1 INTRODUCTORY CONCEPTS AND DEFINITIONS

1.0   INTRODUCTION

Thermodynamics is an engineering science topic, which deals with the science of "motion" (*dynamics*) and/or the transformation of "heat" (*thermo*) and energy into various other energy – containing. The flow of energy is of great importance to engineers involved in the design of power generation and process industries. The formal study of thermodynamics began in the eighteenth century through consideration of the motive power of *heat*: the capacity of hot bodies to produce work. Today the scope is larger, generally dealing with *energy* and with relationships among the *properties* of matter.

Thermodynamics is both a branch of physics and an engineering science. Engineers are generally interested in studying *systems* and how they interact with their *surroundings*. To facilitate this, engineers extend the subject of thermodynamics to the study of systems through which matter flows.

Engineers use principles drawn from thermodynamics and other engineering sciences, such fluid mechanics and heat and mass transfer, to analyse and design things intended to meet human needs. The wide realm of the application of these principles is suggested by Table 1.1, which lists a few areas where engineering thermodynamics is important.

The objective of this chapter is to introduce you to some of the fundamental concepts and definitions that are used in our study of engineering thermodynamics.

Table 1.1 Selected areas of application of engineering thermodynamics

Automotive engines
Turbines, Compressors, pumps
Fossil- and nuclear-fuelled power stations
Propulsions systems for aircraft and rockets
Combustions systems
Gas separation and liquefaction
Heating, ventilating and air-conditioning
    Vapour compressors and absorption refrigeration
    Heat pumps
Alternate energy systems
  Fuel cells
  Geothermal systems
  Ocean thermal, wave, and tidal power
  Wind power
Biomedical applications
  Life support systems
  Artificial organs

LIMITATIONS OF THERMODYNAMICS

It is not possible to determine the rates of transport processes using thermodynamics analysis alone. For example, thermodynamics demonstrates that heat flows from higher to lower temperatures, but does not provide a relation for the heat transfer rate.   Rate processes are discussed in texts pertaining to heat, mass and momentum transport.

1.1 THERMODYNAMIC SYSTEMS

System

In thermodynamics the term *system* is used to identify a region containing energy/and/or matter that is separated from its *surroundings* by arbitrarily imposed walls or boundaries. Once the system is defined and the relevant interactions with other systems are identified, one or more physical laws or relations are applied.

The system is whatever we want to study. We may want to study a quantity of matter contained within a closed, rigid-tank, or we may want to consider something such as a gas pipeline through which matter flows. Note that even vacuum which devoid of matter, may be the focus of interest. The composition of matter inside a system may be fixed or may be changing through chemical or nuclear reactions. The shape or volume of the system being analysed is not necessarily constant, as when a piston compresses a gas in a cylinder or a balloon is being inflated.

Surrounding

The portions of matter or space which are external to the system and which either affect or is affected by the system are the surroundings.

Boundary

A boundary is a closed surface, either real or imaginary, surrounding a system through which energy and mass may enter or leave the system and which separates the system from its surroundings. The boundary may be rigid in which case it cannot be deformed and has a fixed shape. *Permeable* and process boundaries allow mass transfer to occur. Mass transfer cannot occur across *impermeable* boundaries. A *diathermal* boundary allows heat transfer to occur across it as in the case of thin metal walls. Heat transfer cannot occur across the *adiabatic* boundary. In this case, the boundary is impermeable to heat flux, e.g. as in the case of a Thermos Flask.

A *moveable/deformable* boundary is capable of performing "boundary work". No boundary work transfer can occur across a rigid *boundary*. However, energy transfer can occur via shaft work, e.g., through the stirring of fluid in a blender.

Surroundings

Everything external to the system is considered to be part of the system's *surroundings*. The system is distinguished from its surroundings by a specified boundary, which may be at rest or in motion. The interactions between the system and its surroundings take place across the boundary.

A simple system is one which is macroscopically homogeneous and isotropic and involves a single work mode. The term macroscopically homogeneous implies that properties such as the density are uniform over a large dimensionally region several times larger than the mean free path during a relatively large time period.

An isotropic system is one in which the properties do not vary with direction, e.g., a cylindrical metal block is homogeneous in terms of density and isotropic, since its thermal conductivity is identical in the radial and axial directions.

A simple *compressible* system utilises the modes of compression and/or expansion, and is devoid of body forces due to gravity, electrical and magnetic fields, inertia, and capillary effects. Therefore, it involves only volumetric changes in the work term.

<u>Example 1</u>: Suppose we are interested in the behaviour of air when it is heated or compressed:
Figure 1.1 shows the sketch of the experimental set-up, which could be used to carry out the study.
The system is the 1.0 kg of air, the surroundings comprise the cylinder walls and the areas adjacent
to it from where heat may be supplied, and the inner surface of the piston. Note that one side of the
boundary, namely the surface of the piston, is deformable while the others are rigid. Also the
boundary is *diathermal* as it allows heat to be transferred to the system. The boundaries are usually
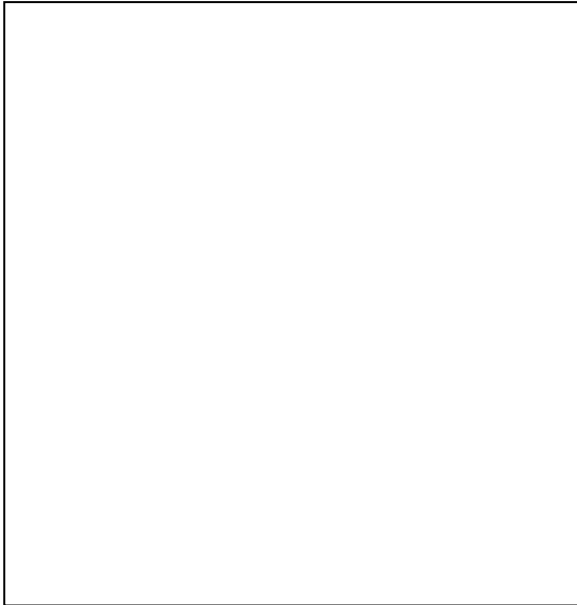indicated with dotted lines as shown.

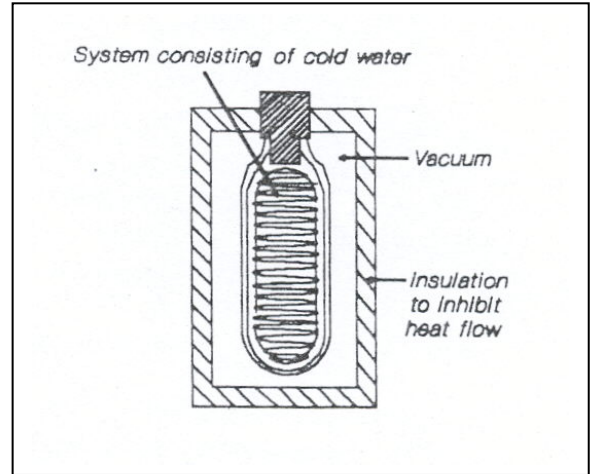Figure 1.1   Thermodynamic system   Figure 1.2   Thermos flask

1.1.1   Types of systems

Depending on the nature boundary, two kinds of systems are distinguished. These are referred to,
respectively, as *closed systems* (fixed mass system or control mass system) and the *open systems*
(control volume system).

Closed system
A closed system is defined when a particular quantity of matter is under study. A closed system
always contains the same matter. There can be no transfer of mass across the boundary. A closed
system may exchanges only heat and work with the surroundings. Figure 1.1 shows an example of
a closed system. A special type of a closed system that does not interact in any way with its
surroundings is called an *isolated system* since the boundaries of such a closed system does not
allow either heat, work or matter to flow. An example of an isolated system is shown in Figure 1.2.

Open system
An open system is a region in space defined by a boundary across which heat, work and matter may
flow. Note that when the region within a prescribed boundary is studied the region is called a
control volume (open system). A schematic diagram of an engine (open system) is shown in Figure
1.3. The dashed line defines a control volume that surrounds the engine. Observe that air, fuel, and
exhaust gases cross the boundary.   In addition, we have heat flow to the cooling water and work
output from the crankshaft to the drive wheel.
Figure 1.4 a, b show examples of open systems. In figure 1.4a, the system the system is water
which flows through a region containing a water wheel. As the water turns the wheel, work flows

across the boundaries of the open system in the form of the shaft rotating. The water is the source of the shaft work. The boundaries of the system are fixed.

Fig. 1.4b consists of food being cooked on a simple stove: work is transferred to the system (the food in this case) from the stirrer whilst heat is supplied by means of wood fuel. Matter in the form of water or dough could be added and steam (matter accompanied by heat loss) leaves the system.
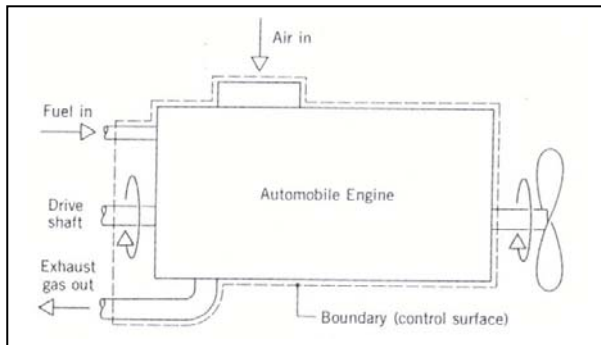

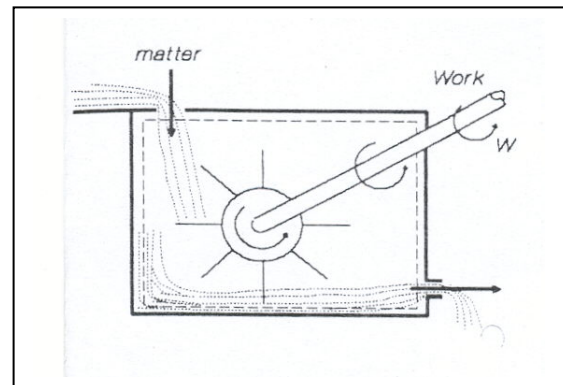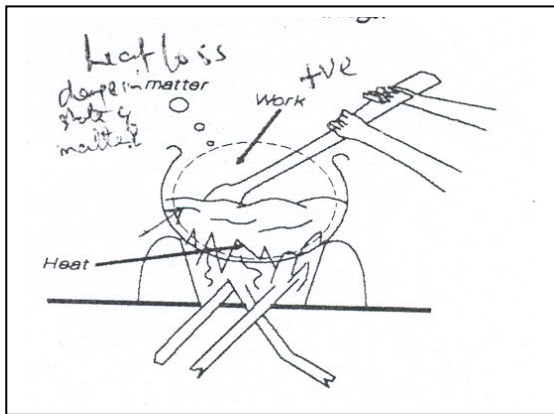Figure 1.3 An open system (an automobile engine)

Figure 1.4.   An open system (Food being cooked)

Concluding remarks.

Note that the definition of a system depends entirely on the observer's interest. Consider the case of a hot block of metal being dropped into a bowl of cold water, as shown in Figure 1.5.

If the interest is in the cooling of the block, then we choose it as the system and perhaps insert a thermometer into it to measure its temperature.   On the other hand, if we are interested in the heating of the water, then we select it (cold water) as the system and insert the thermometer in the water. If we consider the block, water and container as the system then we shall have a system, which is isolated from the surroundings.
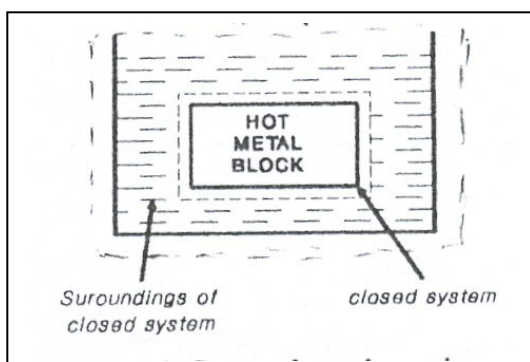
Figure 1.5.   System depends on the observer

1.1.2 Macroscopic and microscopic views of thermodynamics

Systems may be studied from the macroscopic or microscopic views. The macroscopic approach to thermodynamics is concerned with the gross or overall behaviour. This attention is sometimes called classical thermodynamics.   The microscopic approach, known as statistical thermodynamics, is concerned directly with the structure of matter. The macroscopic viewpoint is what is generally adopted in engineering thermodynamics but for understanding concepts are interpreted from the microscopic viewpoint.

1.2 PROPERTY, STATE, PROCESS, AND CYCLE

Property
To describe a system and predict its behaviour requires the knowledge of its properties and how these properties are related. *Properties* are macroscopic characteristics of a system such as mass, volume, energy, pressure, and temperature to which numerical values can be assigned at a given time without knowledge of the *history* of the system.

If X is a property then its value is independent of path, hence,

$$\int_1^2 dx \; = \; X_2 \; - \; X_1$$

- The above statement suggests that a property must be: macroscopic, measurable, have a single value that does not depend on how the condition of that property was attained.

Thermodynamics also deals with quantities that are not properties such as work and heat. A way to distinguish properties from non-properties will follow in due course.

State
The word state refers to the condition of a system as described by its properties.   Providing values of a subset of the properties can often specify the state.   The state can be specified by two thermodynamic properties. You should note that a doctor needs a few macroscopic measurements (temperature and pressure) to determine the patient's medical condition or state.

When a thermodynamic system is in motion the mechanical state, as specified by the velocity and position coordinates relative to a fixed point, must be specified. In the hydro-electric plant, for example, the source of energy is the potential energy of water in the dam or the kinetic energy of a river.
Process
When any of the properties of a system change, the state changes and the system is said to have undergone a *process*. A process is a transformation from one state to another.

If a system exhibits the same values of its properties at two different times, it is in the same state at those times. A system is said to be at *steady state* if none of its properties change with time.

Thermodynamic cycle

A *thermodynamic cycle* is a sequence of processes that begins and ends at the same state. At the conclusion of a cycle all properties have the same values they had at the beginning. Consequently, over the cycle the system experiences no net change of the state. Cycles that are repeated periodically play prominent roles many areas of application. For example, steam circulating through an electrical power plant executes a cycle.

At a given state each property has a definite value that can be assigned without knowledge of how the system arrived at that state. Therefore, the change in the value of a property as the system is altered from one state to another is determined solely by two end states and is independent of the particular way the change of state occurred. The change is independent of the details or history of the process. Conversely, we can say that if the value of a quantity is independent of the process between two states then that quantity is the change in a property.

- *A necessary and sufficient test for whether a quantity is a property or not*
  A quantity is a property if, and only if, its change in value between states is independent of that process. That is, if the value of a particular quantity depends on the details of the process, and not solely on the end states, that quantity cannot be a property.

1.2.1   Extensive and Intensive Properties

A property is called *extensive* if its value for an overall system is the sum of its values for the parts into which the system is divided. Mass, volume, energy are all examples of extensive properties. Extensive properties depend on the size or extent of a system. The extensive properties of a system can change with time as the system interacts with its surroundings.

Intensive properties are not additive. Their values are independent of the size or extent of change of a system and may vary from place to place within the system at any moment. Thus, intensive properties may be functions of both position and time, whereas extensive properties vary most with time. Specific volume, pressure and temperature are all intensive properties.

1.2.2   Phase and Pure Substance

The term *phase* refers to a quantity of matter that is homogeneous throughout in both chemical composition and physical structure. Homogeneity in physical structure means that the matter is all *solid*, or all *liquid*, or all *vapour* (or equivalently all gas).

A system can contain one or more phases. For example, a system of liquid water and water vapour contains *two* phases. When more than one phase is present, the phases are separated by *phase boundaries*. Gases like say oxygen and nitrogen can be mixed in any proportion to form a single phase. Oil and water, which are not miscible, form *two* liquid phases.

1.2.3   Equilibrium

If we isolate a system from its surroundings and watch for changes in its observable properties and there are no changes it may be concluded that the system is in equilibrium at the moment it was isolated. The system can be said to be at an *equilibrium state*.

When a system is isolated, it cannot interact with its surroundings; however, its state can change as a consequence of spontaneous events occurring internally as its intensive properties such as temperature and pressure, tend toward uniform values. When all such changes cease, the system is in equilibrium.

Hence, for a system to be in equilibrium it must be a single phase or consist of a number of phases that have no tendency to change their conditions when the overall system is isolated from its surroundings. At equilibrium, temperature is uniform throughout the system. Pressure can be regarded to uniform if gravity is neglected, otherwise pressure variation can exist, as in vertical column of liquid.

1.3 UNITS FOR MASS, LENGTH, TIME, AND FORCE

SI units: SI is the abbreviation for Systeme International d'Unites (International System of Units).

Table 1.2 SI Units for Mass, Length, Time, and Force

Quantity	Unit	Symbol
mass	kilogram	kg
length	metre	m
time	second	s
force	Newton	N

Table 1.3 SI Unit prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{12}	tera	T	10^{-2}	centi	c
10^{9}	giga	G	10^{-3}	milli	m
10^{6}	mega	M	10^{-6}	micro	μ
10^{3}	kilo	k	10^{-9}	nano	n
10^{2}	hecto	h	10^{-12}	pico	p

1.4 SPECIFIC VOLUME AND PRESSURE

The density, or local mass per unit volume, is an intensive property that may vary from point to point within a system. Thus, the mass associated with a particular volume V is determined in principle by integration $m = \int_V \rho \, dV$ and *not* simply as the product of density and volume.

The specific volume v is defined as the reciprocal of density, $v = 1/\rho$. It is the mass per unit mass. Like density, specific volume is an intensive property and may vary from point to point. SI units for density and specific volume are kg/m^3 and m^3/kg, respectively. However, they can be written in other units as well.

The thermodynamic pressure, P, of a system is defined as the total normal force, per unit area, exerted by the system within and at the boundary. In solids, the pressure is referred to as the normal stress.

The SI unit of pressure and stress is the pascal (Pa).

$$1 \text{ pasacl} = 1 \text{ N/m}^2$$

It is however convenient to work with multiples of the pascal: the kilopascal, the bar, and the megapascal.

$$1 \text{ kPa} = 10^3 \text{ N/m}^2$$
$$1 \text{ bar} = 10^5 \text{ N/m}^2$$
$$1 \text{ MPa} = 10^6 \text{ N/m}^2$$

Another unit of pressure that continues to be used is the atmosphere (atm.).

1 atm = 101 325 Pa = 1.013 25 bar = 760 mm Hg

The 760 mm Hg refers to the height of mercury column that the atmosphere can support; the force per unit area exerted by the mercury column is the atmospheric pressure.

The pressure of a system is usually measured relative to the atmosphere, and it is called "gauge pressure". The pressure used in thermodynamics is the absolute pressure and is defined by:

Absolute pressure = gauge pressure + atmospheric pressure

Gauge pressure below atmospheric pressure is gauge negative and is referred to as vacuum pressure.

$$p(\text{vacuum}) = p_{atm}(\text{absolute}) - p(\text{absolute})$$

The relationships among the various ways of expressing pressure measurements is shown in Fig. 1.6.
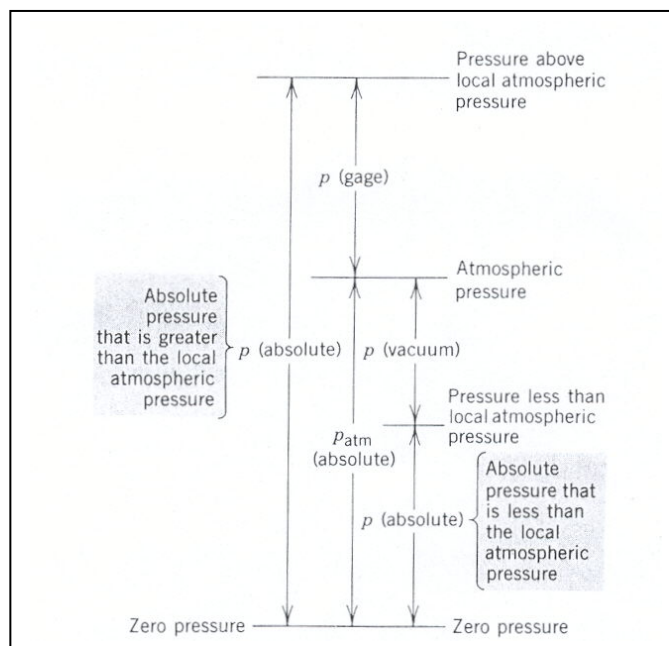

Fig. 1.6   Relationships between the absolute, atmospheric, gauge, and vacuum pressures.

Pressure Measurement
Two commonly used devices for measuring pressure are the manometer and the Bourdon tube. Manometers measure pressure differences in terms of the length of a column of liquid such as water, mercury, or oil. The manometer shown in Fig. 1.7 has one end open to the atmosphere and the other attached to a closed vessel containing a gas at uniform pressure. The difference between the gas pressure and that of the atmosphere is
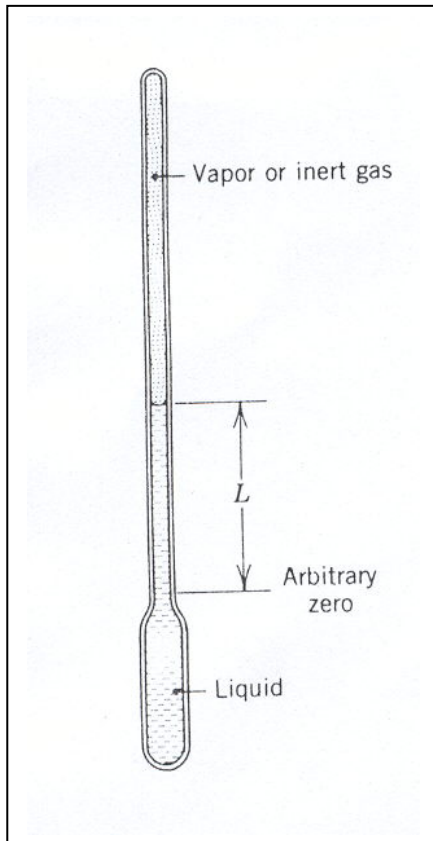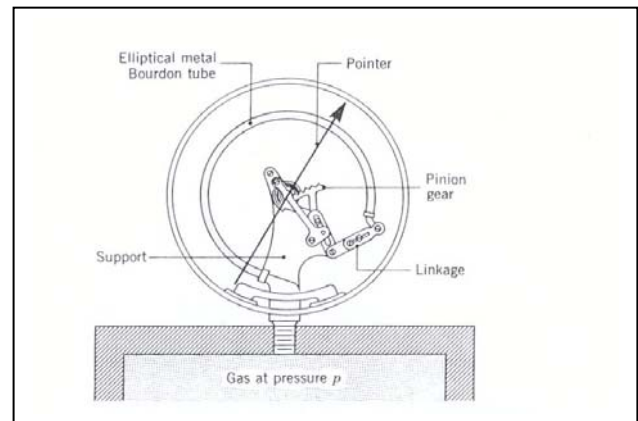
$$p = p_{atm} - \rho g L$$

Fig. 1.7   Pressure measurement by a monometer

Figure 1.8 Bourdon tube

A Bourdon tube gauge is shown in Fig. 1.8. The figure shows a curved tube having an elliptical cross section with one end attached to the pressure to be measured and the other end connected to a pointer by a mechanism. When the fluid under pressure fills the tube, the elliptical section tends to become circular, and the tube straightens. This motion is transmitted by the mechanism to the pointer. By calibrating the deflection of the pointer for known pressures, a graduated scale can be determined from which any applied pressure can be read in suitable units. Because of its construction, the Bourdon tube measures the pressure relative to the pressure of the surroundings existing at the instrument. Accordingly, the dial reads zero when the inside and outside of the tube are at the same pressure.

1.5 TEMPERATURE

If two bodies are kept together for a sufficiently long period, experience shows that the bodies appear to attain the same degree of hotness and the changes in their resistance also cease. This state is defined as the state of thermal equilibrium, and the two bodies are then said to have the same temperature. Temperature is, therefore, *a property of a system which determines whether or not they are in thermal equilibrium with other systems or their surroundings*.

1.5.1   Zeroth Law of Thermodynamics

It states that two systems in thermal equilibrium with a third system individually are in equilibrium with each other. The law is tacitly assumed in every measurement of temperature. Thus, if we want to know if two bodies are at the same temperature, it is not necessary to bring them together and see whether their observable properties change with time. It is necessary

only to see if they are individually in thermal equilibrium with the third body. The third body is usually a *thermometer*.

1.5.2 Thermometers

Any body with at least one measurable property that changes as its temperature changes can be used as a thermometer. Such a property is called a *thermometric* property. The particular substance that exhibits changes in the thermometric property is known as a *thermometric substance*.

