

KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI

DEPARTMENT OF MECHANICAL ENGINEERING

THERMODYNAMICS I (ME 265/266)

FOR ENGINEERING STUDENTS

(Mechanical Engineering Level 200 and Agricultural Engineering Level 200)

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INTRODUCTORY CONCEPTS AND DEFINITIONS

Introduction

Unit 1 contains the introductory concepts and definitions of thermodynamics. The sessions will cover thermodynamic systems, aspects on specific volume, specific weight and pressure.

Learning Objectives

After studying this unit, you should be able to:

1. Explain the unique vocabulary associated with engineering thermodynamics through the precise definition of fundamental concepts to form a sound foundation for the development of the principles of Applied Thermodynamics
2. Review the metric SI unit system that will be used throughout the text
3. Explain the fundamental concepts of thermodynamics such as system, state, state postulate, property, equilibrium, process, path, and cycle
4. Review the concepts of temperature, temperature scales, pressure, absolute and gauge pressures
5. Explain terms such as specific volume, specific weight
6. Identify the different kinds of thermodynamic processes and appreciate their relevance in real life situations
7. Distinguish between extensive and intensive properties
8. Handle different temperature conversion scales

SESSION 1-1: DEFINITION AND LIMITATIONS OF THERMODYNAMICS

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 plants and processing plants in 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 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.

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.

<p><u>Note</u> that even vacuum which is devoid of matter, may be the focus of interest. The composition of matter inside a system <u>may be fixed</u> or may <u>be changing</u> through chemical or nuclear reactions. <u>The shape or volume of the system being analysed is not necessarily constant</u>, as when a piston compresses a gas in a cylinder or a balloon is being inflated.</p>
--

Surroundings or Environment of System

Everything external to a 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.

A **boundary** is a closed surface, either real or imaginary, surrounding a system through which energy and/or 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 or *permeable* in which the 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 an *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 1.1: 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.

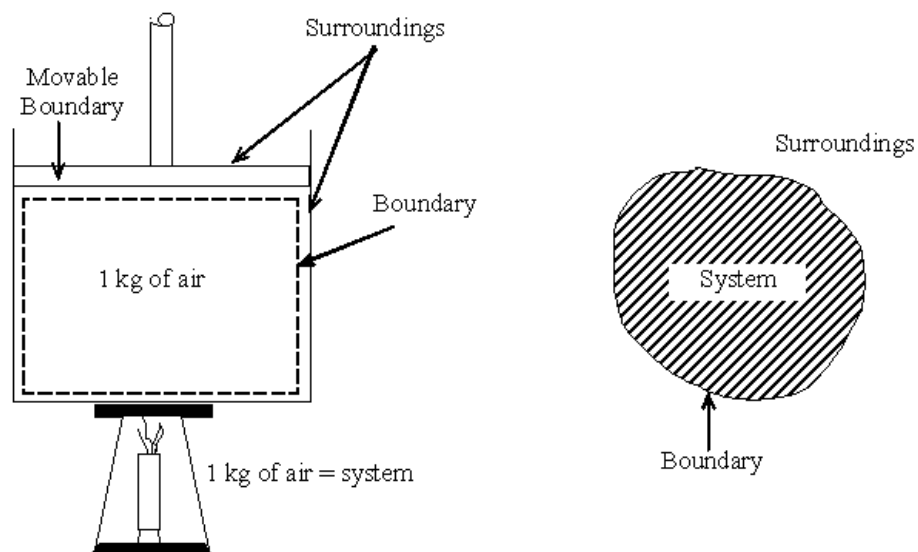


Figure 1: Sketch of an experimental set-up

1-1.1.1 Types of systems

Depending on the nature of the 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 given 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.

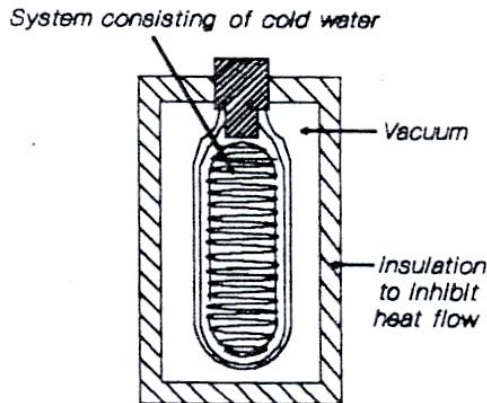


Figure 2: Thermos flask

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 (b), 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 energy of the shaft work. The boundaries of the system are fixed.

Fig. 4 (a) consists of food (banku) 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.

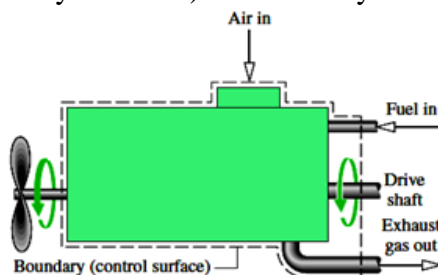
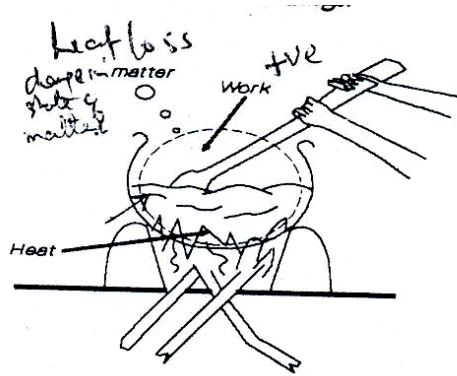
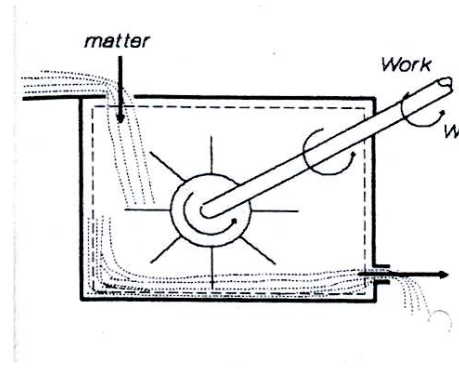


Figure 3: An open system (an automobile engine)



(a) food (banku) being cooked



(b) water flowing through a region containing a water wheel

Figure 4: Other open systems

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.

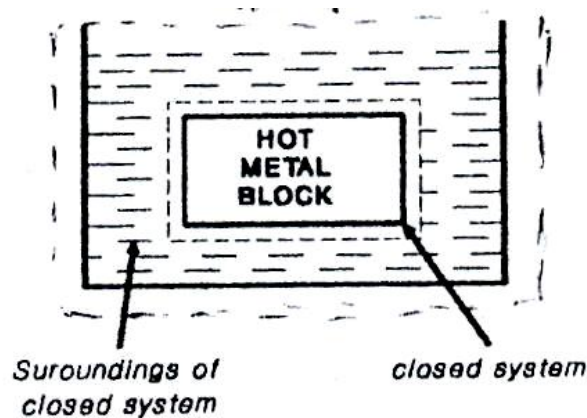


Figure 5: System depends on the observer

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, also 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, for 1 kg of water at a temperature of 100°C and pressure of 1 atm. (1.01325 bar), the volume $V = 0.001044 \text{ m}^3$ but when it is heated at the same temperature and pressure the volume increases to 1.673 m^3 . Explain why?

1-1.2 Property, State, Process, Path 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. Simply put, a property must be *macroscopic*, *measurable* and have a *single numerical value* that does not depend on how the condition of the system was attained.

State

The word state refers to the condition of a system as prescribed or 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 like 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 thermodynamic 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 otherwise it is in a *transient state*.

Path

The series of states through which a system passes during a process is called the path of the process. To describe a process completely, one should specify the initial and final states of the process, as well as the path it follows, and the interaction with the surroundings.

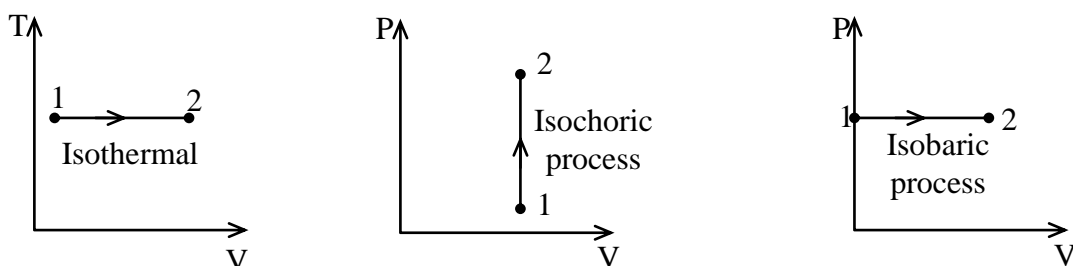


Figure 6: Examples of processes

Point and Path Functions

The value of a property of a system is independent of the path of the process undergone by the system and is therefore referred to as a point function. Quantities

such as heat and work which are not properties of the system but are dependent on the path of the process undergone by the system are classified as path functions. If X is a property, then the change in its value is independent of path, hence,

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

For heat (Q) and work (W) which are path dependent:

$$\int_1^2 \delta Q = Q_{12} \quad \text{and} \quad \int_1^2 \delta W = W_{12}$$

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 in the value of a thermodynamic property during a process 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 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/mass 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/mass 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. Specific extensive properties are intensive properties since their values no longer depend on the mass of the system.

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*, 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 necessarily 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 throughout the processes. The process path for a reversible process is indicated by a solid line.

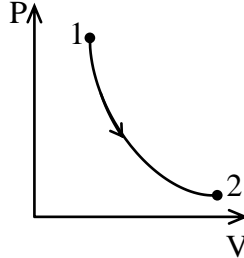


Figure 7: Reversible process on a P-V diagram

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. Irreversible processes include doing work against friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, inelastic deformation of solids, chemical reactions and the transfer of current against electrical resistance.

Consider the unrestrained expansion of a gas: With the diaphragm removed, the gas fills the entire volume when equilibrium is established.

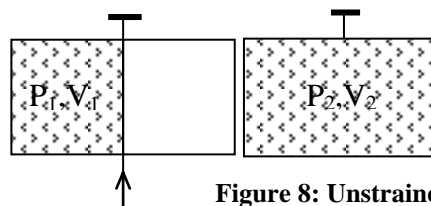


Figure 8: Unrestrained expansion of a gas

Note: We cannot establish the intermediate state. The process diagram is shown below.

We join initial and final equilibrium state by broken lines.

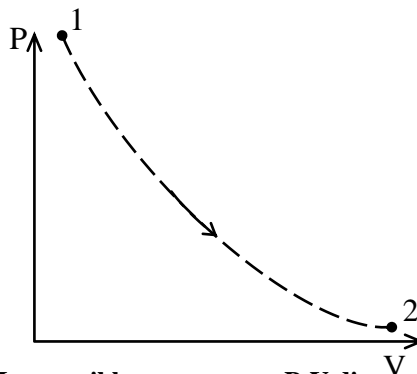


Figure 9: Irreversible process on a P-V diagram

Quasi Static Process

Process is said to be *quasi-static* if it proceeds in such a manner that at any instance 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 establish equilibrium must be shorter than the time it takes to travel.

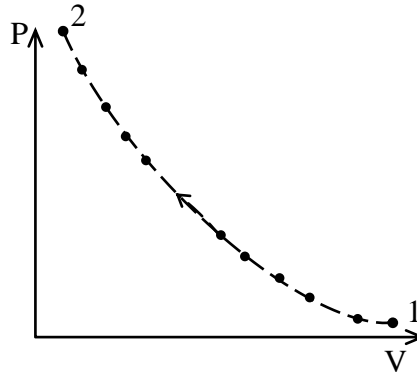


Figure 10: Quasi-Static process on a P-V diagram

Adiabatic Process

A process during which there is no heat transfer is called an adiabatic process. There are two ways a process can be adiabatic: Either the system is well insulated so that only a negligible amount of heat can pass through the boundary, or both the system and the surroundings are at the same temperature and therefore there is no driving force (temperature difference) for heat transfer.

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
- Phase equilibrium

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 commonly encountered in the study of thermodynamics

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			
10^3	Kilo	k			
10^{-6}	Micro	μ			

Self Assessment 1-1

1. The temperature of a system rises by 15°C during a heating process. Express this rise in temperature in Kelvin.
2. The water tank is pressurised by air, and the pressure is measured by a multi-fluid manometer as shown in Fig. Q.2. Determine the gage pressure of air in the tank if $h_1 = 0.2$ m, $h_2 = 0.3$ m, and $h_3 = 0.46$ m. Take the densities of water, oil and mercury to be 1000 kg/m^3 , 850 kg/m^3 , and $13,600 \text{ kg/m}^3$, respectively.
3. Determine the atmospheric pressure at a location where the barometric reading is 750 mmHg. Take the density of mercury to be $13,600 \text{ kg/m}^3$.
4. The gage pressure in a liquid at a depth of 3 m is read to be 28 kPa. Determine the gage pressure in the same liquid at a depth of 9 m.
5. A gas is contained in a vertical, frictionless piston-cylinder device. The piston has a mass of 4 kg and a cross-sectional area of 35 cm^2 . A compressed spring above the piston exerts a force of 60 N on the piston. If the atmospheric pressure is 95 kPa, determine the pressure inside the cylinder.

