

**KWAME NKRUMAH UNIVERSITY OF SCIENCE AND  
TECHNOLOGY, KUMASI**

FACULTY OF DISTANCE LEARNING

**ME 166: APPLIED THERMODYNAMICS**

By  
**DR F.K. FORSON**  
SENIOR LECTURER  
**KNUST**  
AUGUST 2006

## ***Contact Address***

**Dean  
Faculty of Distance Learning  
New Library Building  
Kwame Nkrumah University of Science and Technology  
Kumasi, Ghana**

**Phone:**     **+233-51-60013  
                  +233-51-60014**

**Fax:**         **+233-51-60023  
                  +233-51-60014**

**E-mail:**     **[cdce@fdlknust.edu.gh](mailto:cdce@fdlknust.edu.gh)  
                  [kvcit@fdlknust.edu.gh](mailto:kvcit@fdlknust.edu.gh)  
                  [kvcit@avu.org](mailto:kvcit@avu.org)**

**Web:**        **[www.fdlknust.edu.gh](http://www.fdlknust.edu.gh)**

## ***Course Author***

F.K. FORSON received his BSc. (1982) and MSc (1993) degrees in Mechanical Engineering from the University of Science and Technology (UST), now Kwame Nkrumah University of Science and Technology (KNUST), in Kumasi – Ghana. He received his PhD (1999) from De Montfort University in Leicester, United Kingdom. He worked with the Department of Mechanical Engineering of the then University of Science and Technology, Kumasi from October 1982 to September 1984 as a National Service Person. He then joined the Department as an academic staff in the capacity as an Assistant Lecturer in October 1984.

Dr F. K. Forson has been the Head of the Department of Mechanical Engineering (Jan. 2005 – Sept. 2006) and he is currently the Dean of the Faculty of Mechanical and Agricultural Engineering, KNUST. He is a Senior Lecturer and has published technical papers in international journals like *Ambient Energy*, *Renewable Energy*, *Energy Conversion and Management*, and *Solar Energy*. He is a member of the University Council of KNUST.

## ***Course Introduction***

This course is an introductory course in thermodynamics designed to introduce students to:

- Fundamental concepts and definitions of terms used in the study of thermodynamics
- Energy and the First Law of Thermodynamics
- The Second Law of Thermodynamics
- Application of the First and Second Laws of Thermodynamics to systems devised for the production of mechanical power in which the working fluid is alternately vapourised and condensed.

Several textbooks have been consulted and materials from them have been assembled to provide the needed information that addresses the course content.

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# INTRODUCTORY CONCEPTS AND DEFINITIONS

## 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 forms. 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.

Hence, *thermodynamics is defined as the study of energy, its forms and transformations, and the interactions of energy with 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 as 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, which lists a few areas where engineering thermodynamics is important.

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

Table 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.

## SESSION 1-1:

### 1-1.1 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 is 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.

#### Surroundings of Environment of System

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.

The portions of matter or space which are external to the system and which either affects 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. Mathematically, a boundary will have no thickness and can neither contain mass nor contain any volume in space.

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.

Example 1: Suppose we are interested in the behaviour of air when it is heated or compressed: Figure 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.

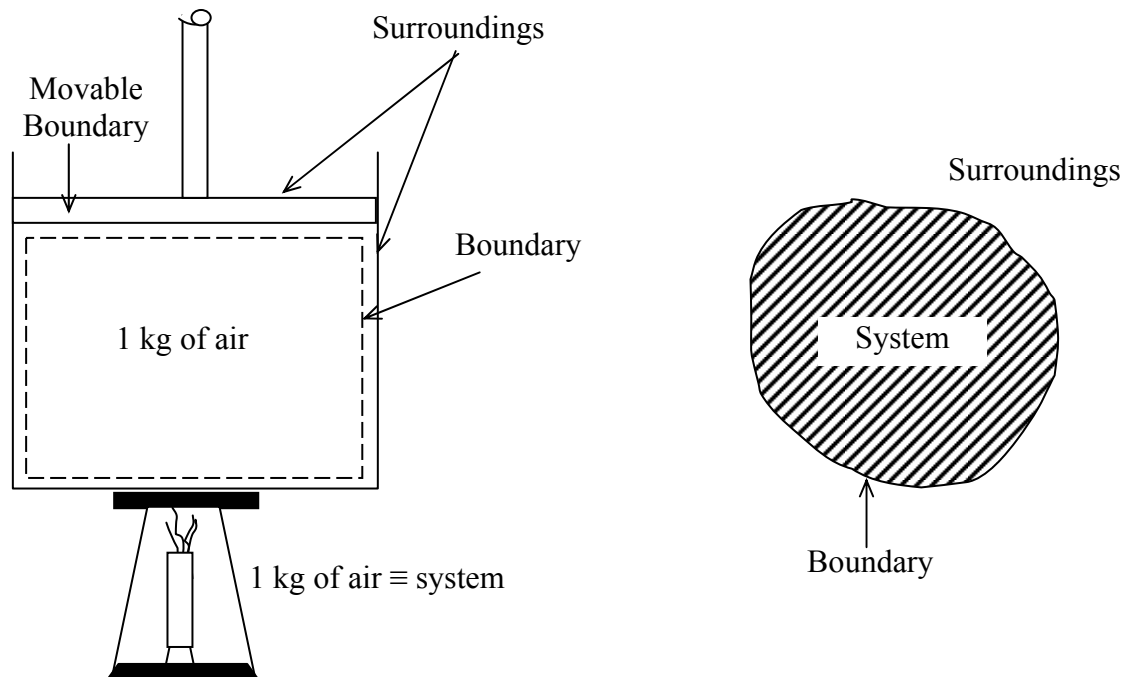


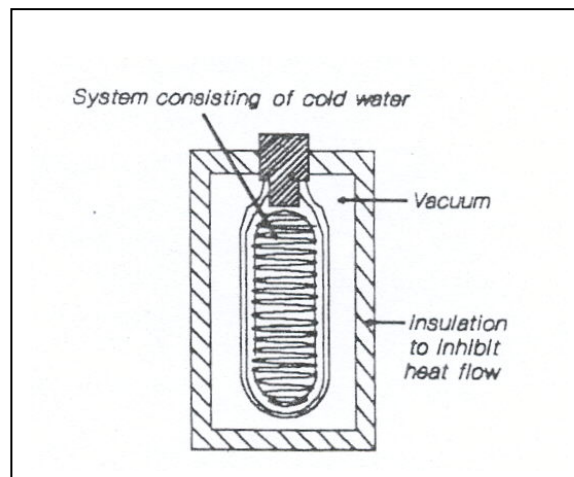
Figure 1: Sketch of an experimental set-up

### 1-1.1.1 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 exchange only heat and work with the surroundings. Figure 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 2.



**Figure 2: Thermos Flask**

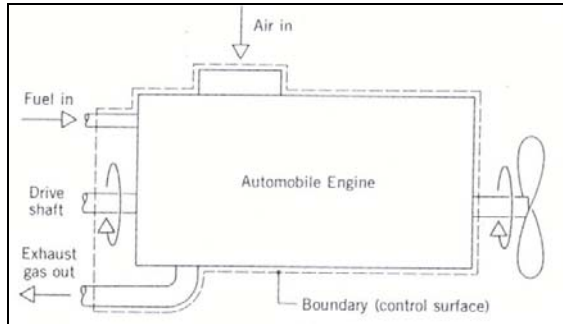
### Open system

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 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.

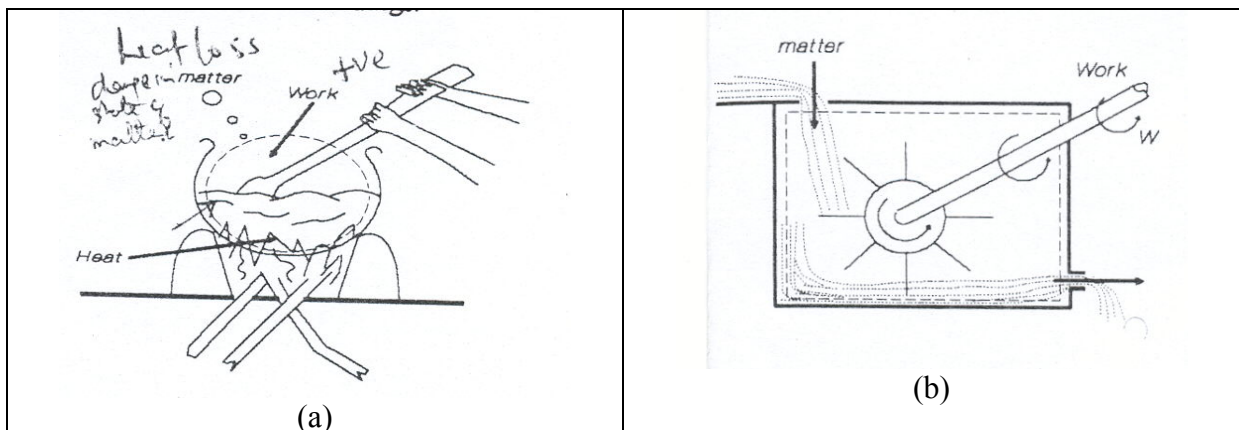
Figure 4 (a) and (b), show examples of open systems. In Figure 4 (a), ~~the system~~ the system is water which flows through a region containing a water wheel. As the water turns the wheel, work flows across the boundaries of the open system in the form of the shaft rotating. The water is the source of the shaft work. The boundaries of the system are fixed.

Fig. 4 (b) 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 3: An open system (an automobile engine)**



**Figure 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 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.

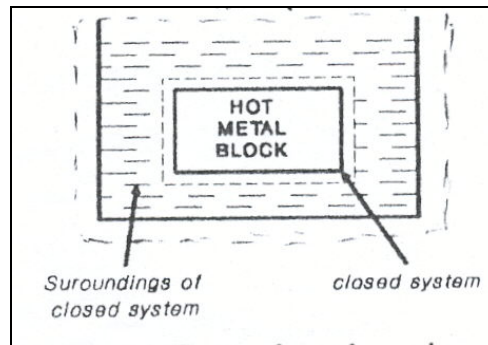


Figure 5: System depends on the observer

### 1-1.1.2 Macroscopic and microscopic views of thermodynamics

The study of properties of materials is conducted in the ways:

1. the substance is considered to consist of atoms or molecules whose individual characteristics are known
2. a few measurable quantities which are suggestions by senses are used to describe average properties of the substance (volume, mass)

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.

**Limitation of macroscopic view point:** it is unable to explain why the relationships have their particular form and hence their underlying physical structure and mechanisms. We therefore use microscopic viewpoint to explain the fundamental basis of thermodynamic phenomena and relations. For example, 1 kg of water at a temperature of  $100^{\circ}\text{C}$  and pressure 1 atm (1.01325 bar),  $v = 0.001044 \text{ m}^3$  when it heated at same temperature and pressure the volume increases to  $1.673 \text{ m}^3$ . Explain why?



## 1-1.2 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 the change in 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

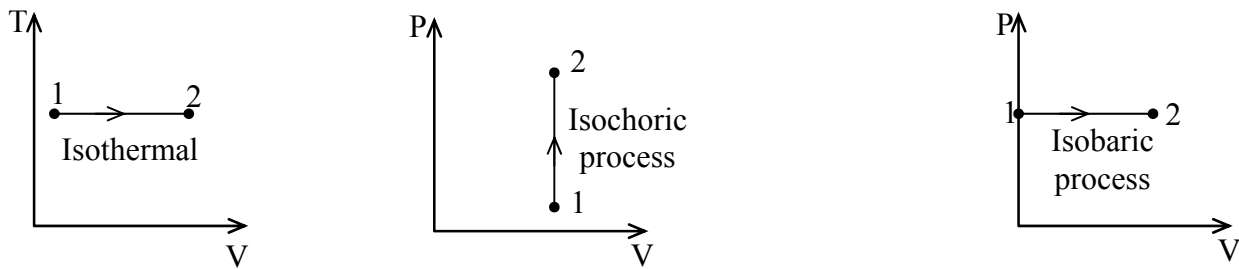
The word state refers to the condition of a system as described by its properties. Providing values of a subset of the properties can often specify the state. The state can be specified by two thermodynamic properties. You should note that a doctor needs a few macroscopic measurements (temperature and 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 in 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.

### **1-1.2.1 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 mostly with time. Specific volume, pressure and temperature are all intensive

properties. It must be noted that for some intensive properties, a corresponding extensive property can be defined.

### 1-1.2.2 Phase and Pure Substance

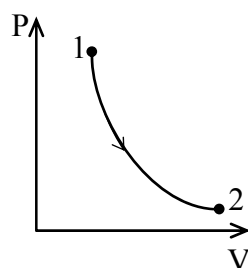
The term *phase* refers to a quantity of matter that is homogeneous throughout in both chemical composition and physical structure. Homogeneity in physical structure means that the matter is all *solid*, or all *liquid*, or all *vapour* (or equivalently all gas).

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.

### Types of Processes

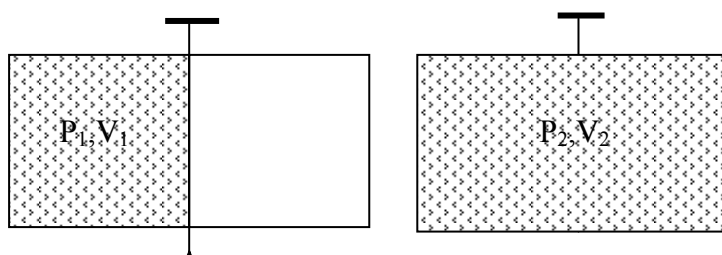
#### Reversible Process:

A process is said to be *reversible* if after it has been carried out it is possible by any means whatsoever to restore the system and surroundings to exactly the same initial states as before. Since thermodynamics deals only with systems in equilibrium, it follows that it deals necessary with reversible processes. In practice, the reversible process represents the optimum path for all energy conversion processes. A good example of reversible processes is the evaporation of liquid in which temperature and pressure remains essentially the same through out the processes. Process path is indicated by solid line.



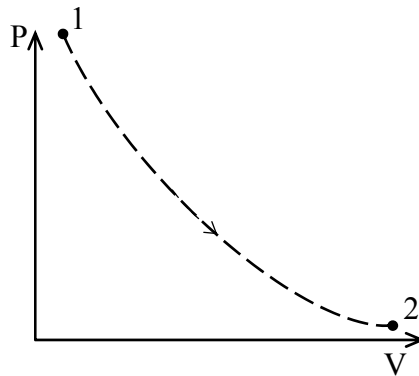
#### Irreversible process

If the system departs significantly from equilibrium during the process, both internally and externally, the process is irreversible. The direction of such a process cannot be interchanged because of the differences in the values of properties within the system and also between the system and surroundings.



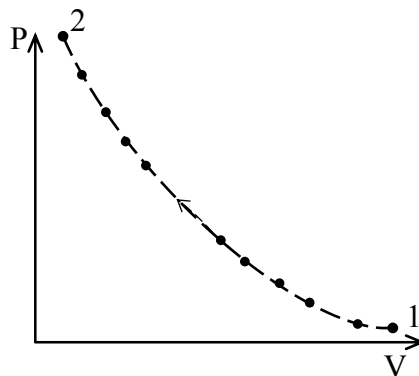
Diaphragm removed. Gas fills entire volume when equilibrium is established. **Note:** We cannot establish the intermediate state. The process diagram is shown below.

We join initial and final equilibrium state by broken lines.



### Quasi Static Process

Process is said to be *quasi-static* if it proceeds in such a manner that any instant the system is only infinitesimally displaced from the equilibrium with the surroundings. A *quasi-static* process implies the system is essentially in internal equilibrium so that the properties are uniform. Time taken to established equilibrium must be shorter time it takes to travel.



### **1-1.2.3 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*. That is a system is in equilibrium with given surroundings if no further change occur in its properties. This can occur if and only if the properties are uniform throughout the system and are equal to those in the surroundings.

