liquid water to produce work?

15. A 400 MW steam power plant uses coal as its fuel. The average efficiency of the plant is 38% and the plant operates for 84% of the time annually. Determine:

    a) The electricity in kWh and kJ produced by the plant annually.
    b) The amount of heat in kJ produced by the boiler of the plant.
    c) Assuming that the coal burned is pure carbon and that 1 kg of carbon when burned produces 32,770 kJ of heat and 44/12 kg of carbon dioxide, determine the mass of coal consumed by this plant and the mass of CO_2 released annually.

16. It has been suggested that, in order to reduce the amount of CO_2 that is released to the atmosphere, the boiler of the power plant in problem 14 is refitted to burn propane (C_3H_8), which produces 46,360 kJ/kg of heat.

    a) Determine the mass of propane that will be consumed by this plant and the mass of CO_2 released annually.
    b) What conclusions can you make about the substitution of coal with hydrocarbons for the reduction of CO_2 released? Are there other alternatives to produce electric power without CO_2 emissions?

17. A 600 MW coal power plant uses bituminous coal as a fuel, which has the following consistency by mass: carbon 62%, moisture 27%, ash 10% and sulfur 1%. You may assume that, only carbon provides heat with $\Delta h = 32{,}770$ kJ/kg when it is burned. The power plant operates with an average efficiency of 40% for 83% of the year. Determine:

    a) The annual amount of electricity in kWh the plant produces.
    b) The annual amount of heat produced by the boiler of the plant.
    c) The mass or carbon necessary to produce this amount of heat and the total mass of coal that produces it.
    d) The masses of carbon dioxide, ash and sulfur dioxide generated annually.

References

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