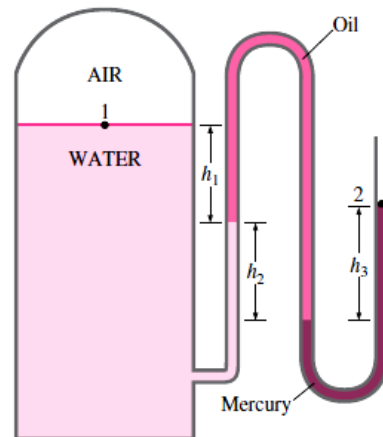


Fig. Q.2

Suggested answers

[15 K] 2. [56.9 kPa] 3. [101.1 kPa] 4. [84 kPa] 5. [123.4 kPa]

SESSION 2-1:

2-1.1 Specific Volume, Specific Weight 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 volume per unit mass. Like density, specific volume is an intensive property and may vary from point to point. SI units for density and specific volume are kg/m^3 and m^3/kg , respectively. However, they can be written in other units as well.

The specific weight (γ) is defined as the weight per unit volume of a system. It is related to the density of the system by the relation: $\gamma = \rho g$, where g is the local acceleration due to gravity. Specific weight has the unit Newton per cubic meter (N/m^3)

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.

$$1 \text{ kPa} = 10^3 \text{ N/m}^2$$

$$1 \text{ bar} = 10^5 \text{ N/m}^2 = 100 \text{ kPa}$$

$$1 \text{ MPa} = 10^6 \text{ N/m}^2 = 1000 \text{ kPa}$$

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

$1 \text{ atm} = 101\,325 \text{ Pa} = 101.325 \text{ kPa} = 1.013\,25 \text{ bar} = 760 \text{ mm Hg}$

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. 11.

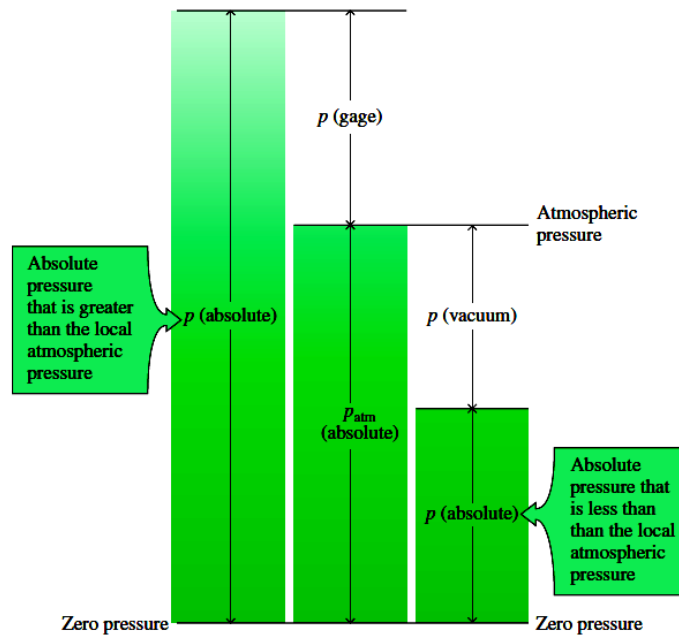


Figure 11: Relationships between the absolute, atmospheric, gauge, and vacuum pressures

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. 12 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 $p = p_{atm} + \rho g L$

A Bourdon tube gauge is shown in Fig. 13. 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.

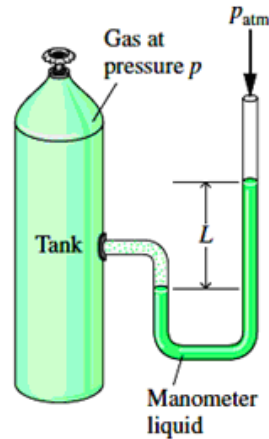


Figure 12: Mercury Manometer

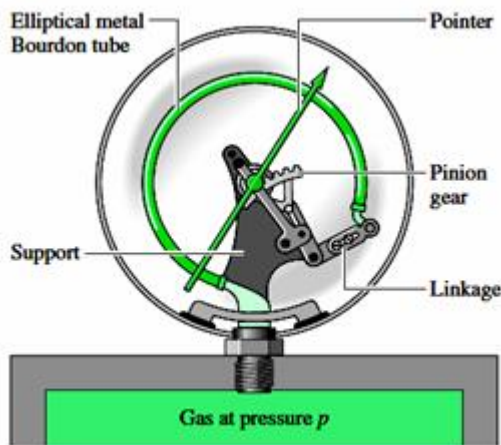


Figure 13: Bourdon Tube

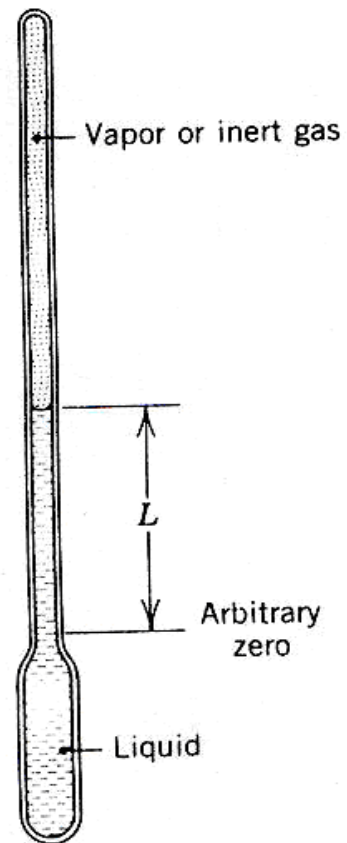


Figure 14: Liquid in glass thermometer

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 substance 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.14, 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.

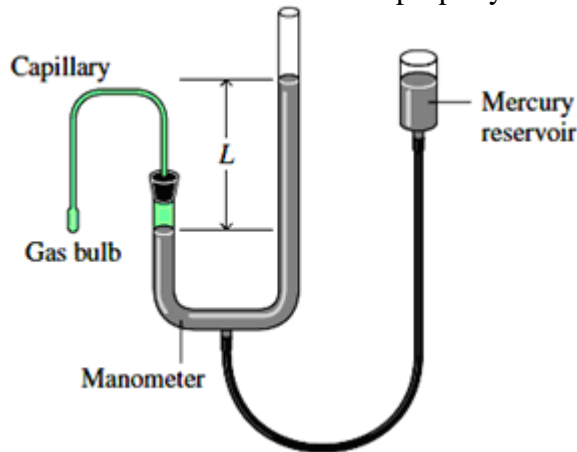


Figure 15: Constant-volume gas thermometer

The gas thermometer shown in Fig. 15 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. 16, 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.

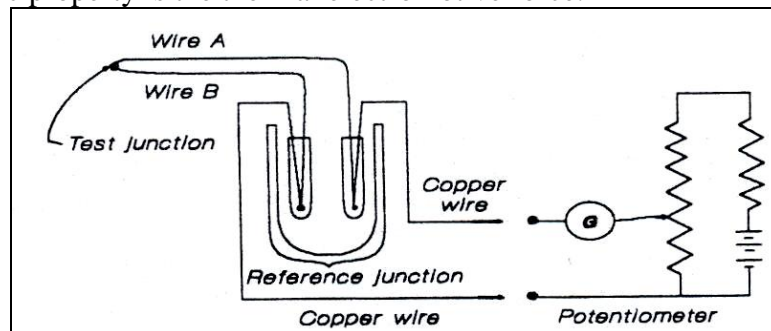


Figure 16: Thermocouple of wires A and B

Absolute Temperature Scale and calibration of Thermometers

An absolute temperature scale may be established as follows:

Let X represents 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 relate the 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 is 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 difference in 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

$$T(^{\circ}\text{C}) = T(\text{K}) - 273.15 \quad (1.1)$$

Thus, from Equation (1.1) we see that on the Celsius scale the triple point of water is 0.01°C and 0 K corresponds to -273.15°C . (Figure 12)

The temperature of at the steam point, 373.15 K is 100.0°C . Accordingly, there are 100 Celsius degrees in this interval of 100 Kelvin.

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

$$T(^{\circ}\text{R}) = 1.8 T(\text{K}) \quad (1.2)$$

The Rankine scale is also an absolute temperature scale.

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

$$T(^{\circ}\text{F}) = T(^{\circ}\text{R}) - 459.67 \quad (1.3)$$

Substituting Eqs. 1.1 and 1.2 into Eq. 1.3, it follows that

$$T(^{\circ}\text{F}) = 1.8T(^{\circ}\text{C}) + 32 \quad (1.4)$$

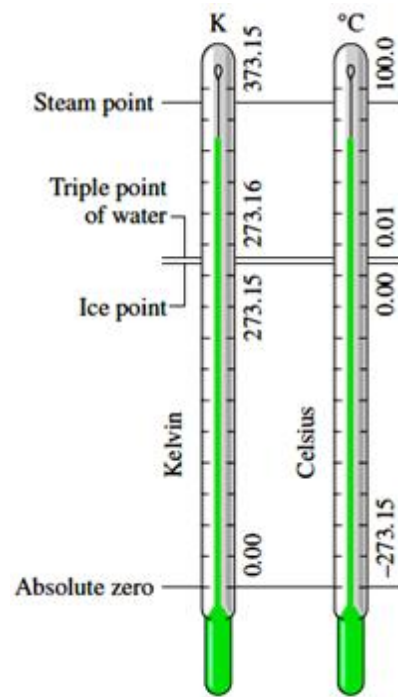


Figure 17: Comparison of temperature

Equation (1.4) shows that the Fahrenheit temperature of the ice point (0°C) is 32°F and the steam point (100°C) is 212°F .

Comparison of magnitudes of the change in the various temperature units defined earlier:



That is, in terms of temperature *changes*, $\Delta 1\text{K} = \Delta 1^{\circ}\text{C} = \Delta 1.8\text{R} = \Delta 1.8^{\circ}\text{F}$

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°C . This rise in temperature in K is 10 K. The rise in temperature in $^{\circ}\text{F}$ is $1.8(10) = 18^{\circ}\text{F}$.

Self Assessment 2-1

1. A mercury ($\rho = 13,600 \text{ kg/m}^3$) manometer is connected to an air duct to measure the pressure inside. The difference in the manometer levels is 15 mm, and the atmospheric pressure is 100 kPa. (a) Judging from Fig. Q.1, determine if the pressure in the duct is above or below the atmospheric pressure. (b) Determine the absolute pressure in the duct.

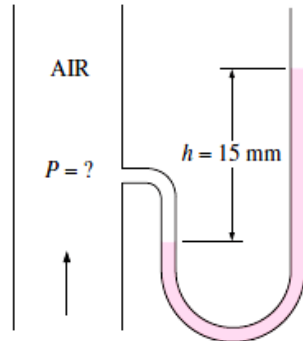


Fig. Q.1

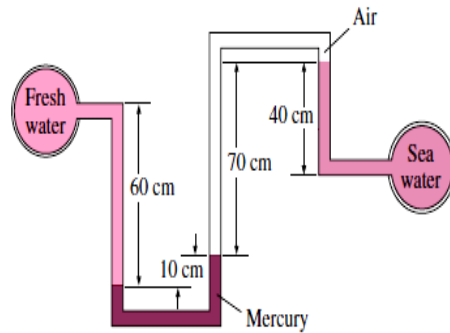


Fig. Q.2

2. Freshwater ($\rho = 1000 \text{ kg/m}^3$) and seawater ($\rho = 1035 \text{ kg/m}^3$) flowing in parallel horizontal pipelines are connected to each other by a double U-tube manometer, as shown in Fig. Q.2. Determine the pressure difference between the two pipelines. Take the density of sea water at that location to be $\rho = 1035 \text{ kg/m}^3$. Can the air column be ignored in the analysis? Assume the density of air, $\rho_{\text{air}} = 1.15 \text{ kg/m}^3$.

Suggested answers

1. [a. Above atmospheric b. 102 kPa]
2. [3.39 kPa; yes]

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.

Learning Objectives

After studying this unit, you should be able to:

1. Organise ideas about energy into forms suitable for engineering analysis
2. Identify the first law of thermodynamics as simply a statement of the conservation of energy principle for closed (fixed mass) and open (control volume) systems
3. Develop the general energy balance applied to closed and open thermodynamic systems
4. Apply the first law in solving energy balance problems for closed and open systems that involve heat and work interactions
5. Solve energy balance problems for common steady-flow devices like nozzles, diffusers, turbines, compressors, pumps, boilers, condensers, heat exchangers, mixers, heaters
6. Identify the energy carried by a fluid stream crossing a control surface as the sum of internal energy, flow work, kinetic energy, and potential energy of the fluid and relate the combination of the internal energy and the flow work to the property enthalpy.

SESSION 1-2:

1-2.1 Mechanical Concepts of Energy

1-2.1.1 Work and Kinetic Energy

The curved line in Fig. 18 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 2nd Law, the magnitude of the component F_s is related to the change in the magnitude of V by

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

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

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

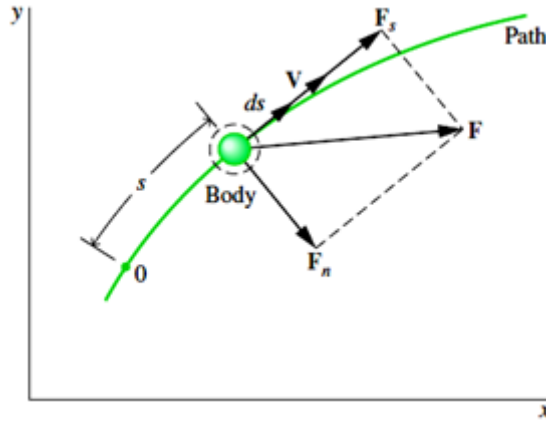


Figure 18: Forces acting on a moving system

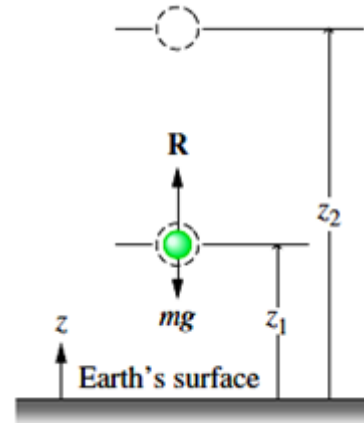


Figure 19: Illustration of potential energy

The integral on the left of Equation (2.2) is evaluated as follows:

$$\int_{V_1}^{V_2} mV dV = \frac{1}{2} mV^2 \Big|_{V_1}^{V_2} = \frac{1}{2} m (V_2^2 - V_1^2) \quad (2.3)$$

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, ΔKE , of the body is

$$\Delta KE = KE_2 - KE_1 = \frac{1}{2} m (V_2^2 - V_1^2).$$

The integral on the right side of Equation (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 Equations (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. 19. 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,

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

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

$$W = \int_{s_1}^{s_2} F_s \cdot ds \quad (2.9)$$

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 or decrease 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 δW , but the differential of every property is exact and is represented by a total derivative dX . Where, X is a property.