A familiar device for temperature measurement is the liquid-in-glass thermometer pictured in Fig. 1.9, which consists of a glass capillary tube connected to a bulb filled with a liquid such as mercury or alcohol and sealed at the other hand. The space above the liquid is occupied by vapour of the liquid or an inert gas. As temperature increases, the liquid expands in volume and rise in the capillary. The length L of the liquid in the capillary depends on the temperature. Accordingly, the liquid is the thermometric substance and L is the thermometric property.
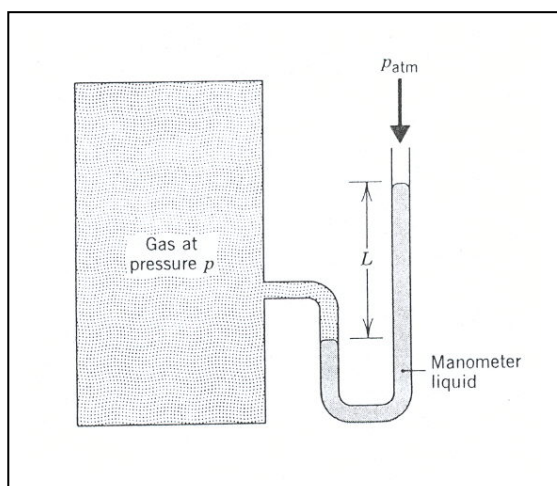

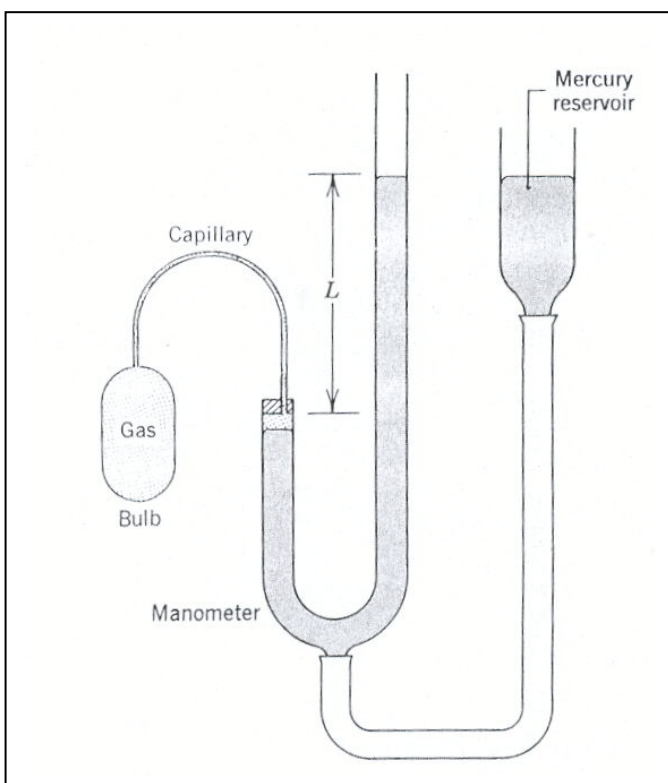Fig. 1.9 Liquid-in-glass thermometer

Figure 1.10 Constant-volume gas thermometer

The gas thermometer shown in Fig. 1.10 is so exceptional in terms of precision and accuracy that it has been adopted internationally as the standard instrument for calibrating other thermometers. The thermometric substance is the gas, and the thermometric property is the pressure exerted by the gas. As shown in the figure, the gas is contained in a bulb, and the pressure exerted by it is measured by open-tube mercury thermometer. As the temperature increases, the gas expands, forcing the mercury up in the open tube. The gas is kept at constant volume by raising or lowering the reservoir. Gas thermometers require elaborate apparatus and

are large, and hence they are responding devices that demand painstaking experimental procedures.

Thermocouples
Sensors known as thermocouples are based on the principle that when two dissimilar metals are joined, a thermal electromotive force, t_{emf}, that is primarily a function of temperature will exist in a circuit. If two different metals, or semiconductors, are connected with their junctions held at different temperatures, as shown in Fig. 1.11, the thermal electromotive force develops.
The relationship between the thermal electromotive force and temperature may be represented by the cubic equation:

$$t_{emf} = a + bt + ct^2 + dt^3$$

where a, b, c, and d are constants which depend on the materials. An example of a suitable pair is copper-constantan. Thermocouples are suitable for measuring temperatures which are changing rapidly with time.
In the above example the thermometer is the thermocouple and the thermometric property is the thermal electromotive force.
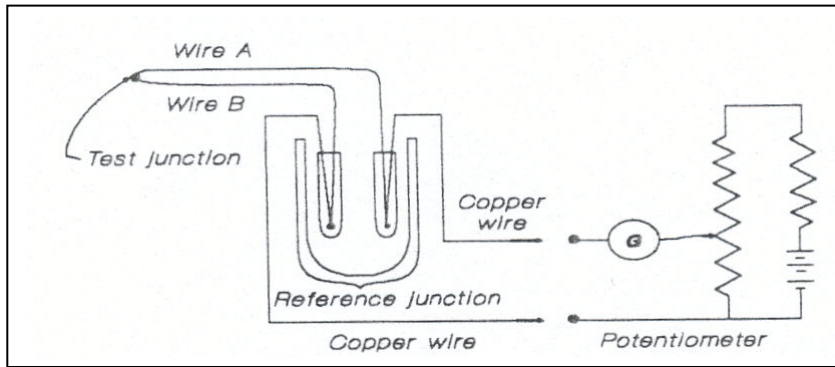

Fig. 1.11   Thermocouple of wires A and B

Absolute Temperature Scale and calibration of Thermometers
An absolute temperature scale may be established as follows:

Let X represent the value of a thermometric property. Then for a given thermal equilibrium state between the system and the thermometer we choose a linear temperature relation such that T(X) = aX, where *a* is a constant.

We therefore two arbitrary temperatures by the relation:
$$\frac{T(X_1)}{T(X_2)} = \frac{X_1}{X_2}$$

To ensure that temperatures measured by different thermometers are comparable, an internationally accepted reference system is used to calibrate all thermometers. The temperature at which ice, liquid water and water vapour coexist in equilibrium, cal;led the triple point of water, is chosen as the fixed-point for all thermometers and the temperature is arbitrary chosen as 273.16 K. Since all thermometers will indicate different values of temperatures for systems, which are not at the triple point because of the different characteristics of the thermometric properties, the temperature at other point is calculated as follows:

$$T(X) = 273.16 \frac{X}{X_0}$$

where X_0 is the value of the thermometric property at the fixed point and X that at the temperature T.

1.5.4   Celsius, Rankine, and Fahrenheit Scales

The Celsius temperature scale uses the unit degree Celsius (^{0}C), which has the same magnitude as the Kelvin. Thus, temperature differences are identical on both scales. However, the zero point on the Celsius scale is shifted to 273.15 K, as shown by the following relationship between the Celsius temperature and the Kelvin temperature

$$T(^0C) \;=\; T(\text{K}) - 273.15 \tag{1}$$

Thus, from equation (1) we see that on the Celsius scale the triple point of water is 0.01 ^{0}C and 0 K corresponds to $-273.15\ ^0$C.

The temperature of at the steam point, 373.15 K is 100.00 ^{0}C. Accordingly, there are 100 Celsius degrees in this interval of 100 kelvins.

The Rankine scale, the unit of which is the degree rankine (^{0}R), is proportional to the Kelvin temperature according to

$$T(^0R) = 1.8\,T(K) \tag{2}$$

The Rankine scale is also an absolute temperature scale.

The Fahrenheit scale is related to the Rankine scale by the relation

$$T(^0F) \;=\; T(^0R) - 459.67 \tag{3}$$

Substituting Eqs. 1 and 2 into Eq. 3, it follows that

$$T(^0F) \;=\; 1.8\,T(^0C) + 32 \tag{4}$$

Equation (4) shows that the Fahrenheit temperature of the ice point (^{0}C) is 32 ^{0}F and the steam point (100 ^{0}C) is 212 ^{0}F.

TUTORIAL PROBLEMS

1. Determine the weight, in newtons, of an object whose mass is 10 kg at a location where the acceleration due to gravity is 9.81 m/s^2.

2. An object occupies a volume of 25 ft^3 and weighs 20 lbf at a location where the acceleration of gravity is 31.0 ft/s^2. Determine its weight, in lbf, and its average density, in lbf/ft^3, on the moon, where g = 5.57 ft/s^2.

3. A spring stretches 0.2 cm per Newton of applied force. An object is suspended from the spring and a deflection of 3 cm is observed. If g = 9.81 m/s^2, what is the mass of the object, in kg?

4. The following table lists temperatures and specific volumes of water at two pressures.

P = 0.1 MPa		P = 0.12 MPa	
T/(^{0}C)	V/m^{3}kg	T/(^{0}C)	V/m^{3}kg
200	2.172	200	1.808
240	2.359	240	1.965
280	2.546	280	2.120

Data encountered in solving problems often do not exactly on the grid values provided by property tables and linear interpolation between adjacent tables entries becomes necessary. Using the data provided, estimate

(a) the specific volume at $T = 200$ ^{0}C, $p = 0.113$Mpa.
(b) the temperature at p = 0.12 MPa, $v = 1.85$ m^3/kg in ^{0}C
(c) the temperature at p = 0.11 MPa, $v = 2.20$ m^3/kg, in K

5. Write out the meanings of the following terms: system, control volume, property, intensive property, equilibrium state, process, thermodynamic cycle, phase, adiabatic process, closed system, isolated system, steady state, extensive property, pure substance, Zeroth law of thermodynamics.

6. Determine the gauge pressure, in bars, equivalent to a manometer reading 1 cm of

     (a)   water (density = 1000 kg/m^3).
     (b)   Mercury (the density of mercury is 13.59 times that of water.

7. Determine the absolute pressure exerted on an object submerged 1000 m below the surface of the sea, in bars. The density of seawater is 1020 kg/m^3 and the acceleration of gravity is 9.7 m/s^2. The local atmospheric pressure is 0.98 bar.

8. Convert the following temperatures from ^{0}F to ^{0}C:

     (a)   70 ^{0}F   (b) 0 ^{0}F   (c) -30 ^{0}F   (d) 500 ^{0}F   (e) 212 ^{0}F

A.   *ANSWER TRUE OR FALSE in Questions 9 – 14.*

9.   When a System undergoes a thermodynamics cycle, the change in internal energy is positive

10. A perpetual motion machine of the first kind is possible to invent

11. For a closed system undergoing a constant pressure process the heat transfer is given by the change in the enthalpy of the system.

12. For a closed system undergoing an adiabatic process, there is decrease in the internal energy of the system.

13. Enthalpy is particularly important for open systems.

14. Heat, work and internal energy have the same units and therefore they are all properties of thermodynamics systems.

B.   Each line in the table 1 below gives information about the same process for a closed system. Every entry has the same energy units. Fill in the blank spaces in the table for the different paths of that process for Q7 to Q12.

PATH	Q	W	U_1	U_2	$\underline{\Delta U}$
A	+50	-20	30		
B		-30			
C		-40			
D		-50			
E		-60			

C.   Select from Table 2 the letter corresponding to the expression that best completes each of the following statements.

15. The internal energy of an ……… remains unchanged

16. According to the First Law of Thermodynamics, the total amount of energy is ------------ in all transformations and transfers.

13. The objective of a ----------- is to provide energy for industrial processes or dwelling units at elevated temperatures.

14. The thermal efficiency of a power cycle can never be ------------------ than unity (100%)

15. The value of ---------- depends on the details of the process and not just the end states.

16. The performance of a ---------------- can be described as the ratio of the amount of energy received by a system undergoing a cycle from a cold space to the net work transfer of energy into the system to accomplish this effect.

17. For a simple compressible substance undergoing an ---------- process the energy transfer by heat is equal to the change in enthalpy.

18. ------------ is the capacity to do work.

TABLE 2

A.	Energy	F.	Heat pump	K.	Closed system
B.	Work	G.	Refrigeration cycle	L.	Isolated system
C.	Less	H.	Power cycle	M.	Conserved
D.	Greater	I.	Internal energy	N.	Isothermal
E.	Adiabatic process	J.	Reversible process	O.	Property

2 ENERGY AND THE FIRST LAW OF THERMODYNAMICS

2.0 INTRODUCTION

Energy is simply defined as the capacity to do work. It is required for all aspects of productive and social activities. Energy is expended in agriculture for land clearing, planting, plant protection, harvesting and processing of produce; energy in the form of petrol and diesel oil is required for automobiles and farm tractors; energy in the form of sunshine is required to dry agricultural produce; nuclear energy is used to generate electricity. In whatever form of application, the essential practical characteristic of energy is that it can be *transformed* from one form to another and *transferred* between systems by *work* and *heat* transfer. Note that the total amount of energy is *conserved* in all transformations and transfers. The purpose of this chapter is to organise the above ideas into suitable forms for engineering analysis.

2.1 MECHANICAL CONCEPTS OF ENERGY

2.1.1 Work and Kinetic Energy

The curved line in Fig. 2.1 represents the path of a body of mass m (closed system) moving relative to the x-y coordinate frame shown. Let us consider the body as it moves from $s = s_1$, where the magnitude of its velocity is V_1, to $s = s_2$, where its velocity is V_2. If we assume that the only interaction between the body and its surroundings involves the force F, then by Newtons 2nd Law, the magnitude of the component F_s is related to the change in the magnitude of V by
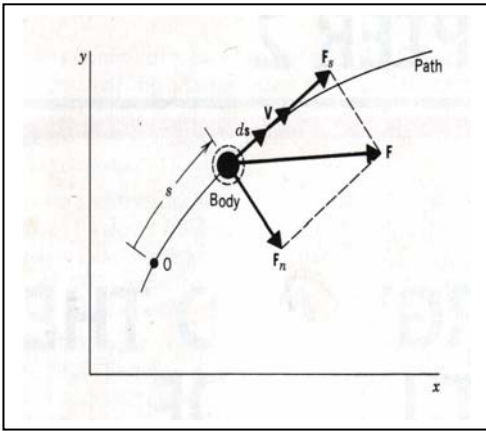

Fig. 2.1 Forces acting on a moving system

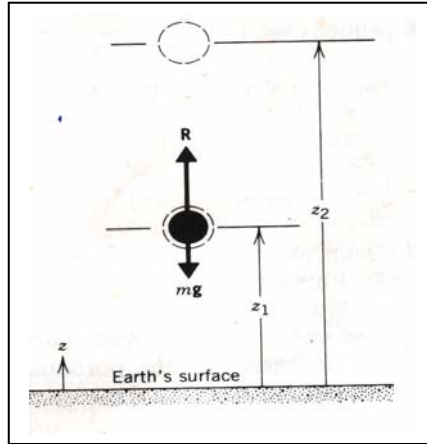**Fig. 2.2** Illustration of potential energy concept

$$F_s = m\frac{dV}{dt} = m\frac{dV}{ds}\frac{ds}{dt},$$

(2.1)

where, $V = ds/dt$. Rearranging Eq. 2.1 and integrating from s_1 and s_2 gives

$$\int_{V_1}^{V_2} mV\,dV = \int_{s_1}^{s_2} F_s\,ds$$

(2.2)

The integral on the left of Eq. 2.2 is evaluated as follows:

$$\int_{V_1}^{V_2} mV\,dV = \frac{1}{2}mV^2\Bigg]_{V_1}^{V_2} = \frac{1}{2}m\left(V_2^2 - V_1^2\right)$$

(2.3)

The quantity $\frac{1}{2}mV^2$ is the *kinetic energy*, KE, of the body. Kinetic energy is a scalar quantity. The *change* in kinetic energy, ΔKE, of the body is $\Delta KE = KE_2 - KE_1 = \frac{1}{2}m(V_2^2 - V_1^2)$.

The integral on the right side of Eq. 2.2 is the work of the force F_s as the body moves from s_1 to s_2 along the path. Work is also a scalar quantity.

Combining Eqs. 2.2 and 2.3 we have

$$\frac{1}{2}m(V_2^2 - V_1^2) = \int_{s_1}^{s_2} F_s \cdot ds \qquad (2.4)$$

Equation 2.4 states that the work of the resultant force on the body equals the change in its kinetic energy. When the resultant force accelerates the body, the work done on the body can be considered a *transfer* of energy *to* the body, where it is *stored* as the kinetic energy.

Kinetic energy can be assigned a value knowing only the mass of the body and the magnitude of its instantaneous velocity relative to a specified coordinate frame, without regard for how this velocity was attained. Hence, kinetic energy is a *property* of the body. Since kinetic energy is associated with the body as a whole, it is an *extensive* property of the body.

The units of kinetic energy are the same as that of work. The SI unit of work is the Newton-metre, N m, called the joule, J.

2.1.2   Potential Energy

Consider a body of mass m that moves vertically from an elevation z_1 to an elevation z_2 relative to the surface of the earth, as shown in Fig. 2.2. Two forces are shown acting on the system: a downward force due to gravity with magnitude mg and a vertical force with magnitude ***R*** representing the resultant of all *other* forces acting on the system.

In accordance with Eq. 2.4, the total work equals the change in kinetic energy. That is,

$$\frac{1}{2}m(V_2^2 - V_1^2) = \int_{z_1}^{z_2} R\,dz \quad - \quad \int_{z_1}^{z_2} m\,g\,dz \qquad (2.5)$$

Assuming acceleration due to gravity to be constant we obtain

$$\frac{1}{2}m(V_2^2 - V_1^2) + m\,g(z_2 - z_1) = \int_{z_1}^{z_2} R\,dz \qquad (2.6)$$

The quantity $m\,g\,z$ is called the gravitational potential energy. Like kinetic energy, potential energy is an *extensive property*.

Equation 2.6 states that when a resultant force causes the elevation of a body to be increased, the body to be accelerated, or both, the work done by the force can be considered a *transfer* of energy *to* the body, where it is stored as gravitational potential energy and/or kinetic energy. If we consider a body on which the only force acting is that due to gravity, the right side of equation (2.6) vanishes and it reduces to

$$\frac{1}{2}m(V_2^2 - V_1^2) + m\,g(z_2 - z_1) = 0 \qquad (2.7)$$

or

$$\frac{1}{2}mV_2^2 + mgz_2 = \frac{1}{2}mV_1^2 + mgz_1 \qquad (2.8)$$

17

Equation 2.8 also illustrates that energy can be transformed from one form to another: For the object falling under the influence of gravity only, the potential energy would decrease as the kinetic energy increases by an equal amount.

2.2   ENERGY TRANSFER BY WORK

The work W done *by*, or *on*, a system evaluated in terms of macroscopically observable forces and displacements is

$$W \ = \ \int_{s_1}^{s_2} F_s \cdot ds \tag{2.7}$$

This definition is important in thermodynamics however; a broader interpretation of thermodynamic definition of work is now presented.

A particular interaction is categorised as work interaction if it satisfies the following criterion: *Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight.* Note that the raising of a weight is, in effect, force acting through a distance. The test of whether a work interaction has taken place is not that the elevation of a weight has actually taken place, or that a force has actually acted through a distance, but that the sole effect *could have been* an increase in the elevation of a weight.

Work is a means of transferring energy. Accordingly, the term work does not refer to what is being transferred between systems or what is stored within the system. Energy is transferred and stored when work is done.

2.2.1   Sign convention and notation

$W > 0$: work is done *on* the system
$W < 0$: work is done *by* the system

The value of W depends on the details of the interactions taking place between the system and surroundings during a process and not just the initial and the final states. Hence, work is *not a property* of a system and its differential is *inexact* and it is expressed as δW, but the differential of every property is exact and is represented by a total derivative.

2.2.2   Expansion or Compression Work

Let us evaluate the work done by the closed system shown in Fig 2.3 consisting of a gas (or liquid) contained in a piston-cylinder assembly as the gas expands. During the process the gas pressure exerts a normal force on the piston. Let p denote the pressure acting at the interface between the gas and the piston. The force exerted by the gas on the piston is simply the product pA, where A is the area of the piston face. The work done by the system as the piston is displaced a distance dx is

$$\delta W \ = - \ p \, A \, dx = \ - \ p \, dV \tag{2.8}$$

Since dV is positive when the volume increases, the work at the moving boundary is negative when the gas expands. For compression, dV is negative, and so the work done from Eq. 2.8 is positive. For a change in volume from V_1 to V_2, the work is obtained by integrating Eq. 2.8.

$$W \ = \ - \int_{V_1}^{V_2} p \, dV \tag{2.9}$$

Although Eq. 2.9 is derived for the case of a gas (or liquid) in a piston-cylinder assembly, it is applicable to systems of any shape provided the pressure is uniform with position over the moving boundary. To perform the integral of Eq. 2.9 requires a relationship between the gas pressure at the moving boundary and the system volume. Where there is the lack of pressure-volume relationship to merit the application of Eq. 2.9, the work can be determined from an energy balance (See section 2.5).

2.2.3 Work in Quasi-equilibrium Expansion or Compression processes

The quasi-static work given by equation (2.9) can be obtained from a graph of the process on a p-V diagram as shown in Fig. 2.4. The work done W is the area under the curve on the p-V diagram. The curve is obtained by plotting the variation of pressure with volume during the process and it depends on the details of the process as defined by the particular curve and not just on the end states hence work is **not** a property.
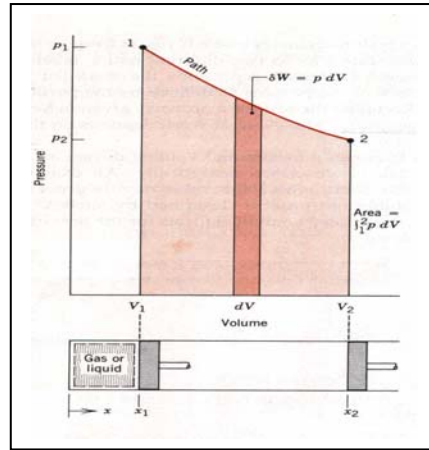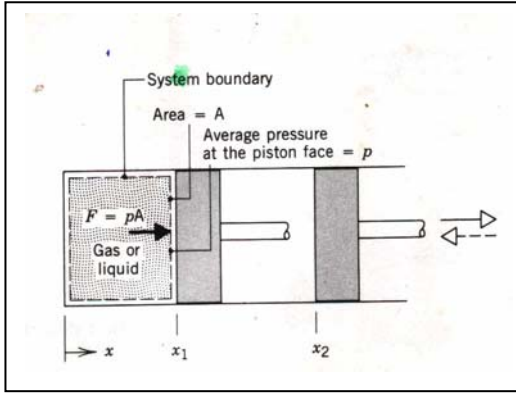

Fig.2.3 Expansion or compression of a gas or liquid   **Fig. 2.4** Work of quasi-equilibrium process

The relationship between pressure and volume during an expansion or compression process also can be described analytically. An example is provided by the expression $pV^n = $ constant, where the value of n is a constant for the particular process. A quasi-equilibrium process described by such an expression is called a *polytropic process*.

Note that
$$W = -\int_{V_1}^{V_2} p\, dV = -\int_{V_1}^{V_2} \frac{\text{constant}}{V^n} dV = -\text{constant}\left(\frac{V_2^{1-n} - V_1^{1-n}}{1-n}\right) \qquad (2.10)$$

The constant in this expression can be evaluated at either end state: **i.e.** constant $= p_1 V_1 = p_2 V_2$. The work expression then becomes

$$W = -\frac{\left(p_2 V_2^n\right)V_2^{1-n} - \left(p_1 V_1^n\right)V_1^{1-n}}{1-n} = \frac{p_2 V_2 - p_1 V_1}{n-1} \qquad (2.11)$$

This expression is valid for all values of n except $n = 1$. The case $n = 0$ is also treated under special cases (See 2.2.4).

2.2.4 *Special cases of the polytropic process:*

(a)   The case of $n = 1$: In this case, the pressure-volume relationship is $pV = $ constant. The work done is

$$W = -\text{constant}\int_{V_1}^{V_2}\frac{dV}{V} = -(\text{constant})\ln\frac{V_2}{V_1} = -(p_1V_1)\ln\frac{V_2}{V_1} \qquad (2.12)$$

(b)   The case of $n = 0$: The pressure-volume relation reduces to $p = $ constant, and the integral becomes

$$W = -p(V_2 - V_1) \qquad (2.13)$$

(c)   The pressure-volume relation for some processes may also be of the form $p = aV + b$. The work expression, in this case, is given by

$$W = -\int_{V_1}^{V_2}pdV = -\int_{V_1}^{V_2}(aV + b)dV = -\left(a\frac{V^2}{2} + bV\right)_{V_1}^{V_2} \qquad (2.14)$$

By inserting the upper and lower limits into Eq. 2.14, the wok done is evaluated. It can be shown that the expression for the work done reduces to $\boxed{W = -\left(\frac{p_1 + p_2}{2}\right)(V_2 - V_1)}$ where the subscripts refer 1 and 2 refer to the initial and final states respectively. The latter expression is equivalent to the area under the p-V diagram for the process 1-2.