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.

Complete equilibrium occur under three conditions:

- Mechanical equilibrium - forces balance
- Thermal equilibrium - temperature uniformity
- Chemical equilibrium - no change in composition and transfer of matter

### 1-1.3 Units for Mass, Length, Time, and Force

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

**Table 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 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	$\mu$
$10^3$	Kilo	k	$10^{-9}$	nano	n
$10^2$	Hector	h	$10^{-12}$	pico	p

## SESSION 2-1:

### 2-1.1 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  $\text{kg/m}^3$  and  $\text{m}^3/\text{kg}$ , 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).

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

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

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

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

$1 \text{ atm} = 101\,325 \text{ Pa} = 1.013\,25 \text{ bar} = 760 \text{ mm Hg}$
---

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.

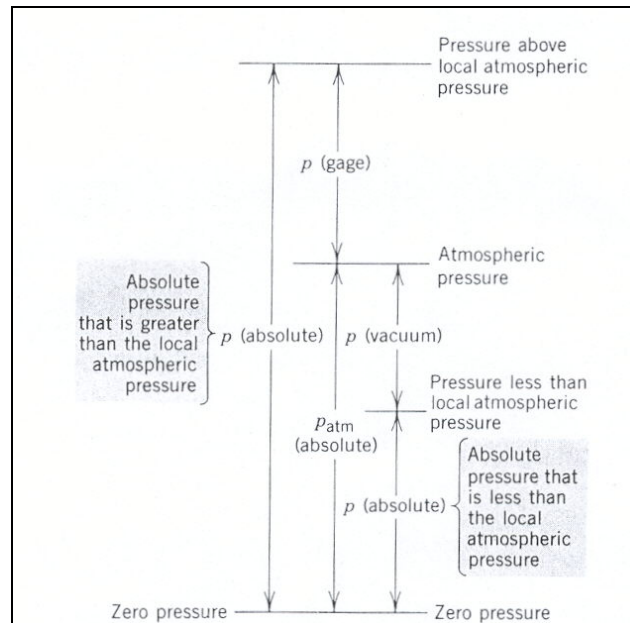
The pressure of a system is usually measured relative to the atmosphere, and it is called “gauge pressure”. The pressure used in thermodynamics is the absolute pressure and is defined by:

$$\text{Absolute pressure} = \text{gauge pressure} + \text{atmospheric pressure}$$

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

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

The relationships among the various ways of expressing pressure measurements are shown in Fig. 6.

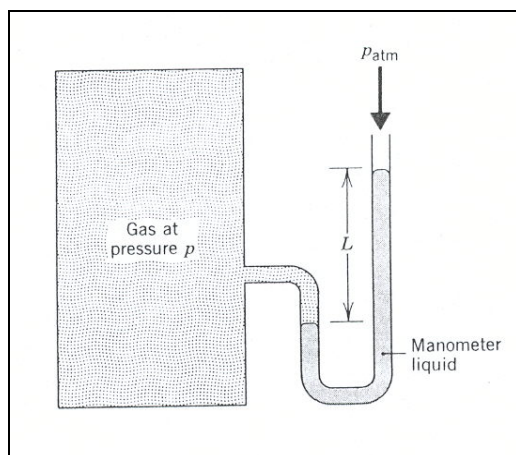


**Figure 6: Relationships between the absolute, atmospheric, gauge, and vacuum pressures**

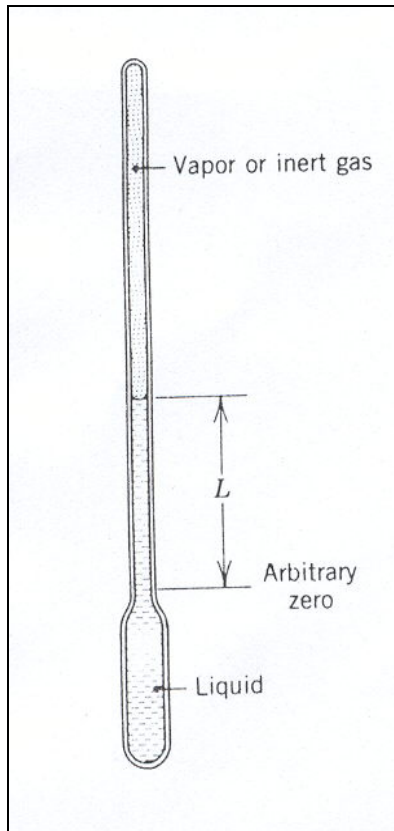
### Pressure Measurement

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. 7 has one end open to the atmosphere and the other attached to a closed vessel containing a gas at uniform pressure.

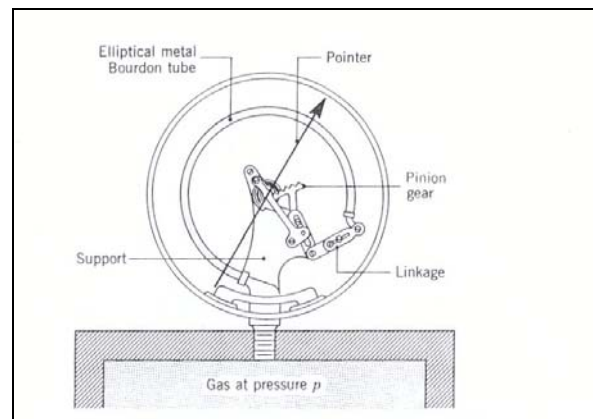
The difference between the gas pressure and that of the atmosphere is given by  $p = p_{\text{atm}} + \rho g L$



**Figure 7: Mercury Manometer**



**Figure 9: Liquid-in-glass thermometer**



**Figure 7: Bourdon tube**

A Bourdon tube gauge is shown in Fig. 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.

## 2-1.2 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.*

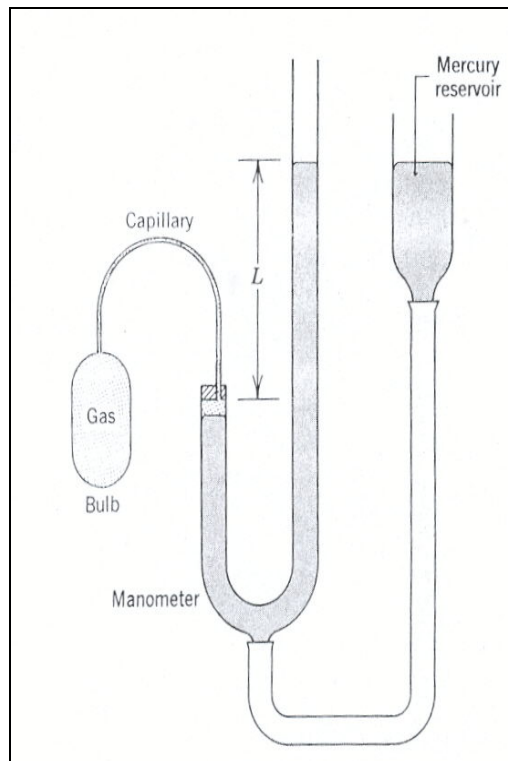
### **2-1.2.1 Zeroth Law of Thermodynamics**

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*.

### **2-1.2.2 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. 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.



**Figure 8: Constant-volume gas thermometer**

The gas thermometer shown in Fig. 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

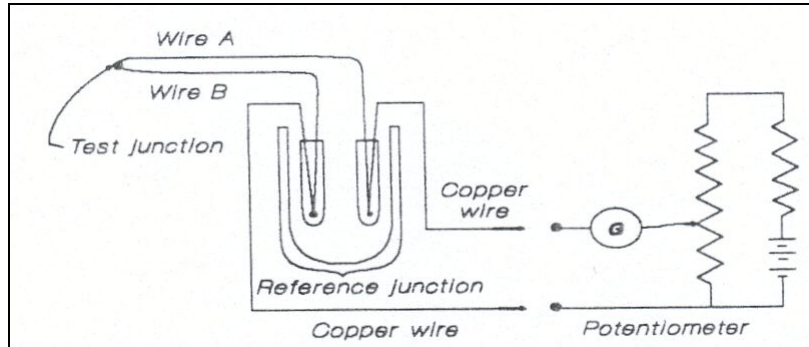
Sensors known as thermocouples are based on the principle that when two dissimilar metals are joined, a thermal electromotive force,  $t_{emf}$ , that is primarily a function of temperature will exist in a circuit. If two different metals, or semiconductors, are connected with their junctions held at different temperatures, as shown in Fig. 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 thermometric substance is the thermocouple and the thermometric property is the thermal electromotive force.



**Figure 9: 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, called 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  $T$ .

### 2-1.2.3 Celsius, Rankine, and Fahrenheit Scales

The Celsius temperature scale uses the unit degree Celsius ( $^{\circ}\text{C}$ ), 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

$$T(^{\circ}\text{C}) = T(\text{K}) - 273.15 \quad (1)$$

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

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

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

$$T(^{\circ}\text{R}) = 1.8 T(\text{K}) \quad (2)$$

The Rankine scale is also an absolute temperature scale.

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

$$T(^{\circ}\text{F}) = T(^{\circ}\text{R}) - 459.67 \quad (3)$$

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

$$T(^{\circ}\text{F}) = 1.8T(^{\circ}\text{C}) + 32 \quad (4)$$

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

Comparison of magnitudes of various temperature units defined earlier:

$$1\text{K} = 1^{\circ}\text{C} = 1.8^{\circ}\text{R} = 1.8^{\circ}\text{F}$$

Expressing Temperature Rise in Different Units:

When dealing with temperature interval on the different scales defined the following must be noted

$$\Delta T(\text{K}) = \Delta T(^{\circ}\text{C})$$

$$\Delta T(\text{R}) = \Delta T(^{\circ}\text{F})$$

During a heating process, the temperature of a system rises by  $10^{\circ}\text{C}$ . This rise in temperature in K is 10 K. The rise in temperature in  $^{\circ}\text{F}$  is  $1.8(10) = 18^{\circ}\text{F}$ .

## TUTORIAL SET 1

1. Determine the weight, in newtons, of an object whose mass is 10 kg at a location where the acceleration due to gravity is  $9.81 \text{ m/s}^2$ .
2. An object occupies a volume of  $25 \text{ ft}^3$  and weighs 20 lbf at a location where the acceleration of gravity is  $31.0 \text{ ft/s}^2$ . Determine its weight, in lbf, and its average density, in  $\text{lbf/ft}^3$ , on the moon, where  $g = 5.57 \text{ ft/s}^2$ .
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  $g = 9.81 \text{ m/s}^2$ , what is the mass of the object, in kg?
4. The following table lists temperatures and specific volumes of water at two pressures.

**Table 4: Temperature and specific volumes of water at two selected pressures**

P = 0.1 MPa		P = 0.12 MPa	
T/(°C)	V/m <sup>3</sup> kg	T/(°C)	V/m <sup>3</sup> 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  $T = 200^\circ\text{C}$ ,  $p = 0.113 \text{ MPa}$ .
  - (b) the temperature at  $p = 0.12 \text{ MPa}$ ,  $v = 1.85 \text{ m}^3/\text{kg}$  in  $^\circ\text{C}$
  - (c) the temperature at  $p = 0.11 \text{ MPa}$ ,  $v = 2.20 \text{ m}^3/\text{kg}$ , 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 =  $1000 \text{ kg/m}^3$ ).
    - (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  $1020 \text{ kg/m}^3$  and the acceleration of gravity is  $9.7 \text{ m/s}^2$ . The local atmospheric pressure is 0.98 bar.
  8. Convert the following temperatures from  $^\circ\text{F}$  to  $^\circ\text{C}$ :
    - (a)  $70^\circ\text{F}$
    - (b)  $0^\circ\text{F}$
    - (c)  $-30^\circ\text{F}$
    - (d)  $500^\circ\text{F}$
    - (e)  $212^\circ\text{F}$

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.

**Table 5: Incomplete information for several paths of a given process**

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

C. Select from Table 6 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.
17. The objective of a ----- is to provide energy for industrial processes or dwelling units at elevated temperatures.
18. The thermal efficiency of a power cycle can never be ----- than unity (100%)
19. The value of ----- depends on the details of the process and not just the end states.
20. 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.
21. For a simple compressible substance undergoing an ----- process the energy transfer by heat is equal to the change in enthalpy.
22. ----- is the capacity to do work.

**Table 6: Possible answers for Questions 15 – 22 of Tutorial set I**

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

# ENERGY AND THE FIRST LAW OF THERMODYNAMICS

## 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. The total amount of energy is *conserved* in all transformations and transfers. The purpose of this unit is to organise the above ideas into suitable forms for engineering analysis.

## SESSION 1-2:

### 1-2.1 Mechanical Concepts of Energy

#### 1-2.1.1 Work and Kinetic Energy

The curved line in Fig. 12 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 Newton's 2<sup>nd</sup> Law, the magnitude of the component  $F_s$  is related to the change in the magnitude of  $V$  by

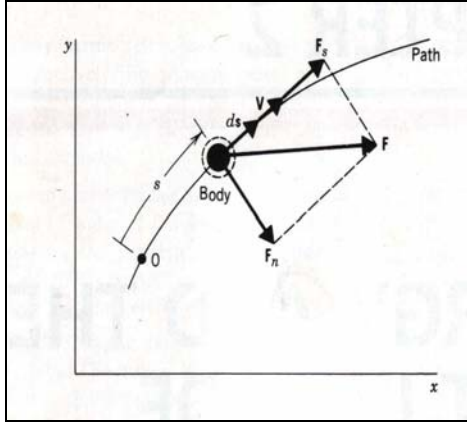


Figure 10: Forces acting on a moving system

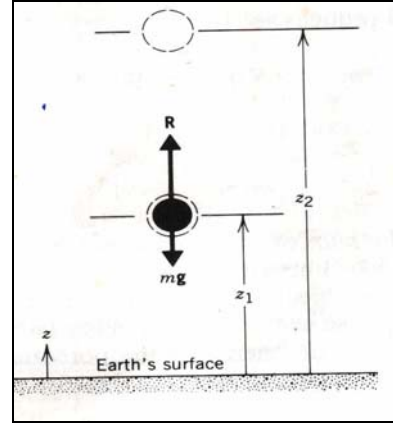


Figure 11: Illustration of potential energy concept

$$F_s = m \frac{dV}{dt} = m \frac{dV}{ds} \frac{ds}{dt} \quad (2.1)$$

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

$$\int_{V_1}^{V_2} mV dV = \int_{s_1}^{s_2} F_s ds \quad (2.2)$$

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

$$\int_{V_1}^{V_2} mV dV = \left[ \frac{1}{2} mV^2 \right]_{V_1}^{V_2} = \frac{1}{2} m (V_2^2 - V_1^2) \quad (2.3)$$

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,  $\Delta KE$ , 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 Eqns. 2.2 and 2.3 we have

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

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.

### 1-2.1.2 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. 13. 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 Eqn. 2.4, the total work equals the change in kinetic energy. That is,

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

Assuming acceleration due to gravity to be constant we obtain

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

The quantity  $mgz$  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

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

or

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

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.

## 1-2.2 Energy Transfer by Work

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

$$W = \int_{s_1}^{s_2} F_s \cdot ds \quad (2.7)$$

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.**

### 1-2.2.1 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  $\delta W$ , but the differential of every property is exact and is represented by a total derivative.**

### 1-2.2.2 Expansion or Compression Work

Let us evaluate the work done by the closed system shown in Fig 14 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

$$\delta W = - p A dx = - p dV \quad (2.8)$$

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.

$$W = - \int_{V_1}^{V_2} p dV \quad (2.9)$$

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 2-2.2).

### 1-2.2.3 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. 15. 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.