1-2.2.2 Expansion or Compression Work

Let us evaluate the work done by the closed system shown in Fig. 20 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

$$\delta W = - p A dx = - p dV \quad (2.10)$$

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 Equation (2.10) is positive. For a change in volume from V_1 to V_2 , the work is obtained by integrating Equation (2.10).

$$W = - \int_{V_1}^{V_2} p dV \quad (2.11)$$

Although Equation (2.11) 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. 2.11 requires a relationship between the system (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. 2.11, the work can be determined from an energy balance (See 2-2.2).

1-2.2.3 Work in Quasi-equilibrium Expansion or Compression Process

The quasi-static work given by Equation (2.11) can be obtained from a graph of the process on a p - V diagram as shown in Fig. 21. The magnitude of 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.

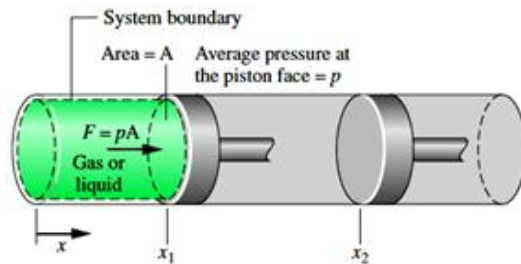


Figure 20: Expansion or compression of a gas or liquid

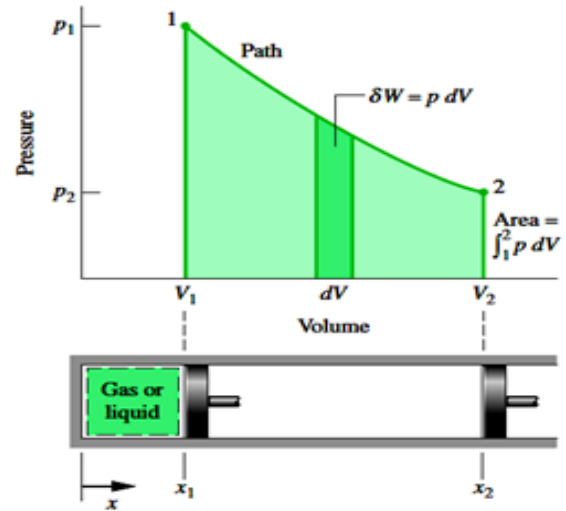


Figure 21: Work of quasi-equilibrium process

Polytropic Process

The relationship between pressure and volume during an expansion or compression process can also 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*.

To appreciate the idea of the polytropic process, consider the mathematical differentiation of the expression:

$$pV^n = C \quad \Rightarrow p = CV^{-n}$$

$$\frac{dp}{dV} = -nCV^{-n-1}$$

$$= -n(pV^n)V^{-n}V^{-1}$$

The differential then simplifies to

$$\frac{dp}{dV} = -n \frac{p}{V}$$

When $n = 0$ $\frac{dp}{dV} = 0$, $\Rightarrow dp = 0$ (constant pressure process)

When $n = \pm \infty$ $\frac{dp}{dV} = \infty$, $\Rightarrow dV = 0$ (constant volume process)

The process described by $n = 0$ being a constant pressure one is represented by a horizontal line on the p - V diagram. A constant-volume process given by $n = \pm \infty$ is represented by a vertical line on the p - V diagram. Intermediate values of n , both positive and negative, are possible. Negative values are only encountered when the p - V processes are approximated that involve internal energy generation by chemical reaction or when significant heat transfer to the control mass or control volume is present. In such cases, the pressure may increase as the system volume increases.

Determination of the quasi-static work for polytropic processes.

Note that

$$W = -\int_{V_1}^{V_2} p dV = -\int_{V_1}^{V_2} \frac{\text{constant}}{V^n} dV = -\text{constant} \left(\frac{V_2^{1-n} - V_1^{1-n}}{1-n} \right) \quad (2.12)$$

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

$$W = -\frac{(p_2 V_2^n) V_2^{1-n} - (p_1 V_1^n) V_1^{1-n}}{1-n} = \frac{p_2 V_2 - p_1 V_1}{n-1} \quad (2.13)$$

This expression is valid for all values of n except $n = 1$. The cases $n = 0$ and $n = \pm \infty$ are also treated under special cases (See 1-2.2.4).

1-2.2.4 Special Cases of the Polytropic Process

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

$$W_{12} = -\text{constant} \int_{V_1}^{V_2} \frac{dV}{V} = -(\text{constant}) \ln \frac{V_2}{V_1} = -(p_1 V_1) \ln \frac{V_2}{V_1} \quad (2.14)$$

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

$$W_{12} = -p(V_2 - V_1) \quad (2.15)$$

- (c) The case of $n = \pm \infty$: This refers to a constant volume process as derived earlier. In this case the quasi-static work given by $W = \int -p dV = 0$.
- (d) 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

$$W_{12} = -\int_{V_1}^{V_2} p dV = -\int_{V_1}^{V_2} (aV + b) dV = -\left[a \frac{V^2}{2} + bV \right]_{V_1}^{V_2} \quad (2.16)$$

By inserting the upper and lower limits into Eq. 2.16, the work done is evaluated. It can be shown that the expression for the work done reduces to $W = -\left(\frac{P_1 + P_2}{2}\right)(V_2 - V_1)$ 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. 22.

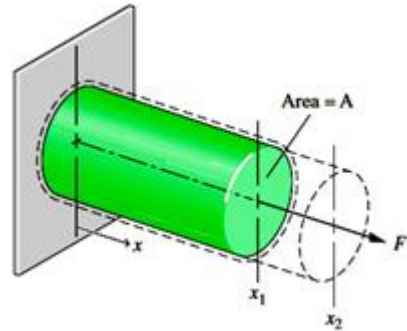
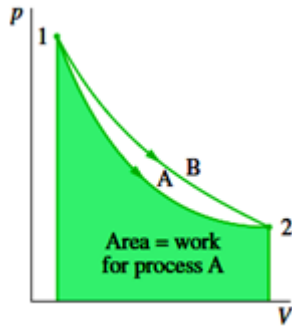


Figure 22: Illustration that work depends on process

Figure 23: Elongation of a 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. 23. The bar is fixed at $x = 0$, and a force F is applied at the other end. The force $F = \sigma A$, where A is the cross-sectional area of the bar and σ the normal stress acting at the end of the bar. The work done as the end of the bar moves a distance dx is given by $\delta W = +\sigma A dx$. The plus sign is required because work is done *on* the bar when dx

is positive. $W = \frac{1}{2}EA_0L_0(\epsilon_x)^2$ 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 ϵ_x is the strain in the bar defined as the change in length divided by the original length.

Stretching of a Liquid Film: Fig. 24 shows a system consisting of, a liquid film suspended on a wire frame. The two surfaces of the film support the thin liquid layer inside by the effect of *surface tension*. Denoting the *surface tension acting at the movable wire* by τ , the force F indicated on the figure can be expressed as $F = 2l\tau$, where the factor 2 is introduced because two film surfaces act at the wire. If the movable wire is displaced by dx , the work done is given by $\delta W = +2l\tau dx$. The plus sign is required because work is done *on* the system when dx is positive.

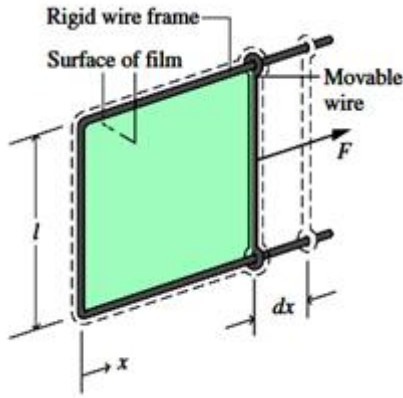


Figure 24: Stretching of a liquid film

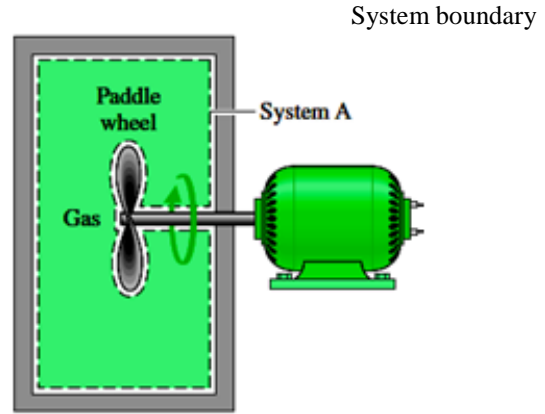


Figure 25: Power transmitted to a gas by a paddle wheel

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

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

$$\dot{W} = F \cdot V \quad (2.17a)$$

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

$$\dot{W} = F_t V = (\tau/R)(R\omega) = \tau \omega \quad (2.17b)$$

A related case involving a gas stirred by a paddle wheel is shown in Fig. 25.

Electrical work: Shown in Fig. 26 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 $\dot{W} = Ei$.

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.

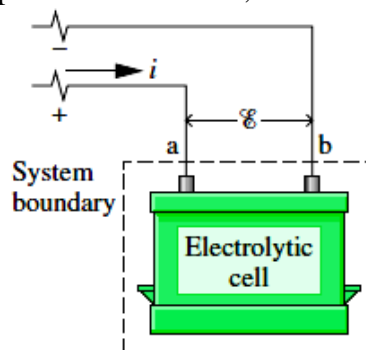


Figure 26: Electrolytic cell used to discuss electrical work

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 δQ . The amount of energy transfer by heat for a process is given by the integral

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

Self Assessment 1-2

A gas expands from an initial state where $p_1 = 500$ kPa and $V = 0.1$ m³ 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 done by the expanding gas, in kJ.

Answer Tip : 80.5 kJ

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

$$\sum_1^2 \delta Q + \sum_1^2 \delta W = \Delta E \quad (2.25)$$

The sum of all forms of energy of a system is the total energy. In the absence of magnetic, electrical and surface tension effects, the total energy of a system consists of the potential, kinetic and internal energies and is expressed as:

$$\text{Total energy} = PE + KE + U \quad (2.26)$$

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)

$$Q_{12} + W_{12} = \Delta U = U_2 - U_1 \quad (2.27)$$

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

Equation 2.27 may also be expressed in the differential form as

$$\delta Q + \delta W = dU \quad (2.28)$$

The thermal energy is actually the sensible and latent forms of internal energy and is referred to as heat in daily life.

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 2.28, 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 is, 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

$$\sum \delta Q + \sum \delta W = 0 \quad \text{or} \quad \oint \delta Q = - \oint \delta W \quad (2.29)$$

That is the cyclic sum of the heat transfers and the work transfers should be zero. We can deduce from Eq. 2.29 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 2.29 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

$$\Delta E_{cycle} = Q_{cycle} + W_{cycle} \quad (2.30)$$

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. 2.30 reduces to $Q_{cycle} = -W_{cycle}$ (as Eq. 2.29)

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

$$\eta = \frac{|W_{cycle}|}{Q_{in}} = \frac{-W_{cycle}}{Q_{in}} \quad (\text{Power cycle}) \quad (2.31a)$$

The negative sign 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

$$COP_{ref} = \frac{Q_{in}}{W_{cycle}} \quad (\text{Refrigeration cycle}) \quad (2.31b)$$

For a household refrigerator, Q_{out} is discharged to the 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:

$$COP_{hp} = -\frac{Q_{out}}{W_{cycle}} \quad (\text{heat pump}) \quad (2.31c)$$

2-2.2 Application of The 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:

$$\int_1^2 \delta Q = U_2 - U_1 - \int_1^2 \delta W \quad (2.32)$$

Or

$$\begin{aligned} \int_1^2 \delta q &= u_2 - u_1 + \int_1^2 p dv = u_2 - u_1 + p(v_2 - v_1) \\ &= (u_2 + p v_2) - (u_1 + p v_1) = h_2 - h_1 \end{aligned} \quad (2.33)$$

That is,

$$\boxed{Q_{12} = H_2 - H_1} \quad (2.34)$$

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

Hence,

$$\boxed{h = u + pv} \quad (2.35)$$

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 (u) of the system.

2-2.2.2 Polytropic process

The relation between pressure and volume is given by $p v^n = \text{constant}$, where n is the polytropic index. The expression for the work transfer can be expressed by any of the relations derived in 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 which is thermally insulated from its surroundings. Work is done at the expense of its internal energy. For such a process since $Q = 0$, and from the First Law,

$$\boxed{W_{12} = U_2 - U_1} \quad (2.36)$$

In adiabatic expansion, there is a 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

$$\delta q + \delta w = du \quad (2.37)$$

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

For a simple compressible substance, $du = c_v dT$ 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

$$Q_{12} = -W_{12} \quad (2.38)$$

Note that from the ideal gas equation of state, $PV = mRT$. For an ideal gas of fixed mass at constant temperature, $PV = \text{constant}$ since R is also constant for a particular gas.