It must be noted that in whatever process, the work done can be evaluated as the area under the p-V diagram. The area interpretation of work in a quasi-equilibrium expansion or compression process allows for a simple demonstration of the idea that work depends on the process and therefore it is not a property. This can be confirmed with reference to Fig. 2.5.
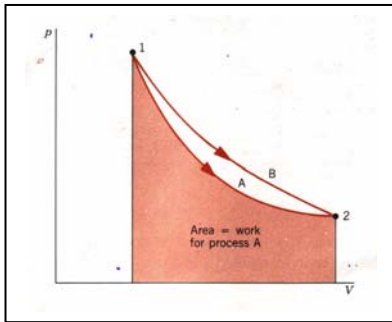

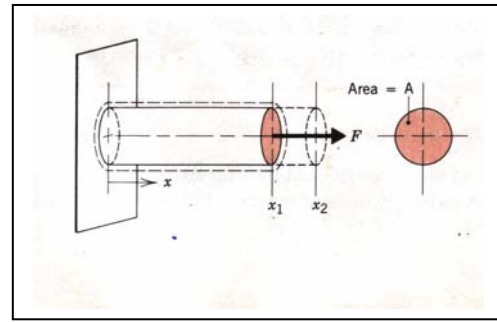Fig. 2.5 Illustration that work depends of process   **Fig. 2.6**. Elongation of solid bar

2.2.4   Further examples of work in quasi-equilibrium processes

Extension of a Solid Bar: Consider a system of a solid bar, as shown in Fig. 2.6. The bar is fixed at $x = 0$, and a force F is applied at the other end. The force $F = \sigma A$, where A is the cross-sectional area of the bar and σ the normal stress acting at the end of the bar. The work done as the end of the bar moves a distance dx is given by $\boxed{\delta W = +\sigma A\,dx}$. The plus sign is required because work is done *on* the bar when dx is positive.

Stretching of a Liquid Film: Fig. 2.7 shows a system consisting of a liquid film suspended on a wire frame. The two surfaces of the film support the thin liquid layer inside by the effect of *surface tension*. Denoting the *surface tension acting at the movable wire* by τ, the force F indicated on the

figure can be expressed as $F = 2l\tau$, where the factor 2 is introduced because two film surfaces act at the wire. If the movable wire is displaced by dx, the work done is given by $\boxed{\delta W = +2l\tau\,dx}$. The plus sign is required because work is done *on* the system when dx is positive.
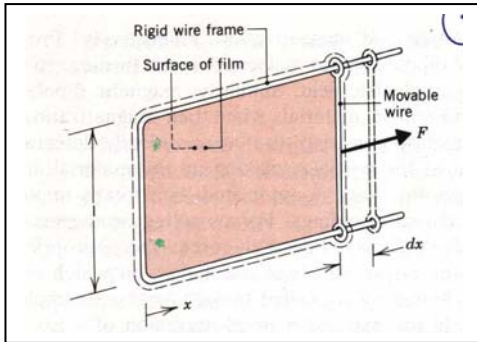

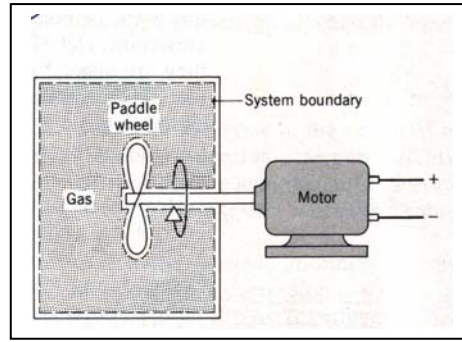**Fig. 2.7**. Stretching of a liquid film

Fig. 2.8. Power transmitted to a gas by a paddle wheel

Power Transmitted by a shaft: Consider a shaft rotating with angular velocity ω and exerting a torque τ on its surroundings. The torque can be expressed in terms of a tangential force F_t and radius R: $\tau = F_t R$. The velocity at the point of application of the force is V = Rω, where ω is in radians per unit time.

The rate of energy transfer by work is called *power* and is denoted by $\dot{W}$. The rate of energy transfer by work is the product of the force and the velocity at the point of application of the force

$$\dot{W} = F \cdot V \tag{2.15a}$$

Therefore, the expression for the *power* transmitted from the shaft to the surroundings is given by

$$\dot{W} = -F_t V = -(\tau/R)(R\omega) = -\tau\omega \tag{2.15b}$$

A related case involving a gas stirred by a paddle wheel is shown in Fig. 2.8.

Electrical work: Shown in Fig. 2.9 is a system consisting of an electrolytic cell. The cell is connected to an external circuit through which an electric current is flowing. Work is done on the system whenever electrons cross the boundary of the system in response to the force associated with an electric field. The flow of electrons is manifested as the current, i, driven by the electric potential difference, E, existing across the terminals a and b. It can be envisioned that the current is supplied to an electric motor that lifts a mass in the surroundings.

The rate at which work is done, or power, is $\boxed{\dot{W} = Ei}$.

Since the current i equals dZ/dt, the work can be expressed in differential form as $\boxed{\delta W = E\,dZ}$.

When the power is evaluated in terms of the watt, and the unit of current is the ampere, the unit of electric potential is the volt, defined as 1 watt per ampere.
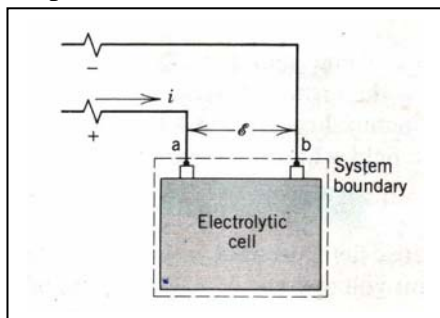

Fig. 2.10 Electrolytic cell used to discuss electrical work

2.3   ENERGY TRANSFER BY HEAT

The quantity denoted by *Q* accounts for the amount of energy transferred to a system during a process by means other than work. Such an energy transfer is induced only as a result of a temperature difference between the system and its surroundings and occurs only in the direction of decreasing temperature. This means of energy transfer is called *energy transfer by heat*.

The symbol *Q* denotes an amount of energy transferred across the boundary of a system in a heat interaction with the system's surroundings. Heat transfer *into* a system is taken to be *positive*, and heat transfer *from* the system is taken as *negative*.

2.3.1   Sign convention for Q

$Q > 0$: heat transfer *to* the system
$Q < 0$: heat transfer *from* the system

Like work, heat is not a property and its differential is δQ. The amount of energy transfer by heat for a process is given by the integral

$$Q = \int_1^2 \delta Q \ = Q_{12}$$

The principal modes of heat transfer are conduction, convection and radiation.

2.3.2. Heat transfer modes

Energy transfer by conduction can take place in solids, liquids, and gases. Fourier's Law quantifies the time rate of energy transfer by conduction macroscopically. As an illustration, consider the system shown in Fig 2.11, in which the temperature distribution is T(x). The time rate at which energy enters the system by conduction through a plane area A perpendicular to the coordinate x is given by Fourier's law as

$$\dot{Q} = -k A \frac{dT}{dx} \qquad\qquad\qquad (2.16a)$$

The proportionality factor *k*, which may vary with position, is a property of the material called the thermal conductivity. The minus in Eq. 2.17 is a consequence of the requirement that energy flow is in the direction of decreasing temperature.

Thermal radiation is emitted by matter as a result of the changes in the electronic configurations of the atoms or molecules within it. Unlike conduction, thermal radiation requires no intervening medium to propagate and can even take place in a vacuum. Solid surfaces, gases, and liquids all emit, absorb, and transmit thermal radiation to varying degrees. The rate at which energy is emitted, $\dot{Q}_e$, *from* a system with a surface A is quantified macroscopically by a modified form of the *Stefan-Boltzmann law* as

$$\dot{Q}_e = \varepsilon \sigma A T_s^{\ 4} \qquad\qquad\qquad (2.16b)$$

T$_s$ is the temperature of the surface, ε is a property of the surface that indicates how effectively the surface radiates (0 ≤ ε ≤ 1) and σ is the Stefan-Boltzmann constant and its value is 5.67 x 10^{-8} W/(m^2 K^4).

Energy transfer between a solid surface at one temperature and an adjacent moving gas or liquid at another temperature is called convection. The rate of energy transfer from the system to the fluid can be quantified by the following empirical expression called the Newton's Law of cooling

$$\dot{Q} = h\,A\,(T_b - T_f) \tag{2.16c}$$

Refer to Fig. 2.12 for the schematic representation of this mode of energy transfer by heat. The proportionality factor in the Newton's law of cooling is called the *heat transfer coefficient* and is *not* a thermodynamic property. It is an empirical parameter that incorporates into heat transfer relationship the nature of the fluid flow pattern near the surface, the fluid properties, and the geometry of the system.
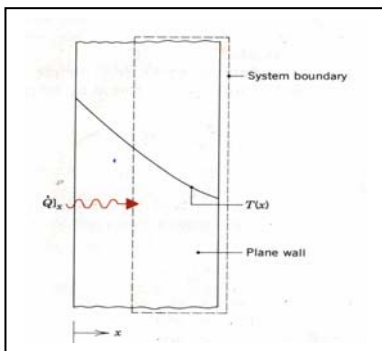

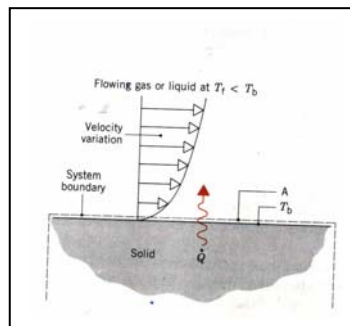**Fig. 2.11** Illustration of Fourier's conduction law   **Fig. 2.12** Illustration of Newton's Law of cooling

2.4   FIRST LAW OF THERMODYNAMICS

Under this section, the various forms of the First Law Thermodynamics (Non flow energy equation, steady flow energy equation and the general energy equation) will be studied and applied to solve thermodynamic problems.

2.4.1   Conservation of Energy and Matter

The Principle of Conservation of Energy states "Energy is neither created nor destroyed"

The Principle of Conservation of Matter states "Matter is neither created nor destroyed"

2.4.2   First Law of Thermodynamics for Closed Systems

Because of the historical association of the First Law with heat engine cycles, namely cycles producing a net amount of work on the surroundings, the law is usually stated in the form:

When any closed system is taken through a cycle, the net work delivered to the surroundings is proportional to the net heat taken from the surroundings.

However, the converse is also true, namely:

When a closed system is taken through a cycle, the work done on the system by its surroundings is proportional to the net heat delivered to the surroundings.

In its latter form, the statement refers to heat pump and refrigerator cycles.

Corollary 1

There exists a property of a closed system such that a change in its value is equal to the sum of the net heat and work transfers during any change of state. This property is the total energy, E, of the system.

Thus, the First Law can be stated mathematically as

$$\sum_1^2 \delta Q + \sum_1^2 \delta W = \Delta E \tag{2.17}$$

However, in thermodynamics we are often concerned with stationary closed systems in which case the total energy, E, equals the internal energy, U, of the system. The First Law is, therefore, expressed mathematically in a form referred to as the *non-flow energy equation* (NFEE)

$$Q_{12} + W_{12} = \Delta U = U_2 - U_1, \tag{2.18}$$

where, $\sum_1^2 \delta Q = Q_{12}$ and $\sum_1^2 \delta W = W_{12}$.

Equation 2.17 may also be expressed in the differential form as

$$\delta Q + \delta W = dU \tag{2.19}$$

The first law of thermodynamics establishes the internal energy as a property of the system. As a property, the internal energy of a closed system in any given state would have only one value independent of the process through which the system arrived at the state.

For an isolated system the heat and work transfer are zero. It follows from equation (2.19), that the change in internal energy must be zero, which means that the internal energy of an isolated system is constant.

Corollary 2

The internal energy of a closed system remains unchanged if the system is isolated from the surroundings.

That for isolated system $W = 0$, $Q = 0$ and it implies that $U_1 = U_2$.

All what happens in this case is spontaneous redistribution of energy between parts of the system, which continues until a state of equilibrium is reached; there is no change in total quantity of energy within the system during the process. This corollary is the Principle of Conservation of Energy.

2.4.3   First Law for a cyclic Process

When a system undergoes a cycle all the thermodynamic properties, including internal energy; return to their initial values. The change in internal energy is, therefore, zero for the cyclic process. It follows from the First Law Thermodynamics that

$$\sum \delta Q + \sum \delta W = 0 \quad \text{or} \quad \oint \delta Q = - \oint \delta W . \tag{2.20}$$

That is the cyclic sum of the heat transfers and the work transfers should be zero. We can deduce from Eq. 2.20 that if a net amount of heat is not supplied by the surroundings during a cycle, no net amount of work can be delivered by the system. One can conclude from Equation (2.20) that whenever a system operates in a cycle and the net heat transfer equals zero, then the net work transfer must also be zero. A machine that operates in contravention to this conclusion is impossible. Such a machine is described as *perpetual motion machine of the first kind*, which is a machine that will produce a continuous supply of work without absorbing energy from the surroundings. It is, therefore, impossible for a closed system to operate in a cycle and do a net amount of work without heat being transferred to the system and, therefore, it is impossible for a perpetual motion machine of the first kind to exist. This fact is presented as the third corollary of the First Law:

Corollary 3

A perpetual motion machine of the first kind is impossible

However, it is always possible to devise a machine to deliver a limited quantity of work without requiring a source of energy from the surroundings. For example, a gas compressed behind a piston will expand and do some amount of work at the expense of internal energy of the gas. Note that such a device <u>cannot</u> produce work <u>continuously</u>.

2.4.4 Energy analysis of cycles

In this section, the energy concepts developed are illustrated further by application to systems undergoing cycles. Recall that when a system at a given initial state goes through a sequence of processes and finally returns to that state, the system has executed a thermodynamic cycle. In this section, cycles are considered from the point of view of conservation of energy.

The energy balance for any system undergoing a thermodynamic cycle takes the form

$$\Delta E_{cycle} = Q_{cycle} + W_{cycle},$$
(2.21)

where, Q_{cycle} and W_{cycle} represent the *net* amounts of energy transfer by heat and work, respectively, for the cycle. Since the system is returned to its initial state after the cycle, there is *no* net change in its energy. Therefore, Eq. 2.21 reduces to $Q_{cycle} = -W_{cycle}$ (as Eq. 2.20)

In a power cycle, the system delivers a net work transfer of energy to their surroundings during each cycle for a net heat transfer to the system. The performance of a system undergoing a power cycle can be described in terms of the extent to which the energy added by heat Q_{in}, is *converted* to a net work output, $W_{cycle.}$ The extent of the energy conversion from heat to work is expressed by the following ratio commonly called the *thermal efficiency*:

$$\eta = -\frac{W_{cycle}}{Q_{in}} \text{ (Power cycle)}$$
(2.22a)

The negative is introduced to make the thermal efficiency positive since W_{cycle} is the net work done by the system on its surroundings and is considered negative according to the sign convention of work that we have adopted in this course.

For refrigeration cycles and heat pump, Q_{in} is transferred by heat into the system undergoing the cycle from a cold body, and Q_{out} is the energy discharged by heat transfer from the system to the hot body. To accomplish these energy transfers requires a net work input, W_{cycle}. The performance

of a refrigeration cycle is described as the ratio of the amount of *energy received by the system* undergoing the cycle from the cold body, Q_{in}, to the net work transfer of energy into the system to accomplish this effect, W_{cycle}. This parameter is called the coefficient of performance and is given by

$$COP_{ref} = \frac{Q_{in}}{W_{cycle}} \quad \text{(Refrigeration cycle)} \tag{2.22b}$$

For household refrigerator, Q_{out} is discharged to space in which the refrigerator is located. W_{cycle} is usually provided in the form of electricity to run the motor that drives the refrigerator.

For a heat pump the coefficient of performance is

$$COP_{hp} = -\frac{Q_{out}}{W_{cycle}} \quad \text{(heat pump)} \tag{2.22c}$$

2.5 APPLICATION OF FIRST LAW TO NON-FLOW PROCESSES (CLOSED SYSTEMS)

2.5.1 Constant pressure process

For a closed system undergoing a constant pressure process between states 1 and 2, the First Law can be written as

$$\int_1^2 \delta Q = U_2 - U_1 - \int_1^2 \delta W \tag{2.23}$$

Or

$$\int_1^2 \delta q = u_2 - u_1 + \int_1^2 p\, dv = u_2 - u_1 + p(v_2 - v_1) = (u_2 + p v_2) - (u_1 + p v_1) = h_2 - h_1 \tag{2.24}$$

$$\text{i.e. } \boxed{Q_{12} = H_2 - H_1} \tag{2.25}$$

Thus, for a closed system undergoing a constant pressure process the heat transferred is given by the change in the enthalpy of the system.

Hence, $\boxed{h = u + pv}$ (2.26)

Enthalpy is particularly useful in the analysis of closed systems undergoing a constant pressure process and open systems undergoing all kinds of process (as will be seen in section 2.6 of this chapter) because it includes the flow work given by the term "*pv*" as well as the internal energy of the system.

2.5.2 Polytropic process

The relation between pressure and volume is given by $p v^n = \text{constant}$, where n is the polytropic index. The expression for the work transfer can be expressed by any of the relations derived in section 2.2.4 depending on the relationship between p and v.

The energy transferred by heat between states 1 and 2 is given as $Q_{12} + W_{12} = U_2 - U_1$. When the relevant values of the work transfer and the internal energy are inserted the energy transferred by heat can be evaluated.

2.5.3   Adiabatic process

This is the process undergone by a system thermally insulated from its surroundings. Work is done at the expense of its internal energy. For such a process since $Q = 0$, from the First Law

$$\boxed{W_{12} = U_2 - U_1}$$
(2.27)

In adiabatic expansion, there is decrease in the internal of the system whereas in adiabatic compression there is increase in the internal energy of the system.

2.5.4   Isothermal process

This is a constant temperature process. From the First Law

$$\delta q + \delta w = d u$$
(2.28)

But for a reversible process $\delta q = T\,ds$ and since T is constant for an isothermal process it is possible to integrate this expression directly. Thus, for a reversible isothermal process $q_{12} = T(s_2 - s_1)$. Therefore, $\boxed{w_{12} = u_2 - u_1 - q_{12}}$, in general for an isothermal process.

For a simple compressible substance, $\boxed{d u = c_v\,dT}$ and therefore the *change* in internal energy for a simple compressible substance is zero. Therefore, for simple compressible substance undergoing an isothermal process between states 1 and 2.

$$Q_{12} = - W_{12}$$
(2.29)

2.5.5   Constant volume process

Applying the First Law and noting that $W = 0$ since $dV = 0$, we have

$$\boxed{Q_{12} = U_2 - U_1}$$
(2.30)

In the differential form, $\delta Q = du$. If the heat addition process is reversible then we write the differential for a constant volume process in the form $\boxed{d Q = du}$

2.6   FIRST LAW OF THERMODYNAMICS FOR OPEN SYSTEMS

2.6.1   General Energy Equation

Figure 2.13 is the sketch of a typical open system. In practice an open system may have several inlets and outlets but it is usual to have one inlet and one outlet. It is also possible for the actual system boundaries to move but for most engineering applications the boundaries may be fixed. Considering an open system with fixed boundaries we pursue the analysis.
We consider the events that take place over a short time interval dt. At the beginning of the time interval (i.e. at the time t) the mass of the fluid in the open system is $m_{s,t}$ and a small mass of fluid dm_i is just about to enter the system. During this time interval, the small mass of fluid, dm_i, enters

the system and another small mass of fluid dm_o, leaves the system such that the mass of fluid at the end of the interval is $m_{s,t+dt}$. During this time interval, small amounts of heat and work, δQ and δW, cross the system boundaries and the properties of the fluid inside the system may change such that the energy of the system also changes from $E_{s,t}$ to $E_{s,t+dt}$. Figure 2.13 shows the imaginary closed system at the beginning and end of the time interval. It is assumed that all properties are uniform at the inlet and outlet portions of the system. From the First Law we can write

$$\delta Q + \delta W = E_{x,t+dt} - E_{x,dt},$$ (2.31)

where, the subscript x refers to the imaginary closed system.

At the time t the total energy of the imaginary closed system is given by

$$E_{x,t} = E_{s,t} + dm_i(u_i + \frac{1}{2}C_i^2 + g z_i)$$ (2.32)

and at the time $t + dt$ the total energy is

$$E_{x,t+dt} = E_{s,t+dt} + dm_o(u_o + \frac{1}{2}C_o^2 + g z_o)$$ (2.33)
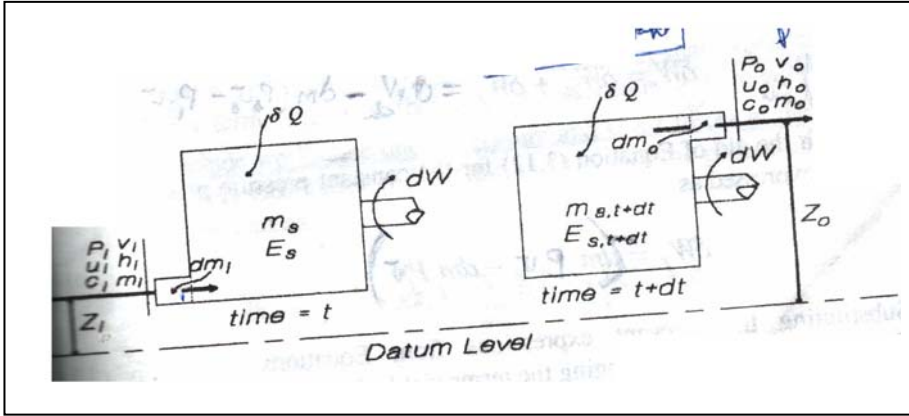

Fig. 2.13 Diagram showing an imaginary closed system at the beginning and end of a differential change of state.

The work done during the time interval is the sum of the shaft work and the flow work, which is the work, required to push the small mass dm_i into the original system and push dm_o out. The work transfer term in equation 2.31 is therefore given by

$$\delta W = \delta W_{sh} + \delta W_f = \delta W_{sh} - dm(p_o v_o - p_i v_i)$$ (2.34)

Substituting Eqs. 2.32 – 2.34 into Eq. 2.31 yields

$$\delta Q + \delta W_{sh} = (E_{s,t+dt} - E_{s,t}) + dm_o(u_o + p_o v_o + \frac{1}{2}C_o^2 + g z_o) - dm_i(u_i + p_i v_i + \frac{1}{2}C_i^2 + g z_i)$$ (2.35)

Substituting for enthalpy and dividing by dt yields

$$\frac{\delta Q}{dt} + \frac{\delta W_{sh}}{dt} = \frac{(E_{s,t+dt} - E_{s,t})}{dt} + \frac{dm_o}{dt}(h_o + \frac{1}{2}C_o^2 + g z_o) - dm_i(h_i + \frac{1}{2}C_i^2 + g z_i)$$ (2.36)

In the limit as dt approaches zero, Eq. 2.36 becomes

$$\dot{Q} + \dot{W}_{sh} = \frac{dE_s}{dt} + \sum_{outlets} \dot{m}_o (h_o + \frac{1}{2}C_o^{\,2} + g\,z_o) \; - \; \sum_{inlets} \dot{m}_i (h_i + \frac{1}{2}C_i^{\,2} + g\,z_i) \qquad (2.37)$$

Finally, it is necessary to account for the possibility of moving boundaries which may be rotating or undergoing a displacement. Since when the boundary moves more work terms may be considered and the shaft work in equation (2.37) is replaced by a more general work term $\dot{W}$. With this substitution, Eq. 2.37 becomes

$$\dot{Q} + \dot{W} = \frac{dE_s}{dt} + \sum_{outlets} \dot{m}_o (h_o + \frac{1}{2}C_o^{\,2} + g\,z_o) \; - \; \sum_{inlets} \dot{m}_i (h_i + \frac{1}{2}C_i^{\,2} + g\,z_i) \qquad (2.38)$$

2.6.2   Steady-Flow Energy Equation (SFEE)

The assumptions for the SFEE may be summarised as follows:

1. The boundaries of the system are fixed
2. The mass flow rate of the fluid is constant and is the same at inlet and outlet of the system ($\dot{m}_o = \dot{m}_i = \dot{m}$)
3. The properties of the fluid at any point in the system remain constant with time ($\frac{dE_s}{dt} = 0$)
4. Heat and work transfer cross the boundaries of the system at uniform rates.