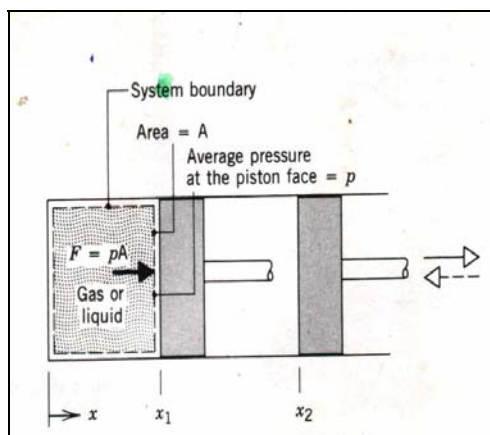


Figure 12: Expansion or compression of a gas or liquid

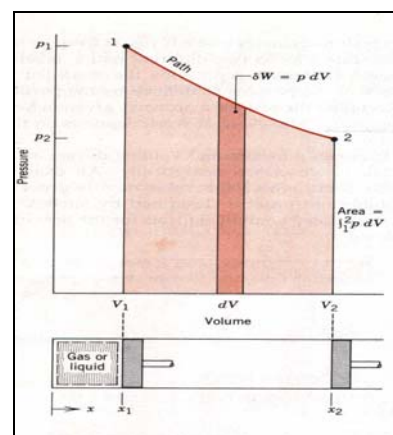


Figure 13: Work of quasi-equilibrium process

The relationship between pressure and volume during an expansion or compression process also can be described analytically. An example is provided by the expression

$pV^n = \text{constant}$ , 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*.

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

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

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

This expression is valid for all values of  $n$  except  $n = 1$ . The case  $n = 0$  is also treated under special cases (See 1-2.2.5).

#### 1-2.2.4 Special cases of the polytropic process

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

$$W = -\text{constant} \int_{V_1}^{V_2} \frac{dV}{V} = -(\text{constant}) \ln \frac{V_2}{V_1} = -(p_1 V_1) \ln \frac{V_2}{V_1} \quad (2.12)$$

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

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

- (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

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

By inserting the upper and lower limits into Eq. 2.14, the work done is evaluated. It can be shown that the expression for the work done reduces to

$$\boxed{W = -\left( \frac{p_1 + p_2}{2} \right) (V_2 - V_1)} \text{ where the subscripts 1 and 2 refer to the initial and}$$

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. 16.

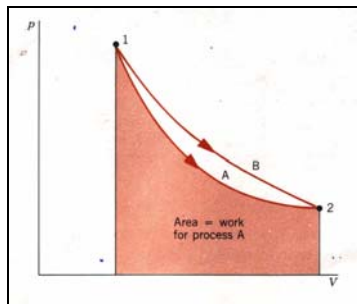


Figure 14: Illustration that work depends of process

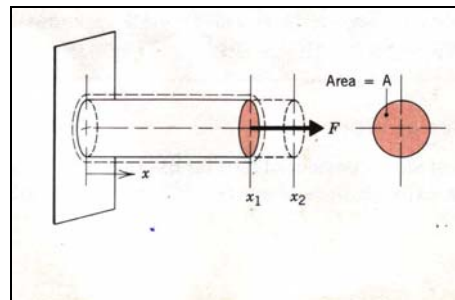


Figure 15: Elongation of solid bar

### 1-2.2.5 Further examples of work in quasi-equilibrium processes

**Extension of a Solid Bar:** Consider of system of a solid bar, as shown in Fig. 17. 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  $\sigma$  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.  $W = \frac{1}{2} EA_0 L_0 (\epsilon_x)^2$  where  $E$  is the Young's Modulus of elasticity of the bar defined as stress in the bar divided by the corresponding strain,  $A_0$  is the original cross-sectional of the bar,  $L_0$  is the original length of the bar, and  $\epsilon_x$  is the strain in the bar defined as the change in length divided by the original length.

**Stretching of a Liquid Film:** Fig. 18 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  $\tau$ , 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.

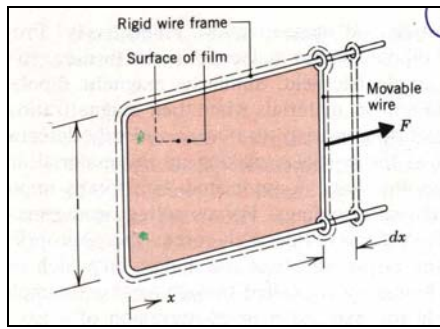


Figure 16: Stretching of a liquid film

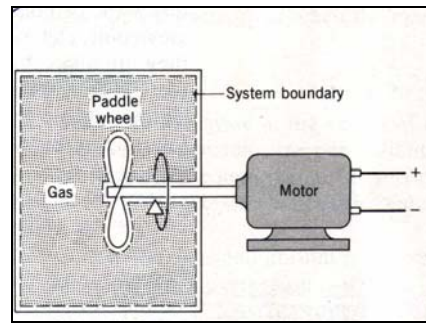


Figure 17: Power transmitted to a gas by a paddle wheel

**Power Transmitted by a shaft:** Consider a shaft rotating with angular velocity  $\omega$  and exerting a torque  $\tau$  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  $V = R\omega$ , where  $\omega$  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

$$\dot{W} = F \cdot V \quad (2.15a)$$

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

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

A related case involving a gas stirred by a paddle wheel is shown in Fig. 19.

**Electrical work:** Shown in Fig. 20 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  $\dot{W} = E i$ .

Since the current  $i$  equals  $dZ/dt$ , the work can be expressed in differential form as

$$\delta W = E dZ.$$

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.

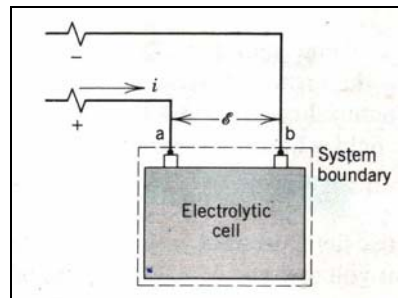


Figure 18: Electrolytic cell used to discuss electrical work

### 1-2.3 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*.

#### 1-2.3.1 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  $\delta Q$ . 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.

#### 1-2.3.2 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 21, 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

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

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

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

$T_s$  is the temperature of the surface,  $\varepsilon$  is a property of the surface that indicates how effectively the surface radiates ( $0 < \varepsilon \leq 1$ ) and  $\sigma$  is the Stefan-Boltzmann constant.

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**

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

Refer to Fig. 22 to 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.



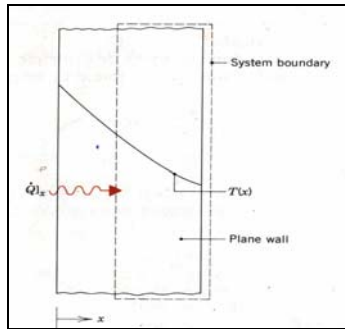


Figure 19: Illustration of Fourier's conduction law

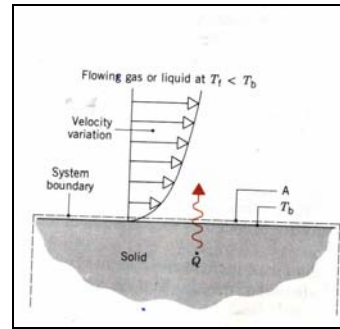


Figure 20: Illustration of Newton's Law of cooling

## SESSION 2-2:

### 2-2.1 First Law of Thermodynamics

In this session, 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.

#### 2-2.1.1 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”

#### 2-2.1.2 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 the 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

$$\sum_1^2 \delta Q + \sum_1^2 \delta W = \Delta E \quad (2.17)$$

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)

$$Q_{12} + W_{12} = \Delta U = U_2 - U_1 \quad (2.18)$$

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

$$\delta Q + \delta W = dU \quad (2.19)$$

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.

### 2-2.1.3 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

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

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 cannot produce work continuously.

### 2-2.1.4 Energy analysis of cycles

Here, 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. Again here, 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

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

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)

For a power cycles 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*:

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

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 or heat pump 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

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

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

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

## 2-2.2 Application of First Law to Non-Flow Processes (Closed Systems)

### 2-2.2.1 Constant pressure process

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

$$\int_1^2 \delta Q = U_2 - U_1 - \int_1^2 \delta W \quad (2.23)$$

Or

$$\int_1^2 \delta q = u_2 - u_1 + \int_1^2 p dv = u_2 - u_1 + p(v_2 - v_1) = (u_2 + pv_2) - (u_1 + pv_1) = h_2 - h_1 \quad (2.24)$$

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

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

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

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 2-2.3) because it includes the flow work given by the term “ $pv$ ” as well as the internal energy of the system.

### 2-2.2.2 Polytropic process

The relation between pressure and volume is given by  $pv^n = \text{constant}$ , where  $n$  is the polytropic index. The expression for the work transfer can be expressed by any of the relations derived in 1-2.2.5 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.

### 2-2.2.3 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

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

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.

### 2-2.2.4 Isothermal process

This is a constant temperature process. From the First Law

$$\delta q + \delta w = du \quad (2.28)$$

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

$$q_{12} = T(s_2 - s_1). \text{ Therefore, } \boxed{W_{12} = u_2 - u_1 - Q_{12}}, \text{ in general for an isothermal process.}$$

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

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

### 2-2.2.5 Constant volume process

Applying the First Law and noting that  $W_{12} = 0$  since  $dV = 0$ , we have

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

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

## 2-2.3 First Law of Thermodynamics for Open Systems

### 2-2.3.1 General Energy Equation

Figure 23 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,  $\delta Q$  and  $\delta W$ , 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 23 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

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

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

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

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

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

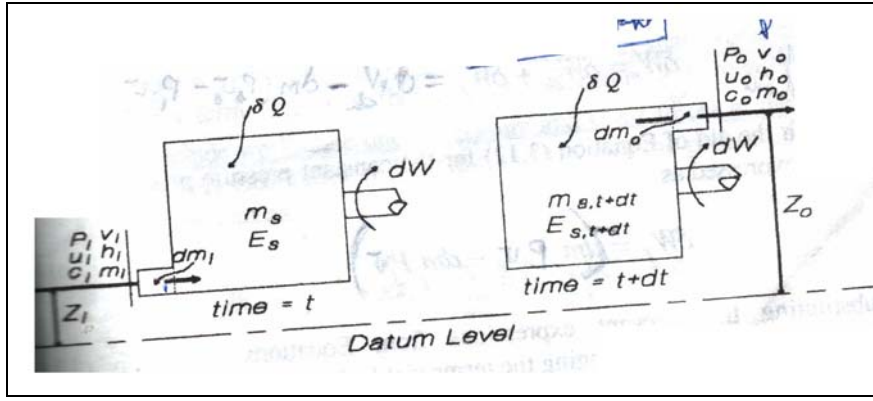


Figure 21: Diagram showing an imaginary closed system at the beginning and end of a differential change of state

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

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

Substituting Equ. 2.32 – 2.34 into Equ. 2.31 yields

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

Substituting for enthalpy and dividing by dt yields

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

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

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

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



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

### 2-2.3.2 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

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

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

### 2-2.3.3 Practical applications of the SFEE

#### 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 24 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  $\dot{W}$  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

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

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

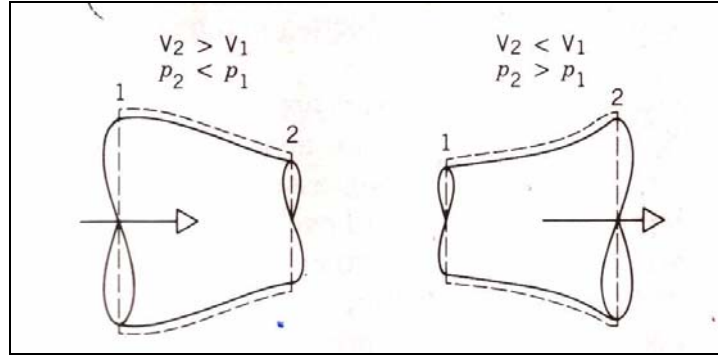


Figure 22: Illustration of a nozzle and a diffuser

### Turbines, compressors, fans and pumps

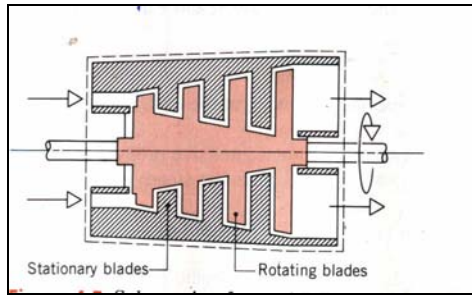
A turbine is a device in which work is developed as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate. A schematic of an axial-flow steam or gas turbine is shown in Fig. 25 and 26. Turbines are widely used in vapour power plants, gas turbines power plants, 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.

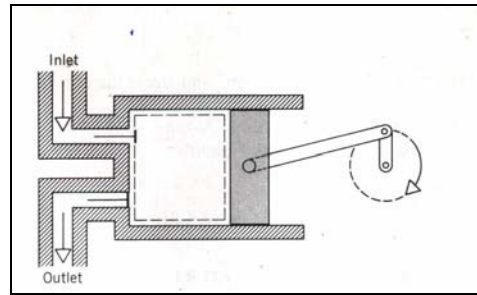
The processes that take place inside turbines, compressors, fans and pumps are usually assumed to be adiabatic and therefore  $\dot{Q} = 0$ . Secondly, kinetic and potential energy terms are assumed to be negligible compared to the other terms in the SFEE. The resulting equation for this class of thermodynamic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

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

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



**Figure 23: Schematic of an axial flow turbine**



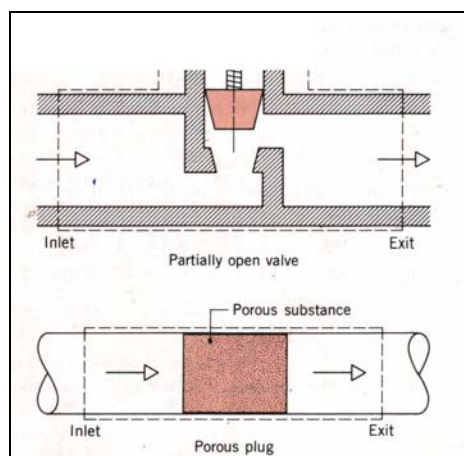
**Figure 24: Reciprocating compressor**

### 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

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

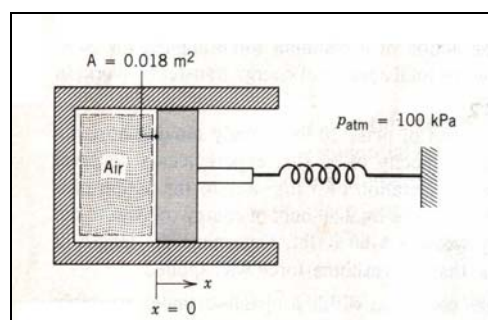
That is a throttling process is an isentropic process. Throttling valves are used extensively to reduce the pressure refrigerant flowing through the valve. In the vapour-compression refrigerator a valve is used to reduce the pressure of the refrigerant from the pressure at the exit of the condenser to the power pressure existing in the evaporator. Schematic representations of throttling devices are illustrated in Figure 27.



**Figure 25: 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<sup>3</sup> to  $V_2 = 0.03$  m<sup>3</sup>. 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<sup>3</sup>, 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<sup>3</sup> to a final state where  $p_2 = 100$  kPa. The relationship between pressure and volume during the process is  $pV = \text{constant}$ . 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. 28. Initially,  $p_1 = 100$  kPa,  $V_1 = 2 \times 10^{-3}$  m<sup>3</sup>, 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<sup>2</sup>. The air expands slowly until its volume is  $V_2 = 3 \times 10^{-3}$  m<sup>3</sup>. During the process, the spring exerts a force on the piston that varies with  $x$  according to  $F = kx$ , where  $k = 1.62 \times 10^3$  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.



**Figure 26: Piston-cylinder assembly in horizontal position**

- 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.