2-2.2.5 Constant Volume Process

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

$$Q_{12} = U_2 - U_1 \quad (2.39)$$

If the heat addition process is reversible then we write the differential in the form for a constant volume process in the form $\delta Q = dU$

2-2.3 First Law of Thermodynamics for Open Systems

2-2.3.1 General Energy Equation

Figure 27 is the sketch of a typical open system. In practice an open system may have several inlets and outlets but it is usual to have one inlet and one outlet. It is also possible for the actual system boundaries to move but for most engineering applications the boundaries may be fixed. Considering an open system with fixed boundaries we pursue the analysis.

We consider the events that take place over a short time interval dt . At the beginning of the time interval (i.e. at the time t) the mass of the fluid in the open system is $m_{s,t}$ and a small mass of fluid dm_i is just about to enter the system. During this time interval, the small mass of fluid, dm_i , enters the system and another small mass of fluid dm_o , leaves the system such that the mass of fluid at the end of the interval is $m_{s,t+dt}$. During this time interval, small amounts of heat and work, δQ and δW , cross the system boundaries and the properties of the fluid inside the system may change such that the energy of the system also changes from $E_{s,t}$ to $E_{s,t+dt}$. Figure 27 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

$$\delta Q + \delta W = E_{x,t+dt} - E_{x,t} \quad (2.40)$$

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:

$$E_{x,t} = E_{s,t} + dm_i(u_i + \frac{1}{2}C_i^2 + g z_i) \quad (2.41)$$

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

$$E_{x,t+dt} = E_{s,t+dt} + dm_o(u_o + \frac{1}{2}C_o^2 + g z_o) \quad (2.42)$$

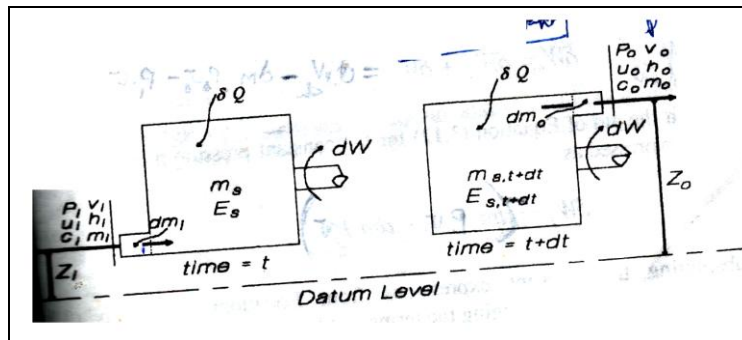


Figure 27: Diagram showing an imaginary closed system at the beginning and end of a differential change of state

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 2.40 is therefore given by

$$\delta W = \delta W_{sh} + \delta W_f = \delta W_{sh} - \delta m(p_o v_o - p_i v_i) \quad (2.43)$$

Substituting Eq. 2.41 – 2.43 into Eq. 2.40 yields

$$\delta Q + \delta W_{sh} = (E_{s,t+dt} - E_{s,t}) + dm_o(u_o + p_o v_o + \frac{1}{2}C_o^2 + g z_o) - dm_i(u_i + p_i v_i + \frac{1}{2}C_i^2 + g z_i) \quad (2.44)$$

Substituting for enthalpy and dividing by dt yields

$$\frac{\delta Q}{dt} + \frac{\delta W_{sh}}{dt} = \frac{(E_{s,t+dt} - E_{s,t})}{dt} + \frac{dm_o}{dt}(h_o + \frac{1}{2}C_o^2 + g z_o) - \frac{dm_i}{dt}(h_i + \frac{1}{2}C_i^2 + g z_i) \quad (2.45)$$

In the limit as dt approaches zero, Eq. 2.45 becomes

$$\dot{Q} + \dot{W}_{sh} = \frac{dE_s}{dt} + \sum_{outlets} \dot{m}_o(h_o + \frac{1}{2}C_o^2 + g z_o) - \sum_{inlets} \dot{m}_i(h_i + \frac{1}{2}C_i^2 + g z_i) \quad (2.46)$$

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 (2.46) is replaced by a more general work term \dot{W} . With this substitution, Eq. 2.46 becomes

$$\dot{Q} + \dot{W} = \frac{dE_s}{dt} + \sum_{outlets} \dot{m}_o(h_o + \frac{1}{2}C_o^2 + g z_o) - \sum_{inlets} \dot{m}_i(h_i + \frac{1}{2}C_i^2 + g z_i) \quad (2.47)$$

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 from the above assumptions, the SFEE becomes:

$$\dot{Q} + \dot{W} = \dot{m}(h_o - h_i) + \frac{1}{2}\dot{m}(C_o^2 - C_i^2) + \dot{m}g(z_o - z_i) \quad (2.48)$$

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

$$\dot{m} = \frac{AV}{v}$$

2-2.3.3 Engineering 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 28 shows a nozzle in which the cross-sectional area decreases in the direction of flow and a diffuser in which the walls of the flow passage diverge. For nozzles and diffusers, the only work is the flow work at locations where the mass enters and exits the control volume and so the term, W drops out of the energy rate equation for these devices. The change in the potential energy from the inlet to exit is negligible under most conditions. By combining these into a single expression and dropping the potential energy change from inlet to exit

$$\dot{Q}_{12} = \dot{m} (h_2 - h_1) + \dot{m} \frac{C_2^2 - C_1^2}{2} \quad (2.49)$$

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

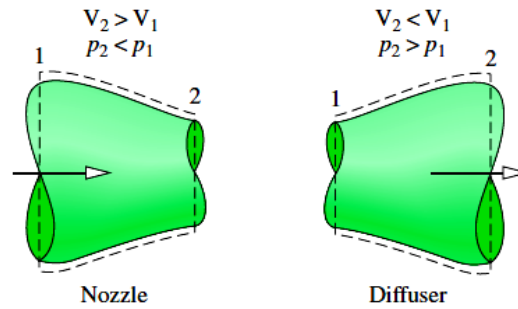


Figure 28: Illustration of a nozzle and a diffuser

Worked Example on nozzle

Fluid with a specific enthalpy of 2800 kJ/kg enters a horizontal nozzle with negligible velocity at the rate of 14 kg/s. At the outlet from the nozzle, the specific enthalpy and specific volume of the fluid are 2250 kJ/kg and 1.25 m³/kg, respectively. Assuming adiabatic flow, determine the exit velocity and the required outlet area of the nozzle.

Solution

For an adiabatic flow, equation 2.49 becomes

$$0 = \dot{m} \left[(h_2 - h_1) + \frac{C_2^2 - C_1^2}{2} \right]$$

since the inlet velocity C_1 is negligible, the equation is written as;

$$C_2 = \sqrt{2(h_1 - h_2)} = \sqrt{2(2800 - 2250) \times 10^3} = 1050 \text{ m/s}$$

Applying the equation of continuity at outlet gives

$$\dot{m} = \frac{A_2 C_2}{v_2} \Rightarrow A_2 = \frac{\dot{m} v_2}{C_2} = \frac{14 \times 1.25}{1050} = 0.01668 \text{ m}^2$$

Turbines, compressors, fans and pumps

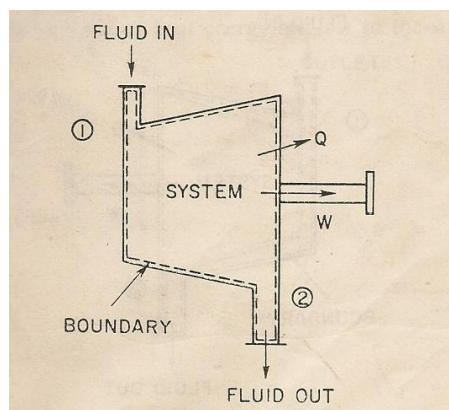
A turbine is a device in which work is developed as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate. In other words, a turbine is a device which uses a pressure drop to produce work energy which is used to drive an external load. Turbines are widely used 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. In other words, the action of a compressor, fan or pump is the reverse of that of a turbine, i.e. it uses external work energy to produce a pressure rise. A schematic of a turbine and a compressor are shown in Fig. 29.

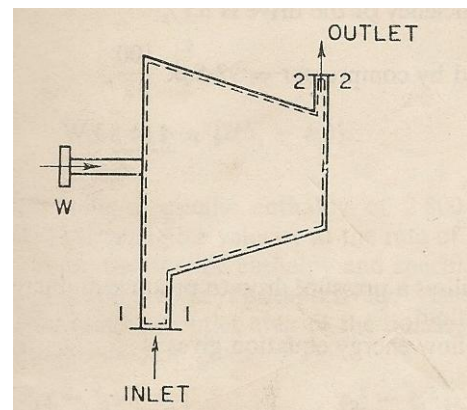
The processes that take place inside turbines, compressors, fans and pumps are usually assumed to be adiabatic and therefore $\dot{Q} = 0$. Secondly, kinetic and potential energy terms are assumed to be negligible compared to the other terms in the SFEE. The resulting equation for this class of thermodynamic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

$$\dot{W}_{12} = \dot{m} (h_2 - h_1) \quad (2.50)$$

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



(a) Turbine



(b) compressor

Figure 29: Schematic diagram of a turbine and compressor

Worked Example on a turbine

A fluid flows through a turbine at the rate of 45 kg/min. Across the turbine, the specific enthalpy drop of the fluid is 580 kJ/kg and the turbine loses 2100 kJ/min in the form of heat energy. Determine the power produced by the turbine, assuming that changes in the kinetic and potential energy may be neglected.

Solution

Steady flow energy equation gives;

$$\dot{Q} + \dot{W} = \dot{m} \left[(h_2 - h_1) + \frac{c_2^2 - c_1^2}{2} + g(z_2 - z_1) \right]$$

\dot{Q} is the heat energy per minute leaving the system = -2100 kJ/min

\dot{W} is the work energy per minute leaving system

\dot{m} is the fluid flow rate = 45 kg/min

Neglecting changes in kinetic and potential energies, the steady flow energy equation becomes

$$\dot{Q} + \dot{W} = \dot{m} (h_2 - h_1) \Rightarrow -2100 + \dot{W} = 45(-580)$$

$$\dot{W} = -26100 + 2100 = -24000 \text{ kJ/min} = -400 \text{ kW}$$

Mechanical Energy of a Flowing Fluid: Application to Wind Turbine

The mechanical energy of a flowing fluid is made up of the flow energy (PV), kinetic energy and potential energy. Flow energy per unit mass is expressed as P/ρ which is equivalent to P/ρ . Therefore, the mechanical energy of a flowing fluid can be expressed on a unit mass basis as:

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz \quad (2.51)$$

where P/ρ is the *flow energy*, $V^2/2$ is the *kinetic energy*, and gz is the *potential energy* of the fluid, all per unit mass. It can also be expressed in rate form as

$$\dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = \dot{m} \left(\frac{P}{\rho} + \frac{V^2}{2} + gz \right) \quad (2.52)$$

where \dot{m} is the mass flow rate of the fluid. Then the mechanical energy change of a fluid during incompressible ($\rho = \text{constant}$) flow becomes:

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \quad (\text{kJ/kg}) \quad (2.53)$$

and

$$\dot{\Delta E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m} \left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right) \quad (\text{kW}) \quad (2.54)$$

Therefore, the mechanical energy of a fluid does not change during flow if its pressure, density, velocity, and elevation remain constant. In the absence of any losses, the mechanical energy change represents the mechanical work supplied to the fluid (if $\Delta e_{\text{mech}} > 0$) or extracted from the fluid (if $\Delta e_{\text{mech}} < 0$)

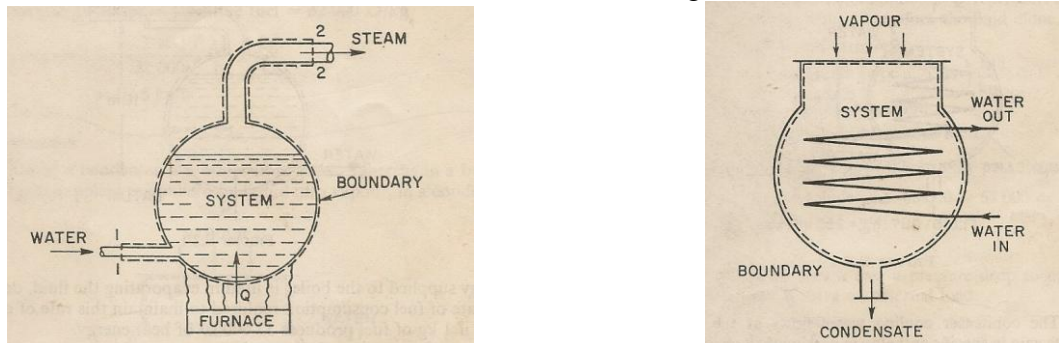
Tip speed

For a fan (or wind turbine) having a diameter D (in metres) and running at a speed of N rev/s, the tip speed of the blade in m/s is given by

$$V_{\text{tip}} = \pi DN \quad (2.55)$$

Boilers and Condensers

In a boiler operating under steady conditions, water will be pumped into the boiler along the feed line at the same rate as the steam leaves the boiler along the steam main, and heat energy will be supplied from the furnace at a steady rate. Whereas in a boiler, heat energy is supplied to convert the liquid into vapour, in a condenser heat energy is removed in order to condense the vapour into a liquid. If the condenser is in a steady state, then the amount of liquid, usually called condensate, leaving the condenser must be equal to the amount of vapour entering the condenser. A schematic of a boiler and a condenser are shown in Fig. 30.