Following the above assumptions, the SFEE becomes

$$\boxed{\dot{Q} + \dot{W} = \dot{m}(h_o - h_i) + \frac{1}{2}\dot{m}(C_o^{\,2} - C_i^{\,2}) + \dot{m}\,g\,(z_o - z_i)} \qquad (2.39)$$

Note when the flow is one-dimensional, the mass flow rate becomes $\boxed{\dot{m} = \rho\,A V}$ and in terms of specific volume, υ, the relation is $\boxed{\dot{m} = \dfrac{A V}{v}}$.

2.6.3   Practical applications of the SFEE

2.6.3.1 Nozzles and diffusers

A nozzle is a flow passage of varying cross-sectional area in which the velocity of the gas or liquid increases in the direction of flow. In a diffuser, the liquid decelerates in the direction of flow. Figure 2.14 shows a nozzle in which the cross-sectional area decreases in the direction of flow and a diffuser in which the walls of the flow passage diverge. For nozzles and diffusers, the only work is the *flow work* at locations where the mass enters and exits the control volume and so the term W drops out of the energy rate equation for these devices. The change in the potential energy from the inlet to exit is negligible under most conditions. By combining these into a single expression and dropping the potential energy change from inlet to exit

$$\dot{Q}_{12} = \dot{m}\,(h_2 - h_1) + \dot{m}\frac{C_2^{\,2} - C_1^{\,2}}{2} \qquad (2.40)$$

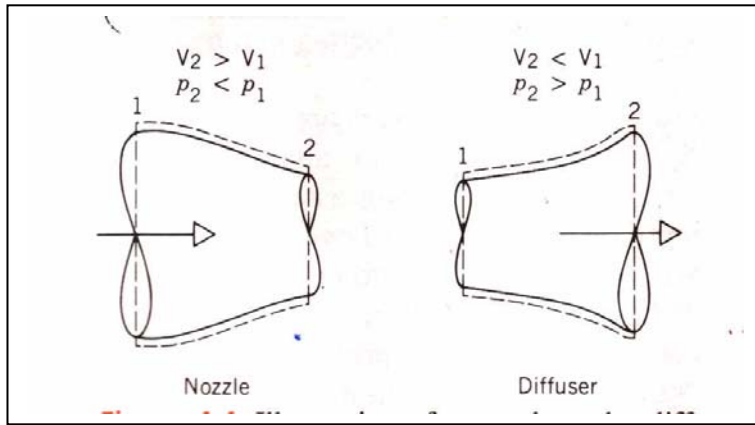The subscripts 1 and 2 denote the inlet and exit, respectively.

Fig. 2.14   Illustration of a nozzle and a diffuser

2.6.3.2 Turbines, compressors, fans and pumps

A turbine is a device in which work is developed as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate. A schematic of an axial-flow steam or gas turbine in shown in Figure 2.15. Turbines are widely used in vapour power plants, gas turbines power plants, and aircraft engines. In these applications, superheated steam or gas enters the turbine and expands to a lower exit pressure as work is developed. Water turbines are used in electric power plants.

Compressors, fans and pumps, on the other hand, are devices that require mechanical power to compress fluid or, simply put, to move a fluid from a low pressure to a relatively high-pressure zone.

The processes that take place inside turbines, compressors, fans and pumps are usually assumed to be adiabatic and therefore $Q = 0$. Secondly, kinetic and potential energy terms are assumed to be negligible compared to the other terms in the SFEE. The resulting equation for this class of thermodynamic application is

$$\dot{W}_{12} \; = \; \dot{m} \; (h_2 \; - \; h_1) \tag{2.41}$$

Note that turbines are work-producing devices, while compressors, fans, and pumps are work-requiring devices.
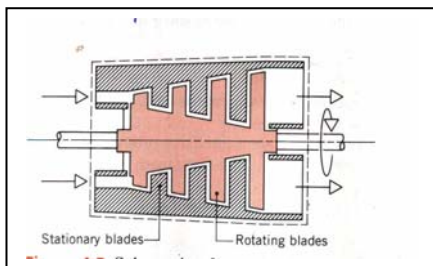

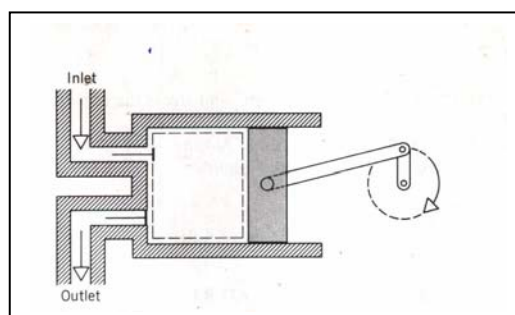**Fig. 2.15a** Schematic of an axial flow turbine

Fig. 2.15b Reciprocating compressor

2.6.3.3 Throttling devices

A throttling device is a restriction in a fluid flow channel, which is designed to effect a significant pressure drop with no work transfer and no change in potential and kinetic energies. In this regard,

the ordinary valve in pipeline may be considered as a throttling device. The throttling process takes place over a short distance so that heat transfer is also considered negligible. The SFEE then reduces to

$$h_2 = h_1 \qquad\qquad (2.42)$$

That is a throttling process is an isentropic process. Throttling valves are used extensively to reduce the pressure refrigerant flowing through the valve. In the vapour-compression refrigerator a valve is used to reduce the pressure of the refrigerant from the pressure at the exit of the *condenser* to the power pressure existing in the *evaporator*. Schematic representations of throttling devices are illustrated in Figure 2.16.
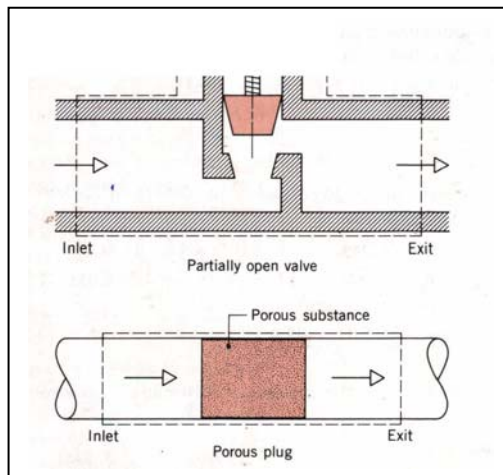

Fig. 2.16 Throttling devices

TUTORIAL SET 2

1. A 5 kg of steam is contained within a piston-cylinder assembly. The steam undergoes an expansion from state 1, where the specific internal energy is $u_1 = 2709$ kJ/kg to state 2, where $u_2 = 2659.6$ kJ/kg. During this process, there is heat transfer of energy to the steam with a magnitude of 80 kJ. Also, a paddle wheel transfers energy to the steam by work in the amount of 18.5 kJ. There is no significant change in the kinetic or potential energy of the steam. Determine the amount of energy transfer by work from the steam to the piston during the process, in kJ. **[- 350 kJ]**

2. A gas is compressed from $V_1 = 0.09$ m^3 to $V_2 = 0.03$ m^3. The relation between pressure and volume during the process is p = -14 V + 2.44, where the units of p and V are bar and m^3, respectively. For the gas, find the work, in kJ. **[+ 9.6 kJ]**

3. A gas expands from an initial state where $p_1 = 500$ kPa and $V = 0.1$ m^3 to a final state where $p_2 = 100$ kPa. The relationship between pressure and volume during the process is $pV =$ constant. Sketch the process on a p-V diagram and determine the work, in kJ.

4. Air is trapped in a piston-cylinder assembly oriented horizontally as shown in Fig. 1. Initially, $p_1 = 100$ kPa, $V_1 = 2$ x 10^{-3} m^3, and the face of the piston is at $x = 0$. The spring exerts no force on the piston in the initial position. The atmospheric pressure is 100 kPa, and the area of the piston face is 0.018 m^2. The air expands slowly until its volume is $V_2 = 3$ x 10^{-3} m^3. During the process, the spring exerts a force on the piston that varies with x according to $F = kx$, where $k = 1.62$ x 10^3 N/m. There is no friction between the piston and the cylinder wall. Determine the final pressure of the air, in kPa, and the work done by the air on the piston, in kJ.
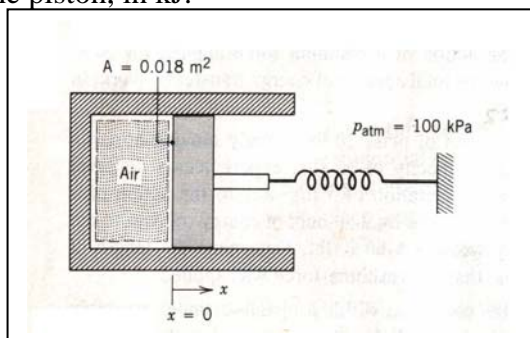
5 Each line in the table below gives information about a process of a closed system. Every entry has the same energy units. By adopting a sign convention for which heat and work inflows into the system are considered positive, copy and complete the table below.

Process	Q	W	U_1	U_2	ΔU
a	+ 50	+ 20	+ 20		
B		− 20		+ 50	+ 30
C	− 25	+ 80		+ 160	
D		+ 90	+ 50		0
E		− 150	+ 20		− 100

6.   Gas undergoes a thermodynamic cycle consisting of the following processes:

Process 1 – 2 constant pressure $p = 1.4$ bars, $V_1 = 0.028$ m^3, $W_{12} = -10.5$ kJ
Process 2 – 3 compression with $pV =$ constant, $U_3 = U_2$
Process 3 – 1 constant volume, $U_1 - U_3 = -26.4$ kJ

There are no significant changes in the kinetic or potential energy.

(i)   Sketch the cycle on a $p - V$ diagram.
(ii)   Calculate the net work for the cycle, in kJ.
(iii)   Calculate the heat transfer for process $1 - 2$, in kJ.
(iv)   Determine the pressure of the gas at state 3.

7.   Water vapour in a piston-cylinder assembly undergoes a process from saturated vapour at 150 ^{0}C to a pressure of 3 bars. During the process, the pressure and specific volume are related by $pv^{1.2} =$ constant. Neglecting kinetic and potential energy effects, determine the heat transfer and the work per unit mass of water vapour, each in kJ/kg.

8.   A gas undergoes a thermodynamic cycle consisting of three processes beginning at an initial state where $p_1 = 1$ bar, $V_1 = 1.5$ m^3, and $U_1 = 512$ kJ. The processes are as follows:

Process 1-2:   compression with $pV =$ constant to $p_2 = 2$ bar, $U_2 = 690$ kJ
Process 2-3: $W_{23} = 0$, $Q_{31} = -150$ kJ
Process 3-1: $W_{31} = -50$ kJ

There are no significant changes in kinetic or potential energy. Determine the heat transfers Q_{12} and Q_{31}, each in kJ.

9.   Steam enters a nozzle operating at steady state with $p_1 = 40$ bars, and a velocity of 10 m/s. The steam flows through the nozzle with negligible heat transfer and no significant change in potential energy. At the exit, $p_2 = 15$ bars, and the velocity is 665 m/s. The mass flow rate is 2 kg/s. Determine the exit area of the nozzle. [Ans. **4.89 x 10^{-4} m^2**]

10.   Air is contained in a rigid well-insulated tank with a volume of 0.2 m^3. The tank is fitted with a paddle wheel that transfers energy to the air at a constant rate of 4 W for 20 min. The initial density of the air is 1.2 kg/m^3. If no changes in kinetic or potential energy occur, determine

(a)   The specific volume at the final state, in m^3/kg.
(b)   The change in specific internal energy of the air, in kJ/kg.
                                                  [**0.833 m^3/kg, 20 kJ/kg**]

11.   The mass flow rate into a steam turbine is 1.5 kg/s and heat transfer from the turbine is estimated at 8.5 kW. The properties of the steam at inlet and outlet of the turbine are as follows:

	Inlet	Outlet
Enthalpy	3137.7 kJ/kg	2675.5 kJ/kg
Velocity	80 m/s	200 m/s
Elevation	6 m	3 m

What is the power output of the turbine?   [**658.9 kW**]

12. A cylinder-piston arrangement containing a gas has a spring, which makes contact with the piston. As the gas is heated the piston moves outward and compresses the spring such that the spring force is proportional to the displacement of the piston. The initial volume and pressure of the gas are 0.1 m³ and 1 bar, respectively and the final pressure is 3 bar. If the volume of the gas doubles during the process and the internal energy also increases by 30 kJ, calculate the heat transferred during the process. **[50 kJ]**

13. A cylinder-piston arrangement containing a gas has a spring located a certain distance above the piston. Initially, the volume and pressure of the gas are 1×10^{-3} m³ and 150 kPa, respectively, and the gas pressure just balances the external atmospheric pressure and the cylinder piston weight. The gas is heated until its volume doubles and at this point the piston just makes contact with the spring. The gas is then heated further such that the change in gas pressure is directly proportional to the displacement of the spring. The final pressure and volume are 300 kPa and 3×10^{-3} m³, respectively.

    (a) Draw the p-V diagram for the two heating processes.
    (b) Show that for the secong heating process (i.e. when the piston is in contact with the spring) the relationship between p and V is given by
    $$p = 1.5 \times 10^5 (V - 10^{-3})$$
    where p is in kPa and V is in m³.
    (c) Use an analytical approach to calculate the work done in the two processes and check your answers using the graphical approach.
    (d) Determine the overall change in internal energy of the gas if the total amount of heat transferred is 765 kJ.

    [-150 J, -225 J, 300 J]

14. A gas contained within a piton-cylinder assembly is shown in Fig. 4. Initially, the piston face is at $x = 0$, and the spring exerts no force on the piston. As a result of heat transfer, the gas expands, raising the piston until it hits the stops. At this point the piston face is located at $x = 0.05$ m, and the heat transfer ceases. The force exerted by the spring on the piston as the gas expands varies linearly with x according to $F = k x$
    where $k = 10,000$ N/m. Friction between the piston and the cylinder wall can be neglected. The acceleration due to gravity is $g = 9.81$ m/s². Additional information is given on Fig. 4.

    (a) What is the initial pressure of the gas, in kPa?
    (b) Determine the work done by the gas on the piston, in J.
    (c) If the specific internal energies of the gas at the initial and final states are 214 and 337 kJ/kg, respectively, calculate the heat transfer, in J.

34
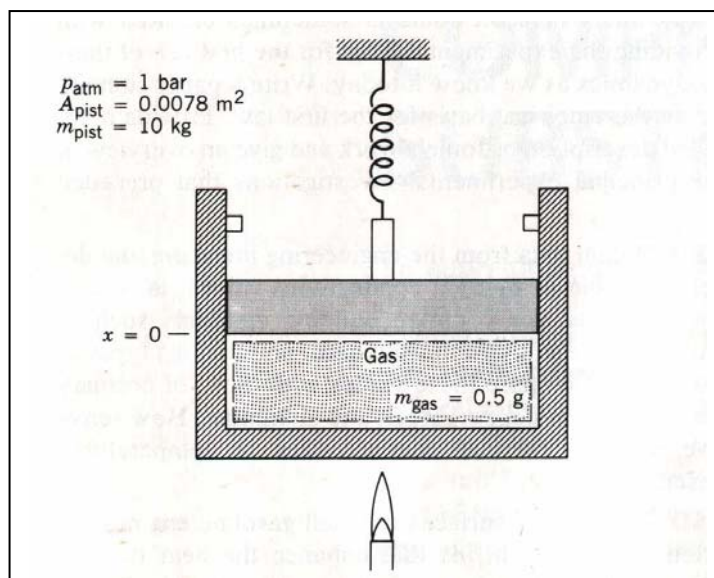
15. For a power cycle the total heat transfer to the cycle is, Q_{in} is 500 MJ. What is the net work delivered, in MJ, if the thermal efficiency is 30 %. **[150 MJ]**

16. The coefficient of performance of a heat pump cycle is 3.5 and the net work *input* is 500 kJ. Determine the heat transfers Q_{in} and Q_{out}, in kJ. **[12,500 kJ; - 17,500 kJ]**

17. A block of mass 10.0 kg is pushed along an incline a distance of 5.0 m as its centre of gravity is elevated by 3.0 m. The block is acted on by a constant force R parallel to the incline having a magnitude of 70 N and by the force of gravity. Assume frictionless surfaces and g = 9.8 m/s^2. Determine in J.
   (a) the work done on the block by the constant force R.
   (b) the change in potential energy of the block.
   (c) The change in kinetic energy of the block.

   [**350 J; 294 J; 56 J**]

18. A system with a mass of 10 kg, initially at rest, experiences a constant horizontal acceleration of 4 m/s^2 due to the action of a resultant force applied for 20 s. Determine the total amount of energy transfer by work, in kJ. **[32 kJ]**

19. An object whose mass is 40 kg falls freely under the influence of gravity from an elevation of 100 m above the earth's surface. The initial velocity is directed downward with a magnitude of 100 m/s. Ignoring the effect of air resistance, what is the magnitude of the velocity, in m/s, of the object just before it strikes the earth? The acceleration of gravity is
   g = 9.81 m/s^2.

   [109.4 m/s]

20. A gas contained in piston-cylinder assembly expands in a constant-pressure process at 4 bar from $V_1 = 0.15$ m^3 to a final volume of $V_2 = 0.36$ m^3. Calculate the work, in kJ.

3   SECOND LAW OF THERMODYNAMICS

3.0   INTRODUCTION

The Second Law of Thermodynamics together with the First Law constitutes the fundamental laws governing thermodynamics processes. <u>The First Law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to quality</u>. The First Law provides us with guidelines for energy conversion processes; it places no restriction on the direction of a process but in practice satisfying the first law does not ensure that a process will actually take place. They inadequacy of the first law to identify whether a process can take place is remedied by introducing the second law of thermodynamics. All that the First Law states is that work cannot be produced during a cycle without some supply of heat, i.e. t*hat a perpetual- motion machine of the first kind is impossible*. The second law is an expression of the fact that some heat must always be rejected during a cycle, and therefore that the cycle efficiency is always less than unity.

The objective of this chapter is to motivate the need for the usefulness of the second law, which asserts that <u>processes occur in a certain direction and that energy has quality as well as quantity</u>. In the presentation of the contents of this chapter, the thermal energy reservoirs, reversible and irreversible process, heat engines, refrigerators and heat pumps are introduced first. A number of deductions called corollaries of the second law are also considered and are followed by a discussion of perpetual-motion machines and the concept of quality of energy.

3.1   DEFINITIONS

Before <u>stating the Second Law</u> it is important to clarify the concept of the thermal energy reservoir and bring into perspective the meaning and working principles of heat engines, refrigerators and heat pumps.

3.1.1   Thermal Energy Reservoirs (Heat Rservoirs)

A *<u>heat reservoir (thermal energy reservoir</u>* is a closed system whose temperature is not affected by the flow of heat across as boundaries. The heat reservoir is hypothetical body with a relatively <u>large thermal energy (heat) capacity</u> that can supply or absorb finite amounts of heat without undergoing any change in temperature. The only significant property of a heat reservoir is that <u>its temperature must remain constant</u> so that any processes that take place in the reservoir must be reversible.

Examples of heat reservoirs are atmosphere, industrial furnace, air in a room in the analysis of heat dissipation from a TV set in the room, oceans, lakes, and rivers. <u>A two-phase system</u> (a mixture of solid and its liquid or a liquid and its vapour) <u>can be modelled as a reservoir since it cannot absorb and release large quantities of heat while remaining at a constant temperature</u>.

A reservoir that supplies energy in the form of heat is called a *source*, and one that absorbs energy in the form of heat is called a *sink*. Thermal energy reservoirs are often referred to as heat reservoirs since they supply or absorb energy in the form of heat.

3.1.2   A heat engine <u>is a closed system which operates in a cycle and produces a net quantity of work from a supply of heat</u>. The schematic representation of a heat engine operating between two heat reservoirs, a heat source and a heat sink, is shown in Fig. 3.1a
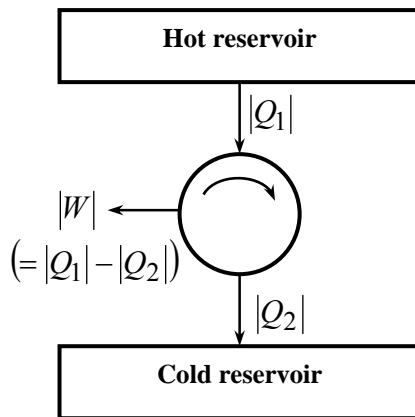
| Fig.3.1a Schematic representation of heat engine | Fig.3.1b Heat Pump or refrigerator |
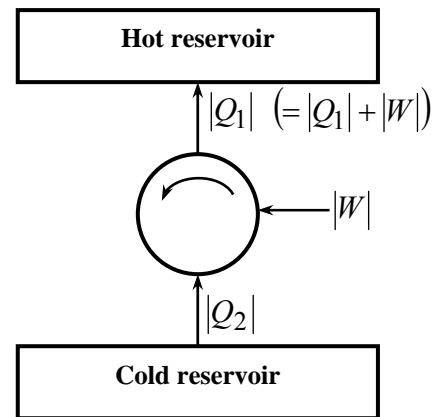
Heat engines differ considerably from one another, but all can be characterised by the following: (Fig.3.2)

1. They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.)
2. They convert part of this heat to work (usually in the form of rotating shaft)
3. They reject the remaining waste heat into a low-temperature sink (atmosphere, rivers, etc.) thus causing thermal pollution.
4. They operate in a cycle.
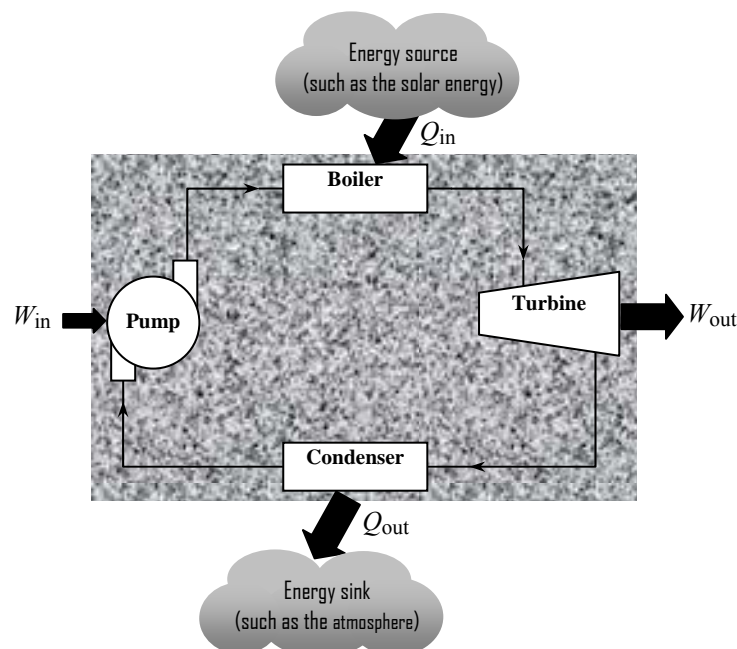
Fig.3.2   Schematic of a steam power plant

From the first law of thermodynamics, $\boxed{Q_{net} + W_{net} = 0 \Rightarrow Q_{in} + Q_{out} + W_{in} + W_{out} = 0}$

37

3.1.3 Thermal Efficiency of a heat engine

The fraction of the heat input that is covered to net work is a measure of the performance of a heat engine and is called the thermal efficiency η_{th}.

Performance or efficiency, in general, can be expressed in terms of the desired output and the required input as:

$$\text{Performance} = \frac{\text{Desired output}}{\text{Required input}}$$

For a hat engine the desired output is the net work output, and the required input is the amount of heat supplied to the working fluid. Steam power plant is a net work producing plant, and from the sign convention adopted it is a negative quantity and therefore the thermal efficiency of a heat engine can be expressed as

$$\eta_{th} = \frac{\left|W_{net,out}\right|}{Q_{in}} = \frac{\left|Q_{in}\right| - \left|Q_{out}\right|}{\left|Q_{in}\right|} = 1 - \frac{\left|Q_{out}\right|}{\left|Q_{in}\right|} \qquad (3.1)$$

The quantities $\left|Q_{in}\right|$ and $\left|Q_{out}\right|$ may be regarded as the heat supplied and rejected, respectively. The First Law of thermodynamics says that the net work can never be greater than the heat supplied, while the Second Law goes further and states that it must always be less. If $\left|W_{net,out}\right| < \left|Q_{in}\right|$, then it follows from equation (3.1) that $\left|Q_{out}\right|$ must have some definite value.

3.1.4 Refrigerator and heat pump

A refrigerator is a reversed heat engine. Thus, it is a closed system which operates in a cycle such that it extracts heat from a low-temperature reservoir and rejects heat to a high-temperature reservoir, while a net work is done one the system by the surroundings.

The refrigerator, therefore, receives a net quantity of work from the surroundings and rejects a net quantity of heat to the surroundings. Again, in accordance with the First Law, the magnitudes quantities of net heat and net work are equal. It is known that a refrigerator extracts heat from a cold space and, therefore, some heat is absorbed by the refrigerating system. A schematic representation of a refrigerator operating between two heat reservoirs, a heat source and heat sink, is shown in fig. 3.1b.