Table 7: Incomplete table for closed system

Process	$\underline{Q}$	$\underline{W}$	$U_1$	$U_2$	$\Delta U$
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,  $V_1 = 0.028 \text{ m}^3$ ,  $W_{12} = -10.5 \text{ kJ}$

Process 2 – 3 compression with  $pV = \text{constant}$ ,  $U_3 = U_2$

Process 3 – 1 constant volume,  $U_1 - U_3 = -26.4 \text{ kJ}$

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  $150^\circ \text{C}$  to a pressure of 3 bars. During the process, the pressure and specific volume are related by  $pv^{1.2} = \text{constant}$ . 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,  $V_1 = 1.5 \text{ m}^3$ , and  $U_1 = 512 \text{ kJ}$ . The processes are as follows:

Process 1-2: compression with  $pV = \text{constant}$  to  $p_2 = 2$  bar,  $U_2 = 690 \text{ kJ}$

Process 2-3:  $W_{23} = 0$ ,  $Q_{23} = -150 \text{ kJ}$

Process 3-1:  $W_{31} = -50 \text{ kJ}$

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.  $4.89 \times 10^{-4} \text{ m}^2$ ]



10. Air is contained in a rigid well-insulated tank with a volume of  $0.2 \text{ m}^3$ . 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  $1.2 \text{ kg/m}^3$ . If no changes in kinetic or potential energy occur, determine

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

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

	<u>Inlet</u>	<u>Outlet</u>
Enthalpy	3137.7 $\text{kJ/kg}$	2675.5 $\text{kJ/kg}$
Velocity	80 $\text{m/s}$	200 $\text{m/s}$
Elevation	6 $\text{m}$	3 $\text{m}$

What is the power output of the turbine? **[658.9  $\text{kW}$ ]**

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  $0.1 \text{ m}^3$  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  $\text{kJ}$ , calculate the heat transferred during the process.

**[50  $\text{kJ}$ ]**

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  $1 \times 10^{-3} \text{ m}^3$  and 150  $\text{kPa}$ , 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  $\text{kPa}$  and  $3 \times 10^{-3} \text{ m}^3$ , respectively.

- (a) Draw the  $p$ - $V$  diagram for the two heating processes.  
 (b) Show that for the second 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  $\text{kPa}$  and  $V$  is in  $\text{m}^3$ .  
 (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  $\text{kJ}$ .

**[-150  $\text{J}$ , -225  $\text{J}$ , 300  $\text{J}$ ]**

14. A gas contained within a piston-cylinder assembly is shown in Fig. 29. 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  $x = 0.05 \text{ m}$ , and the heat transfer ceases. The force exerted by the spring on the piston as the gas expands varies linearly with  $x$  according to  $F = kx$

where  $k = 10,000 \text{ N/m}$ . Friction between the piston and the cylinder wall can be neglected. The acceleration due to gravity is  $g = 9.81 \text{ m/s}^2$ . Additional information is given on Fig. 29.

- What is the initial pressure of the gas, in kPa?
- Determine the work done by the gas on the piston, in J.
- 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.

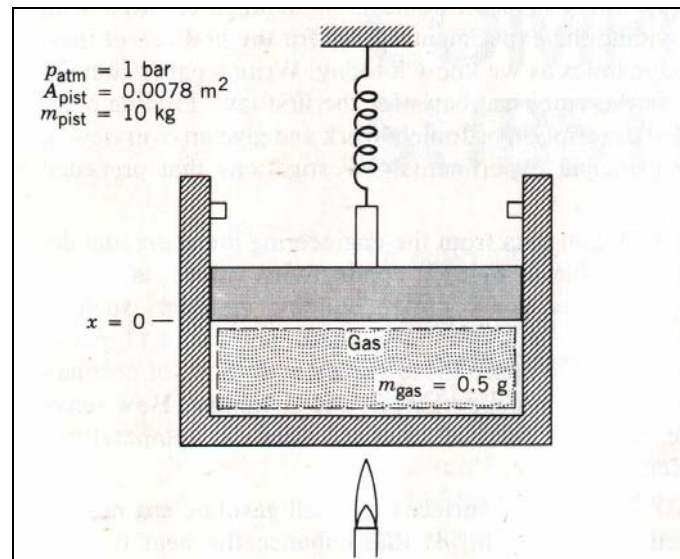


Figure 27: Piston-cylinder assembly in vertical position

- For a power cycle the total heat transfer to the cycle is,  $Q_{\text{in}}$  is 500 MJ. What is the net work delivered, in MJ, if the thermal efficiency is 30 %.

**[150 MJ]**

- The coefficient of performance of a heat pump cycle is 3.5 and the net work *input* is 500 kJ. Determine the heat transfers  $Q_{\text{in}}$  and  $Q_{\text{out}}$ , in kJ.

**[12,500 kJ; - 17,500 kJ]**

- 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  $g = 9.8 \text{ m/s}^2$ . Determine in J.

- the work done on the block by the constant force  $R$ .
- the change in potential energy of the block.
- The change in kinetic energy of the block.

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

- A system with a mass of 10 kg, initially at rest, experiences a constant horizontal acceleration of  $4 \text{ m/s}^2$  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  $g = 9.81 \text{ m/s}^2$ .  
[109.4 m/s]
20. A gas contained in piston-cylinder assembly expands in a constant-pressure process at 4 bar from  $V_1 = 0.15 \text{ m}^3$  to a final volume of  $V_2 = 0.36 \text{ m}^3$ . Calculate the work, in kJ.



## SECOND LAW OF THERMODYNAMICS

### Introduction

The Second Law of Thermodynamics together with the First Law constitutes the fundamental laws governing thermodynamics processes. 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.

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. The 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. *that 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 unit is to motivate the need for the usefulness of the second law, which asserts that processes occur in a certain direction and that energy has quality as well as quantity. In the presentation of the contents of this unit, 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.

### SESSION 1-3:

#### 1-3.1 Definitions

Before stating the Second Law, 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.

### 1-3.1.1 Thermal Energy Reservoirs (Heat Reservoirs)

A heat reservoir (thermal energy reservoir) is a closed system whose temperature is not affected by the flow of heat across its boundaries. The heat reservoir is a hypothetical body with a relatively large thermal energy (heat) capacity 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 its temperature must remain constant so that any processes that take place in the reservoir must be reversible.

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

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.

### 1-3.1.2 Heat Engines

A heat engine is a closed system which operates in a cycle and produces a net quantity of work from a supply of heat. The schematic representation of a heat engine operating between two heat reservoirs, a heat source and a heat sink, is shown in Fig. 30.

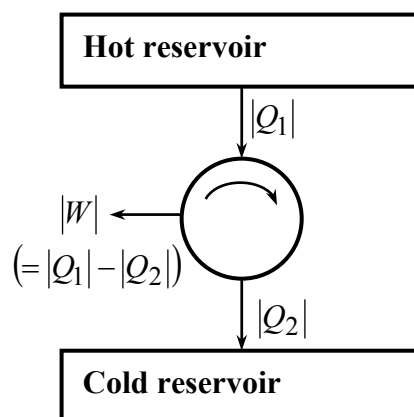
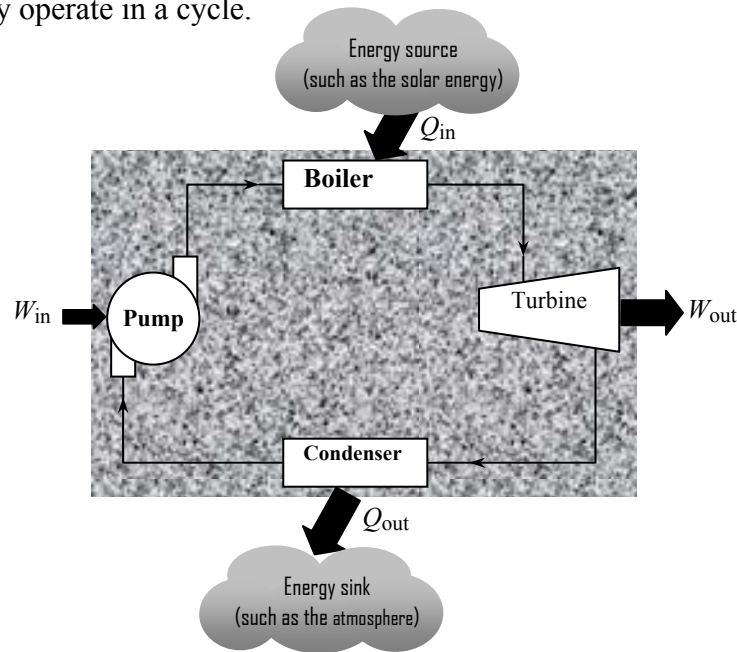


Figure 28: Schematic representation of a heat engine

Heat engines differ considerably from one another, but all can be characterised by the following: (Fig. 31)

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.



**Figure 291: Schematic of a steam power plant**

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

### 1-3.1.3 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  $\eta_{th}$ .

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 heat 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

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

The quantities  $|Q_{in}|$  and  $|Q_{out}|$  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  $|W_{net,out}| < |Q_{in}|$ , then it follows from equation (3.1) that  $|Q_{out}|$  must have some definite value.

### 1-3.1.4 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 on 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. 32.

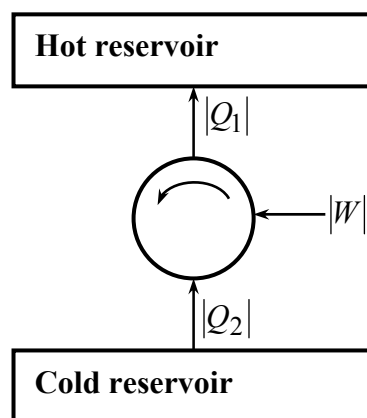


Figure 302: Heat Pump or refrigerator

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

$$\boxed{COP_{ref} = \frac{Q_{in}}{W_{cycle}}} \text{ (Refrigeration cycle)} \quad (3.2)$$

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

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

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

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

### 1-3.2 The Second Law of Thermodynamics

The law can 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* (PPM2) ; 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%* (Fig. 33) 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.

### 1-3.3 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. 34. 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 could 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  $(|W|+|Q|-|Q|=|W|)$  units of heat from a reservoir, and delivering an equivalent amount of work. This is impossible according to the Second law.

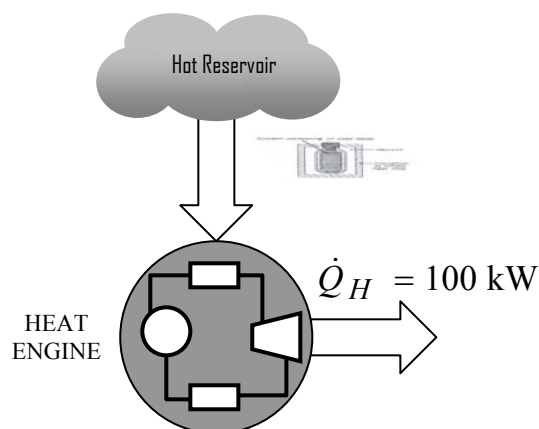


Figure 31: A heat engine that violates Kelvin-Planck statement

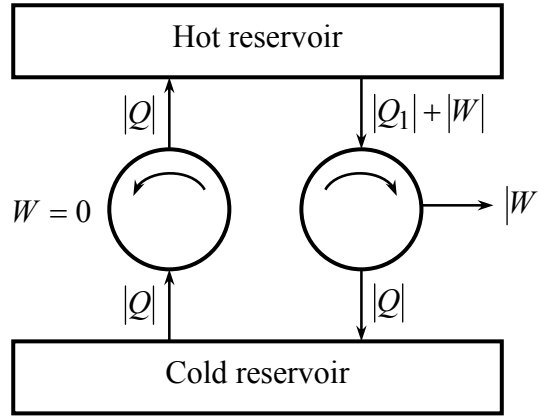


Figure 32: Can a heat pump operate without a work input

### 1-3.4 Other Corollaries

Reversible engines operating between only two temperature reservoirs

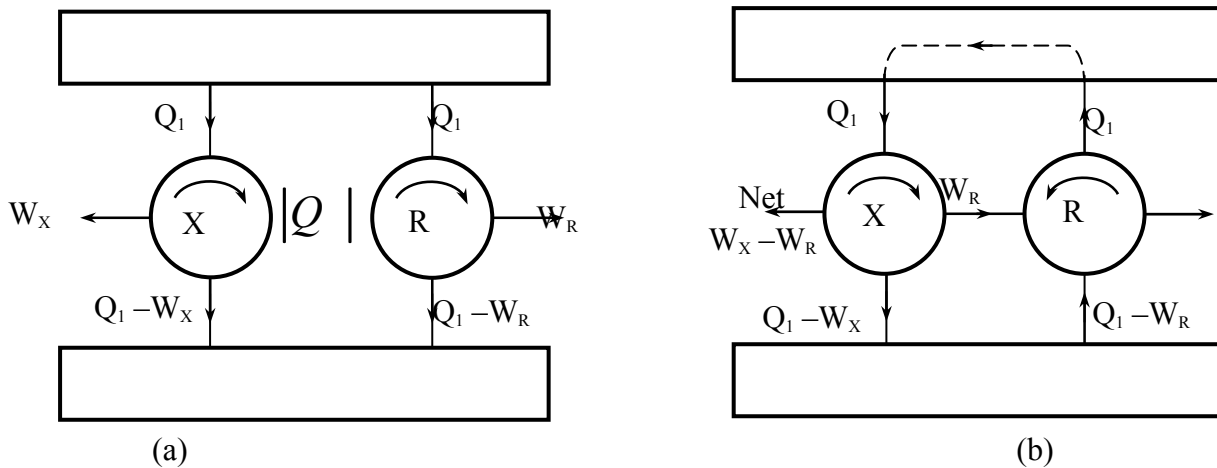
*Corollary 2: it is impossible to construct an engine operating between only two reservoirs, which will have a higher efficiency than a reversible engine operating between the same two reservoirs.*

**Proof:** Assume the converse is true. Let  $X$  be such an engine, having efficiency  $\eta_X$ . Let it receive heat  $Q_1$  from the source, do work  $W_X$ , and reject  $(Q_1 - W_X)$  to the sink. Then, it is assumed that  $\eta_X > \eta_R$  where  $\eta_R$  is the efficiency of a reversible engine  $R$  operating between the same two reservoirs. See Fig. 35 (a). 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. 35 (b). 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.



**Figure 33: 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*

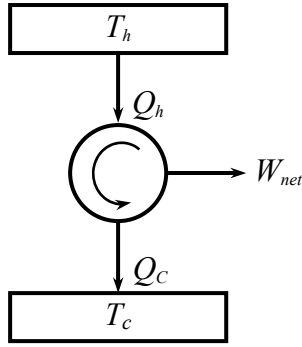
Once the second corollary is proved there is no need for the proof of the third. The Corollaries 2 and 3 are referred to as the Carnot Principles.

### 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 the efficiency of the reversible engine depends solely on the temperatures of the reservoirs with which the engine exchanges heat. 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 Figure 36 and Equation 3.1, the efficiency of a heat engine is given as



$$\eta_{th} = \frac{|Q_h| - |Q_c|}{|Q_h|} = 1 - \frac{|Q_c|}{|Q_h|} \quad (3.5)$$

**Figure 34: Schematic representation of a Heat Engine**

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.

$$\frac{|Q_c|}{|Q_h|} = f(T_h, T_c) \quad (3.6)$$

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

$$\frac{|Q_c|}{|Q_h|} = \frac{T_c}{T_h} \quad T_h = T_c \cdot \frac{|Q_h|}{|Q_c|} \quad (3.7)$$

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

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

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  $\frac{Q_{c,rev}}{Q_{h,rev}} = \frac{T_c}{T_h}$

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

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

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

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

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 a 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  $\int_1^2 \left( \frac{dQ}{T} \right)_{rev} = S_2 - S_1$ . Entropy is an extensive 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 this effect is always to increase entropy (pump, turbine work).