(a) Boiler

(b) condenser

Figure 30: Schematic diagram of a boiler and condenser

In applying the steady flow energy equation to the boiler or condenser, the following points must be noted:

- \dot{Q} is be the amount of heat energy transferred to the fluid per second in the case of a boiler or the amount of heat energy transferred from the fluid per second in the case of a condenser.
- \dot{W} will be zero, since a boiler or condenser has no moving parts capable of effecting a work transfer.
- $\frac{c_2^2 - c_1^2}{2}$ is small compared with other terms and may usually be neglected.
- \dot{m} will be the rate of flow of the fluid

Hence the equation reduces to

$$\dot{Q} = \dot{m}(h_2 - h_1) \quad (2.56)$$

Worked Example on a boiler

A boiler operates at a constant pressure of 15 bar, and evaporates fluid at a rate of 1000 kg/h. At entry to the boiler, the fluid has a specific enthalpy of 165 kJ/kg and on leaving the boiler, the specific enthalpy of the fluid is 2200 kJ/kg. The outlet pipe from the boiler is at a height of 16 m above the inlet pipe, and the inlet and outlet velocities of the fluid are 13 m/s and 33 m/s, respectively. If 65% of heat energy supplied to the boiler is used in evaporating the fluid, determine the rate of fuel consumption required to maintain this rate of evaporation, if 1 kg of fuel produces 32000 kJ of heat energy.

Solution

$$\dot{Q} + \dot{W} = \dot{m} \left[(h_2 - h_1) + \frac{c_2^2 - c_1^2}{2} + g(z_2 - z_1) \right]$$

\dot{Q} is the heat energy per second entering system

\dot{W} is the work energy per second leaving system = 0

\dot{m} is the fluid flow rate = 1000 kg/h = 0.278 kg/s

$h_2 = 2200$ kJ/kg $h_1 = 165$ kJ/kg, $c_2 = 33$ m/s, $c_1 = 13$ m/s, $(z_2 - z_1) = 16$ m, $g = 9.807$ m/s²

Steady flow energy equation becomes

$$\dot{Q} + 0 = \frac{1000}{3600} \left[(2200 - 165) + \left(\frac{33^2 - 13^2}{2} \right) \times 10^{-3} + 9.81(16) \times 10^{-3} \right]$$

$$\dot{Q} = 0.278(2035 + 0.46 + 0.157) = 566 \text{ kW}$$

Alternatively,

The terms representing the changes in kinetic and potential energy are small compared with the change in enthalpy and may be neglected.

$$\dot{Q} = \frac{1000}{3600} [(2200 - 165)] = 565.3 \text{ kW}$$

$$\text{Heat energy required per second from fuel, } \dot{Q}_{\text{fuel}} = \frac{\dot{Q}}{\eta_c} = \frac{566}{0.65} = 871 \text{ kW}$$

Heat energy obtained from the fuel, $Q_{\text{fuel}} = 32000$ kJ/kg

$$\text{Fuel required, } \dot{m}_{\text{fuel}} = \frac{\dot{Q}_{\text{fuel}}}{Q_{\text{fuel}}} = \frac{871}{32000} \frac{\text{kJ}}{\text{s}} \times \frac{\text{kg}}{\text{kJ}} = 0.02722 \text{ kg/s} = 98 \text{ kg/h}$$

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

$$h_2 = h_1 \quad (2.57)$$

That means a throttling process is an isenthalpic process. Throttling valves are used extensively to reduce the pressure of refrigerant flowing through the valve. In the mechanical vapour-compression refrigerator, a valve is used to reduce the pressure of the refrigerant from the higher pressure at the exit of the condenser to the lower pressure existing in the evaporator. Schematic representations of throttling devices are illustrated in Figure 31.

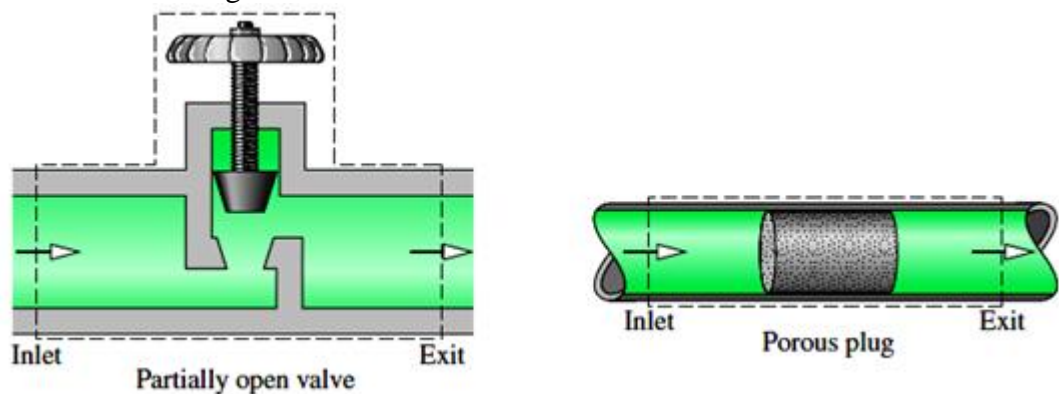


Figure 31: Throttling devices

Worked Example on throttling device

A fluid flowing along a pipe line undergoes a throttling process from 10 bar to 1 bar in passing through a partially open valve. Before throttling, the specific volume of the fluid is $0.3 \text{ m}^3/\text{kg}$ and after throttling, it is $1.8 \text{ m}^3/\text{kg}$. Determine the change in specific internal energy during the throttling process.

Solution

For a throttling process, the steady flow energy equation becomes,

$$h_2 = h_1 \quad \text{but} \quad h_1 = u_1 + p_1 v_1 \quad \text{and} \quad h_2 = u_2 + p_2 v_2$$

$$\text{Hence} \quad u_2 + p_2 v_2 = u_1 + p_1 v_1 \Rightarrow u_2 - u_1 = p_1 v_1 - p_2 v_2$$

$$\Delta u = (1000 \times 0.3) - (100 \times 1.8) = 300 - 180 = 120 \text{ kJ/kg}$$

2-2.4 Thermodynamic Aspects of Biological Systems

Some complex and fascinating energy transfer and energy transformation processes have been observed to occur in biological systems. Such systems are however quite difficult to analyse since they are not in thermodynamic equilibrium. Four main elements constitute biological systems: hydrogen, oxygen, carbon and nitrogen. The percentage of these elements in the human body for instance are 63 % hydrogen, 25.5 % oxygen, 9.5 % carbon, and 1.4 % nitrogen. The remaining 0.6 % comes from 20 other elements essential for life. The human body is made up of 72 % of water by mass.

A biological system could be composed of a single cell or several cells. Chemical reactions occur in cells during which some molecules are broken down resulting in

the release of energy and the formation of new molecules. Chemical activity within the cells of the human body maintains the body at a temperature of 37 °C. This is referred to as metabolism. The rate of metabolism in the resting state is called the *basal metabolic rate*, which is the rate of metabolism required to keep a body performing the necessary functions e.g. breathing and blood circulation at zero external activity level. The basal metabolic rate varies with sex, body size, general health conditions, etc. and decreases significantly with age. For an average male (30 years, 70 kg, 1.8-m² body surface area), the basal metabolic rate is 84 W. This implies that the body dissipates energy to the environment at a rate of 84 W; which can also be translated as the body converting chemical energy of the food (or of the body fat if the person has not eaten) into thermal energy at a rate of 84 W.

Metabolic rate increases with the level of activity. The fraction of sensible heat varies from about 40 % in the case of heavy work to about 70 % in the case of light work. The rest of the energy is rejected from the body by perspiration in the form of latent heat. The brain and the liver are responsible for almost 50 % of the basal metabolic rate of an adult human although they make up only about 4 % of the body mass.

Biological reactions in cells occur essentially at constant temperature, pressure and volume. Any heat generated as a result of the reactions is transferred to the circulatory system and then to other parts of the body and ultimately to the environment through the skin. Muscle cells function very much like engines, converting the chemical energy into mechanical energy (work) with a conversion efficiency of about 20 percent. The work is converted to heat and transferred to the environment when no activity is being performed by the body.

Food and Exercise

Food provides a means of meeting the energy requirements of the body. Food nutrients are considered in three major groups: carbohydrates, proteins, and fats. The energy content of a given food is determined by burning a small sample of the food in a device called a bomb calorimeter, which is essentially a well-insulated rigid tank. (Fig. 32). The tank contains a small combustion chamber surrounded by water. The food is ignited and burned in the combustion chamber in the presence of excess oxygen, and the energy released is transferred to the surrounding water.

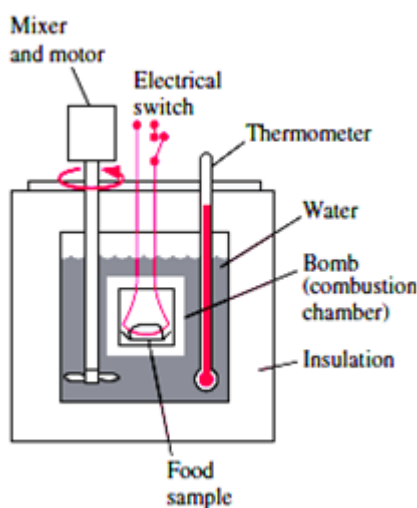


Figure 32: Bomb Colorimeter

The energy content of the food is calculated on the basis of the conservation of energy principle by measuring the temperature rise of the water. The carbon in the

food burns to CO_2 and the hydrogen is converted to H_2O . The same chemical reactions occur in the body, and thus the same amount of energy is released.

Using dry samples, the average energy contents of the three basic food groups are determined by bomb calorimeter measurements to be 18.0 MJ/kg for carbohydrates, 22.2 MJ/kg for proteins, and 39.8 MJ/kg for fats. The fraction of metabolizable energy contents are 95.5 percent for carbohydrates, 77.5 percent for proteins, and 97.7 percent for fats. This corresponds to 4.1 Calories/g for proteins and carbohydrates and 9.3 Calories/g for fats commonly seen in nutrition books and on food labels. The energy contents of the food that we normally eat are much lower than the values above because of the large water content. Water adds bulk to the food but cannot be metabolized or burned, and thus it has no energy value. The average metabolizable energy contents of the three basic food groups are 4.2 MJ/kg for carbohydrates, 8.4 MJ/kg for proteins, and 33.1 MJ/kg for fats. From the quoted values it can be observed that 1 kg of natural fat contains almost 8 times the metabolizable energy of 1 kg of natural carbohydrates. Thus, a person who fills his stomach with fatty foods is consuming much more energy than a person who fills his stomach with carbohydrates such as bread or rice.

The metabolizable energy content of foods is usually expressed by nutritionists in terms of the capitalized *Calories*.

$$1 \text{ Cal (Calorie)} = 1000 \text{ calories} = 1 \text{ kcal (kilocalorie)} = 4.1868 \text{ kJ}$$

When the topic is food or fitness, a calorie normally means a kilocalorie whether it is capitalised or not.

The daily calorie needs of people vary greatly with age, gender, the state of health, the activity level, the body weight, and the composition of the body as well as other factors. A small person needs fewer calories than a large person of the same sex and age. An average man needs about 2400 to 2700 Calories a day. The daily need of an average woman varies from 1800 to 2200 Calories. The daily calorie needs are about 1600 for sedentary women and some older adults; 2000 for sedentary men and older adults; 2200 for most children, teenage girls, and active women; 2800 for teenage boys, active men, and some very active women; and above 3000 for very active men. The average value of calorie intake is usually taken to be 2000 Calories per day. The daily calorie needs of a person can be determined by multiplying the body weight in pounds (which is 2.205 times the body weight in kg) by 11 for a sedentary person, 13 for a moderately active person, 15 for a moderate exercise or physical labourer, and 18 for an extremely active exerciser or physical labourer. The extra calories a body consumes are usually stored as fat, which serves as the back-up energy of the body for use when the energy intake of the body is less than the needed amount.

Human body fat contains 33.1 MJ of metabolizable energy just like other natural fat. Therefore, a starving person (zero energy intake) who uses up 2200 Calories (9211 kJ) a day can meet his daily energy intake requirements by burning only $9211/33,100 = 0.28$ kg of body fat. It is therefore no surprise that people are known to survive over 100 days without eating. They still need to drink water, however, to replenish the water lost through the lungs and the skin to avoid the dehydration that may occur in just a few days. Although the desire to get rid of the excess fat in a thin world may be overwhelming at times, starvation diets are not recommended because the body soon starts to consume its own muscle tissue in addition to fat. A healthy diet should involve regular exercise while allowing a reasonable amount of calorie intake.

Table 4: Approximate metabolizable energy content of some common foods

Approximate metabolizable energy content of some common foods

(1 Calorie = 4.1868 kJ =

3.968 Btu)

Food	Calories	Food	Calories	Food	Calories
Apple (one, medium)	70	Fish sandwich	450	Milk (skim, 200 ml)	76
Baked potato (plain)	250	French fries (regular)	250	Milk (whole, 200 ml)	136
Baked potato with cheese	550	Hamburger	275	Peach (one, medium)	65
Bread (white, one slice)	70	Hot dog	300	Pie (one $\frac{1}{8}$ slice, 23 cm diameter)	300
Butter (one teaspoon)	35	Ice cream (100 ml, 10% fat)	110	Pizza (large, cheese, one $\frac{1}{8}$ slice)	350
Cheeseburger	325	Lettuce salad with French dressing	150		
Chocolate candy bar (20 g)	105				
Cola (200 ml)	87				
Egg (one)	80				

The average metabolizable energy contents of various foods and the energy consumption during various activities are given in Tables 4 and 5.