For refrigeration cycles and heat pump, Q_{in} is transferred by heat into the system undergoing the cycle from a cold body, and Q_{out} is the energy discharged by heat transfer from the system to the hot body. To accomplish these energy transfers requires a net work input, W_{cycle}. The performance of a refrigeration cycle is described as the ratio of the amount of *energy received by the system* undergoing the cycle from the cold body, Q_{in}, to the net work transfer of energy into the system to

accomplish this effect, W_{cycle}. This parameter is called the coefficient of performance and is given by

$$\boxed{COP_R = \frac{Q_{in}}{W_{cycle}}}\text{(Refrigeration cycle)} \qquad (3.2)$$

For household refrigerator, Q_{out} is discharged to space in which the refrigerator is located. W_{cycle} is usually provided in the form of electricity to run the motor that drives the refrigerator.
For a heat pump the coefficient of performance is

$$\boxed{COP_{HP} = \frac{Q_{out}}{W_{cycle}}}\text{(heat pump)} \qquad (3.3)$$

From the First Law for a closed cycle, $Q_{in} + Q_{out} + W_{cycle} = 0$. Dividing through expression and rearranging the term we obtain:

$$\boxed{COP_{HP} = COP_R + 0} \qquad (3.4)$$

3.2 The Second Law of Thermodynamics

The law be stated as follows: It is impossible to construct a system, which will operate in a thermodynamic cycle, extract heat from a single reservoir, and do an equivalent amount of work on the surroundings.

This is often referred to as the Kelvin-Planck's statement of the Second Law, which is related to heat engines.

If energy is to be supplied to a system in the form of heat, the system must be in contact with a reservoir at a temperature higher than that of the system at some point in the cycle. Similarly, if heat is to be rejected, the system must at some time be in contact with a reservoir of lower temperature than the system. Thus the Second Law implies that if a system is to undergo a cycle and produce work, it must operate between at least two reservoirs of different temperature, however small this temperature may be. A machine which will produce work continuously, while exchanging heat with only a single reservoir, is known as a *perpetual motion machine of the second kind*; and such a machine contradicts the Second Law.

The Kelvin-Planck statement can also be expressed as *no heat engine can have a thermal efficiency of 100%* (**See Fig. 3.3**) or as *for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace.*

It is now possible to see why an engine using the ocean as the source of heat cannot drive a ship, or why a power station could not be run using the atmosphere as the source of heat. There is nothing in the First law to say that these desirable projects are not feasible. Neither project will contradict the principle of conservation of energy; their impossibility is a consequence of the Second Law. They are impossible because there is no natural infinite

sink of heat at a lower temperature than the atmosphere or ocean, and they would therefore be perpetual motion machines of the second kind. Another example of perpetual-motion machine of the second kind is a car engine without neither an exhaust nor a cooling system.

It should be noted that the Second Law does not imply that work cannot be continuously and completely converted into heat. Indeed, any process involving friction achieves this without the need for the system to operate in a cycle. An important consequence of the Second Law is, therefore, that *work is a more valuable energy transfer than heat*; heat can never be transformed continuously and completely into work, whereas work can always be transformed continuously and completely into heat and, if properly used, can even result in a supply of heat which is greater than the work expended.

The following statement summarise the more obvious consequences of the Second Law:

a.   If a system is taken through a cycle and does a net amount of work on the surroundings, it must be exchanging heat with at least two reservoirs at different temperatures.

b.   If a system is taken through a cycle while, exchanging heat with only one reservoir, the work transfer must either be zero or positive.

c.   Since heat can never be converted continuously and completely into work, whereas work can always be converted continuously and completely into heat, work is more valuable form energy transfer than heat.

3.3   The Clausius Statement of the Second Law

This statement of the Second Law, which is related to refrigerators and heat pumps

> *Corollary 1: it is impossible to construct a system, which will operate in a cycle and transfer heat from a cooler to a hotter body without work being done on the system by the surroundings.*

Proof: We assume the converse is true. The system could be represented by a heat pump for which $|W|=0$, as in Fig. 3.4. If it takes $|Q|$ units of heat from the cold reservoir, it must deliver $|Q|$ units to the hot reservoir to satisfy the First Law. A heat engine cold also be operated between the two reservoirs, let it be such as size that it delivers $|Q|$ units of heat to a cold reservoir while performing $|W|$ units of work. Then the First Law states that the engine must be supplied with $|W|+|Q|$ units of heat from the hot reservoir. The combined plant represents a heat engine extracting $\left(|W|+|Q|-|Q|=|W|\right)$ units of heat from a reservoir, and delivering an equivalent amount of work. This is impossible according to the Second law.
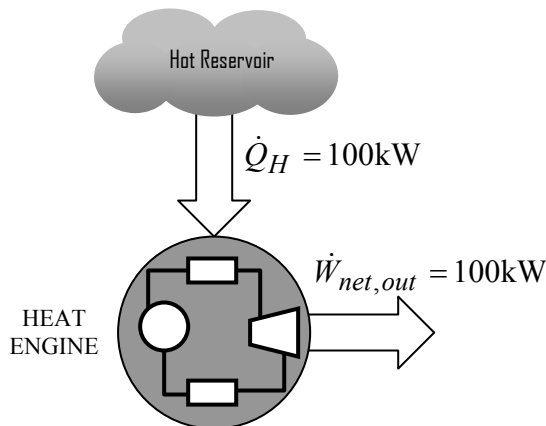
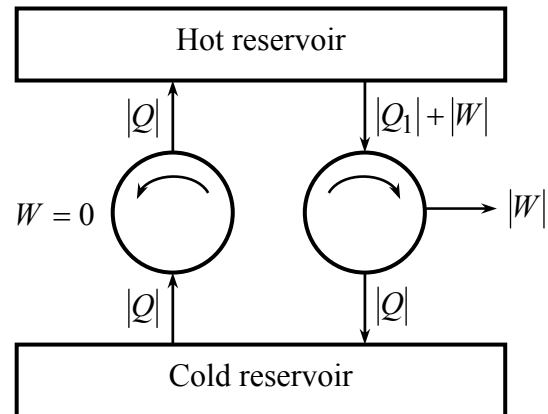**Fig.3.3** A heat engine that violates Kelvin-Planck statement

Fig.3.4 Can a heat pump operate without a work input

3.4 Other Corollaries

Reversible engines operating between only two temperature reservoirs

> *Corollary 2: it is impossible to construct an engine operating between only two reservoirs, which will have a higher efficiency than a reversible engine operating between the same two reservoirs.*

Proof: Assume the converse is true. Let X be such an engine, having efficiency η_X. Let it receive heat Q_1 from the source, do work W_X, and reject () to the sink. Then it is assumed that $\eta_X > \eta_R$ where η_R is the efficiency of a reversible engine R operating between the same two reservoirs (See Fig. 3.5). If the reversible engine also receives heat Q_1 from the source, it will do work W_R such that $W_R < W_X$ and the heat rejected will be $(Q_1 - W_R)$ which is greater $(Q_1 - W_X)$.

Let the reversible engine be reversed and act as a heat pump (See Fig. 3.5b). It now receives heat $(Q_1 - W_X)$ from the low-temperature reservoir, receives work W_R from the surroundings, and rejects heat Q_1 to the high-temperature reservoir. If the engine X is coupled to the heat pumps, and the latter feeds heat Q_1 directly into the former,   the combined plant represents a heat engine receiving heat $(Q_1 - W_R) - (Q_1 - W_X) = (W_X < W_R)$ from the surroundings, and delivering an equivalent amount of work. According to the Second law this is impossible, and the assumption that $\eta_X > \eta_R$ cannot be true. Consequently, the original proposition must be true.
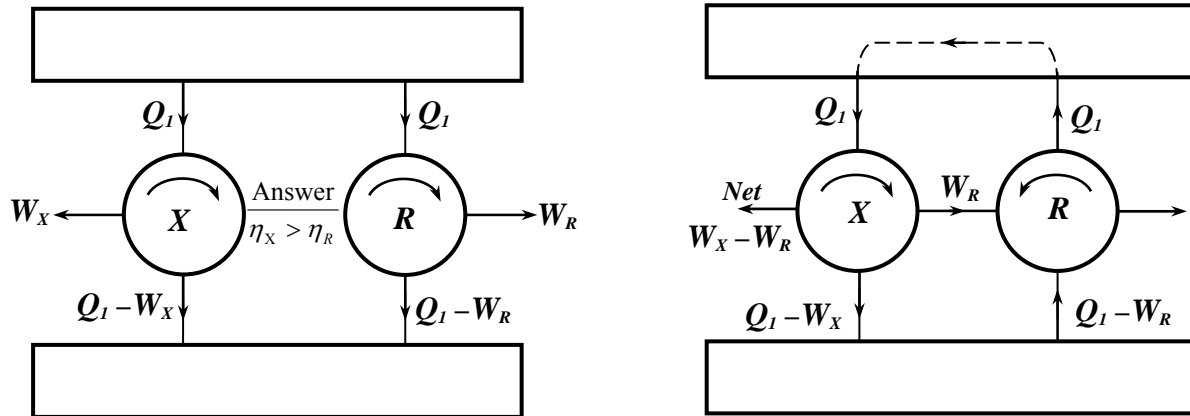
Fig.3.5 Can an engine have a higher efficiency than its reversible equivalent?

> *Corollary 3: All reversible engines operating between the same two reservoirs have the same efficiency*

Once the second corollary is proved there is no need for the proof of the third. The Corollaries 2 and 3 are referred to as the Carnot Principles.

Thermodynamic temperature scale

> *Corollary 4: A scale of temperature can be defined which is independent of any particular thermometric substance, and which provides an absolute zero of temperature*

The scale is based on the fact that <u>the efficiency of the reversible engine depends solely on the temperatures of the reservoirs with which the engine exchanges heat</u>. By definition the only significant property of a heat reservoir is temperature, not its substance. Therefore, for any reversible engine operating between two reservoirs the thermal efficiency of the engine must be a function of the temperature of the reservoirs.

With the aid of Fig.6 and equ.(3.1), the efficiency of a heat engine is given as
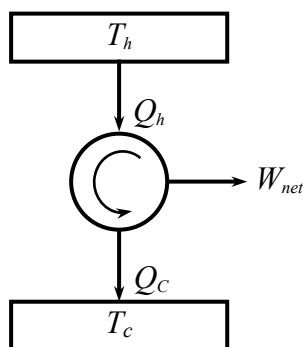

$$\eta_{th} = \frac{|Q_h| - |Q_C|}{|Q_h|} = 1 - \frac{|Q_C|}{|Q_h|} \tag{3.5}$$

Fig. 3.6

It follows that $|Q_C|/|Q_h|$ must be a function of only the temperatures of the hot and cold reservoirs, T_h and T_C, i.e.

$$\frac{|Q_C|}{|Q_h|} = f(T_h, T_C) \qquad (3.6)$$

The simplest relationship chosen for the definition of the absolute temperature scale is

$$\frac{|Q_C|}{|Q_h|} = \frac{T_C}{T_h} \qquad T_h = T_C \bullet \frac{|Q_h|}{|Q_C|} \qquad (3.7)$$

This is called the Kelvin scale and the temperatures on this scale are called absolute temperatures. On this scale temperatures vary between zero and infinity. The triple point of water is assigned the temperature of 273.16 K. The absolute temperature of any reservoir is given by

$$T = 273.16 \frac{Q}{Q_{tp}} \qquad (3.8)$$

where Q and Q_{tp} are the heat transfers from a reversible engine operating between the reservoir and another reservoir at the triple point of water. Note when $T = 0$ then $Q = 0$. A reversible engine operating between any reservoir and another at absolute zero must convert all heat supplied into work since zero heat would be rejected to the reservoir at absolute zero. The Second Law says such a system is impossible. Therefore, the temperature absolute is unattainable, it can be approached but never realised.

Hence, for reversible engine $\quad \dfrac{Q_{C,rev}}{Q_{h,rev}} = \dfrac{T_C}{T_h}$

The efficiency of a reversible heat engine (Carnot Cycle) is given by

$$\boxed{\eta_{th,rev} = 1 - \frac{T_C}{T_h}} \qquad (3.9)$$

Note that for a given sink temperature, as the source temperature increases the efficiency of the engine increases. This shows that energy has quality and the higher the temperature the more heat can be converted to work.

Note that

$$\eta_{th} \begin{cases} < \eta_{th,rev} \text{ irreversible heat engine} \\ = \eta_{th,rev} \text{ reversible heat engine} \\ > \eta_{th,rev} \text{ impossible heat engine} \end{cases} \qquad (3.10)$$

It can be inferred from equation (3.9) that the efficiency of actual cycles can be maximised by supplying heat to the engine at the highest possible temperature, and rejecting heat from the engine at the lowest possible temperature.

Engines operating between more than two reservoirs

In many practical cycles, the heat is received and rejected during processes which involve a continuous change in the temperature of the fluid. These cycles can still be considered reversible if the source and sink are each assumed to consist of an infinite number of reservoirs differing infinitesimally from one another in temperature. At any instant during a heating and cooling process, heat must be exchanged between the system and a source or sink which differs infinitesimally in temperature from the fluid in the system.

We note that the efficiency with which a given quantity of heat can be converted into work in a reversible engine operating reservoirs at T_1 and T_2 is given by $(T_1 - T_2)/T_1$ or $(1- T_2/T_1)$. Let T_1' and T_2' be maximum and minimum temperatures of the working fluid in a reversible engine operating between more than two reservoirs. Only a fraction of the heat can be supplied at T_1' and only a fraction of the heat can be rejected at T_2'. The remaining part of the heat supplied must be converted into work with an efficiency less than $(1- T_2'/T_1')$, because the temperatures of the remaining sources are less than T_1' and the temperatures of the remaining sinks are greater than T_2'. Thus the efficiency with which the total heat received is converted into work must be less than $(T_1'-T_2')/T_1'$. This result is summarised as the following corollary:

> *Corollary 5: The efficiency of any reversible engine operating between more than two reservoirs must be less than that of a reversible engine operating between two reservoirs which have temperatures equal to the highest and lowest temperatures of the fluid in the original engine.*

The Clausius Inequality

> *Corollary 6: Whenever a system undergoes a cycle. $\oint(\delta Q/T)$ is zero if the cycle is reversible and negative if irreversible, i.e. in general $\oint(\delta Q/T) \leq 0$*

Consequences of the Second Law for non-flow processes

> *Corollary 7: There exists is property of a closed system such that a change in its value is equal to $\int_1^2 dQ/T$ for any reversible process undergone by the system between states 1 and 2.*

This property is called entropy and therefore $\int_1^2 \left(\dfrac{dQ}{T}\right)_{rev} = S_2 - S_1$. Entropy is an exclusive property.

> *Corollary 8: The entropy of any closed system, which is thermally isolated from the surroundings, either increases or, if the process undergone by the system is reversible, remains constant.*

Entropy of isolated closed system never decreases. In the absence of heat transfer, the entropy change is due to irreversible only, and these effect is always to increase entropy. (pump, turbine work)

NOTES

1. None that any process that does not produce a net entropy is reversible. During a heat transfer process, the net disorder (entropy) increases. That is the increase in the disorder of the cold body will be more than the decrease in the disorder of the hot body.

2. The quantity of energy is always preserved during an actual process (the first law) but the quality is bound to decrease (the second law). This decrease in quality is always accompanied by an increase in entropy. As an example, consider the transfer of 10 *kJ* of energy as heat from a hot medium to a cold one. At the end of the process, we still have the 10 *kJ* of energy, but at lower temperature and thus at a lower quality.

3. It is possible to increase entropy but is not possible to destroy it.

4. Heat transfer, irreversibilities and entropy transport with mass cause entropy of a control volume to change.

5. There is no entropy transfer associated with energy transfer as work.

3.5 Equivalence of the Kelvin-Planck and the Clausius Statements of the Second Law

Any device that violates the Kelvin-Planck statement violates the Clausius statement, and vice versa. This can be demonstrated as follows:

Consider the heat-engine-refrigerator combination shown in Fig. 3.7a operating between the same two reservoirs. The heat engine is assumed to have, in violation to the Kelvin-Planck statement an efficiency of 10%, and therefore it converts all the heat Q_H it receives to work W. This work is then supplied to a refrigerator that removes heat in the amount of Q_L from the low-temperature reservoir and rejects heat in the amount of $Q_H + Q_L$ to the high-temperature reservoir. During this process, the high-temperature reservoir receives and net amount of heat Q_L (the difference of $Q_H + Q_L$ and Q_H). Thus, the combination of these two devices can be viewed as a refrigerator, as shown in Fig. 3.7b, that transfers heat in an amount of Q_L from a cooler body to a warmer one without requiring any input from outside. This clearly violates the Clausius statement. Therefore, a violation of the Kelvin-Planck statement results in the violation of the Clausius statement.
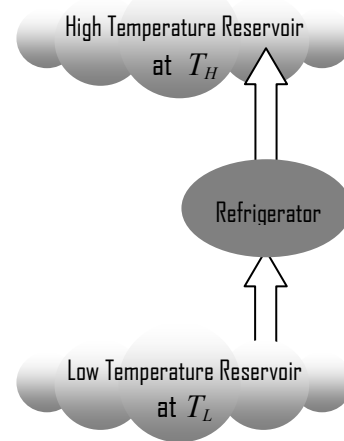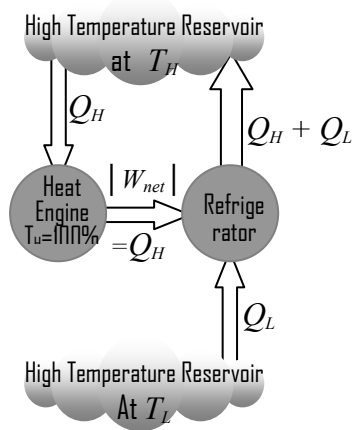
3.6 Perpetual-motion machines

Any device that violates either the First Law or the Second Law of Thermodynamics is called a perpetual-motion machine (PMM).

A device that violates the First Law of Thermodynamics (by *creating* energy) is called a ***Perpetual-motion machine of the first kind (PMM1)*** and a device that violates the Second Law of Thermodynamics is called a ***Perpetual-motion machine of the second kind (PMM2)***.

Examples of PMM1 and PMM2 are shown in Fig.3.8a and Fig.3.8b, respectively.
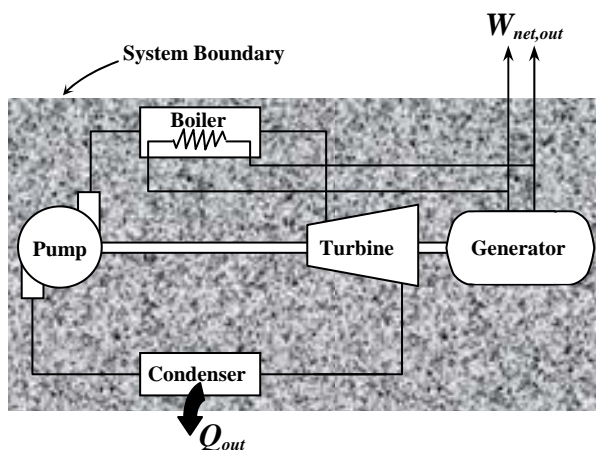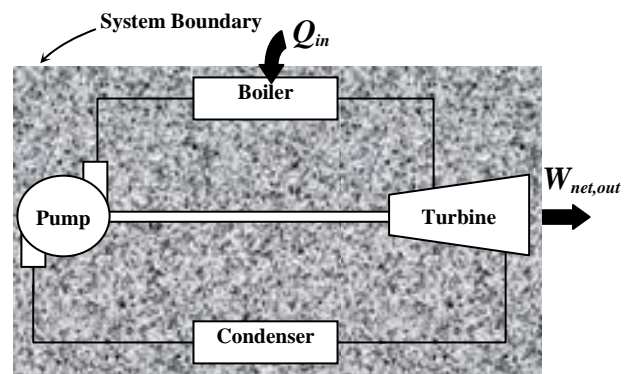
Fig. 3.8a   PMM1   **Fig. 3.8b   PMM2**

3.7 The quality of Energy

Let us consider a heat engine that receives heat from a source at 1000 *K* and rejects heat to a sink at 300 *K*. This heat engines is able to convert 70% of the heat supplied to work and rejects 30% to a sink. Let us now examine how the thermal efficiency varies with the source temperatures of 800 *K*, 700 *K*, 600 *K*, 500 *K*, and 400 *K* when the sink temperature is held constant.

The thermal efficiency of a Carnot heat engine that rejects heat to a sink at 300 *K* is evaluated at various source temperatures using Eq. 3.9. if can be shown that he thermal efficiency decreases with as the source temperature decreases. When the source temperature is 400 *K* the efficiency drop to 25%.

These efficiency values show that energy has quality as well as quantity. It can be shown from the thermal efficiency values that *more of the high-temperature thermal energy can be converted to work.* Therefore, *the higher the temperature, the higher the quality of the energy.*

TUTORIAL SET 3

1 An inventor claims to have developed a car that runs on water instead of gasoline. What is your response to this claim?

2 Describe an imaginary process satisfies the first law but violates the second law of thermodynamics.

3 Describe an imaginary process that satisfies the second law but violates the first law.

4 Describe an imaginary process that violates both the first and the second laws of thermodynamics.

5 Does a heat engine that has a thermal efficiency of 100% necessarily violate (a) the first law and (b) the second law of thermodynamics.

6 In absence of any friction and other irreversibilities, can a heat engine have an efficiency of 100%? Explain.

7 Are the efficiencies of all the work producing devices, including hydroelectric power plants, limited by Kelvin-Planck statement of the second law?

8 A cold canned drink is left in a warmer room where its temperature rises as result of heat transfer. Is this a reversible process? Explain.

9 A hot baked potato is left on a table where it cools to the room temperature. Is this a reversible or irreversible process?

10 Why are engineers interested in reversible process even though they can never be achieved?

11 A refrigerator has a COP of. 1.5. That is, the refrigerator receives 1.6 *KWh* of energy from the refrigerated space for each 1.5 *kWh* of electricity it consumes. Is this a violation of the first law of thermodynamics? Explain.

12 A household refrigerator with a COP of 1.8 removes heat from the refrigerated space at a rate of 90 *kJ*/min. Determine
   a) the electric power consumed by the refrigerator and
   b) the rate of heat transfer to the kitchen air   [a.0.83 *kW*, b.140 *kJ*/min]

13 An air conditioner removes heat steadily from a house at a rate of 750 *kJ*/min while drawing electric power at a rate of 5 *kW*. Determine
   a) the COP of this air conditioner and
   b) the rate of heat transfer to the outside air   [a.2.08 , b.1110 *kJ*/min]

14 Determine the COP of a heat pump that supplies energy to a house at a rate of 8000 *kJ/h* for each *kW* of electric it draws. Also determine the rate of energy absorption from the outside air.   [2.22, 4400 *kJ/h*]

15 A Carnot heat engine receives 500 kJ of heat from a source of unknown temperature and rejects 200 kJ of it to a sink at 17°C. Determine

a) the temperature of the source and
b) the thermal efficiency of the heat engine

16 An air-conditioning system is used to maintain a house at a constant temperature of 20°C. The house is gaining heat from outdoors at rate of 20,000 kJ/h, and the heat generated in the house from the people, lights, and appliances amounts to 8000 kJ/h. For a COP of 2.5, determine the required power input to this air-conditioning system.

17 A power cycle operating between two reservoirs receives energy Q_H by heat transfer from a hot reservoir at $T_H = 2000K$ and rejects energy Q_C by heat transfer to a cold reservoir at $T_C = 400K$. For each of the following cases, determine whether the cycle operates reversibly, irreversibly, or is impossible.

a) $Q_H = 1000\ kJ,\ |W_{cycle}| = 850\ kJ$
b) $Q_H = 2000\ kJ,\ |Q_C| = 400\ kJ$
c) $|W_{cycle}| = 1600\ kJ,\ |Q_C| = 500\ kJ$
d) $Q_H = 1000\ kJ,\ \eta = 30\%$

18 The data listed below are claimed for a power cycle operating between reservoirs at 727 and 127°C. For each case, determine if any principles of thermodynamics would be violated.