### **NOTES:**

1. Note 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  $10\text{ kJ}$  of energy as heat from a hot medium to a cold one. At the end of the process, we still have the  $10\text{ kJ}$  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.

## SESSION 2-3:

### 2-3.1 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. 37 (a) 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. 37 (b) 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.

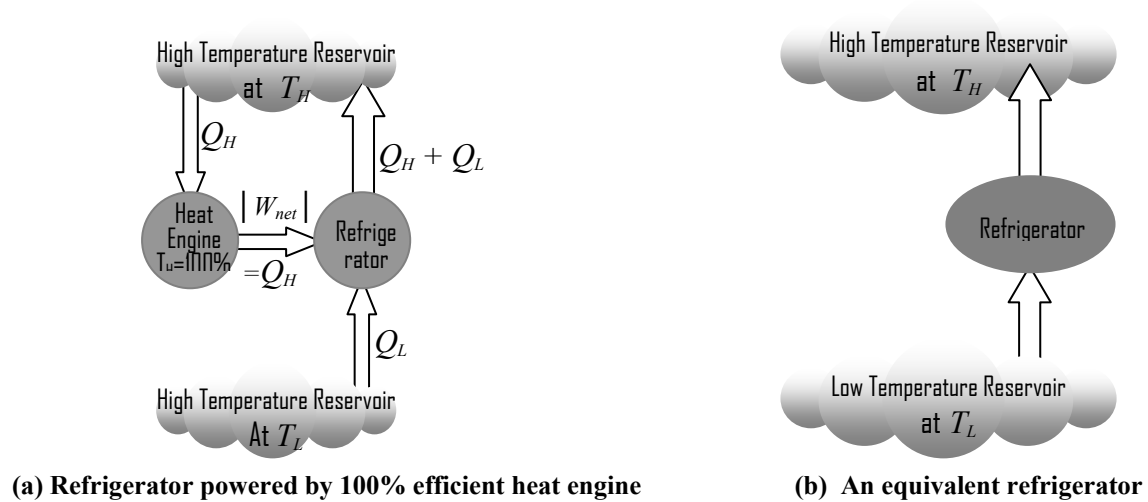


Figure 35: A heat-engine-refrigerator combination

## 2-3.2 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. 38 (a) and Fig. 38 (b), respectively.

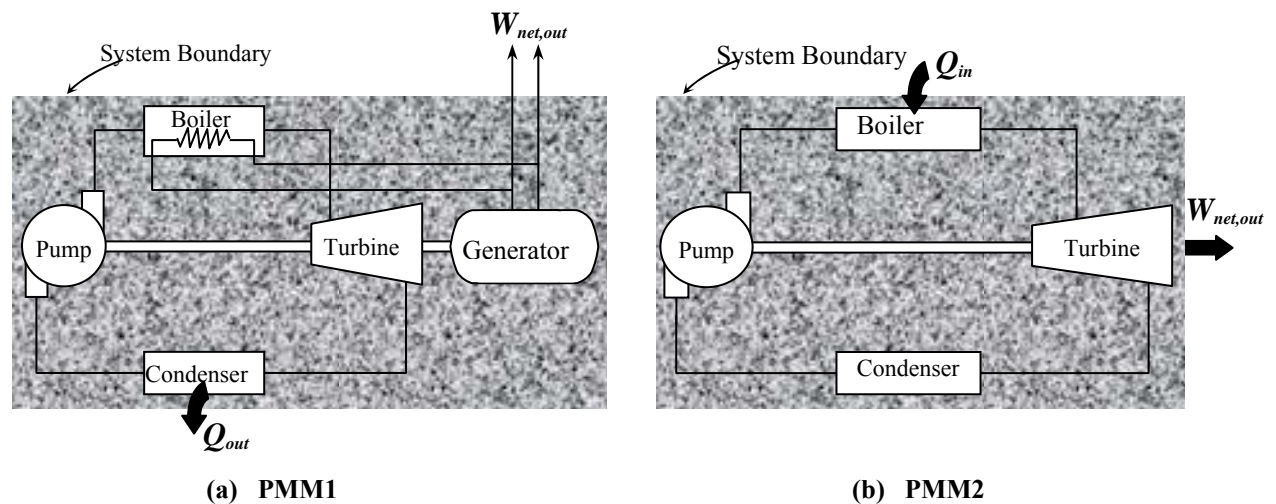


Figure 36: Schematic representation of Perpetual Motion Machines

### 2-3.3 The Quality of Energy

Let us consider a heat engine that receives heat from a source at  $1000\text{ K}$  and rejects heat to a sink at  $300\text{ K}$ . This heat engine 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  $800\text{ K}$ ,  $700\text{ K}$ ,  $600\text{ K}$ ,  $500\text{ K}$ , and  $400\text{ K}$  when the sink temperature is held constant.

The thermal efficiency of a Carnot heat engine that rejects heat to a sink at  $300\text{ K}$  is evaluated at various source temperatures using Eq. 3.9. It can be shown that the thermal efficiency decreases as the source temperature decreases. When the source temperature is  $400\text{ K}$  the efficiency drops 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 there is*.

### 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  $1.6\text{ kWh}$  of energy from the refrigerated space for each  $1.5\text{ kWh}$  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  $T_H = 2000\text{K}$  and rejects energy  $Q_C$  by heat transfer to a cold reservoir at  $T_C = 400\text{K}$ . For each of the following cases, determine whether the cycle operates reversibly, irreversibly, or is impossible.
  - a)  $Q_H = 1000\text{ kJ}$ ,  $|W_{\text{cycle}}| = 850\text{ kJ}$
  - b)  $Q_H = 2000\text{ kJ}$ ,  $|Q_C| = 400\text{ kJ}$
  - c)  $|W_{\text{cycle}}| = 1600\text{ kJ}$ ,  $|Q_C| = 500\text{ kJ}$
  - d)  $Q_H = 1000\text{ kJ}$ ,  $\eta = 30\%$
- 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  $T_C = 250\text{ K}$  and rejects energy  $Q_H$  to a hot reservoir at  $T_H = 300\text{ K}$  for each of the following cases, determine whether the cycle operates reversibly, irreversibly, or is impossible.
  - a)  $|Q_C| = 1000\text{kJ}$ ,  $|W_{\text{cycle}}| = 400\text{kJ}$
  - b)  $|Q_C| = 2000\text{kJ}$ ,  $|W_{\text{cycle}}| = 2200\text{kJ}$
  - c)  $|Q_H| = 3000\text{kJ}$ ,  $|W_{\text{cycle}}| = 500\text{kJ}$
  - d)  $|W_{\text{cycle}}| = 400\text{kJ}$ ,  $\text{COP}_R = 6$
- 20 A reversible engine employs a cycle consisting of three different processes which constitute a triangle such that

$$T_1 = T_3 = 323\text{ K}; \quad T_2 = 573\text{ K}; \quad s_2 = s_3$$

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.



## 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 unit is to introduce property relations relevant to engineering thermodynamics.

### SESSION 1-4:

#### 1-4.1 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.

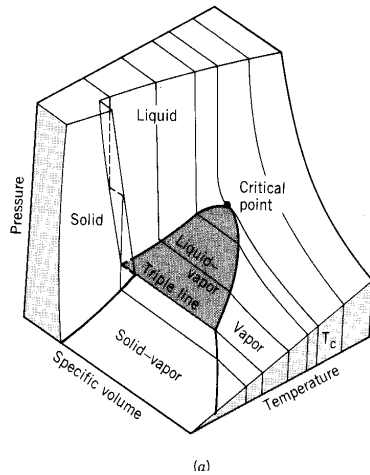
## 1-4.2 Pure Substance

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.

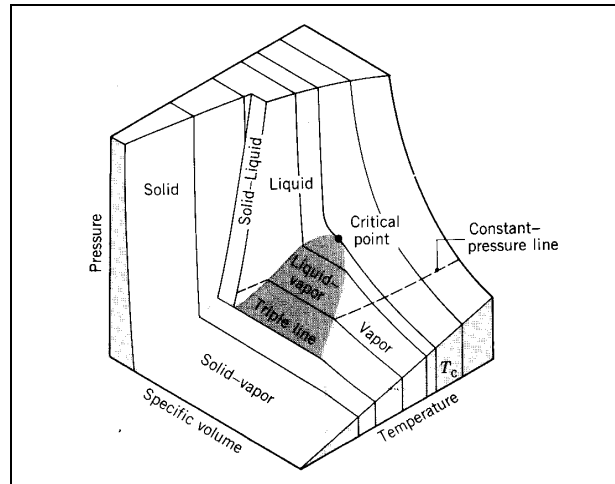
## 1-4.3 p-v-T Relation

In this session, 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 39 and 40 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.



**Figure 37:  $p$ - $v$ - $T$  surface of a substance that expands on freezing**



**Figure 38:  $p$ - $v$ - $T$  surface of a substance that contracts on freezing**

There are regions on the  $p$ - $v$ - $T$  surfaces of Figs. 39 and 40 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*.

### 1-4.3.1 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 Fig. 41. 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.

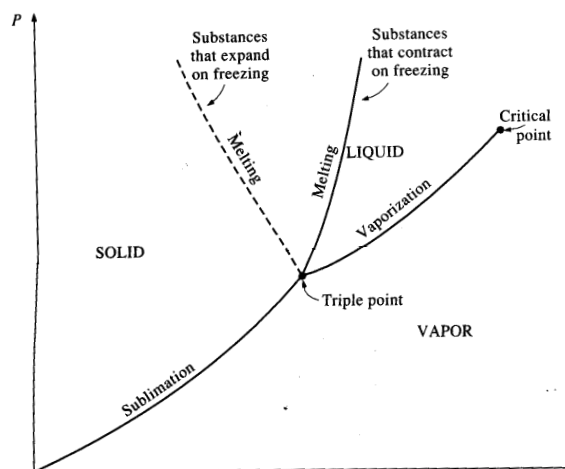
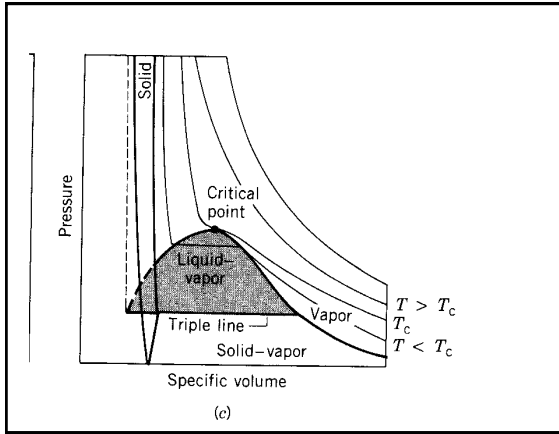


Figure 39:  $p$ - $T$  diagram of a pure substance diagram

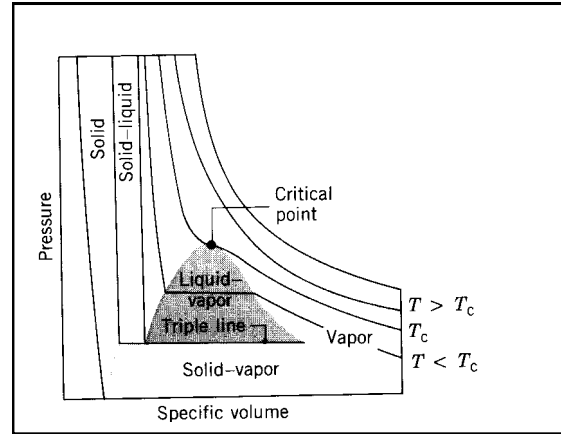
### $p$ - $v$ Diagram

Projecting the  $p$ - $v$ - $T$  surface onto the pressure-specific volume plane, results in a  $p$ - $v$  diagram, as shown in Figs. 42 and 43.

*Notes:* It can be noted from Figs. 42 and 43 ( $p$ - $v$  diagrams) that:



**Figure 40:  $p$ - $v$  diagram for a substance that expands on freezing**



**Figure 41:  $p$ - $v$  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.

## 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. 44. Since consistent patterns are revealed in the  $p$ - $v$ - $T$  behaviour of all substances, Fig. 44 showing a  $T$ - $v$  diagram for water can be regarded as representative.

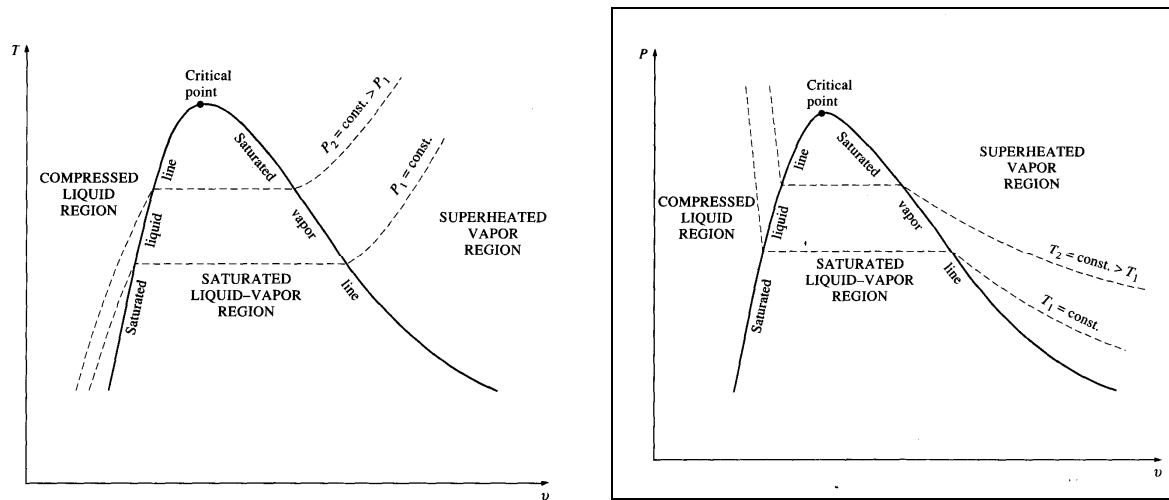


Figure 42: T-v diagram for a pure substance

**NOTES:** It can be noted from Fig. 44 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.

### 1-4.3.2 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 be distinguished from one another by the *quality*, an intensive property. The amount of energy absorbed or released during a phase change is called **latent heat**. The amount of energy released during vaporization is called the enthalpy of vaporization, which is equivalent to energy released during 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:

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

Quality has significance for *saturated mixtures* only. It has no meaning in the compressed liquid or superheated vapour regions. Its values range between 0 and 1.

But the total volume of the mixture is the sum of the volume of the saturated liquid and the saturated vapour. That is:

$$V = V_f + V_g$$

$$\text{But } V = m v \quad \rightarrow \quad m_{\text{total}} v_{\text{av}} = m_f v_f + m_g v_g \quad (4.2)$$

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

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

$$\text{where } v_{fg} = v_g - v_f$$

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

## SESSION 2-4:

### 2-4.1 Thermodynamic Property Data

Thermodynamic property data for engineering use appears in various forms, including tables, graphs and equations. The emphasis of the current session 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 (Refer to *Thermodynamic and Transport Properties of Fluids*, 4<sup>th</sup> 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 the page 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 the pages 3 thru 5 are 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 the pages 6 thru 9. On the 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 1-4.3.2 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 ( $p < p_{\text{sat}}$  at a given  $T$ )

Higher temperature ( $T > T_{\text{sat}}$  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 2-4.2)**

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.

**2-4.2 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:

$$v(T, p) \approx v_f(T) \quad ; \quad u(T, p) \approx u_f(T) \quad (4.5)$$

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

$$h(T, p) \approx u_f(T) + pv_f(T) \quad (4.6)$$

Equation 4.6 can be expressed alternatively as

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

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*.

### 2-4.3 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 4

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 °C than it would to vaporise 1 kg of saturated liquid at 120 °C?
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.