Note that you may find different values in other books and magazines for the same items.

Table 5 relates to a 68-kg adult but the energy consumed for smaller or larger adults can be determined using the proportionality of the metabolism rate and the body size. For example, the rate of energy consumption by a 68-kg bicyclist is listed in Table 5 to be 639 Calories/h. The rate of energy consumption by a 50-kg bicyclist is

$$(50 \text{ kg}) \frac{639 \text{ Cal/h}}{68 \text{ kg}} = 470 \text{ Cal/h}$$

For a 100-kg person, it would be 940 Cal/h.

Table 5: Approximate energy consumption of a 68-kg adult during some activities

The thermodynamic analysis of the human body is rather complicated since it involves mass transfer (during breathing, perspiring etc.) as well as energy transfer. As such, it should be treated as an open system. However, the energy transfer by mass is difficult to quantify. Therefore, the human body is often modelled as a closed system for simplicity by treating energy transported with mass as just energy transfer.

For example, eating is modelled as the transfer of energy into the human body in the amount of the metabolizable energy content of the food.

Approximate energy consumption of a 68-kg adult during some activities
(1 Calorie = 4.1868 kJ = 3.968 Btu)

Activity	Calories/h
Basal metabolism	72
Basketball	550
Bicycling (21 km/h)	639
Cross-country skiing (13 km/h)	936
Driving a car	180
Eating	99
Fast dancing	600
Fast running (13 km/h)	936
Jogging (8 km/h)	540
Swimming (fast)	860
Swimming (slow)	288
Tennis (advanced)	480
Tennis (beginner)	288
Walking (7.2 km/h)	432
Watching TV	72

Dieting

Most diets are based on *calorie counting*; that is, the conservation of energy principle: a person who consumes more calories than his or her body burns will gain weight whereas a person who consumes less calories than his or her body burns will lose weight. Yet, people who eat whatever they want whenever they want without gaining any weight are living proof that the calorie counting technique alone does not work in dieting. Obviously there is more to dieting than keeping track of calories.

It should be noted that the phrases *weight gain* and *weight loss* are misnomers. The correct phrases should be *mass gain* and *mass loss*. A man who goes to space loses practically all of his weight but none of his mass. When the topic is food and fitness, *weight* is understood to mean *mass*, and weight is expressed in mass units.

Several theories on dieting have been proposed by researchers. One theory suggests that some people have “food efficient” bodies. These people need fewer calories than other people do for the same activity, just like a fuel-efficient car needing less fuel for travelling a given distance. One thing that frustrates dieters is that the body interprets dieting as *starvation* and starts using the energy reserves of the body more stringently. Shifting from a normal 2000-Calorie daily diet to an 800-Calorie diet without exercise is observed to lower the basal metabolic rate by 10 to 20 percent. Although the metabolic rate returns to normal once dieting stops, extended periods of low-calorie dieting without adequate exercise may result in the loss of considerable muscle tissue together with fat. With less muscle tissue to burn calories, the metabolic rate of the body declines and stays below normal even after a person starts eating normally. As a result, the person regains the weight he or she has lost in the form of fat, plus more. The basal metabolic rate remains about the same in people who exercise while dieting.

Regular moderate exercise is part of any healthy dieting program for good reason: it builds or preserves muscle tissue that burns calories much faster than the fat tissue does. It is interesting that aerobic exercise continues burning calories for several hours after the workout, raising the overall metabolic rate considerably.

Another theory suggests that people with too many fat cells developed during childhood or adolescence are much more likely to gain weight. Others put the blame for weight problems simply on the genes.

Table 6: The range of healthy weight for adults of various heights

The range of healthy weight for adults is usually expressed in terms of the **body mass index (BMI)**, defined, in SI units, as

$$\text{BMI} = \frac{W \text{ (kg)}}{H^2 \text{ (m}^2\text{)}} \quad \text{with} \quad \begin{array}{ll} \text{BMI} < 19 & \text{under weight} \\ 19 \leq \text{BMI} \leq 25 & \text{healthy weight} \\ \text{BMI} > 25 & \text{over weight} \end{array}$$

The range of healthy weight for adults of various heights (Source: National Institute of Health)			
English Units		SI Units	
Height, in.	Healthy weight, lbm*	Height, m	Healthy weight, kg*
58	91–119	1.45	40–53
60	97–127	1.50	43–56
62	103–136	1.55	46–60
64	111–146	1.60	49–64
66	118–156	1.65	52–68
68	125–165	1.70	55–72
70	133–175	1.75	58–77
72	140–185	1.80	62–81
74	148–195	1.85	65–86
76	156–205	1.90	69–90

*The upper and lower limits of healthy range correspond to mass body indexes of 19 and 25, respectively.

Where W is the weight (actually, the mass) of the person in kg and H is the height in m. Therefore, a BMI of 25 is the upper limit for the healthy weight and a person with a BMI of 27 is 8 percent overweight. It can be shown that the formula above is equivalent in English units to $\text{BMI} = 705 W/H^2$ where W is in pounds and H is in inches. The proper range of weight for adults of various heights is given in Table 6 in both SI and English units.

Example 2.1 Burning Off Lunch Calories

A 90-kg man had two hamburgers, a regular serving of French fries, and a 200-ml Coke for lunch. Determine how long it will take for him to burn the lunch calories off (a) by watching TV and (b) by fast swimming. What would your answers be for a 45-kg man?

Solution A man had lunch at a restaurant. The times it will take for him to burn the lunch calories by watching TV and by fast swimming are to be determined.

Assumptions The values in Tables 4 and 5 are applicable for food and exercise.

Analysis (a) We take the human body as our system and treat it as a closed system whose energy content remains unchanged during the process. Then the conservation of energy principle requires that the energy input into the body must be equal to the energy output. The net energy input in this case is the metabolizable energy content of the food eaten. It is determined from Table 4 to be

$$E_{\text{in}} = 2 \times E_{\text{hamburger}} + E_{\text{fries}} + E_{\text{cola}} = (2 \times 275) + 250 + 87 = 887 \text{ Cal}$$

The rate of energy output for a 68-kg man watching TV is given in Table 5 to be 72 Calories/h. For a 90-kg man it becomes:

$$E_{\text{out}} = (90 \text{ kg}) \frac{72 \text{ Cal/h}}{68 \text{ kg}} = 95.3 \text{ Cal/h}$$

$$\Delta t = \frac{887 \text{ Cal}}{95.3 \text{ Cal/h}} = 9.3 \text{ h}$$

Therefore, it will take 9.3 h to burn the lunch calories off by watching TV.

(b) It can be shown in a similar manner that it takes only **47 min** to burn the lunch calories off by fast swimming.

Discussion The 45-kg man is half as large as the 90-kg man. Therefore, expending the same amount of energy takes twice as long in each case: **18.6 h** by watching TV and **94 min** by fast swimming.

Example 2.2 Losing Weight by Switching to Fat-Free Chips

The fake fat olestra passes through the body undigested, and thus adds zero calorie to the diet. Although foods cooked with olestra taste pretty good, they may cause abdominal discomfort and the long-term effects are unknown. A 1-oz (28.3-g) serving of regular potato chips has 10 g of fat and 150 Calories, whereas 1 oz of the so-called fat-free chips fried in olestra has only 75 Calories. Consider a person who eats 1 oz of regular potato chips everyday at lunch without gaining weight or losing any weight. Determine how much weight this person will lose in one year if he or she switches to fat-free chips.

Solution A person switches from regular potato chips to fat-free ones. The weight the person loses in one year is to be determined.

Assumptions Exercising and other eating habits remain the same.

Analysis The person who switches to the fat-free chips consumes 75 fewer Calories a day. Then the annual reduction in calories consumed becomes:

$$E_{\text{reduced}} = (75 \text{ Cal/day})(365 \text{ day/year}) = 27,375 \text{ Cal/year}$$

The metabolizable energy content of 1 kg of body fat is 33,100 kJ. Therefore, assuming the deficit in the calorie intake is made up by burning body fat, the person who switches to fat-free chips will lose

$$m_{\text{fat}} = \frac{E_{\text{reduced}}}{\text{Energy content of fat}} = \frac{27,375 \text{ Cal}}{33,100 \text{ kJ/kg}} \left(\frac{4.1868 \text{ kJ}}{1 \text{ Cal}} \right) = 3.46 \text{ kg}$$

(about 7.6 pounds) of body fat that year.

SECOND LAW OF THERMODYNAMICS

Introduction

In the presentation of the contents of this unit, the description of 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.

Learning Objectives

After studying this unit you, should be able to:

1. State and explain the usefulness of the second law,
2. Explain how processes occur in a certain direction and that energy has quality as well as quantity.
3. Describe thermal reservoirs, reversible and irreversible processes, heat engines, refrigerators and heat pumps
4. Describe and appreciate the relevance of the Kelvin- Planck and the Clausius statements of the second law of thermodynamics
5. Apply the second law of thermodynamics to cyclic processes
6. Determine expressions for the thermal efficiencies of and coefficient of performance of reversible heat engines, heat pumps, and refrigerators

SESSION 1-3: DEFINITION AND DESCRIPTION OF 2ND LAW OF THERMODYNAMICS

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.

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. 33.

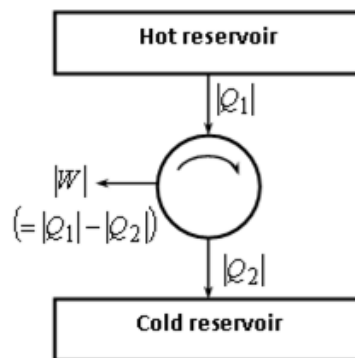


Figure 33: Schematic representation of a heat engine

Heat engines differ considerably from one another, but all can be characterised by the following: (Fig. 34)

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.

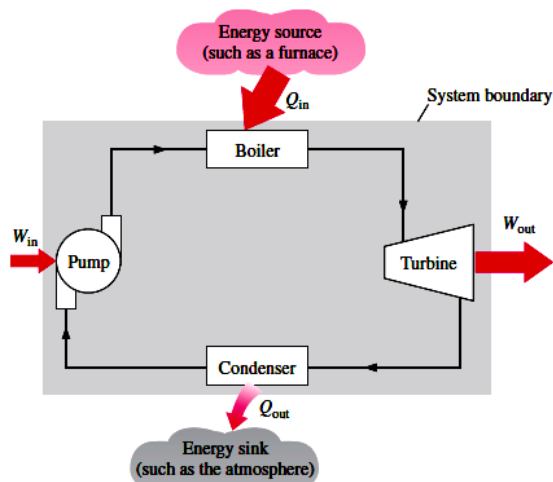


Figure 34: Schematic of a steam power plant

From the First Law of thermodynamics,

$$Q_{\text{net}} + W_{\text{net}} = 0 \Rightarrow Q_{\text{in}} + Q_{\text{out}} + W_{\text{in}} + W_{\text{out}} = 0$$

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 η_{th} .

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

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

For a 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

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

The quantities $|Q_{\text{in}}|$ and $|Q_{\text{out}}|$ 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, $|W_{\text{net,out}}| < |Q_{\text{in}}|$, then it follows from equation (3.1) that $|Q_{\text{out}}|$ 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 of the quantities of net heat and net work are equal, thus $|Q_{\text{net}}| = |W_{\text{net}}|$. 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. 35.

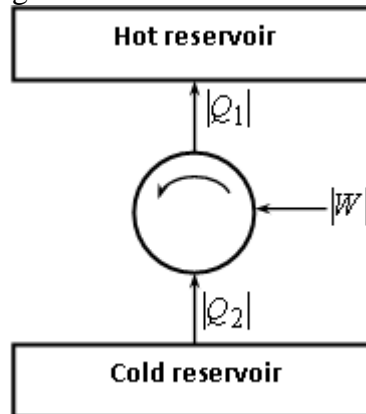


Figure 35: Heat Pump or refrigerator

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

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

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. If the refrigerator is energy efficient, less W_{cycle} is used to produce the desired cooling load, Q_L .

For a heat pump, the coefficient of performance is

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

Note: The fictitious negative sign in equation (3.3) is introduced to make the COP value positive

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

$$\boxed{COP_{HP} = COP_R + 1} \quad (3.4)$$

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. 35. 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.

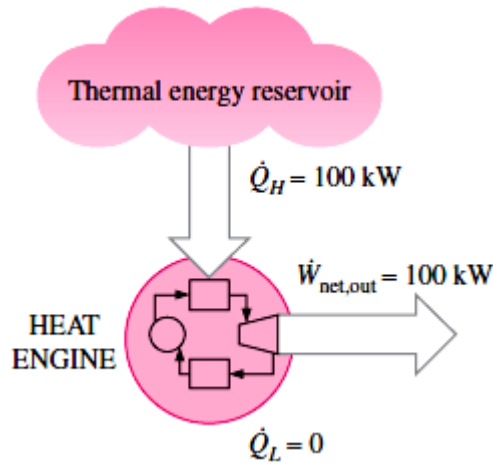


Figure 36: A heat engine that violates Kelvin-Planck statement

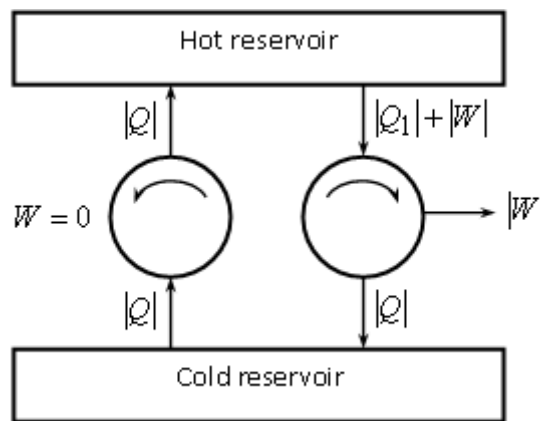


Figure 37: Can a heat pump operate without a work input?