19 A refrigeration cycle operating between two reservoirs receives energy Q_C from a cold reservoir at $T_C = 250\ K$ and rejects energy Q_H to a hot reservoir at $T_H = 300\ K$ for each of the following cases, determine whether the cycle operates reversibly, irreversibly, or is impossible.

a) $|Q_C| = 1000kJ,\ |W_{cycle}| = 400kJ$
b) $|Q_C| = 2000kJ,\ |W_{cycle}| = 2200kJ$
c) $|Q_H| = 3000kJ,\ |W_{cycle}| = 500kJ$
d) $|W_{cycle}| = 400kJ,\ COP_R = 6$

20 A reversible engine employs a cycle consisting of three different processes which constitute a triangle such that

$$T_1 = T_3 = 323\ K; \qquad\qquad T_2 = 573\ K; \qquad\qquad s_2 = s_3$$

Determine the efficiency of an engine operating on this cycle and compare its efficiency with that for a Carnot engine operating between the highest and the lowest temperatures.

4 PROPERTIES OF A PURE, SIMPLE COMPRESSIBLE SUBSTANCE

Introduction

Application of the energy balance to a system of interest requires knowledge of the properties of the system and how these properties are related. The objective of this chapter is to introduce property relations relevant to engineering thermodynamics.

State Principle

The *state* of a closed system at equilibrium is its condition as described by the values of its thermodynamic properties. It must be noted that values of all thermodynamic properties are determined from the independent subset of properties. The *state principle* is a general rule that has been developed to guide in determining the number of independent properties needed to specify the state of a system.

Based on experimental evidence, it is concluded that there is one independent property for each way a system's energy can be varied independently. We have noted that the energy of a closed system can be altered independently by *heat* or by *work*. Accordingly, an independent property can be associated with heat transfer as one way of varying the energy, and another independent property can be counted for each relevant way the energy can be changed through work. From experiments, it can be stated that the number of independent properties for systems is one plus the number of relevant work interactions. *This is the state principle*. Experimental evidence also indicates that, when counting the number of relevant work interactions, it suffices to consider only those that can occur as the system undergoes quasi-equilibrium processes.

The term *simple system* is applied when there is only *one* way the system energy can be significantly altered by work as the system undergoes quasi-equilibrium process. Therefore, counting one independent property for heat transfer and another for the single work mode gives a total of two independent properties needed to fix the state of a simple system. *This is the state principle for simple systems*. Example of simple systems is simple compressible systems, simple elastic and magnetic systems.

The only mode of energy transfer by work that can occur as a simple compressible system undergoes quasi-equilibrium processes is associated with volume change and is given by $\int p \, dV$. Since the influence of the earth's gravitational field is assumed negligible, pressure is uniform throughout the system.

Although any two independent properties are sufficient to fix the state of a simple compressible system in equilibrium, it is convenient to think in terms of a unit mass of substance. Hence, the state principle can be interpreted in terms of *intensive properties*. For example, the temperature, T, and another intensive property such as specific volume, v, might be selected to as the two independent properties. The state

principle asserts that the pressure, specific internal energy, and all other pertinent *intensive* properties could be determined as functions of T and v: $p = p(T, v)$, $u = u(T, v)$, and so on.

Pure Substance

A pure substance is one of uniform and invariable chemical composition. Water, nitrogen, helium, carbon dioxide, for example, are all pure substances. Air a mixture of several gases is regarded as a pure substance because it has a uniform chemical composition. However, a mixture of oil and water is not a chemical substance since oil is not soluble in water.

p-v-T **Relation**

In this section, we begin with consideration of the properties of pure, simple compressible substances and the relations among these properties, starting with pressure, specific volume, and temperature. From experiment, it is known that temperature and specific volume can be regarded as independent and pressure determined as a function of these two: $p = p(T, v)$. The graph of such a function is a surface, the *p-v-T* surface.

Figs 4.1 and 4.2 illustrate the *p-v-T* surfaces of substances that expand and contract on freezing, respectively. The coordinates of a point on the *p-v-T* surfaces represent the values that pressure, specific volume, and temperature would assume when the substance is at equilibrium.
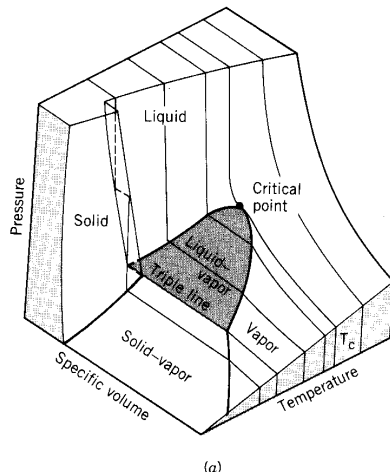
Fig. 4.1 *p-v-T* surface of a substance that expands on freezing
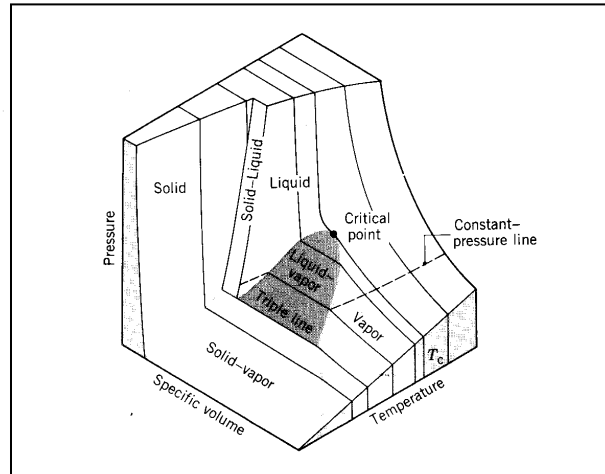
Fig. 4.1 *p-v-T* surface of a substance that contracts on freezing

There are regions on the *p-v-T* surfaces of Figs. 4.1 and 4.2 labelled *solid*, *liquid* and *vapour*. In these *single-phase* regions, the state is fixed by *any* two of the properties pressure, specific volume, and temperature, since all of these are independent when there is a single phase present. Located between the single-phase regions are two-

phase regions where two phases exist in equilibrium: Liquid-vapour, solid-liquid, and solid-vapour. Two phases can coexist during changes in phase such as vaporization, melting, and sublimation. Within the two regions pressure and temperature are not independent; one cannot be changed without changing the other. In these regions, the state cannot be fixed by temperature and pressure alone; however, the state can be fixed by specific volume and either pressure or temperature. Three phases can exist in equilibrium along the line labelled triple line.

A state at which the phase change begins or ends is called a *saturation* state. The dome-shaped region composed of the two-phase liquid-vapour states is called the vapour dome. The lines bordering the vapour dome are called *saturated liquid* and *saturated vapour lines*. At the top of the dome, where the saturated liquid and saturated vapour lines meet, is called the *critical point*. The critical temperature T_c of a pure substance is the maximum temperature at which liquid and vapour phases can coexist in equilibrium. The pressure at the critical point is called the critical pressure, p_c. The specific volume at this state is the *critical specific volume*.

4.3.1 Projections of the *p-v-T* Surface

The phase diagram If the *p-v-T* surface is projected onto the pressure-temperature plane, a property diagram known as a *phase* diagram results. When projected in this way, the two-phase regions reduce to lines as shown in Figs. 4.3. A point on any of these lines represents all two-phase mixtures at that particular temperature and pressure. Substances that expand and contract on freezing differ only in the melting line on the *p-T* diagram.

The term *saturation temperature* designates the temperature at which a phase change takes place at a given pressure, and this pressure is called the *saturation pressure* for the given temperature. It must be noted that for each saturation pressure, there is one saturation temperature, and conversely.
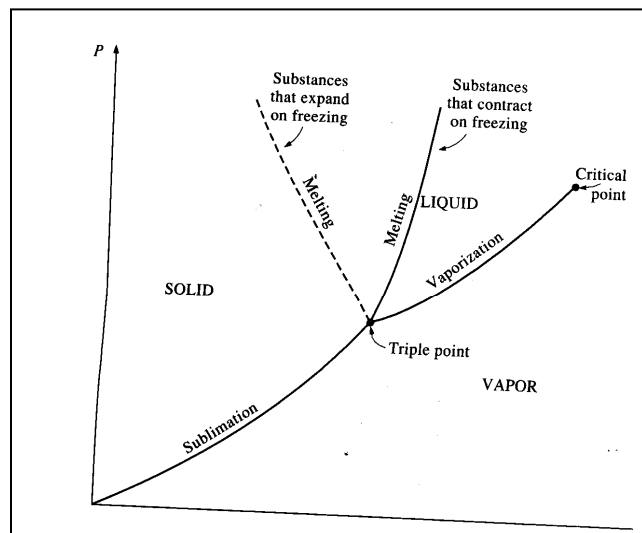
Fig. 4.3 *p-T* diagram of a pure substance

4.3.1.1   *p-v* **Diagram**

Projecting the *p-v-T* surface onto the pressure-specific volume plane results in a *p-v* diagram, as shown in Figs. 4.4 and 4.5.

*Notes*: It can be noted from Figs. 4.4 and 4.5 (*p-v* diagrams) that:
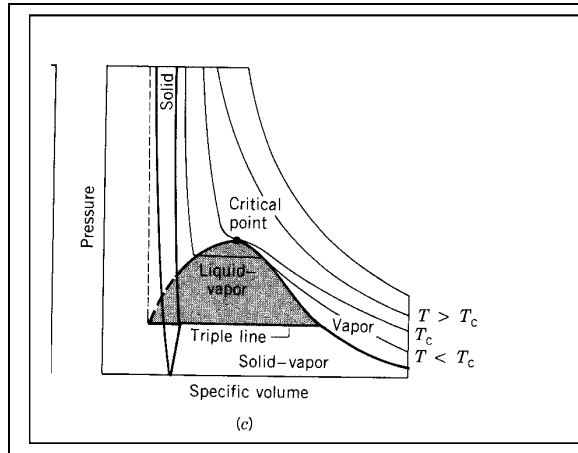
Fig. 4.5 *p-v* diagram for a substance that expands on freezing
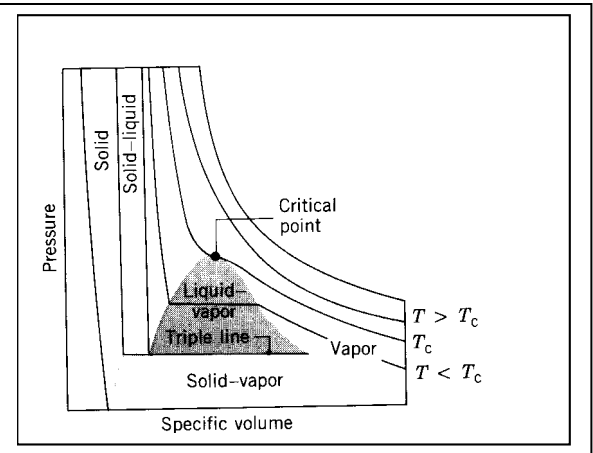
Fig. 4.6 *p-v* diagram for a substance that contracts on freezing

(a) For temperatures less than the critical temperature, pressure remains constant as the two-phase liquid-vapour region is traversed, but in the single-phase liquid and vapour regions the pressure decreases at fixed temperature as specific volume decreases.

(b) For temperatures greater than the critical temperature, pressure decreases continuously at fixed temperature as specific volumes increases. There is no passage across the two-phase liquid-vapour region.

(c) The critical isotherm passes through a point of inflection at the critical point and the slope is zero there.

4.3.1.2   *T-v* **Diagram**

Projecting the liquid, two-phase liquid-vapour, and vapour regions of the *p-v-T* surface onto the temperature-specific volume plane results in a *T-v* diagram as in Figs. 4.6. Since consistent patterns are revealed in the *p-v-T* behaviour of all substances, Fig. 4.6 showing a *T-v* diagram for water can be regarded as representative.
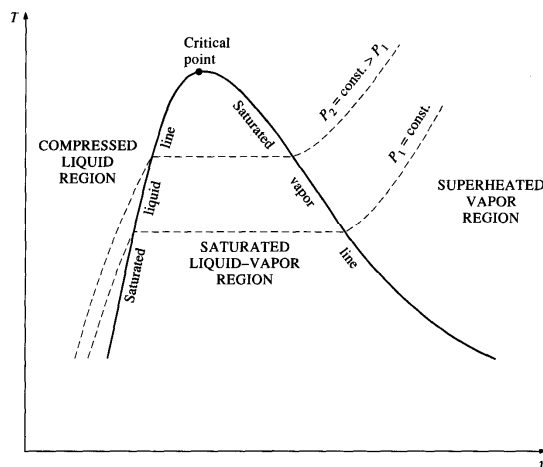
Fig. 4.6 *T-v* diagram for a pure substance
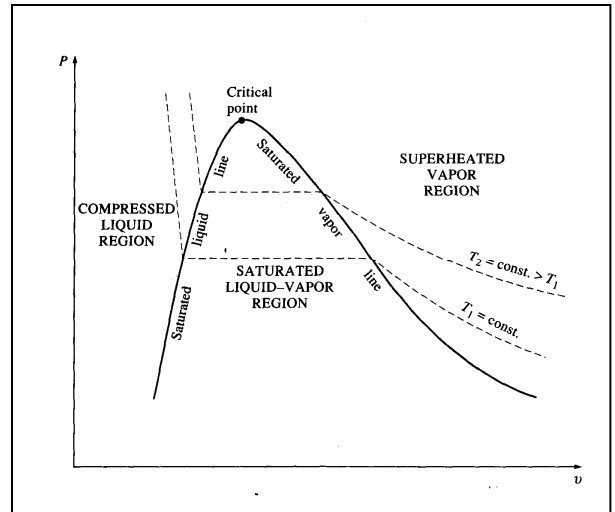
Notes: It can be noted from Fig. 4.6 that:

(a) For pressures less than the critical pressure, the pressure remains constant with temperature as the two-phase region is traversed; but in the single-phase liquid and vapour regions the temperature increases at fixed pressure as the specific volume increases.

(b) For pressures greater than or equal to the critical pressure, temperature increases continuously at fixed pressure as the specific volume increases. There is no passage across the two-phase liquid-vapour region.

4.3.2   Phase Change

It is instructive to study some of the events that occur as a pure substance undergoes a phase change. Consider a closed system consisting of 1 kg of water contained within a piston-cylinder assembly. Suppose the water is slowly heated while its pressure is kept constant and uniform pressure.

As the system is heated at constant pressure, the temperature increases considerably while the specific volume increases slightly. Eventually, the system is brought to the saturated line state corresponding to the specified pressure.

When the system is at the saturated liquid state, additional heat transfer at fixed pressure results in the formation of vapour without any change in the temperature but with considerable increase in specific volume. If the system is heated further until the last bit of liquid has vaporized, it is brought to the saturation vapour state. The intervening two-phase liquid-vapour mixtures can de distinguished from one another by the *quality*, an intensive property. The amount energy absorbed or released during a phase is called **latent heat**. The amount of energy released during vaporization is called the enthalpy of vaporization, which is equivalent to energy released during

54

condensation. The amount of energy absorbed during melting is called enthalpy of fusion, which is equivalent to energy released during freezing.

For a liquid-vapour mixture, the ratio of the mass of water vapour to the total mass of the mixture is defined as the quality, x, and is given by:

$$x = \frac{m_{vapour}}{m_{total}} \quad \text{where } m_{total} = m_{liquid} + m_{vapour} = m_f + m_g \quad (4.1)$$

Quality has significance for *saturated mixtures* only. It has no meaning in the compressed liquid or superheated vapour regions. Its values ranges between 0 and 1. But the total of the mixture is the sum of the volume of the saturated liquid and the saturated vapour. That is:

$$V = V_f + V_g$$
$$\text{But } V = mv \qquad \rightarrow \quad m_{total} v_{av} = m_f v_f + m_g v_g \quad (4.2)$$

Substituting for m_f in terms of m_{total} and m_g in Eq. 4.2 and dividing the resulting expression by m_{total} and replacing m_g / m_{total} by x we obtain

$$v_{av} = (1 - x)v_f + xv_g = v_f + xv_{fg} \quad (4.3)$$

where $v_{fg} = v_g - v_f$

The expression provided in Eq. 4.3 can be repeated for internal energy and enthalpy.

4.4   Thermodynamic Property Data

Thermodynamic property data for engineering use appears in various forms, including tables, graphs, and equations. The emphasis of the current section is on the use of tables of thermodynamic properties, since tables are commonly available for pure, simple compressible substances on engineering interest. The present discussion will centre on the tables giving the properties of water, refrigerants and other simple compressible substances; these are commonly referred to as the *steam tables* (Thermodynamic and Transport properties of Fluids, 4th Edition).

Saturation Tables: The saturation tables, list property values for the saturated liquid and vapour states. The property values at these states are denoted by the subscripts f and g, respectively. Tables in the steam tables as listed on pages 2, is called the temperature table, because temperatures are listed in the first column in convenient increments. The second column gives the corresponding saturation pressures. The next columns list the specific volume of saturated vapour, v_g, specific enthalpy of saturated

liquid h_f, specific enthalpy of vaporization h_{fg}, and specific enthalpy of saturated vapour h_g, specific entropy of saturated liquid s_f, specific entropy of vaporization s_{fg}, and specific entropy of saturated vapour s_g, respectively. Tables as listed on pages 3-5 is called the pressure tables, because pressures are listed in the first column in convenient increments. The corresponding saturation temperatures are given in the second column. The next columns list the specific volume of saturated vapour, v_g, specific internal energy of saturated liquid u_f, specific internal energy of saturated vapour u_g specific enthalpy of saturated liquid h_f, specific enthalpy of vaporization h_{fg}, and specific enthalpy of saturated vapour h_g, specific entropy of saturated liquid s_f, specific entropy of vaporization s_{fg}, and specific entropy of saturated vapour s_g, respectively.

Tables of superheated steam and supercritical steam are presented from pages 6 through to 9. On page 10 further properties of water and steam are provided.

(a) Saturated liquid and saturated vapour states

The subscript f is used to denote properties of a saturated liquid, and subscript g to denote the properties of saturated vapour. The subscript fg denotes the difference between the saturated vapour and the saturated liquid values of the same property. For example, $h_{fg} = h_g - h_f$

The quantity h_{fg} is called the enthalpy of vaporization and it represents the amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure. It decreases as the temperature or pressure increases, and becomes zero at the critical point.

(b) Saturated liquid-vapour mixture

The analysis provided under section 4.3.2 for specific volume is repeated for internal energy and enthalpy.

(c) Superheated vapour

In the region to the right of the saturated vapour line, a substance exists as superheated vapour. The superheated region is a single-phase region and pressure and temperature are no longer dependent properties and they can be conveniently used as independent properties. Superheated vapour is characterised by:

Lower pressures ($p < p_{sat}$ at a given T)
Higher temperature ($T > T_{sat}$ at a given p)
Higher specific volumes ($v > v_g$ at a given p or T)
Higher internal energies ($u > u_g$ at a given p or T)
Higher enthalpies ($h > h_g$ at a given p or T)

(d) Compressed liquid (See also section 4.5)

In the absence of compressed liquid, a general approximation is *to treat compressed liquid as saturated liquid at the given temperature.* This is because the compressed liquid data depend on temperature more strongly than they do on pressure. Thus,

$$y \cong y_f \ @ \ T$$

for compressed liquids, where *y* is *v*, *u*, or *h*. However, the error in h at very high pressure can be reduced by evaluating it using Eq. 4.7.

4.5   **Approximations for liquids using saturated liquid data**.

Approximate values of *v*, *u*, and *h* at liquid states can be obtained using saturated liquid data. Because *v* and *u* vary gradually as pressure changes at fixed temperature, the following approximations are reasonable for many engineering calculations:

$$v(T, p) \approx v_f(T) \qquad ; \qquad u(T, p) \approx u_f(T) \tag{4.5}$$

An approximate value of h at liquid states can be obtained using the Eq. (4.5) and the definition $h = u + pv$; thus

$$h(T, p) \approx u_f(T) + pv_f(T) \tag{4.6}$$

Equation 4.6 can be expressed alternatively as

$$h(T, p) = h_f(T) + v_f(T)[p - p_{sat}(T)] \tag{4.7}$$

where, p_{sat} denotes the saturation pressure at the given temperature. When the contribution of the last term of Eq. 4.7 is small, the specific enthalpy can be expressed by the saturation liquid value i.e. $h(T, p) \approx h_f(T)$. Equation 4.7 is used *when only liquid data available are for saturated liquid states*.

4.6   **Linear interpolation**

The states encountered when solving problems often do not fall exactly on the grid of values provided by property tables. Interpolation between adjacent table entries then becomes necessary. Linear interpolation can be used with acceptable accuracy when using the abridged tables in the steam tables.

Tutorial Set IV

1. Is iced water a pure substance? Why?
2. What is the difference between saturated vapour and superheated vapour?
3. Is there any difference between the properties of saturated vapour at a given temperature and the vapour of a saturated mixture at the same temperature?
4. Is there any difference between the properties of saturated liquid at a given temperature and the liquid of a saturated mixture at the same temperature?
5. Is it true that water boils at higher temperatures at higher pressure?
6. If the pressure of a substance is increased during a boiling process, will the temperature also increase or will it remain constant? Why?
7. A househusband is cooking beef stew for his family in a pan that is (a) uncovered, (b) covered with a tight lid, and (c) covered with a heavy lid. For which case will the cooking time be the shortest? Why?
8. How does the boiling process at supercritical pressures differ from the boiling process at sub-critical pressures?
9. In which kind of pot will a given volume of water boil at a higher temperature: a tall narrow one or a short and wide one? Explain
10. A perfectly fitting pot and its lid often stick after cooking, and it becomes difficult to open the lid when the pot cools down. Explain why this happens and what you would do to open the lid.
11. It is well that warm air in a cooler environment rises. Now consider a warm mixture of air and gasoline on top of an open gasoline can. Do you think this gas mixture will rise in a cooler environment?
12. Is it true that it takes more energy to vaporise 1 kg of saturated liquid water at $100\ ^0C$ than it would to vaporise 1 kg of saturated liquid at $120\ ^0C$?
13. Which requires more energy: completely vaporising 1 kg of saturated liquid water at 1 atm pressure or completely vaporising 1 kg saturated liquid water at 8 atm pressure?
14. Does h_{fg} change with pressure? How?
15. Complete the following table for water.

$T/\ ^0C$	p/kPa	v/(m^3/kg)	Phase description
50		4.16	
	200		Saturated vapour
250	400		
110	600		

16. Complete the following table for water.

$T/\,^0$C	p/kPa	h/(kJ/kg)	x	Phase description
	325		0.4	
160		1682		
	950		0.0	
80	500			
	800	3162		

17. Complete the following table for water.

$T/\,^0$C	p/kPa	v/(m^3/kg)	Phase description
125		0.53	
	1000		Saturated liquid
25	750		
500		0.130	

18. Complete the following table for water.

$T/\,^0$C	p/kPa	u/(kJ/kg)	Phase description
	325	2452	
170			Saturated vapour
190	2000		
	4000	3040	

19. A cooking pan whose inner diameter is 20 cm is filled with water and covered with a 4-kg lid. If the local atmospheric pressure is 101 kPa, determine the temperature at the water will start boiling when it is heated.   [**100.2 ^{0}C**]

20. Water is being heated in a vertical piston-cylinder device. The piston has a mass of 20 kg and a cross-sectional area of 100 cm^2. If the local atmospheric pressure is 100 kPa, determine the temperature at which the water will start boiling.

21. A rigid tank with a volume of 2.5 m^3 contains 5 kg of saturated liquid vapour mixture of water at 75 ^{0}C. Now the water is slowly heated. Determine the temperature at which the liquid in the tank is completely vaporised. Also show the process on a T-v diagram with respect saturation lines. [**140.7 ^{0}C**]

22. A piston-cylinder device initially contains 50 litres of liquid at 25 ^{0}C and 300 kPa. Heat is added to the water at constant pressure until the entire liquid is vaporised.

   (a) What is the mass of the water?
   (b) What is the final temperature?
   (c) Determine the total enthalpy change
   (d) Show the process on a T-v diagram with respect to saturation lines.
   [**(a) 49.85 kg   (b) 133.6 ^{0}C   (c) 130,727 kJ**]

5.0 VAPOUR POWER CYCLES

One method of producing mechanical power is the transfer of heat to a working fluid, which goes through a thermodynamic cycle, converts part of the heat to work and rejects heat to a sink. If the working fluid undergoes a phase change, the cycle is called a <u>Vapour Power Cycle.</u>

5.1 Characteristics of a vapour power cycle

a)   The working fluid is a condensable vapour, which is in the liquid phase during part of the cycle.
b)   The cycle consists of steady flow processes with each process carried out in a separate component specially designed for the purpose.