**Table 8: Incomplete table for Q15 of Tutorial Set 4**

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

16. Complete the following table for water.

**Table 9: Incomplete table for Q16 of Tutorial Set 4**

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

17. Complete the following table for water.

**Table 10: Incomplete table for Q17 of Tutorial Set 4**

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

18. Complete the following table for water.

**Table 11: Incomplete table for Q18 of Tutorial Set 4**

$T/^\circ\text{C}$	$p/\text{kPa}$	$u/(\text{kJ/kg})$	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 °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<sup>2</sup>. 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<sup>3</sup> contains 5 kg of saturated liquid vapour mixture of water at 75 °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 °C]
22. A piston-cylinder device initially contains 50 litres of liquid at 25 °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 °C (c) 130,727 kJ]

## SESSION 3-4:

### 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 Vapour Power Cycle.

#### 3-4.1 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.

#### 3-4.2 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 2<sup>nd</sup> 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.

### 3-4.3 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.

### 3-4.4 Efficiency

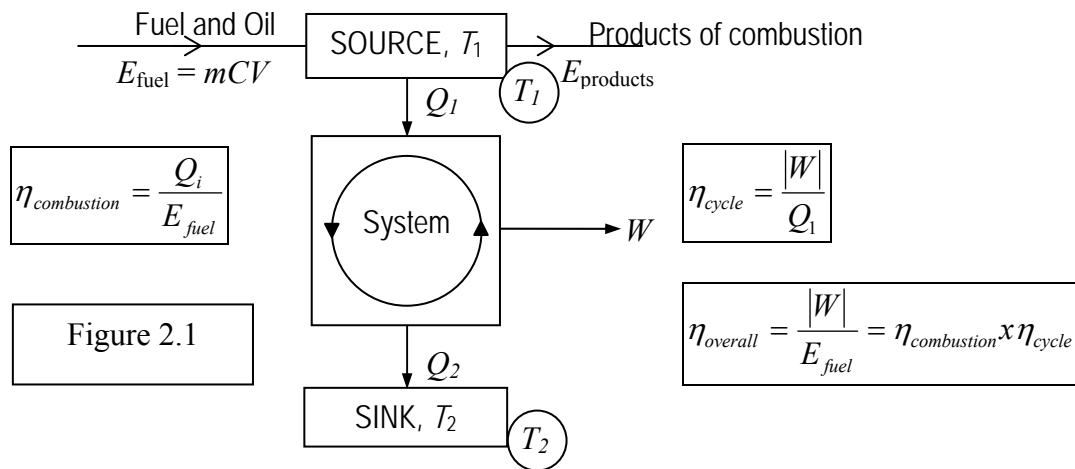


Figure 43: Essential features of a vapour power cycle

The essential features of a vapour power cycle are as illustrated in Fig. 45. 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 2<sup>nd</sup> 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  $\frac{T_1 - T_2}{T_1}$  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.

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

### **3-4.5 Work Ratio**

**Table 12: Comparison of performance parameters of ideal and actual cycles**

	<b>Ideal</b>	<b>Actual <math>\eta_c = \eta_T = 0.90</math></b>		
	<b>Cycle 1</b>	<b>Cycle 2</b>	<b>Cycle 1</b>	<b>Cycle 2</b>
$Q_{in}$	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
$H$	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,

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

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.

### 3-4.6 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 expressed in kg/kWh and if  $|W|$  is the magnitude of the network output per unit mass of steam in kJ/kg,

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

### 3-4.7 Process efficiencies

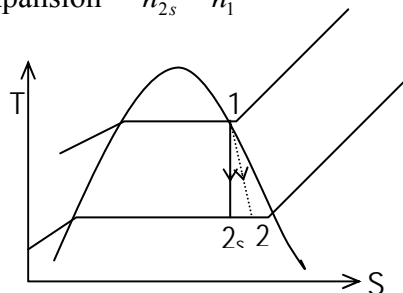
It is a measure of irreversibility and can be defined for a steady flow process as the ratio of isentropic to actual work or vice versa, depending on whether the process is a work producing process, or a work requiring process,

#### Turbine process:

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

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

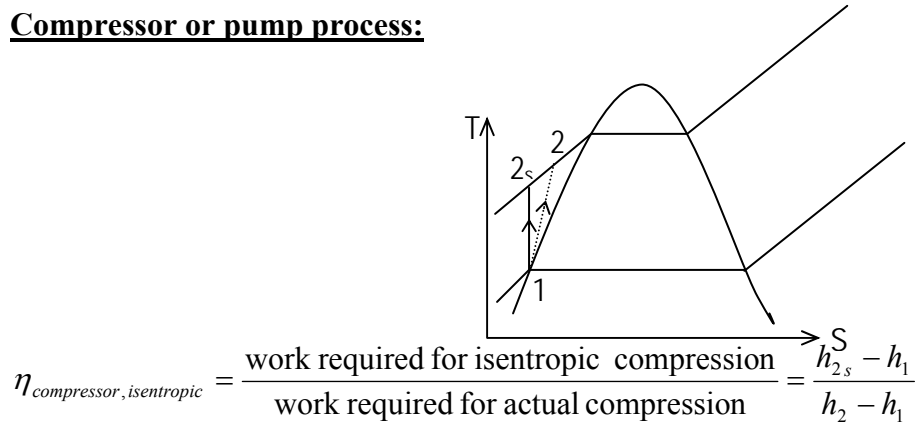
$$\text{Work requiring} = \frac{\text{Isentropic}}{\text{Actual}}$$



Irreversibility within the turbine reduce the net power output of the plant

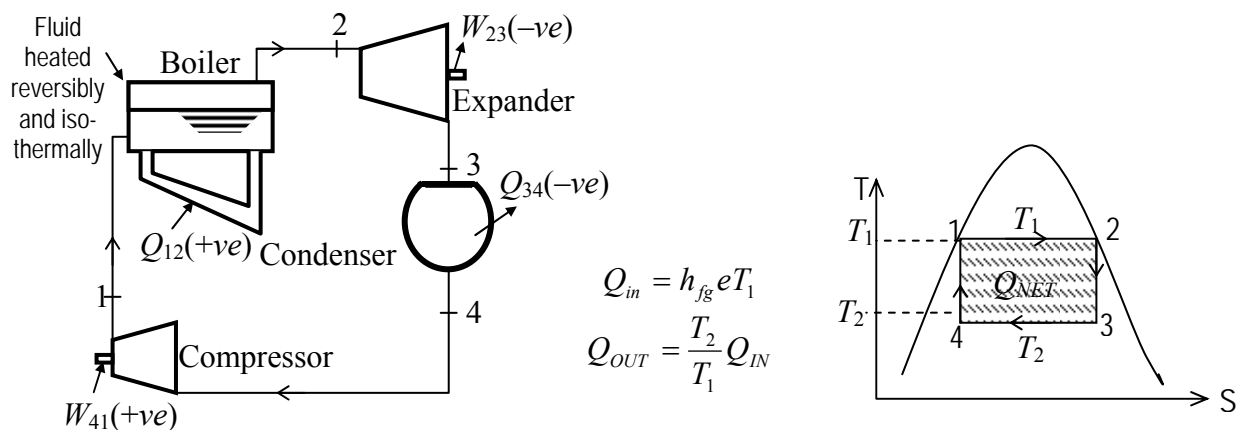


### Compressor or pump process:



### 3-4.8 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.



(a) Flow diagram of the Carnot Cycle (b) T-s diagram of Carnot Cycle  
Figure 44: Carnot Cycle

### Notes For a Cycle, from 1<sup>st</sup> Law

$$Q_{NET} + W_{NET} = 0$$

$$Q_{IN} + Q_{12} = T_1(S_2 - S_1)$$

$$Q_{OUT} + Q_{34} = T_2(S_3 - S_4)$$

$$Q_{NET} = (T_1 - T_2)(S_3 - S_4)$$

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

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

$$Q_{12} + W_{12} = h_2 - h_1 + \Delta(KE) + \Delta(PE), \quad \text{but } \Delta(KE) = 0 \text{ and } \Delta(PE) = 0$$

Hence,

$Q_{12} = h_2 - h_1$	$h_2 - h_g$ 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

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

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.  $x \geq 90\%$  is desirable.

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

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

3-4: After expansion the wet steam is then partially condensed at constant reasure and constant temperature while heat is rejected.

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

**NOTE:**

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

4-1: 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.

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

## NOTE:

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.

## SESSION 4-4:

### 4-4.1 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. 46: 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. 47. The working fluid is water at the new state point 4 in Fig. 48, 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 not 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 constant pressure process, but it is not at constant temperature. 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*.

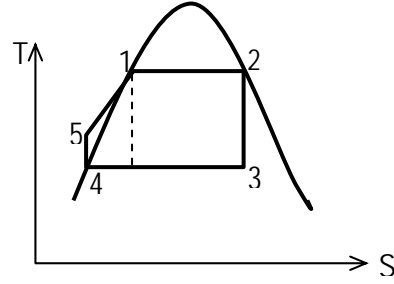
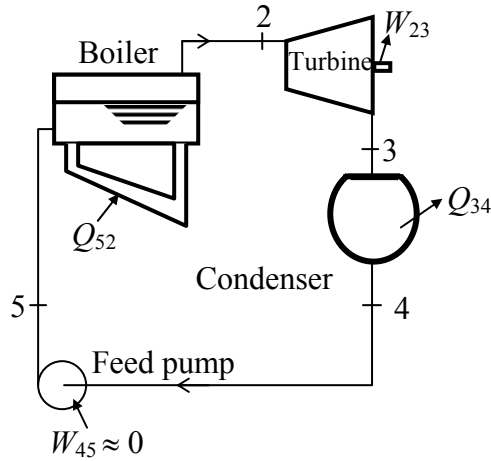


Figure 45: T-s diagram of the Rankine cycle

Figure 46: The Rankine Cycle without superheat

Feed pump work:

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

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

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

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

$$dQ = dh - vdp$$

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

Thus, (4)

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

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. 49.

$$\text{Turbine isentropic efficiency} = \frac{h_2 - h_1}{h_{2s} - h_1} \quad \text{and}$$

$$\text{Compression isentropic efficiency} = \frac{h_{4s} - h_3}{h_4 - h_3}$$

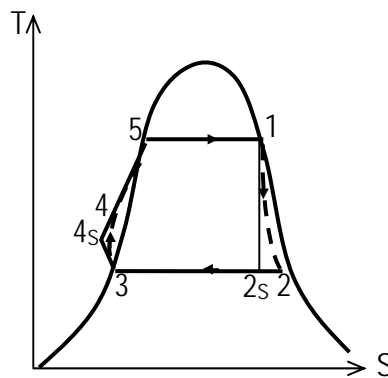


Figure 47: Rankine cycle showing real processes on a T-s diagram

### 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.

$$\text{Condenser heat load per kW of power output} = SSC \times (h_2 - h_3)$$

### **4-4.2 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 ( $T_c \approx 374^\circ\text{C}$  but  $T_{\text{metallurgical}} \approx 620^\circ\text{C}$ ). 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 bank 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. 50.

### The Ideal Rankine Cycle (Cycle employed in practical vapour power cycles)

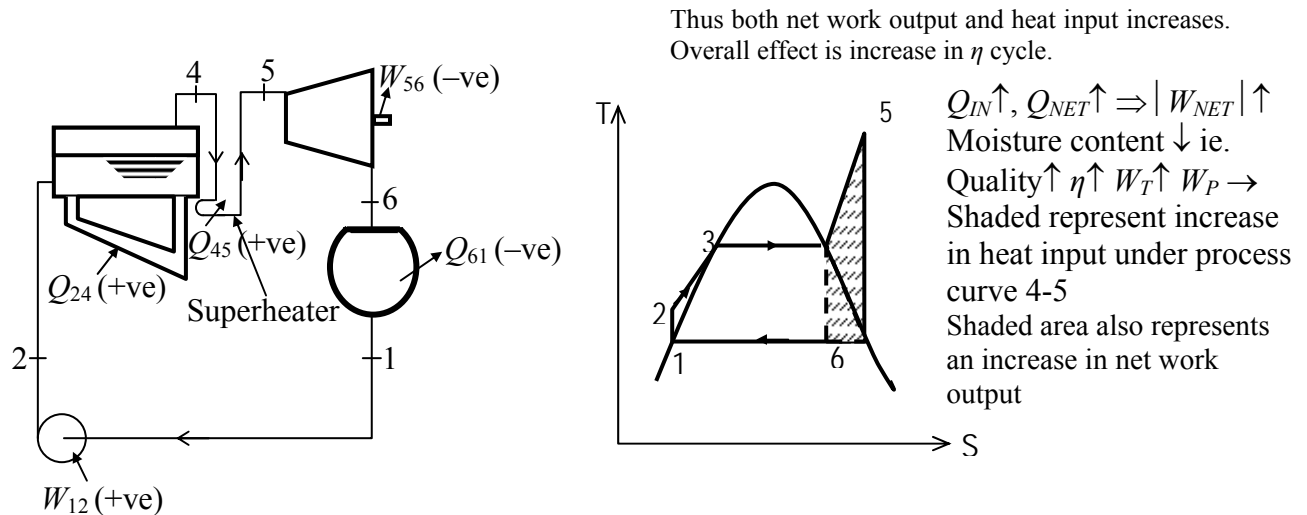


Figure 48: Rankine Cycle

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.

### 4-4.3 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 51. 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.*

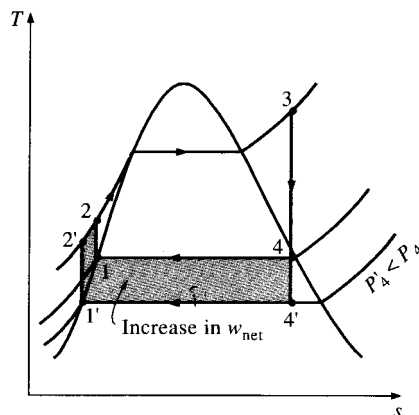


Figure 51: Effect of lowering condenser pressure on Rankine cycle performance

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 nearby water at say 15 °C allowing for difference of 10 °C for effective heat transfer, the steam temperature in the condenser must be above 25 °C. From steam tables, the condenser pressure must be above 3.2 kPa (i.e. the corresponding pressure at 25 °C).

The side effects of lowering the condenser pressure option are:

- ❑ 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 52.

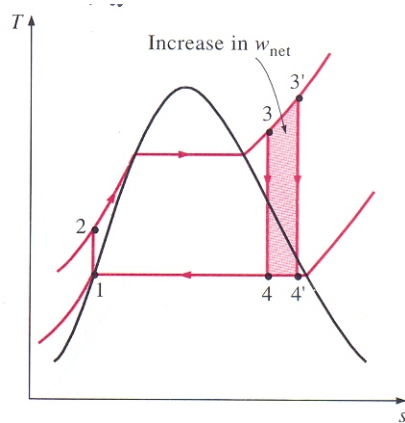


Figure 52: Effect of superheating on Rankine Cycle performance

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.  $T = 620^\circ\text{C}$  is about the present optimum.

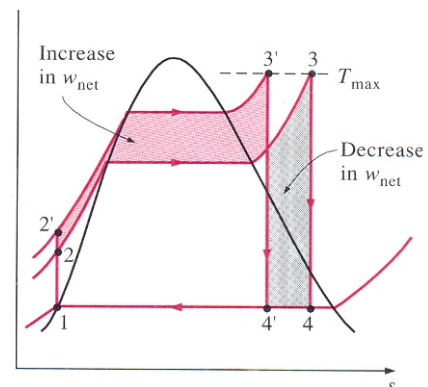


Figure 53: Effect of increasing Boiler pressure on Rankine Cycle performance



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

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 53. 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 ( $P > 22.1 \text{ MPa}$ ) 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.