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 η_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 η_R is the efficiency of a reversible engine R operating between the same two reservoirs. See Fig. 38 (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. 38 (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.

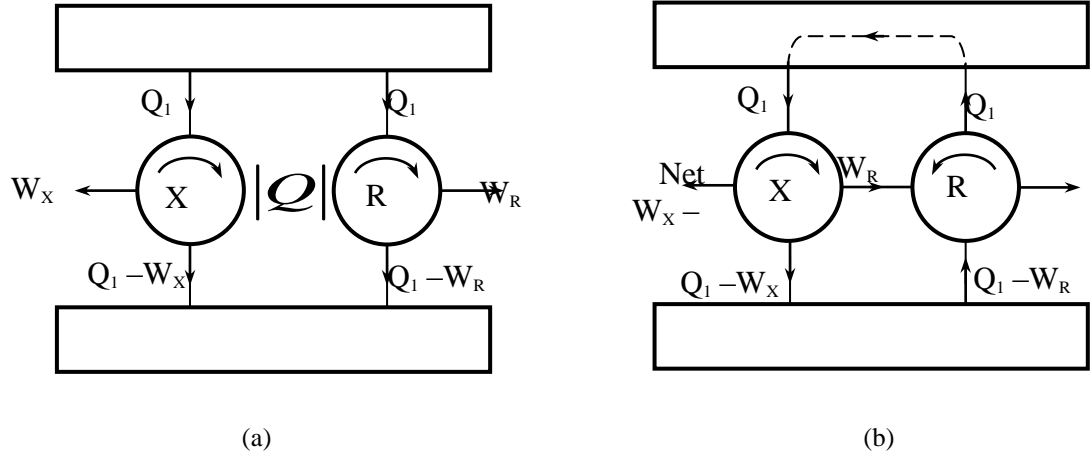


Figure 38: Can an engine have a higher efficiency than its reversible equivalent?

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

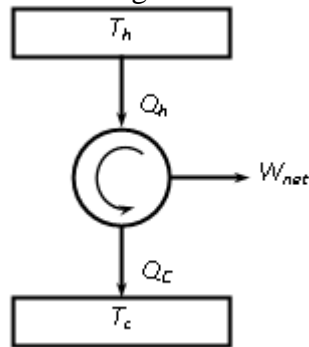
Once the second corollary is proved there is no need for the proof of the third. The Corollaries 2 and 3 are referred to as the Carnot Principles.

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 39 and Equation 3.1, the efficiency of a heat engine is given as



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

Figure 39: 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 $T_h = 0$ then $Q_h = 0$. 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

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

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_h and T_c is given by $(T_h - T_c)/T_h$ or $(1 - T_c/T_h)$.

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 irreversibility 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 kJ of energy as heat from a hot medium to a cold one. At the end of the process, we still have the 10 kJ of energy, but at lower temperature and thus at a lower quality.
3. It is possible to increase entropy but is not possible to destroy it.
4. Heat transfer, irreversibilities and entropy transport with mass cause entropy of a control volume to change.
5. There is no entropy transfer associated with energy transfer as work.

Self Assessment 1-3

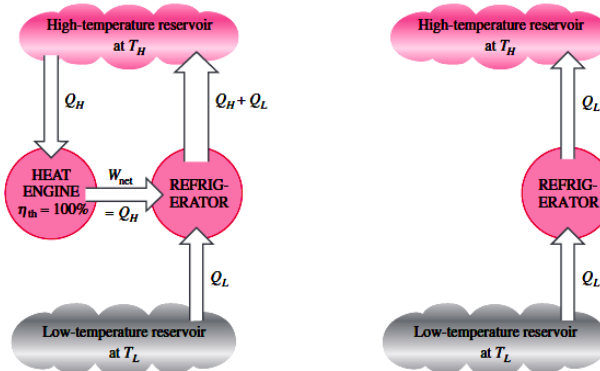
- 1 An inventor claims to have developed a car that runs on water instead of gasoline. What is your response to this claim?
- 2 Describe an imaginary process that satisfies the first law but violates the second law of thermodynamics.
- 3 Describe an imaginary process that satisfies the second law but violates the first law.

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. 40 (a) operating between the same two reservoirs. The heat engine is assumed to have, in violation to the Kelvin-Planck statement an efficiency of 100%, 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 a 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. 40 (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.



(a) Refrigerator powered by 100% efficient heat engine

(b) An equivalent refrigerator

Figure 40: 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. 41 (a) and Fig. 41 (b), respectively.

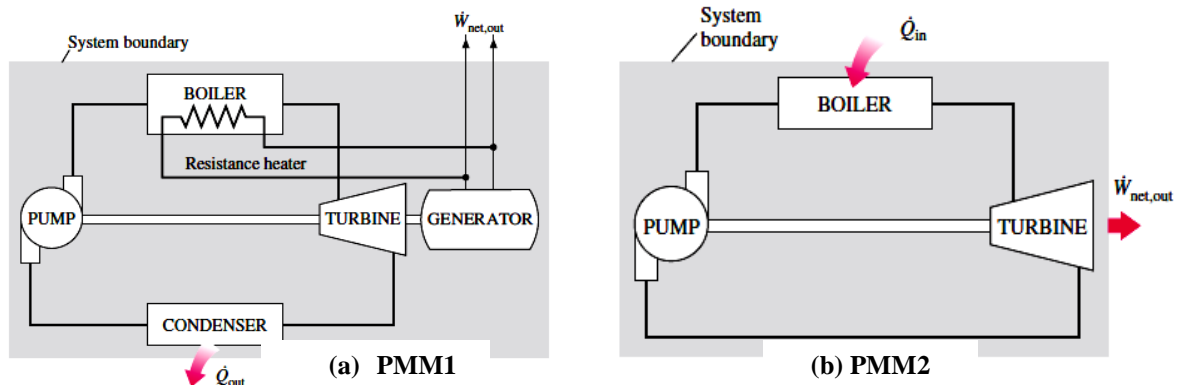


Figure 41: Schematic representation of Perpetual Motion Machines

2-3.3 The Quality of Energy

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

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

Self Assessment 2-3

- Helium in a non-flow device undergoes the reversible process shown in Fig. Q.1. Determine the heat transfer (kJ/kg) and work (kJ/kg) for each process.

Assume:

$$\gamma_{\text{He}} = 1.667, R_{\text{He}} = 2.0771 \text{ kJ/kg K}, C_V = R_{\text{He}}/(\gamma - 1), 0^\circ\text{C} = 273 \text{ K}$$

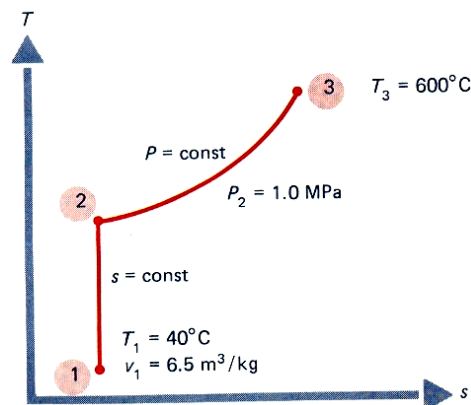


Fig. Q. 1

- An inventor claims she has a steam engine that operates between the temperature extremes of 700 and 10 °C and produces 200 kJ of work while rejecting a heat transfer of 100 kJ. Is her heat engine possible?

Suggested answers

$$1. |W_{12}| = 1474.30 \text{ kJ/kg}, |Q_{12}| = 0, |W_{23}| = 179 \text{ kJ/kg}, |Q_{23}| = 448.55 \text{ kJ/kg}$$

2. [Possible]

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.

Learning Objectives

After studying this unit you should be able to:

1. Illustrate the thermodynamic state of pure substances on p-v, and T-v, property diagrams and p-v- T surfaces of pure substances
2. Demonstrate the procedures for determining the thermodynamic properties of pure substances from tables of property data
3. Specify the phase description of pure substance given specified properties corresponding to the intended state
4. Apply the ideal gas equation in the solution of typical problems
5. Analyse vapour power cycles in which the working fluid is alternately vaporized and condensed
6. Construct simple property tables and energy tables for typical vapor power cycles and use them in analyzing these cycles
7. Compute performance indicators of Carnot cycle and , basic Rankine cycle
8. Investigate ways to modify the basic Rankine vapour power cycle to increase the cycle thermal efficiency and the overall cycle efficiency

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 42 and 43 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.

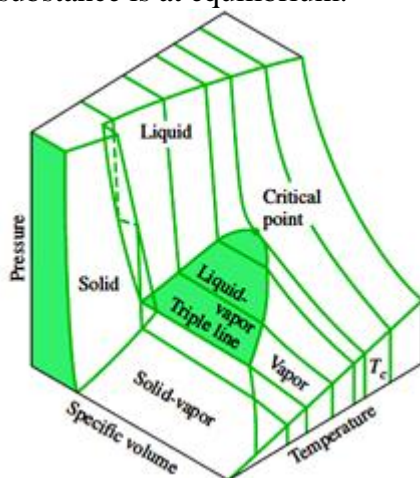


Figure 42: p - v - T surface of a substance that expands on freezing

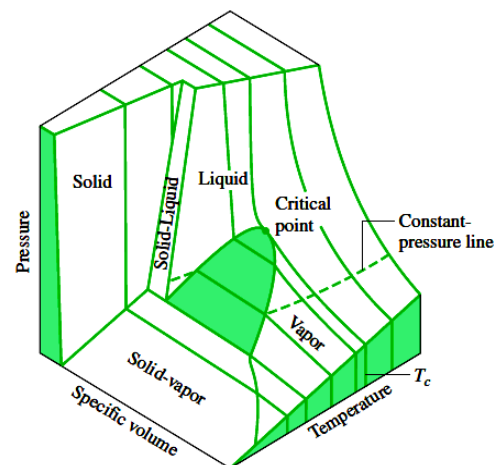


Figure 43: p - v - T surface of a substance that contracts on freezing

There are regions on the p - v - T surfaces of Figs. 42 and 43 labeled *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. 44. 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.

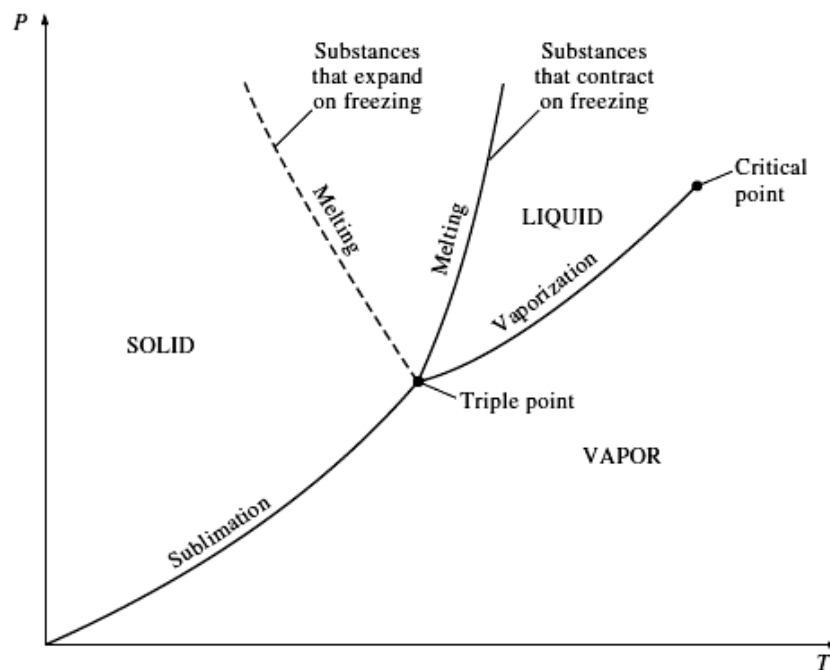


Figure 44: p - T diagram of a pure substance diagram

***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. 45 and 46.

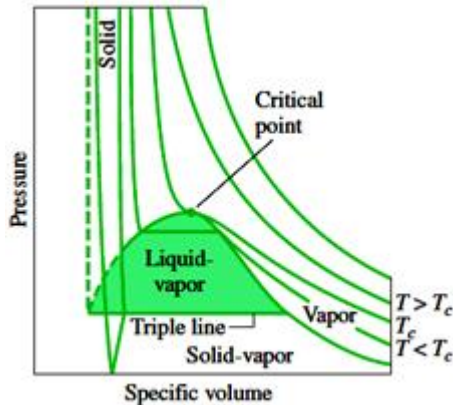


Figure 45: $p-v$ diagram for a substance that expands on freezing

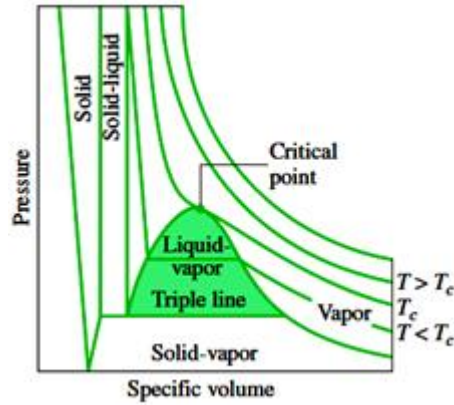


Figure 46: $p-v$ diagram for a substance that contracts on freezing

Notes: It can be noted from Figs. 45 and 46 ($p-v$ diagrams) that:

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

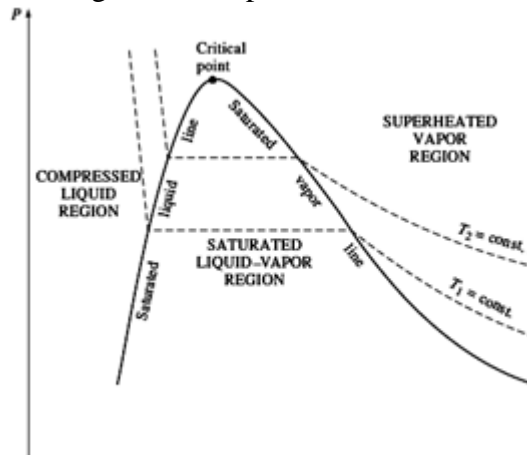
Notice the $p-v$ diagram for water shown in Fig. 47(b)

***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 Fig. 47(a). Since consistent patterns are revealed in the $p-v-T$ behaviour of all substances, Fig. 47(a) showing a $T-v$ diagram for water can be regarded as representative.