Each component constitutes an open system and all the components are connected in series so that each fluid element passes through mechanical and thermodynamic states. In each component, matter flows into and out of region of space as well as heat and work. All the processes are considered to be flow processes.
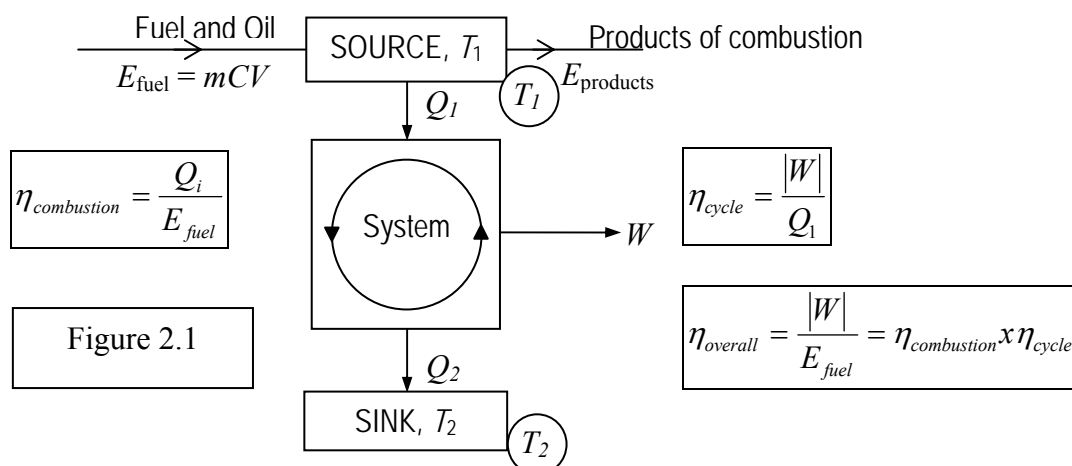
5.2 Decision making in design
- Capacity: Total power output required
- Energy Source: Chemical sources (coal, oil, natural gas, fuel cell and biomass); Nuclear energy; solar radiation etc.
- Energy Sink: From the 2nd Law, we know that all heat engines must reject some heat. Also, the efficiency is higher if the sink temperature is low. Available natural heat sinks are atmosphere, rivers, lakes, and oceans. At the moment about up to approximately 60 % of heat absorbed is rejected. This is a serious ecological problem because of thermal pollution.
- Working Fluid: Water because it is cheap and chemically stable.
- Component selection: Design of hardware. Decision on component arrangement etc. and also work out the economic and technical feasibility of the project.

5.3 Criteria for Comparing cycles
The choice of a power plant is determined largely by:
- Capital cost: This is determined by size and complexity of the plant
- Operating cost: This is determined by the overall efficiency of the plant. In general, the efficiency can be improved by increasing the complexity of the plant. A compromise between low operating and capital costs is therefore required.

5.4 Efficiency

Fuel and Oil → SOURCE, T_1 → Products of combustion

$E_{fuel} = mCV$ $E_{products}$, T_1

Q_1

$$\eta_{combustion} = \frac{Q_i}{E_{fuel}}$$

System → W

$$\eta_{cycle} = \frac{|W|}{Q_1}$$

Figure 2.1

$$\eta_{overall} = \frac{|W|}{E_{fuel}} = \eta_{combustion} \times \eta_{cycle}$$

Q_2

SINK, T_2 T_2

The essential features of a vapour power cycle are as illustrated in Fig. 5.1. The overall efficiency of a vapour power plant is suitably measured by the proportion of latent heat in the fuel, which is converted into useful mechanical work. The overall thermal efficiency can be expressed as a product of two efficiencies:

i)   **Combustion efficiency**: This expresses the proportion of the internal energy or latent energy in the fuel transferred as heat to the working fluid.

ii)   **Cycle efficiency**: This expresses the proportion of heat energy transferred to the working fluid and which is subsequently converted into mechanical work.

The cycle efficiency is **not unity** for the following reasons:

a)   The 2nd law expresses the fact that even in the best power cycle (Carnot cycle), some form of heat must be rejected. The best power cycle is that in which all heat supplied is transferred while the working fluid is at a constant upper temperature T_1 and all the heat rejected leaves while the working fluid is at a constant lower temperature T_2, and all the processes are reversible. The efficiency of such a cycle is given by the expression $\dfrac{T_1 - T_2}{T_1}$ irrespective of the working fluid.

b)   From the practical point of view, all real processes are irreversible and irreversibility in cycles reduces the overall efficiency. The first law is still obeyed, i.e. but the cycle efficiency $|W|/|Q_1|$ is reduced.

Ideal and actual cycle efficiencies and efficiency ratio:
If all the processes of a power cycle are assumed to be reversible, then the efficiency calculated is known as the ideal cycle efficiency. The ratio of the actual cycle efficiency to the ideal cycle efficiency is called the efficiency ratio.

$$\eta_{ratio} = \frac{\eta_{actual}}{\eta_{ideal}}$$

5.5 Work ratio

	Ideal		Actual $\eta_c = \eta_T = 0.90$	
	Cycle 1	Cycle 2	Cycle 1	Cycle 2
Q_{in}	120	120	120	120
W_T	100	40	90	36
W_c	61	1	67.9	1.1
W_{NET}	39	39	22.2	34.9
r_w	0.329	0.975	0.249	0.969
η	0.325	0.325	0.185	0.291

Some cycles are more sensitive to Irreversibilities than others and so high ideal cycle efficiency only is not by itself a good indicator of whether or not the cycle will provide a power plant of high overall efficiency.

The work ratio, r_w, gives an indication of how sensitive a cycle is to any irreversibility introduced into it. It defined as the ratio of the *net work output* to the gross *work output*. That is,

$$\boxed{r_w = \frac{\text{Net work output}}{\text{Gross work output}}}$$

Irreversibilities have the effect of decreasing the work outputs and increasing the work inputs and hence there is a decrease in the network output. Summarising, we may say that a *high ideal cycle efficiency together with a high work ratio provide a reliable indication that the actual power plant will have a good overall efficiency.* A work ratio of unity means that the components producing work will be of least possible size for a given net power output. Work ratio is in itself not very informative.

5.6   Specific steam consumption

A more direct indication of the relative sizes of steam power plant is provided by the specific steam consumption (SSC). It is the mass flow of steam required per unit net power output. It is usually expresses in kg/kWh and if $|W|$ is the magnitude of the network output per unit mass of steam in kJ/kg,

Then,
$$\frac{1}{|W|} = \frac{3600}{W} kg/kWh, \text{ if } |W| \text{ is in kJ/kg}$$

5.7   Process efficiencies

It is a measure of irreversibility and can be defined for a steady flow process as the ratio of isentropic to actual work or vice versa, depending on whether the process is a work producing process, or a work requiring process,

Turbine process:

$$\eta_{turbinr,isentropic} = \frac{\text{work done during actual expansion}}{\text{work done during isentropic expansion}} = \frac{h_2 - h_1}{h_{2s} - h_1}$$

$$\text{Work product} = \frac{\text{Actual}}{\text{Isentropic}}$$

$$\text{Work requiring} = \frac{\text{Isentropic}}{\text{Actual}}$$
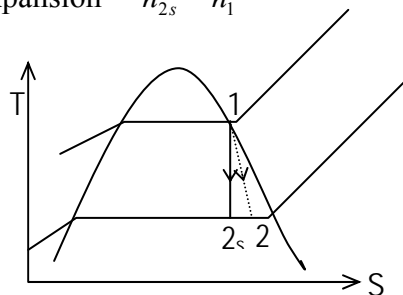
Irreversibility within the turbine reduce the net power output of the plant

Compressor or pump process

$$\eta_{compressor,isentropic} = \frac{\text{work required for isentropic compression}}{\text{work required for actual compression}} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

5.8 CARNOT CYCLE

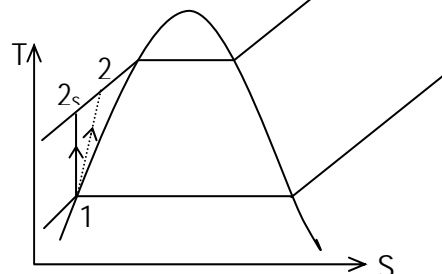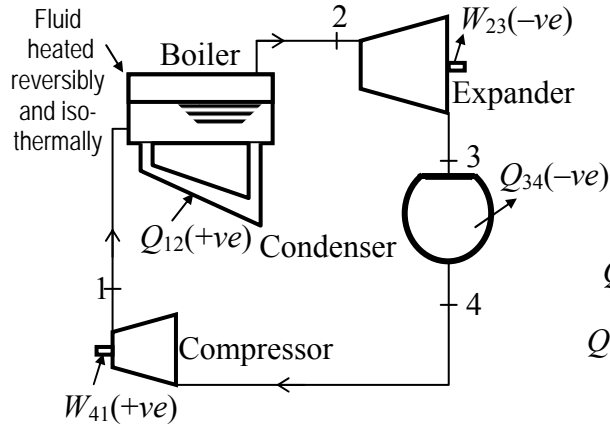It consists of two reversible isothermal processes at T_1 and T_2 respectively, connected by two reversible adiabatic (isentropic) processes. When the working fluid is a condensable vapour the isothermal processes are obtained by heating and cooling at constant pressure while the fluid is a wet vapour.

$$Q_{in} = h_{fg} e T_1$$
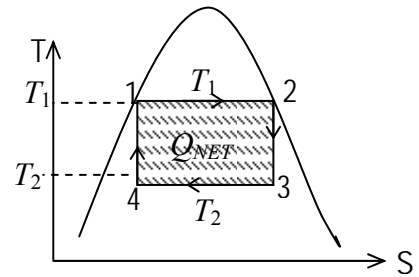
$$Q_{OUT} = \frac{T_2}{T_1} Q_{IN}$$

Fig. 5.2(a) Flow diagram of the Carnot Cycle   *Fig. 5.2(b) T -s diagram of Carnot Cycle*

Notes For a Cycle, from 1st Law

$$Q_{NET} + W_{NET} = 0$$
$$Q_{IN} + Q_{12} = T_1(S_2 - S_1)$$
$$Q_{OUT} + Q_{34} = T_2(S_3 - S_4)$$
$$Q_{NET} = (T_1 - T_2)(S_3 - S_4)$$

$$\boxed{\eta_{cycle} = \frac{|W_{NET}|}{Q_{IN}}}$$

1-2:   Saturated liquid in state 1 is evaporated in a boiler at constant pressure to form saturated steam in state 2.
Using the steady-state open flow energy equation
$Q_{12} + W_{12} = h_2 - h_1 + \Delta(KE) + \Delta(PE),$ but $\Delta(KE) = 0$ and $\Delta(PE) = 0$

Hence,

$$\boxed{Q_{12} = h_2 - h_1}$$

$h_2 - h_g$ at the pressure of the boiler and
$h_1 - h_f$ at the pressure of the boiler

2-3: Steam is expanded isentropically to state 3 while doing work in a turbine ($s_2 = s_3$) Note $s_2 = s_g$ and it evaluated at the pressure of the boiler. Since the entropy at state 3 lies between the s_f and s_g values corresponding to the boiler pressure, s_3 is evaluated as follows:

$$s_3 = s_{f,3} + x_3 s_{fg,3}$$

where, x_3 is the dryness fraction of the working fluid at state 3. $s_{f,3}$ and $s_{fg,3}$ values are read at the pressure corresponding to the condenser pressure at state point 3.

Using the steady-state open flow energy equation, we obtain

$$\boxed{W_{23} = h_3 - h_2}$$

Quality of steam decreases during this process thus, turbine handles steam with low quality (i.e. steam with high moisture content). The impingement of liquid droplets on the turbine blades causes erosion and is a major source of wear. x ≥ 90% is desirable.

$$x = \frac{m_g}{m_t}: \qquad m_t = m_f + m_g \qquad V = V_f + V_g = m_f v_f + m_g v_g$$

$$m_t v_{av} = m_f v_f + m_g v_g \qquad \boxed{v_{or} = (1-x)v_f + x v_g}$$

<u>3-4</u>:   After expansion the wet steam is then partially condensed at constant reassure and constant temperature while heat is rejected.

$$Q_{3,4} = h_4 - h_3 \qquad\qquad s_4 = s_{f4} + x_4 s_{fg,4}$$

Note: $s_1 = s_4$ and s_{f4}, $s_{fg,4}$ are read at the pressure corresponding to the condenser at state point 4. Condensation is stopped at state 4.

<u>4-1</u>:   Wet steam is compressed isentropically in a rotary or reciprocating compressor to state 1 that is the boiler pressure and temperature, the work required being
$$W_{41} = h_1 - h_4$$
$s_1 = s_f$ and is read at the pressure corresponding to that of the boiler pressure.

Thermal efficiency: $\eta_{th,c} = -\dfrac{W_{NET}}{Q_{IN}} = -\dfrac{W_{23} + W_{41}}{Q_{12}} = \dfrac{Q_{12} + Q_{34}}{Q_{12}} = 1 - \dfrac{T_2}{T_1}$

<u>Note:</u> The Carnot Cycle is **not** a realistic model for steam power plants because
1. Limiting the heat transfer processes to two-phase systems to maintain isothermal conditions severely limits the maximum temperature that can be used in the cycle.
2. The turbine would have to handle steam with a high moisture content which causes erosion of turbine blades and
3. It is not practical to design a compressor that will handle two-phase fluid.

5.9 The Rankine cycle [Basic Power Cycle]

Although the Carnot cycle is the most efficient cycle, its work ratio is low. Further, there are practical difficulties in following it. Consider the Carnot cycle of Fig. 5.2: at state 4 the steam is wet at T_2 but it is difficult to stop the condensation process at the point 4 and then compress it just to state 1. It is difficult to compress wet mixtures since the liquid tends to separate out from the vapour and the compressor would have to deal with a non-homogeneous mixture. It is convenient to allow the condensation process to proceed to completion, as in Fig. 5.3. The working fluid is water at the new state point 4 in Fig. 5.3, and this can be conveniently pumped to boiler pressure as shown at state point 5. The pump has much smaller dimensions than it would have if it had to pump a wet vapour, the compression process is carried out more efficiently, and the equipment required is simpler and less expensive.

With the new cycle, we realise that at state point 5; the water is <u>not</u> at the saturation temperature corresponding to the boiler pressure. Thus, heat must be supplied to change the state from water at 5 to saturated water at 1; this is <u>constant pressure process</u>, but it is <u>not at constant temperature</u>. If we let T_{eff} be the effective that temperature at which heat is added or supplied at some constant pressure and temperature, then its value can be evaluated from the relation $Q_{52} = T_{eff} \, \Delta S$. The effective temperature at which is added is lower than the corresponding Carnot temperature. Hence, the efficiency of the modified cycle is **not** as high as that of the Carnot cycle. But the net work output in the modified cycle is greater than that of the Carnot cycle. It follows that the *SSC* is less and the work ratio is greater.

$$r_w = \left(\frac{W_{net}}{W_{turbine}} \right)$$

This resulting ideal cycle, which is more suitable as a criterion for steam cycles rather than the Carnot cycle, is called the *Rankine cycle*.
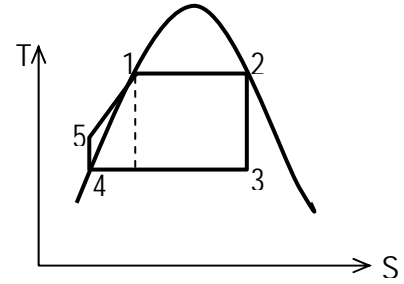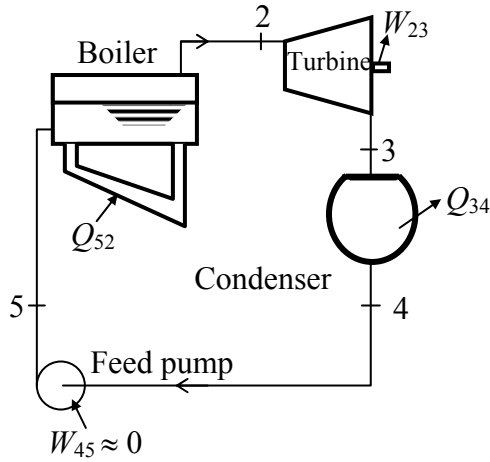
Fig 5.3 The Rankine cycle without superheat   Fig. 5.4 T-s diagram of the Rankine cycle

Feed pump work:

For a reversible process: $dQ = du - dW$ (1st Law)   (1)

   But $dW = -pdv$ and $h = u + pv$ (2)

                $dh = du + pdv + vdp$ (3)

Substituting equations (2) and (3) into (1) we arrive at

                $dQ = dh - vdp$

For isentropic process $dQ = 0$, hence $dh = vdp$

   Thus $\boxed{W_{45} = h_5 - h_4 = v_{f4}(P_5 - P_4)}$ (4)

where v_{f4} can be taken from tables for water at the pressure $P_4 = P_3$ (condenser pressure)

In general for a steady state, for process 1-2, $\dot{m}(s_2 - s_1) - \frac{d\dot{Q}}{T} \geq 0$. But for an adiabatic process $dQ = 0$, hence $s_2 \geq s_1$. Thus, for an irreversible process $s_2 > s_1$ and the irreversibility in process in process 1-2 is accounted for by introducing the process efficiency. The actual expansion and compression processes are irreversible and are indicated by lines 1-2 and 3-4 in Fig. 2-5.

Turbine isentropic efficiency   = $\dfrac{h_2 - h_1}{h_{2s} - h_1}$ and

Compression isentropic efficiency $= \dfrac{h_{4S} - h_3}{h_4 - h_3}$
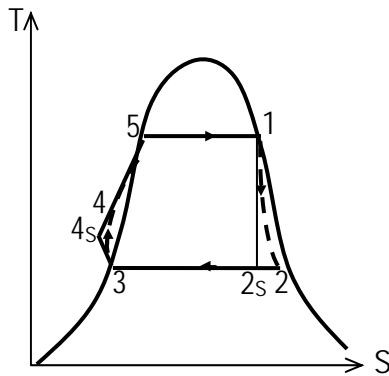
Fig. 5.5 Rankine cycle showing real Processes on a T-s diagram

Condenser heat load:

The rate of heat removal from the condenser, per unit power output is given by the product of *SSC* and the heat removed in the condenser by the cooling water per unit mass of steam.

Condenser heat load per kW of power output $= SSC \, x \, (h_2 - h_3)$

5.10 The Rankine cycle with superheat (The Simple Rankine Cycle)

a) The metallurgical limit of the boiler materials is **not** approached when the steam leaves the boiler in a saturated condition ($T_c \approx 374°C$ but $T_{metallurgical} \approx 620 \ °C$). The quality of steam at turbine exit in the simple Rankine cycle is too low. The isentropic efficiency of turbines is affected by the wetness of steam. (Note that wet steam corrodes the turbine blades). In practice, we require a minimum quality of 0.9 at the turbine exit.

But by placing in the combustion gases a separate batik of tubes (the superheater) leading saturated steam away from the boiler, it is possible to raise the steam temperature without at the time raising the boiler pressure. The resulting cycle with this modification is a *Rankine cycle with superheat,* as in Fig. 5.7.

The Ideal Rankine Cycle (Cycle employed in practical vapour power cycles)
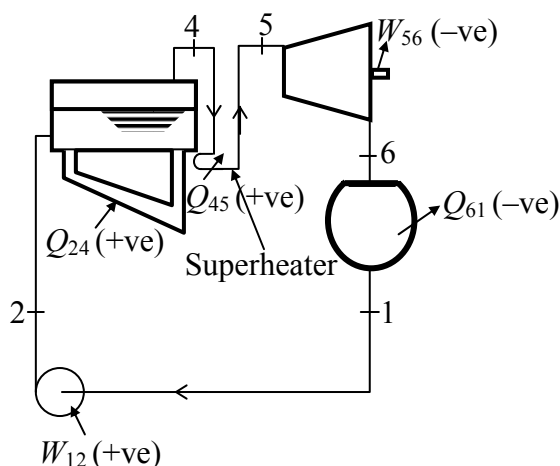
Thus both net work output and heat input increases. Overall effect is increase in η cycle.
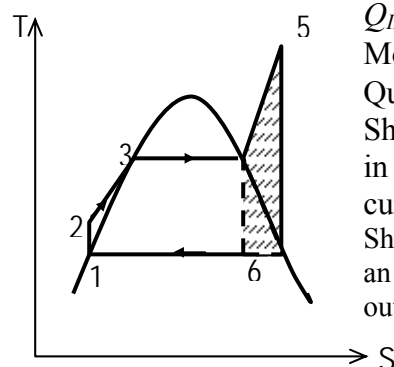
$Q_{IN}\uparrow, Q_{NET}\uparrow \Rightarrow |W_{NET}|\uparrow$
Moisture content $\downarrow$ ie.
Quality$\uparrow$ $\eta\uparrow$ $W_T\uparrow$ $W_P \rightarrow$
Shaded represent increase in heat input under process curve 4-5
Shaded area also represents an increase in net work output

66

Fig. 5.7a The Rankine cycle with superheat   Fig. 5.7b T-s diagram of Rankine cycle

The superheater is a heat exchanger in which heat is transferred to the saturated steam to increase its temperature. It may have its own source of heat or share with the boiler. If it is to share with the boiler the bank is situated such that hot gases from the furnace heat it until the steam reaches the required temperature. Normally, they have smaller bores than the actual boiler tubes.

Comments:
i)   The effective temperature at which heat is added externally is increased. Hence, the efficiency of cycle increases. Unlike the efficiency of a simple Rankine cycle, the efficiency of the Rankine cycle with superheat increases continuously with pressure.
ii)   The work ratio does **not** change since the work ratio in unsuperheated Rankine cycle is very near unity.
iii)   The specific steam consumption is markedly reduced, the net work per unit mass of steam being much greater, so that the added complexity of the superheater is compensated by a reduction in the size of the other components.
iv)   The dryness of the steam at the last stages of the steam turbine is increased, however the required quality of steam at the turbine exit is not attained.

5.11 How do we increase the efficiency of the Rankine Cycle

The basic idea behind all the modifications to increase the thermal efficiency of a power cycle is the same: *Increase the average temperature at which heat is transferred to the working fluid in the boiler, or decrease the average temperature at which heat is rejected from the working fluid in the condenser*.

Three ways of increasing the efficiency of the Rankine Cycle above are discussed below:
   (a)   Lowering the condenser Pressure (Lowers $T_{low, av}$)

   Steam exists as saturated mixture in the condenser at the saturation pressure corresponding to the pressure inside the condenser. Therefore, lowering the condenser pressure lowers the temperature of the steam, and thus temperature at which heat is rejected.

The effect of lowering the condenser pressure is illustrated in Figure 2.8. For purposes of comparison the inlet state temperature is maintained the same. The net work increases. The heat input requirement increases (represented by the area under 2-2'), but this is small compared to the increase in the net work output (i.e. area 1-4-4$^/$-1$^/$). Thus, *the overall effect of lowering the condenser pressure is an increase in the thermal efficiency of the cycle*.

The condensers of steam power plants operate well below the atmospheric pressure. But there is a limit on the condenser pressure that can be used. It cannot be lower than the saturation pressure corresponding to the temperature of the cooling medium. For example, for a condenser that is cooled by a nearby water at say 15 ^{0}C allowing for difference of 10 ^{0}C for effective heat transfer, the steam temperature in the condenser must be above 25 ^{0}C. From steam tables, the condenser pressure must be above 3.2 kPa (i.e. the corresponding pressure at 25 ^{0}C).

The side effects of lowering the condenser pressure option are:

67

- ❏ It creates the possibility of air leakage into the condenser
- ❏ It increases the moisture content of steam at the final stages of the turbine, which is undesirable in turbines because it decreases the turbine efficiency and erodes the turbine blades.

(b)   Superheating the Steam to High Temperatures (increases $T_{high,\ av}$)

The average temperature at which heat is added to the steam can be increased without increasing the boiler pressure by superheating the steam to high temperatures. The effect of superheating on the performance of a vapour power cycle is illustrated in Figure 2.9.

We recognise an increase in the net work. The area under curve 3-3$^/$ represents the increase in heat input. Thus superheating the steam increases both the net work and the heat input. The overall effect is an increase in cycle efficiency since the average temperature at which heat is added is increased.

Other advantages of superheating:
- ❏   It decreases the moisture content of the steam at the turbine exit

Limitation of superheating:
- ❏   The temperature to which steam is superheated is limited by metallurgical limit of material used. T = 620 ^{0}C is about the present optimum.

(c)   Increasing Boiler Pressure (Increases $T_{high,\ av}$)

Another option of increasing the average temperature during the heat-addition process is to increase the operating pressure of the boiler, which automatically increases the temperature at which boiling takes places. This, in turn, raises the average temperature at which heat is added and thus raises the thermal efficiency.

The effect of increasing the boiler pressure is illustrated in Figure 2.10. We note that for a fixed turbine inlet temperature, the moisture content of steam at the turbine exit increases. This undesirable effect is corrected with reheating.

Today modern power plants operate at supercritical pressures (P > 22.1 MPa) and have thermal efficiencies of 40% for fossil-fuel plants and 34 % for nuclear plants. The lower thermal efficiency values for nuclear plants are due to the fact that lower maximum temperatures values are used in those plants for safety reasons.