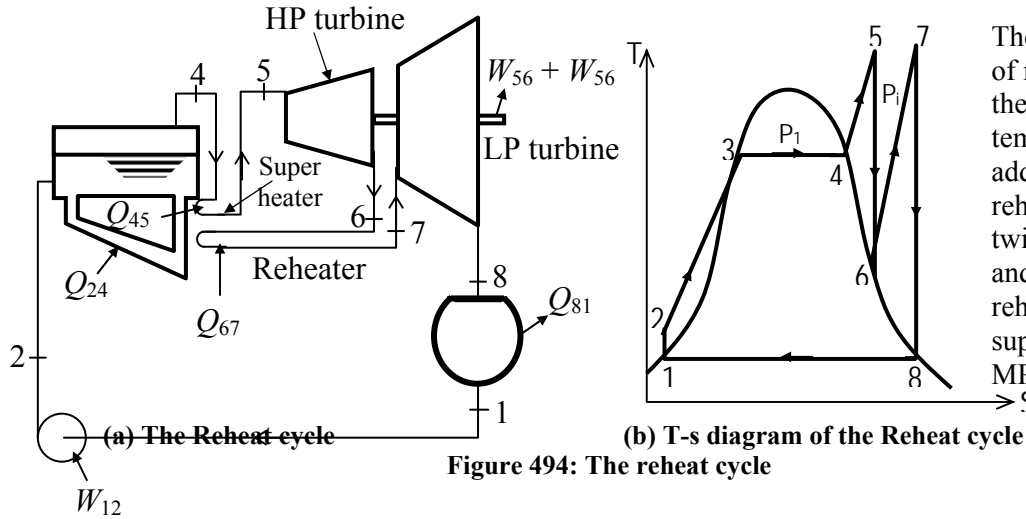
## 4-4.4 Reheat Cycle (Ideal Reheat Cycle)

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. 54.

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 a practical solution to reducing the wetness of steam at the 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.

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*

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

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 production of more than one useful form of energy from the same energy source is called a co-generation plant.

## **4-4.5 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.

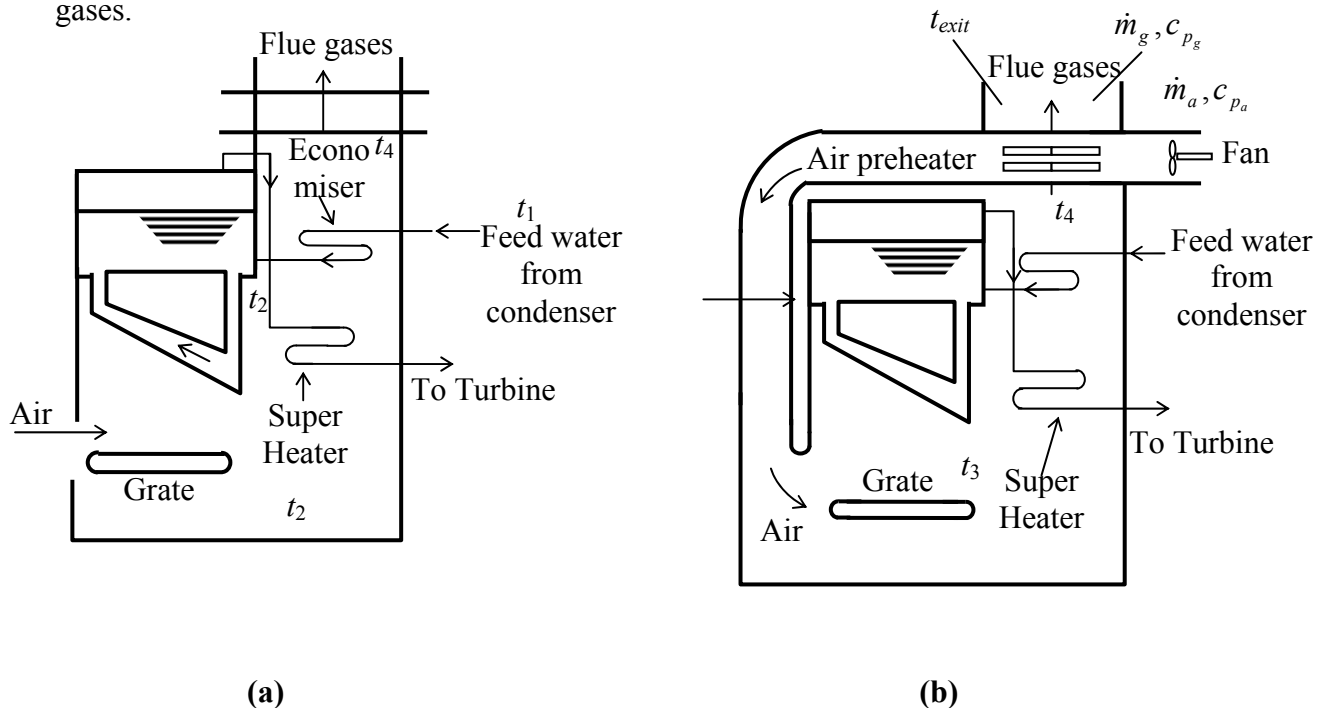
### **The Economiser:**

To utilise some of the energy in the flue gases an *economiser* can be fitted. See Fig. 55 (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. 55 (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.



**Figure 505: Diagrammatic sketch of a boiler plant with (a) an economiser (b) an air preheater**

**TYPICAL FINAL EXAMINATION PAPER FOR REVISION**  
**KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI**

*COLLEGE OF ENGINEERING*

*1.1 B.Sc. (Eng.) SECOND SEMESTER EXAMINATION, 2008*

First Year (Electrical, Computer & Telecommunication Engineering)

**Unit 2    ME: 166                    APPLIED THERMODYNAMICS**

**MAY, 2008**

**THREE HOURS**

---

**INSTRUCTIONS TO CANDIDATES**

- (a) Answer all questions on the question paper. **Show working and do all rough work on the question paper.** For the multiple choice questions, **circle** in PEN the best option or supply the correct answer, in writing, if the appropriate answer is not provided. For other questions, follow specific instructions and answer the questions appropriately.
- (b) Select or provide an answer when you have shown clearly that you have worked towards, and obtained, that answer.
- (c) The paper will last for exactly THREE hours, after which you will be asked to stop work.
- (d) You will be provided with Thermodynamics and Transport Properties of Fluids by G. F. C. Rogers and Y. R. Mayhew and you are to consult it for all constants needed on pages 25 and 26, please.
- (e) Write your index number and department in the space provided below and, additionally, on all pages where there is the indication that you should provide your index number.

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**Unit 3    DEPARTMENT OF CANDIDATE: -----**  
**-----**

**Unit 4**

**4.1.1    INDEX NUMBER: -----**  
**-----**

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For the multiple choice questions, **circle** in PEN the best option or supply the correct answer, in writing, if the appropriate answer is *not* provided. For other questions, follow specific instructions and answer the questions appropriately. **SHOW WORKING AND DO ALL ROUGH WORK ON THE QUESTION PAPER.** Consult the Steam Tables provided for all constants, properties of water and air and other supplementary information needed to solve the questions, if not provided explicitly.

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 bar. The specific volume of the superheated vapour is 0. 2403 m<sup>3</sup>/kg. If the superheated vapour is allowed to cool in an isochoric process from the initial state, at what pressure will the vapour just become saturated?  
  
A. 8.0 bar  
B. 7.5 bar  
C. 7.0 bar  
D. 5.7 bar  
E. 5.3 bar
3. Consider a fish swimming 10m below the free surface of water. The increase in the pressure exerted on the fish when it dives to a depth of 50m below the free water surface is:  
  
A. 392 kPa  
B. 490 kPa  
C. 400 kPa  
D. 392,000 kPa  
E. 400,000 kPa
4. The atmospheric pressures at the top and the bottom of a building are read by a barometer to be 96.0 and 98.0 kPa, respectively. If the density of air is 1.2 kg/m<sup>3</sup>, the height of the building is approximately:  
  
A. 14 m  
B. 17 m  
C. 142 m  
D. 170 m  
E. 210 m

5. An apple loses 0.9kJ of heat as it cools per  $^{\circ}\text{C}$  drop in temperature. The amount of heat loss from the apple per  $^{\circ}\text{F}$  drop in its temperature is :
  - A. 0.25 kJ
  - B. 0.5 kJ
  - C. 1.0 kJ
  - D. 1.62 kJ
  - E. 0.81 kJ
  
6. Consider a 2-m deep swimming pool. The pressure difference between the top and bottom of the pool is:
  - A. 12.0 kPa
  - B. 19.6 kPa
  - C. 38.1 kPa
  - D. 50.8 kPa
  - E. 200 kPa
  
7. During heating process, the temperature of an object rises by  $10^{\circ}\text{C}$ . This temperature rise is equivalent to a temperature rise of
  - A.  $10^{\circ}\text{F}$
  - B.  $42^{\circ}\text{F}$
  - C. 18 K
  - D. 18 R
  - E. 283 K
  
8. A rigid tank contains 5 kg of an ideal gas at 4 atm. and at  $40^{\circ}\text{C}$ . Now a valve is opened, and half of mass of the gas is allowed to escape. If the final pressure in the tank is 1.5 atm. The final temperature in the tank is approximately:
  - A.  $-38^{\circ}\text{C}$
  - B.  $30^{\circ}\text{C}$
  - C.  $40^{\circ}\text{C}$
  - D.  $53^{\circ}\text{C}$
  - E.  $144^{\circ}\text{C}$
  
9. The pressure of an automobile tyre is measured to be 200 kPa gauge before a trip and 220 kPa gauge after the trip at a location where the atmospheric pressure is 90 kPa. If the temperature of air in the tyre before the trip is  $25^{\circ}\text{C}$ , the air temperature after the trip is
  - A.  $45.6^{\circ}\text{C}$
  - B.  $54.8^{\circ}\text{C}$
  - C.  $27.5^{\circ}\text{C}$
  - D.  $26.7^{\circ}\text{C}$
  - E.  $25.0^{\circ}\text{C}$

10. A 500-m<sup>3</sup> rigid tank is filled with saturated liquid-vapour mixture of water at 200 kPa. If 20 percent of the mass is liquid and the 80 percent of the mass is vapour, the total mass in the tank is:
- A. 705 kg
  - B. 500 kg
  - C. 258 kg
  - D. 635 kg
  - E. 2809 kg
11. A rigid 5-m<sup>3</sup> rigid vessel contains steam at 20 MPa and 400 °C. The mass of steam in the vessel is:
- A. 5.0 kg
  - B. 0.322 kg
  - C. 322 kg
  - D. 503 kg
  - E. 680 kg
12. Water is boiled at 1 atmosphere (pressure) in a coffee maker equipped with an immersion-type electric heating element. The coffee maker initially contains 1 kg of water. Once boiling started, it is observed that half of the water in the coffee maker evaporated in 25 minutes. If the heat loss from the coffee maker is negligible, the rating of the heating element is:
- A. 2.15 kW
  - B. 1.50 kW
  - C. 0.50 kW
  - D. 1.00 kW
  - E. 0.75 kW
13. The specific heat of a material is given in a strange units to be  $C = 3.60 \text{ kJ/kg} \cdot ^\circ\text{F}$ . The specific heat of this material in the SI units of  $\text{kJ/kg} \cdot ^\circ\text{C}$  is:
- A. 200  $\text{kJ/kg} \cdot ^\circ\text{C}$
  - B. 3.20  $\text{kJ/kg} \cdot ^\circ\text{C}$
  - C. 3.60  $\text{kJ/kg} \cdot ^\circ\text{C}$
  - D. 4.80  $\text{kJ/kg} \cdot ^\circ\text{C}$
  - E. 6.48  $\text{kJ/kg} \cdot ^\circ\text{C}$
14. A 2-m<sup>3</sup> rigid tank contains nitrogen gas at 500 kPa and 300 K. Now heat is transferred to nitrogen in the tank and the pressure of Nitrogen rises to 800 kPa. The work done during this process by the system is:
- A. 600 kJ
  - B. 100 kJ
  - C. 0 kJ



- D. 500 kJ  
E. 1600 kJ
15. A 2-m<sup>3</sup> tank contains nitrogen gas at 500 kPa and 300 K. Now the gas is compressed isothermally to a volume of 0.1 m<sup>3</sup>. The work done on the system during this compression process is:
- A. 950 kJ  
B. 0 kJ  
C. 1610 kJ  
D. 2996 kJ  
E. 562 kJ
16. A 2- kW electric resistance heater in a room is turned on and kept on for 30 minutes. The amount of energy transferred to the room by the heater is:
- A. 1kJ  
B. 60 kJ  
C. 1800 kJ  
D. 3600 kJ  
E. 7200 kJ
17. A 50-cm long, 0.2 –cm diameter electric resistance wire submerged in water is used to determine the boiling heat transfer coefficient in the water at 1 atm. experimentally. The surface temperature of the wire is measured to be 130 °C when a Wattmeter indicates the electric power consumption to be 4.1 kW. Then the heat transfer coefficient is:
- A. 43,500 W/m<sup>2</sup>. °C  
B. 137 W/m<sup>2</sup>. °C  
C. 68,330 W/m<sup>2</sup>. °C  
D. 10,038 W/m<sup>2</sup>. °C  
E. 37,540 W/m<sup>2</sup>. °C
18. A 3- m<sup>2</sup> hot black surface at 80 °C is losing heat to the surrounding air at 25 °C by convection with a convection heat transfer coefficient of 12 W/m<sup>2</sup>. °C, and by radiation to the surrounding surfaces at 15 °C. The total rate of the heat loss from the surface is:
- A. 1987 W  
B. 3451 W  
C. 2348 W  
D. 2239 W  
E. 3811 W
19. Heat is transferred steadily through a 0.2-m thick 8 m x 4 m wall at a rate of 1.6 kW. The inner and outer surface temperatures of the wall are measured to be 15 °C and 5 °C. The average thermal conductivity of the wall is:

- A. 0.001 W/m.  $^{\circ}\text{C}$
  - B. 0.5 W/m.  $^{\circ}\text{C}$
  - C. 1.0 W/m.  $^{\circ}\text{C}$
  - D. 2.0 W/m.  $^{\circ}\text{C}$
  - E. 5.0 W/m.  $^{\circ}\text{C}$
20. The roof of an electrically heated house is 6-m long, 8-m wide, and 0.25- m thick. It is made of a flat layer of concrete whose thermal conductivity is 0.8 W/m.  $^{\circ}\text{C}$ . During a certain winter night, the temperatures of the inner and outer surfaces of the roof are measured to be 15  $^{\circ}\text{C}$  and 4  $^{\circ}\text{C}$ , respectively. The average rate of the heat loss through the roof that night was:
- A. 35 W
  - B. 422 W
  - C. 3379 W
  - D. 2246 W
  - E. 1690 W
21. A well-sealed room contains 80 kg of air at 200 kPa and 25  $^{\circ}\text{C}$ . Now solar energy enters the room at an average rate of 1 kJ/s while a 100-W fan is turned on to circulate the air in the room. If the heat transfer through the walls is negligible, the air temperature in the room in 30 minutes would be:
- A. 28.3  $^{\circ}\text{C}$
  - B. 49.8  $^{\circ}\text{C}$
  - C. 52.5  $^{\circ}\text{C}$
  - D. 56.0  $^{\circ}\text{C}$
  - E. 59.5  $^{\circ}\text{C}$
22. A 2-kW baseboard electric resistance heater in a vacant room is turned on and kept on for 15 minutes. The mass of the air in the room is 75 kg, and the room is tightly sealed so no air can leak in or out. The temperature rise of air at the end of 15 minutes is:
- A. 8.5  $^{\circ}\text{C}$
  - B. 12.4  $^{\circ}\text{C}$
  - C. 24.0  $^{\circ}\text{C}$
  - D. 33.4  $^{\circ}\text{C}$
  - E. 54.8  $^{\circ}\text{C}$
23. A piston- cylinder device contains 5 kg of air at 400 kPa and 30  $^{\circ}\text{C}$ . During a quasi-equilibrium isothermal expansion process, 15 kJ of boundary work is done by the system, and 3 kJ paddle-wheel work is done on the system. The heat transfer during this process is:
- A. 12 kJ
  - B. 18 kJ
  - C. 2.4 kJ
  - D. 3.6 kJ