5.12   Reheat Cycle (Ideal Reheat Cycle)

It is desirable to increase the average temperature at which heat is supplied to the steam, and also to keep the steam as dry as possible in the lower pressure stages of the turbine. The wetness of steam at the turbine exhaust should be no greater than 10 %.

Higher boiler pressures are required for high efficiency, but expansion in one stage can result in the exhaust steam, which is wet. This condition is somehow improved by superheating but it is further improved by re-heating the steam, the expansion being carried out in two stages. With the reheat cycle, the expansion takes place in two turbines. The steam expands in the high-pressure turbine to some intermediate pressure, and is then passed back to yet another bank of tubes in the boiler where it is reheated at constant pressure, usually to the original superheat temperature. It then expands in the low pressure turbine to the condenser pressure. The Reheat cycle appears as in Fig. 2.11.

Two options to increase quality of steam at the turbine exit:

1) Superheat steam to very high temperature is appropriate but **not** a viable solution since it will require raising the steam to metallurgical unsafe limits.
2) Expands steam in two stages, and reheat in between. This is practical solution to reducing the wetness of steam of turbine exit.
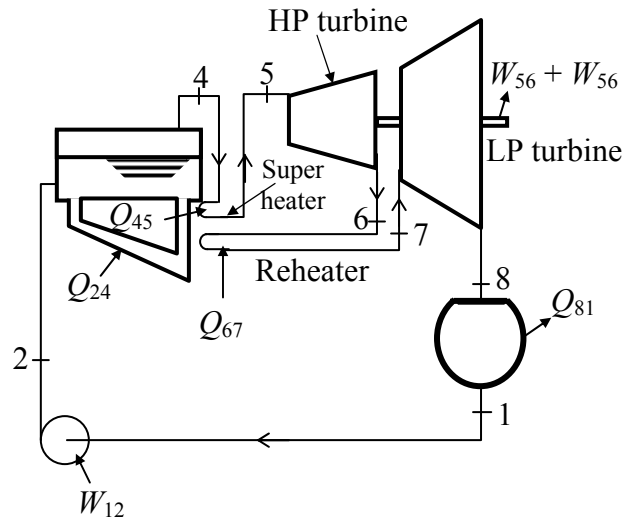

The larger the number of reheats the higher the average temperature of heat addition process. But reheating more than twice is not desirable and practical. Double reheat is only used on supercritical ($P>22.1$ MPa) power plants.

Fig 2.11a The Reheat cycle   Fig. 2.11b T-s diagram of the Reheat cycle
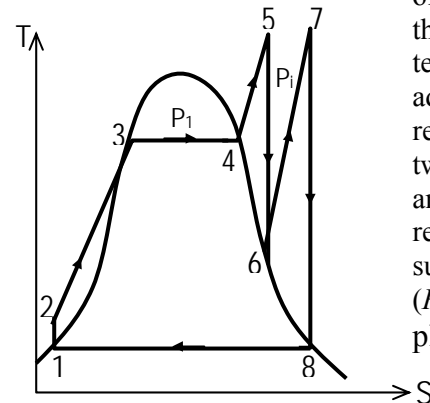
5-6 Isentropic expansion in the high-pressure turbine to an intermediate pressure. To determine the intermediate pressure, we find from the saturation' table the pressure at which $s_g = s_6$ To find s_6 use the superheat tables.

6-7: Isentropic expansion in the low pressure turbine.

Heat supplied $= Q_{245} + Q_{67}$

Work output $= W_{56} + W_{78}$,   Also, $Q_{67} = h_7 - h_6$

Cycle efficiency,
$$\eta = -\frac{W_{56} + W_{78}}{Q_{245} + Q_{67}} = -\frac{h_6 - h_5 + h_8 - h_7}{h_5 - h_2 + h_7 - h_6}$$

If we neglect the feed pump work, $h_2 \approx h_1$ and $\therefore Q_{245} = h_5 - h_1$

Boiler Efficiency:
The boiler efficiency is the heat supplied to the steam in the boiler expressed as a percentage of the chemical energy of the fuel, which is available on combustion. That is;

$$\text{Boiler efficiency} = \frac{\dot{m}_s x[h_5 - (\text{enthalpy of the feed water})]}{\dot{m}_f x(\text{GCV or NCV})}$$

where h_5 is the enthalpy of the steam entering the turbine and $\dot{m}_f$ the mass of fuel burned per unit time and $\dot{m}_s$ the mass flow rate of steam. The GCV and NCV are the higher and lower calorific values of the fuel. The size of a boiler, or its capacity, is quoted as the rate in kilogram per hour at which the steam is generated.

Comments:

Reheating reduces the steam consumption appreciably, because the area of the cycle on the T-S diagram, which equals the network done per unit mass of steam, increases. In high-pressure cycles this implies a smaller boiler (expensive item in high-pressure plant). This decrease in size goes with added complexity. Note that the effective average temperature at which the heat is added may be lower than that in the Rankine cycle if the intermediate pressure is too low. The use of re-heating gives drier steam at the turbine exit thus reducing blade erosion in the latter stages of the turbine. The cost of reheating, however, adds to the capital cost of the plant.

Sole purpose of reheating is to reduce the moisture content of the turbine exit (fluid stages in the expansion process). Therefore, if we had materials that could withstand high temperatures there would be no need for reheating.

Cogeneration System

Utilization factor $\xi = \dfrac{|W_{ST}| + Q_{pa}}{Q_{IN}}$ $\xi = 1 - \dfrac{|Q_{out}|}{Q_{in}}$

In actual cogeneration plants the utilization factor $\xi = 70\%$

In all cycles discussed so far, the sole purpose was to convert a portion of the heat transferred to the working fluid to work, which is the most valuable form of energy. The remaining portion of the heat is rejected to rivers, lakes, oceans or the atmosphere as waste heat. Wasting a large amount of heat is a price we have to pay to produce work. Many systems or devices, however, require energy input in the form of heat, called process heat. A plant that produces electricity while meeting the process-heat requirements of certain plants is called a co-generation plant.

Note: A plant for the productio of more than one useful form of energy from the same energy source is called a co-generation plant.

5.16   Further considerations in improving the efficiency of a steam power plant

Hitherto, considerations of efficiency have been based on the heat, which is actually supplied to the steam, and not the heat, which has been produced by the combustion of the fuel in the boiler. The heat is transferred to the steam from gases, which are at a higher temperature (approx. 2000 K) than the steam, and the exhaust gases pass to the atmosphere at a high temperature.

Energy of the flue gases can be utilized to preheat the feed water before entry into the boiler. The external heat supplied is reduced thus increasing the thermal efficiency of the system.

The Economiser:
To utilise some of the energy in the flue gases an *economiser* can be fitted (see Fig. 2.15(a)). This is heat exchanger placed in the flue gases, which extracts useful energy in the form of heat to preheat the feed water before entry to the boiler. (*For the Carnot, ideal regenerative and complete feed heating cycles, **no** use can be made of an economiser since the feed water enters the boiler at the saturation temperature corresponding to the boiler pressure*).

The Air pre-heater:
To cool the flue gases even further and improve the plant efficiency, the air, which is required for the combustion of the fuel, can be pre-heated (see Fig. 2.15 (b)). For a given temperature

of the combustion gases, the higher the initial temperature of the air then the less will be the energy input required, and hence less fuel will be used.

One practical consequence of cooling the combustion gases is that there is a pressure drop in the chimney and fans may be required to achieve the necessary forced draught for the flue gases.

(a)   *(b)*
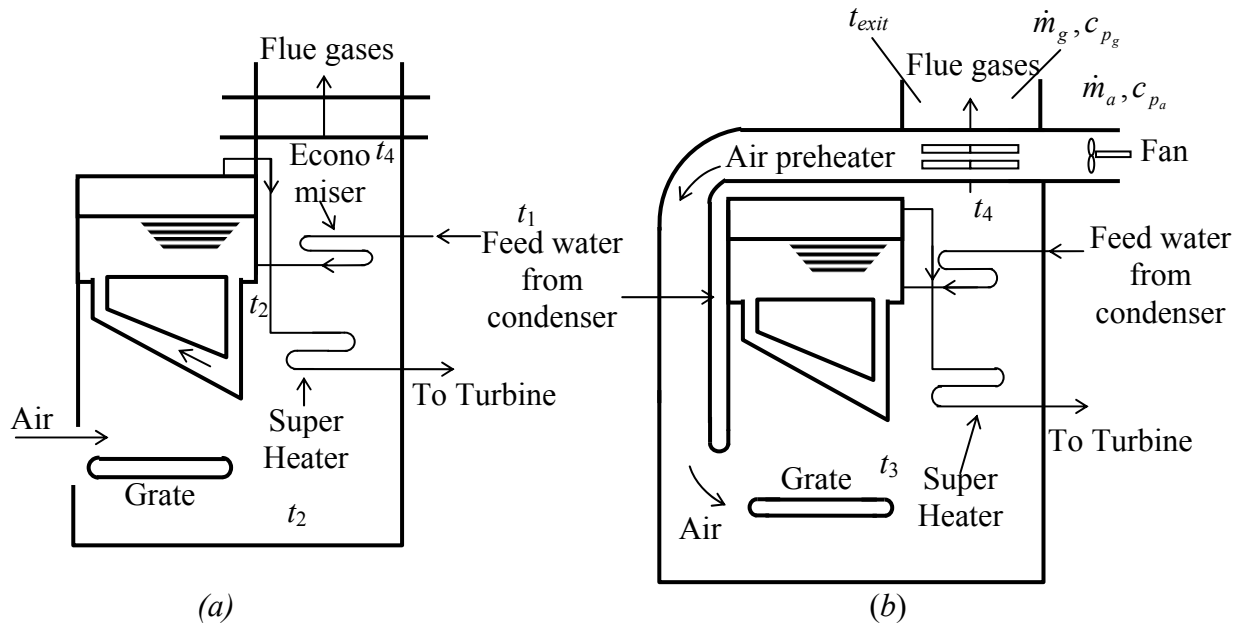
Fig. 5.15 Diagrammatic sketch of a boiler plant with (a) an economiser (b) an air preheater

Analysis of the Economiser

Let us assume that the temperature of the feed water is raised from t_1 to t_2 in the economiser and that the flue gases are also cooled from t_3 to t_4.

For air pre-heater $\dot{m}_a x c_{pa} \Delta t = c_{pg} x \dot{m}_g \left(t_4 - t_{exit} \right)$

Heat Exchanger

We have $\dot{m}_g c_{pg} \left(t_3 - t_4 \right) = \dot{m}_s \left(h_2 - h_1 \right) + m c_p \left(t_{exit} - t_{entry} \right)$

Index Number: --

KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI

COLLEGE OF ENGINEERING

B.Sc. (Eng.) SECOND SEMESTER EXAMINATION, 2005

First Year (Electrical & Computer Engineering)

ME 166   APPLIED THERMODYNAMICS

MAY, 2005   3 HOURS

INSTRUCTIONS TO CANDIDATES

This paper consists of **TWO** sections. Answer Section A on the question paper by **<u>circling</u>** the correct answers **in pencil or pen**, and Section B in your answer book.

<u>Section A</u> will last for **2 hours**, after which the question paper for this section will be collected. Do **NOT** start with Section B until you are told to do so. <u>Section B</u> will last for **1 hour**.

 Answer **all** questions in both Sections A and B.

The invigilator will provide you with Thermodynamics and Transport Properties of Fluids by G. F. C. Rogers and Y. R. Mayhew.

<u>Indicate your index number and department below; and append your signature:</u>

INDEX NUMBER OF CANDIDATE: --

DEPARTMENT: --

SIGNATURE OF CANDIDATE: --

SECTION A, PART I [50 marks]

For each question, circle in PENCIL OR PEN the most correct option. Give **only** one answer to each question. **SHOW WORKING AND DO ALL ROUGH WORK ON THE QUESTION PAPER**.

1. A power cycle operates continuously and receives energy by heat transfer from the combustion of fuel at a rate of 75 kW. If the thermal efficiency of the cycle is 30 %, the rate of power developed, in kW, is:

    A. 250 kW   B. 60 kW   C. 52.5 kW   D. 22.5 kW   E. 11.3 kW

2. Superheated vapour in a closed system is kept at a pressure of 10 bars. The specific volume of the superheated vapour is 0.2403 m^3/kg. If the superheated vapour is allowed to cool at what pressure will the superheated vapour become saturated?

    A. 8.0 bar   B. 7.5 bar   C. 7.0 bar   D. 5.7 bar   E. 0.053 bar

3. The entropy of a closed system which is thermally isolated from the surroundings
    A. never decreases
    B. always increases
    C. always remains constant
    D. either decreases or remains constant
    E. either increases or decreases

4. For a reversible adiabatic process, the change in its entropy is
    A. always a positive quantity
    B. zero
    C. greater than unity
    D. greater than zero
    E. always a negative number.

5. A power cycle operating between two reservoirs receives energy Q_H by heat transfer from a hot reservoir and rejects energy Q_C by heat transfer to a cold reservoir while it does a net - work W_{cycle} on the surroundings. The data listed below are claimed for the power cycle operating between the reservoirs at 1000 K and 400 K. In which of the following cases is *any* principle of thermodynamics violated?
    I. $|Q_H| = 300$ kJ, $|W_{cycle}| = 160$ kJ, $|Q_C| = 140$ kJ
    II. $|Q_H| = 300$ kJ, $|W_{cycle}| = 180$ kJ, $|Q_C| = 120$ kJ
    III. $|Q_H| = 300$ kJ, $|W_{cycle}| = 170$ kJ, $|Q_C| = 140$ kJ
    IV. $|Q_H| = 300$ kJ, $|W_{cycle}| = 300$ kJ, $|Q_C| = 0$ kJ

    A. IV only
    B. III only
    C. I only
    D. III and IV only
    E. None of the above

Use the information below to answer questions **6 to 8** on the operation of a refrigeration cycle.

A refrigeration cycle operating between two reservoirs extracts energy Q_C from a cold reservoir at $T_C = 300$ K and rejects energy Q_H to hot reservoir at temperature $T_H = 350$ K. It is conceived by an engineer that the refrigeration cycle can operate under each of the following cases:

I. $|Q_C| = 1000$ kJ, $W_{cycle} = 400$ kJ
II. $|Q_C| = 2000$ kJ, $|Q_H| = 2200$ kJ
III. $|Q_H| = 3000$ kJ, $W_{cycle} = 500$ kJ
IV. $W_{cycle} = 400$ kJ, $COP_{ref} = 6.0$

6. In which case(s) conceived by the engineer, is/are the operation of the refrigeration cycle impossible?
    A. I only
    B. III only
    C. II only
    D. III and IV only
    E. II and IV only

7. In which case(s) conceived by the engineer, could the refrigeration cycle operate reversibly?
    A. I only
    B. III only
    C. II only
    D. III and IV only
    E. II and IV only

8. In which case(s) conceived by the engineer, could the refrigeration cycle operate irreversibly?
    A. I only
    B. III only
    C. II only
    D. III and IV only
    E. II and IV only

9. There exists a property a closed system such that a change in its value between state 1 and state 2 is independent of the path taken to go from state 1 to state 2. This property of a closed system is referred to as
    A. internal energy
    B. temperature
    C. entropy
    D. enthalpy
    E. work

<u>Use the information below to answer questions **10 to 12** on the operation of a power cycle</u>

A power cycle operating between two reservoirs receives energy Q_H from a heat reservoir at $T_H = 1000$ K and rejects energy Q_H to cold reservoir at temperature $T_C = 600$ K. It is conceived by an engineer that the power cycle can operate under each of the following cases:

    I. $|Q_H| = 1000$ kJ, $|W_{cycle}| = 400$ kJ
    II. $|Q_C| = 1000$ kJ, $|Q_H| = 2000$ kJ
    III. $|Q_C| = 600$ kJ, $|W_{cycle}| = 300$ kJ
    IV. $|W_{cycle}| = 400$ kJ, $\eta_{th} = 30$ %

10.   In which case(s) conceived by the engineer, is/are the operation of the power cycle impossible?
    A. I only
    B. III only
    C. II only
    D. III and IV only
    E. II and IV only

11.   In which case(s) conceived by the engineer, could the power cycle operate reversibly?
    A. I only
    B. III only
    C. II only
    D. III and IV only
    E. II and IV only

12.   In which case(s) conceived by the engineer, could the power cycle operate irreversibly?

    A. IV only
    B. III only
    C. I only
    D. III and IV only
    E. II and IV only

13.   A gas is compressed from $V_1 = 0.09$ m³ to $V_2 = 0.03$ m³. The relation between pressure and volume during the process is $p = -14V + 2.44$, where the units of p and V are bar and m³, respectively. For the gas, find the work done in Joules (J).

    A. 2,400 J   B. 4,800 J   C. 9,600 J   D. 19,200 J   E. 38, 400 J

14.   Saturated steam enters a steam turbine at 55 bar, 269.9 ^{0}C. The flow work of the steam at entry to the turbine is

    A. 196 kJ/kg
    B. 2594 kJ/kg
    C. 1605 kJ/kg
    D. 2794 kJ/kg
    E. 2790 kJ/kg

15. Which of the following parameters is an <u>intensive</u> property?
     A. volume
     B. temperature
     C. entropy
     D. internal energy
     E. enthalpy

16. One of the following diagrams is usually referred to as the phase diagram for a pure substance since it represents all three phases in one diagram.
     A. $p - v$ diagram
     B. $p - T$ diagram
     C. $T - v$ diagram
     D. $T - s$ diagram
     E. $p - h$ diagram

17. The slope of the melting line on the phase diagram for a substance that expands on freezing is
     A. Positive   B. Negative   C. Zero   D. Unity   E. Undefined

18. "Two systems in thermal equilibrium with a third system individually are in thermal equilibrium with each other". This statement is

     A. Kelvin-Planck's statement of the second law
     B. Clausius statement of the second law
     C. The First Law of thermodynamics
     D. The Zeroth Law of thermodynamics
     E. The Third Law of Thermodynamics

19. "It is *impossible* to construct a system which will operate in a cycle, extract heat from a reservoir and do an equivalent amount of work on the surroundings". This statement is referred to as

     A. Kelvin-Planck's statement of the second law
     B. Clausius statement of the second law
     C. The First Law of thermodynamics
     D. The Zeroth Law of thermodynamics
     E. The Third Law of Thermodynamics

20. There exists a property of a closed system such that a change in its value for any reversible process undergone by such a system between state 1 and state 2 is given by the expression
     $\int_1^2 \frac{dQ}{T}\Big|_{rev}$. This property is referred to as

     A. internal energy
     B. enthalpy
     C. entropy
     D. irreversibility
     E. compressibility factor

21-25.   How do the following quantities change when a simple ideal Rankine cycle is modified with reheating? Assume that the mass flow rate is maintained the same.

Pump work input:	(A) increases	(B) decreases	(C) remains the same
Turbine work output:	(A) increases	(B) decreases	(C) remains the same
Heat supplied:	(A) increases	(B) decreases	(C) remains the same
Heat ejected:	(A) increases	(B) decreases	(C) remains the same
Moisture content at turbine exit:	(A) increases	(B) decreases	(C) remains the same

26.   Air at 500 K flows over a flat surface of a plate whose temperature at steady state is 400 K. The heat flux to the plate is 2500 W/m^2. The value of the heat transfer coefficient is

A. 25 W/m K   B. 25 W/m^2 K   C. 0.4 W/m K   D. 0.4 W/m^2 K

27.   A surface of area 2 m^2 emits thermal radiation. The emissivity of the surface is 0.8. The rate at which energy is emitted for the surface whose temperature is 500 K is

A. 0.023 W   B. 11.34 W   C. 5670 W   D. 7087.5 W

28.   A brick wall of an industrial furnace is 0.1 m thick and has a thermal conductivity of 1.5 W/m K. At steady state, the temperatures of the inner and outer wall are 1500 K and 1200 K, respectively. The temperature distribution is linear through the wall. For an area of 10 m^2, the rate of energy transfer through the wall by conduction is

A. 202.5 kW   B. 45 kW   C. 20 kW   D. 4.5 kW

29-30   Consider a simple ideal Rankine cycle with fixed boiler and condenser pressures. What is the effect of superheating the steam to a higher temperature on

Turbine work output:	(A) increases	(B) decreases	(C) remains the same
Heat supplied:	(A) increases	(B) decreases	(C) remains the same

31.   The entropy of a pure crystalline substance at absolute zero temperature is zero. This is the statement of the

A. Zeroth Law of Thermodynamics
B. First Law of Thermodynamics
C. Kelvin – Plancks statement of Second Law of Thermodynamics
D. Clausius statement of the Second Law of Thermodynamics
E. Third Law of Thermodynamics

<u>Use the following provided below to answer questions 32 – 35.</u>

A gas undergoes a thermodynamic cycle consisting of three processes beginning at an initial state where $p_1 = 1$ bar, $V_1 = 1.5$ m^3, and $U_1 = 512$ kJ. The processes are as follows:

Process 1-2: compression with pV = constant to $p_2 = 2$ bar, $U_2 = 690$ kJ.
Process 2-3: $W_{23} = 0$, $Q_{23} = -150$ kJ.
Process 3-1: $W_{31} = -50$ kJ.
There are no significant changes in kinetic or potential energy.

32. The value of the internal energy at state 3 is
    A.   – 1202 kJ
    B.   1202 kJ
    C.   540 kJ
    D.   – 200 kJ
    E.   178 kJ

33. The volume of the gas at state 2 is

    A.   3.0 m^3
    B.   1.5 m^3
    C.   0.75 m^3
    D.   0.5 m^3

34. The heat transfer for the process 3 – 1 is:
    A.   1764 kJ
    B.   - 640 kJ
    C.   22 kJ
    D.   762 kJ
    E.   384 kJ

35. The heat transfer for the process 1 – 2 is:

    A.   0 kJ
    B.   14 kJ
    C.   75 kJ
    D.   283 kJ
    E.   300 kJ

36. A reversible adiabatic process is referred to as an

    A.   Isentropic process
    B.   Isenthalpic process
    C.   Isobaric process
    D.   Isochoric process
    E.   Isothermal process

SECTION A, PART II [14 marks]

In each of the questions, answer by either <u>circling</u> (**T**) under the response column if the statement is TRUE or (**F**) if the statement is FALSE.

		Statement	Response	
37.		Energy can cross the boundaries of a closed system in form of heat and work.	**T**	**F**
38.		Work can always be converted to heat directly and completely, but reverse is not true	**T**	**F**
39.		Heat transfer through a temperature difference is an irreversible process.	**T**	**F**
40.		An engine using the ocean as the source of heat can be used to drive a ship.	**T**	**F**
41.		A power station can be run using the atmosphere as the source of heat.	**T**	**F**
42.		A car engine without neither an exhaust nor a cooling system is a perpetual motion machine of the first kind.	**T**	**F**
43.		An engine operating between two heat reservoirs at different temperatures can have a higher efficiency than its reversible equivalent.	**T**	**F**
44.		Increase in entropy of a system is equivalent to the degradation of energy of the system	**T**	**F**
45.		No heat engine can have a thermal efficiency of 100 %.	**T**	**F**
46.		Work is more valuable energy than heat.	**T**	**F**
47.		A heat pump can operate without a work input.	**T**	**F**
48.		An isolated system is a special kind of an open system.	**T**	**F**
49.		The rate equation for heat transfer through a solid wall is Stefan-Boltzmann's Law.	**T**	**F**
50.		The automobile engine is an example of a closed system.	**T**	**F**

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ME 166   APPLIED THERMODYNAMICS

SECTION B [20 MARKS]   **TIME: 1 hour**

Answer **both** questions. Both questions carry equal marks.

1.   A closed system comprising 1.0 kg of gas in a piston – cylinder arrangement is to undergo a quasi – static process from an initial state, where $p_1 = 30\,kPa$, *and* $V_1 = 0.001\,m^3$ to the final state where $p_2 = 0.1\,kPa$, *and* $V_2 = 0.01\,m^3$.

THREE (3) different processes can be used to achieve the objective as described below:

Process A: PV^2 = constant and the process is adiabatic.

Process B: $P = aV + b$ where *a* and *b* are constants.

Process C: The volume increases to the final value at constant pressure followed by a pressure decrease at constant volume.

For each process, calculate the work done and the heat transferred and state clearly whether work is done *by* or *on* the system.

2.   A 300 MW steam power plant operates on an ideal simple Rankine Cycle. Steam enters the turbine at 10 MPa and 500 ^{0}C and is cooled in the condenser at a pressure of 10 kPa. Show the cycle on a *T – s* diagram with respect to saturation lines, and determine:

    (a)   the quality of the steam at the turbine exit,

    (b)   the thermal efficiency of the cycle, and

    (c)   the flow rate of the steam through the plant.

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