E. 60 kJ

24. A container equipped with a resistance heater and a mixer is initially filled with 3 kg of saturated water vapour at  $100^{\circ}\text{C}$ . Now the heater and the mixer are turned on; the steam is compressed and there is heat loss to the surrounding air. At the end of the process, the temperature and pressure of the steam in the container are measured to be  $300^{\circ}\text{C}$  and 0.5 MPa. The net energy transfer to the steam during this process is:

- A. 196 kJ
- B. 359 kJ
- C. 561 kJ
- D. 892 kJ
- E. 1568 kJ

25. A 6-pack canned drink is to be cooled from  $25^{\circ}\text{C}$  to  $3^{\circ}\text{C}$ . The mass of each can drink is 0.355 kg. The drinks can be treated as water, and the energy stored in the aluminium can itself is negligible. The amount of heat transfer from the 6 canned drinks is:

- A. 33 kJ
- B. 37 kJ
- C. 47 kJ
- D. 196 kJ
- E. 223 kJ

26. Steam expands in a turbine from 4 MPa and  $500^{\circ}\text{C}$  to 0.5 MPa and  $250^{\circ}\text{C}$  at a rate of 1740 kg/h. Heat is lost from the turbine at a rate of 12 kJ/s during the process. The power output of the turbine is:

- A. 222 kW
- B. 233 kW
- C. 438 kW
- D. 717 kW
- E. 246 kW

27. Saturated water vapour at  $40^{\circ}\text{C}$  is to be condensed as it passes through a tube at a rate of 0.2 kg/s. The condensate leaves the tube as saturated liquid at  $40^{\circ}\text{C}$ . The rate of heat transfer from the tube is:

- A. 34 kJ/s
- B. 268 kJ/s
- C. 453 kJ/s

- D. 481 kJ/s
- E. 515 kJ/s

28. Steam enters an adiabatic turbine steadily at  $400^{\circ}\text{C}$  and 3 MPa, and leaves at 50 kPa. The highest possible percentage of mass of steam that condenses at the turbine exit and leaves the turbine as liquid is:

- A. 5 %
- B. 10 %
- C. 15 %
- D. 20 %
- E. 0 %

29. 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  $W_{\text{cycle}}$  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.  $|Q_H| = 300 \text{ kJ}$ ,  $|W_{\text{cycle}}| = 160 \text{ kJ}$ ,  $|Q_C| = 140 \text{ kJ}$
- II.  $|Q_H| = 300 \text{ kJ}$ ,  $|W_{\text{cycle}}| = 180 \text{ kJ}$ ,  $|Q_C| = 120 \text{ kJ}$
- III.  $|Q_H| = 300 \text{ kJ}$ ,  $|W_{\text{cycle}}| = 170 \text{ kJ}$ ,  $|Q_C| = 140 \text{ kJ}$
- IV.  $|Q_H| = 300 \text{ kJ}$ ,  $|W_{\text{cycle}}| = 300 \text{ kJ}$ ,  $|Q_C| = 0 \text{ kJ}$

- 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 30 -32 on the operation of a refrigeration cycle.

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

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

30. In which case(s) conceived by the engineer, is/are the operation of the refrigeration cycle impossible?

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

31. In which case(s) conceived by the engineer, could the refrigeration cycle operate reversibly?

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

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

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

Use the information below to answer questions 33 to 35 on the operation of a power cycle

A power cycle operating between two reservoirs receives energy  $Q_H$  from a heat reservoir at

$T_H = 1000 \text{ K}$  and rejects energy  $Q_C$  to cold reservoir at temperature  $T_C = 600 \text{ K}$ . It is conceived by an 'engineer' that the power cycle can operate under each of the following cases:

- I.  $|Q_H| = 1000 \text{ kJ}$ ,  $|W_{\text{cycle}}| = 400 \text{ kJ}$
- II.  $|Q_C| = 1000 \text{ kJ}$ ,  $|Q_H| = 2000 \text{ kJ}$
- III.  $|Q_C| = 600 \text{ kJ}$ ,  $|W_{\text{cycle}}| = 300 \text{ kJ}$
- IV.  $|W_{\text{cycle}}| = 400 \text{ kJ}$ ,  $\eta_{\text{th}} = 32 \%$

33. In which case(s) conceived by the engineer, is/are the operation of the power cycle impossible?

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

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

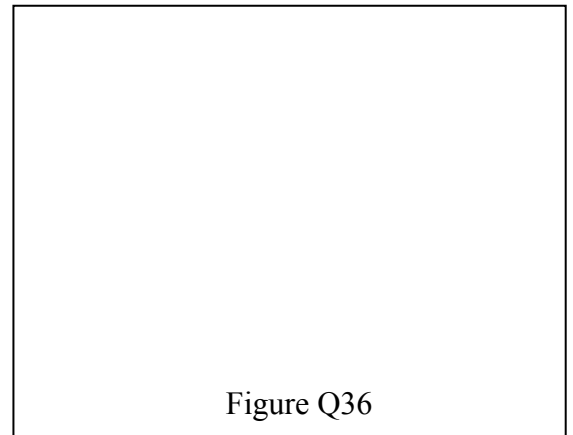
- A. I only
- B. II only
- C. III only
- D. III and IV only
- E. II and IV only

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

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

36. A control mass undergoes the process from an initial state 1 to the final state 2 as shown in Figure Q36. The heat transfer is  $Q_{1,2} = 200 \text{ kJ}$ . The change in the internal energy of the system is

- A.  $-600 \text{ kJ}$
- B.  $-400 \text{ kJ}$
- C.  $-200 \text{ kJ}$
- D.  $+200 \text{ kJ}$
- E.  $+600 \text{ kJ}$

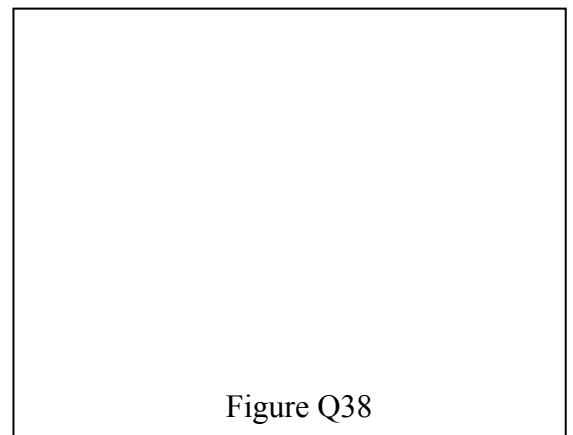


37. Steam enters a steam turbine at 50 bar,  $400^\circ\text{C}$ . The flow work of the steam at entry to the turbine is

- A.  $3196 \text{ kJ/kg}$
- B.  $3000 \text{ kJ/kg}$
- C.  $2907 \text{ kJ/kg}$
- D.  $316 \text{ kJ/kg}$
- E.  $289 \text{ kJ/kg}$

38. The work done, in kJ, by the ideal gas in going from state A to state C along the path shown in the  $P$ - $v$  diagram is

- A.  $14 \text{ kJ}$
- B.  $100 \text{ kJ}$
- C.  $181 \text{ kJ}$
- D.  $186 \text{ kJ}$
- E.  $281 \text{ kJ}$

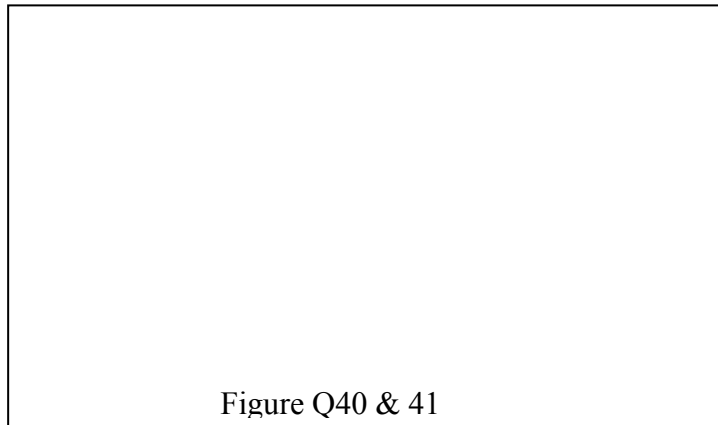


39. One of the following diagrams is usually referred to as the phase diagram for a pure substance since it represents all three phases in one diagram.

- A.  $p - v$  diagram
- B.  $p - T$  diagram
- C.  $T - v$  diagram
- D.  $T - s$  diagram
- E.  $p - h$  diagram

Use the following information to answer questions 40 & 41

A gas initially at 100 kPa is contained within a piston-cylinder arrangement. At state 1, the gas has a volume of  $2 \text{ m}^3$ . The gas is expanded isobarically to state 2, where the volume is  $4 \text{ m}^3$ . The gas is then compressed by a process that follows the relationship  $p v^{1.4} = \text{constant}$  until it returns to state 1. The corresponding  $P$ - $v$  diagram is shown in Figure Q 17 & 18.



40. The value of the pressure at state 3 is:

- A. 33.3 kPa
- B. 37.9 kPa
- C. 50.0 kPa
- D. 66.7 kPa
- E. 263.9 kPa

41. The net work done, in kJ, in completing the cycle of processes 1-2-3-1 outlined in Figure Q40 & 41 is

- A. - 30.5 kJ
- B. - 33.0 kJ
- C. - 79.0 kJ
- D. - 200.0 kJ
- E. - 267.0 kJ

Use the information below to answer questions 42 –44.

The free-moving piston-cylinder device shown Figure Q42-44 contains 5 kg of  $\text{H}_2\text{O}$  at temperature of  $300^\circ\text{C}$ . When 3000 kJ of shaft work is transferred to the medium, the temperature increases to  $500^\circ\text{C}$ .

Figure Q42-44

42. The pressure exerted by the system on the surroundings is
- A. 100.0 kPa
  - B. 200.0 kPa
  - C. 300.0 kPa
  - D. 400.0 kPa
  - E. 500.0 kPa
43. The change in internal energy of the system during the process is
- A. 1600 kJ
  - B. 1610 kJ
  - C. 1615 kJ
  - D. 1620 kJ
  - E. 1625 kJ
44. The net heat transferred, in kJ, during the process is
- A. – 1400 kJ
  - B. – 1390 kJ
  - C. – 1385 kJ
  - D. – 1320 kJ
  - E. – 1375 kJ
45. 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  $2500 \text{ W/m}^2$ . The value of the heat transfer coefficient is
- A. 25 W/m K
  - B.  $25 \text{ W/m}^2 \text{ K}$
  - C. 0.4 W/m K
  - D.  $0.4 \text{ W/m}^2 \text{ K}$
46. A surface of area  $2 \text{ m}^2$  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

47. 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  $10 \text{ m}^2$ , 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

***Use the following information to answer to answer questions 48 and 49:***  
**A rigid vessel of volume  $0.03 \text{ m}^3$  contains dry saturated steam at 17 bar.**

48. The mass of the steam (in kg) in the vessel is:

- A. 0.257 kg
- B. 1.167 kg
- C. 3.89 kg
- D. 4.65 kg
- E. 25.7 kg

49. The enthalpy of steam in the vessel is:

- A. 229.20 kJ
- B. 494.20 kJ
- C. 667.4 kJ
- D. 718.3 kJ
- E. 326.2 kJ

***Use the following information to answer questions 50 and 51.***

0.05 kg of steam at 15 bar is contained in a rigid vessel of volume  $0.0076 \text{ m}^3$ .

50. The temperature of the steam in the vessel is:

- A.  $198.3^\circ\text{C}$
- B.  $250^\circ\text{C}$
- C.  $300^\circ\text{C}$
- D.  $350^\circ\text{C}$
- E.  $400^\circ\text{C}$

51. If the vessel in condition described above is cooled, the temperature at which the steam becomes just saturated is:
- A. 91.4 °C
  - B. 120.4 °C.
  - C. 150.4 °C
  - D. 191.4 °C
  - E. 198.3 °C

Use the following provided below to answer questions 52 –54.

A gas undergoes a thermodynamic cycle consisting of three processes. The processes are as follows:

- Process 1-2:* constant-pressure expansion,  $P_1 = 1.4 \text{ bar}$ ,  $V_1 = 0.028 \text{ m}^3$ ,  $|W_{12}| = 10.5$   
kJ
- Process 2-3:* compression with  $PV = \text{constant}$ ,  $U_2 = U_3$
- Process 3-1:* constant volume,  $U_1 - U_3 = -26.4 \text{ kJ}$

There are no significant changes in kinetic or potential energy.

52. The pressure of the gas at state 3 is:
- A. 2.8 bar
  - B. 5.2 bar
  - C. 37.5 bar
  - D. 38.6 bar
  - E. 38.9 bar
53. The magnitude of the net work for the cycle is:
- A. 1.7 kJ
  - B. 5.9 kJ
  - C. 8.3 kJ
  - D. 10.5 kJ
  - E. 29.3 kJ
54. The heat transfer for the process 1 – 2 is:
- A. -15.9 kJ
  - B. 15.9 kJ
  - C. 18.5 kJ
  - D. 26.4 kJ
  - E. 36.9 kJ

*Use the following information provide to answer questions 55 and 56*

A closed system comprising 1.0kg of gas undergoes a quasi-static process from state 1  $P_1 = 3.0 \text{ kPa}$ ,  $V_1 = 0.001 \text{ m}^3$  and  $u_1 = 210.5 \text{ kJ/kg}$ ; to state 2  $P_2 = 0.1 \text{ kPa}$ ,  $V_2 = 0.01 \text{ m}^3$  and  $u_2 = 221.3 \text{ kJ/kg}$ . Two different paths can be used to achieve the objective between the two states as described below.

- In path A, the relationship between pressure and volume is linear.
- In path B, the volume increases to a final value at constant pressure followed by a constant volume to state 2.

55. In path A, the work done by the system is:

- A. 29.9 J
- B. 27.0 J
- C. 13.95 J
- D. 26.1 J
- E. 0.9 J

56. The heat lost by the system to the surroundings as it undergoes the process 1-2 along path B is:

- A. 27 J
- B. 16.2 J
- C. 0.9 J
- D. 9.9 J
- E. 10.8 J

57. Consider a steady-flow Carnot cycle with water as the working fluid executed under the saturation dome between the pressure limits of 100 bar and 0.2 bar. Water changes from saturated liquid to saturated vapour during the heat addition process. The magnitude of the net work output of this cycle is

- A. 251 kJ/kg
- B. 342 kJ/kg
- C. 566 kJ/kg
- D. 598 kJ/kg
- E. 1317 kJ/kg

58 – 62. Complete the following table for water with the help of Steam Tables.

Question Number.	$t(^{\circ}\text{C})$ (1d.p)	$p(\text{kPa})$	$h(\text{kJ/kg})$	$x(2dp)$	Phase description
58.		4000	2700		
59.	165	800			
60.	500	900			
61.		1000			Saturated vapour
62.	230			0.0	

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

No.	Unit 5 <u>Statement</u>	Response	
63.	The automobile engine is an example of a closed system.	<b>T</b>	<b>F</b>
64.	The state of a pure magnetic substance is specified by two independent properties.	<b>T</b>	<b>F</b>
65.	For any intensive property P a corresponding extensive property can be defined.	<b>T</b>	<b>F</b>
66.	It is impossible for any machine to convert work continuously into heat.	<b>T</b>	<b>F</b>
67.	Temperature is unique in thermodynamics.	<b>T</b>	<b>F</b>
69.	Thermodynamics Laws are theoretically derived.	<b>T</b>	<b>F</b>
70.	Thermodynamics variables are microscopic, many and are suggested by our sense organs.	<b>T</b>	<b>F</b>

**F.K. FORSON**  
**E. RAMDE**  
**P. TAWIAH**  
**F. O. AKUFFO**

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