(a) $T-v$ diagram for a pure substance



(b) $p-v$ diagram for a pure substance

Figure 47: $T-v$ and $p-v$ diagrams for a pure substance

NOTES: It can be noted from Fig. 47(a) 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 energy absorbed or released during a phase is called **latent heat**. The amount of energy released during vaporization is called the enthalpy of vaporization, which is equivalent to energy released during 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 of the mixture is the sum of the volume of the saturated liquid and the saturated vapour. That is:

$$V = V_f + V_g$$

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

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

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

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

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

Note from equation 4.3 that if $v_f \approx 0$, then $x \approx \frac{v}{v_g}$

Self Assessment 1-4

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-known 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?

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, 4th Edition*).

Saturation Tables: The Saturation Tables, list property values for the saturated liquid and vapour states. The property values at these states are denoted by the subscripts f and g, respectively. Tables in the Steam Tables as listed on 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 through 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 pressures 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

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

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.

Worked examples on unit 4 session 2

Example 4.1

Steam at 0.05 bar, 100 °C is to be condensed completely by a reversible constant pressure process. Calculate the heat rejected per kg of steam, and the change of entropy. Sketch the process on a T - s diagram with respect to saturation lines and shade in the area that represents the heat flow. Determine also the average constant temperature at which heat is rejected.

Solution:

For $P = 0.05$ bar, $T_{\text{sat}} = 32.9$ °C

But $T_1 > T_{\text{sat}@0.05 \text{ bar}} \rightarrow$ State 1 is superheated

At state 2 $T = T_{\text{sat}}$ and the system in saturated water.

From tables, $h_1 = 2688$ kJ/kg; $s_1 = 8.768$ kJ/kgK;

After condensation, state 2,

$h_2 = 138$ kJ/kg; $s_2 = 0.476$ kJ/kgK;

Since process 1-2 is at constant pressure

$q_{12} = h_2 - h_1 = (138 - 2688)$ kJ/kg = - 2550 kJ/kg

Heat rejected is therefore 2550 kJ/kg

Change in specific entropy (ds)

= $s_2 - s_1 = (0.476 - 8.768)$ kJ/kgK

= - 8.292 kJ/kgK

Decrease in specific entropy is therefore 8.292

kJ/kgK

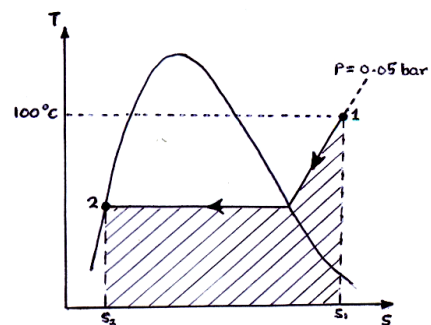


Fig. Ex. 4.1 T - s diagram of problem 4.1

Note that $q_{12} = T_{\text{av}} ds$ where T_{av} is the average constant temperature at which heat is rejected

$$T_{\text{av}} = \frac{q_{12}}{ds} = \frac{2550 \text{ kJ/kg}}{8.292 \text{ kJ/kgK}} = 307.5 \text{ K (34.5 °C)}$$

Example 4.2

0.05 kg of steam at 10 bar, dryness fraction 0.84 is heated reversibly in a rigid vessel until the pressure is 20 bar. Calculate the change in total entropy, the heat supplied and the average temperature at which heat is added. Show the area which represents the heat supplied on a T - s diagram.

Solution:

Analysis: Process is a constant volume or constant specific volume process ($v_1 = v_2$).

$T_1 = T_{\text{sat}@10 \text{ bar}} = 179.9$ °C

$$\begin{aligned}\text{Initially } v_1 &= v_{f1} + x v_{fg,1} \\ &= 0.0011278 + 0.84(0.1944 - 0.0011278) \\ &= 0.1634 \text{ m}^3/\text{kg}\end{aligned}$$

$$\begin{aligned}\text{Also } u_1 &= u_{f1} + x u_{fg,1} \\ &= 762 + 0.84(2584 - 762) \\ &= 2292.48 \text{ kJ/kg}\end{aligned}$$

$$\begin{aligned}\text{and } s_1 &= s_{f1} + x s_{fg,1} \\ &= 2.138 + 0.84(4.448) \\ &= 5.874 \text{ kJ/kgK}\end{aligned}$$

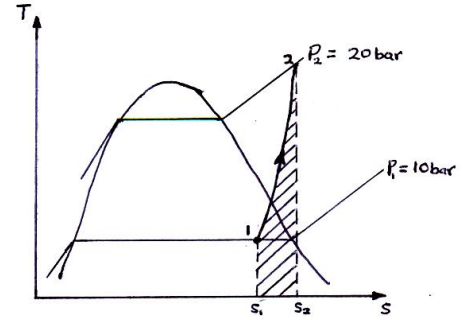


Fig. Ex. 4.2 T-s diagram of problem 4.2

State 2 is superheated and $P_2 = 20$ bar, $v_2 = v_1 = 0.1634 \text{ m}^3/\text{kg}$

From superheated steam tables, for above P_2 and v_2 ,

$$T_2 = 450^\circ\text{C} \quad u_2 = 3030 \text{ kJ/kg} \quad s_2 = 7.283 \text{ kJ/kgK}$$

$$\begin{aligned}\text{Change in total entropy (dS)} &= S_2 - S_1 = m(s_2 - s_1) = 0.05 \text{ kg} (7.283 - 5.874) \text{ kJ/kgK} \\ &= 0.07045 \text{ kJ/K (increase in entropy)}\end{aligned}$$

$$\begin{aligned}\text{Heat supplied } (Q_{12}) &= U_2 - U_1 = m(u_2 - u_1) = 0.05 \text{ kg} (3030 - 2292.5) \text{ kJ/kg} \\ &= 36.88 \text{ kJ}\end{aligned}$$

Average temperature of heat addition:

$$T_{av} = \frac{Q_{12}}{dS} = \frac{36.88 \text{ kJ}}{0.07045 \text{ kJ/K}} = 523.5 \text{ K} (250.5^\circ\text{C})$$

Example 4.3

Steam expands reversibly and adiabatically, hence isentropically, in a turbine from 6 bar, dry saturated, to a pressure of 0.65 bar. Calculate the work done during the expansion per kg of steam. Sketch the process on a T-s diagram.

Solution:

$$h_1 = h_{g@6\text{bar}} = 2757 \text{ kJ/kg}$$

$$s_1 = s_{g@6\text{bar}} = 6.761 \text{ kJ/kgK}$$

for reversible and adiabatic expansion

$$s_2 = s_1 = 6.761 \text{ kJ/kgK}$$

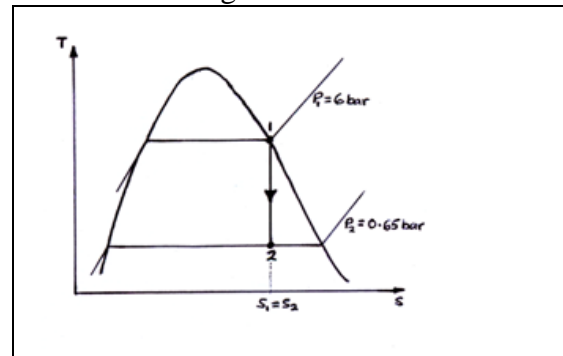


Fig. Ex. 4.3 T-s diagram of problem 4.3

Quality at state 2

$$x_2 = \frac{s_2 - s_{f@0.65\text{bar}}}{s_{fg@0.65\text{bar}}} = \frac{6.761 - 1.169}{6.335} = 0.883$$

Enthalpy at state 2

$$\begin{aligned}h_2 &= h_{f@0.65\text{bar}} + x_2 h_{fg@0.65\text{bar}} \\ &= 369 + 0.883(2288) = 2389.3 \text{ kJ/kg}\end{aligned}$$

Work done per kg of steam

$$\begin{aligned}w_{12} &= h_2 - h_1 = (2389.3 - 2757) \text{ kJ/kg} \\ &= -367.7 \text{ kJ/kg (work output)}\end{aligned}$$

Example 4.4

1 kg of steam enters a boiler, operating at a constant pressure of 30 bar, at a temperature of 60°C. The steam exits the boiler at 400 °C, 30 bar. Determine the amount of heat added per kg of steam and also the average temperature at which heat is added. Sketch the process on a T - s diagram relative to saturation lines and shade in the area that represents the heat flow.

Solution:

$$h_1 = h_f @ 60^\circ C = 251.1 \text{ kJ/kg}$$

$$s_1 = s_f @ 60^\circ C = 0.831 \text{ kJ/kgK}$$

At state 2 $P = 30 \text{ bar}$, $T = 400^\circ \text{C}$ (superheated)

$$h_2 = 3231 \text{ kJ/kg} \quad s_2 = 6.921 \text{ kJ/kgK}$$

Heat supplied per kg of steam:

$$q_{12} = h_2 - h_1 = (3231 - 251.1) \text{ kJ/kg} = 2979.9 \text{ kJ/kg}$$

Average temperature of heat addition :

$$T_{av} = \frac{q_{12}}{(s_2 - s_1)} = \frac{2979.9 \text{ kJ/kg}}{(6.921 - 0.831) \text{ kJ/kgK}} = 489.3 \text{ K} (216.3^\circ \text{C})$$

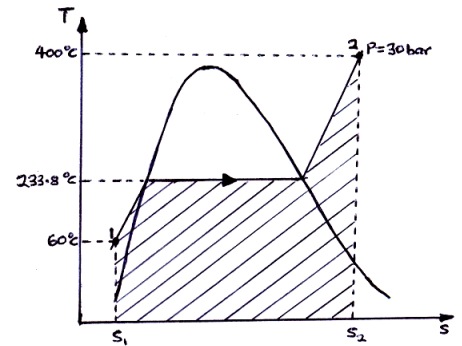


Fig. Ex. 4.4 T - s diagram of problem 4.4

Example 4.5

Saturated liquid at 0.05 bar enters the feed pump of a Rankine cycle and it undergoes an isentropic compression in the pump and exits at a pressure of 30 bar at entry to the boiler of the Rankine Cycle. Sketch the process on a T - s diagram and also find the work required for the feed pump per kg of fluid that enters it.

Solution:

For steady flow isentropic work,

$$\delta w = v dP$$

$$\Rightarrow w_{12} = v_1 (P_2 - P_1)$$

$$v_1 = v_f @ 0.05 \text{ bar} = 0.0010053 \text{ m}^3/\text{kg}$$

$$P_1 = 0.05 \text{ bar} = 5 \text{ kPa}$$

$$P_2 = 30 \text{ bar} = 3000 \text{ kPa}$$

Work input per kg of fluid

$$\begin{aligned} w_{12} &= 0.0010053 \text{ m}^3/\text{kg} \times (3000 - 5) \text{ kPa} \\ &= 3.01 \text{ kJ/kg} \end{aligned}$$

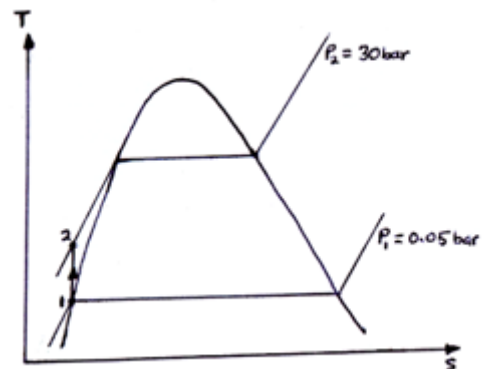


Fig. Ex. 4.5 T - s diagram of problem 4.5

Self Assessment 2-4

1. Given an ideal gas with the following data, determine the molecular weight of the gas.

$$P = 2.1 \text{ MPa} \quad T = 40^\circ\text{C} \quad v = 0.0946 \text{ m}^3/\text{kg}$$

Answer : 13.1 kg/K mol

2. In a rigid tank 1.0 m^3 of O_2 is heated from an initial pressure of 0.25 MPa and temperature of 50°C to a final temperature of 325°C . Determine the mass of the gas and its final pressure. **Answer: 2.98 kg, 0.46 MPa**
3. Air occupies a rigid container at the conditions shown below. Determine the temperature in Kelvin and the total volume of the container.

$$P = 0.1 \text{ MPa} \quad \rho = 1.00 \text{ kg/m}^3 \quad m = 453.6 \text{ kg}$$

Answer : 348.43 K, 453.6 m³

4. A sealed volume of 2.0 cm^3 contains saturated water. The container is heated from an initial pressure of 0.10 MPa until the vessel contains a single phase. Determine the final state (Phase, Temperature) of the water if the vessel contains (a) 0.10 g and (b) 1.0 g.

Answers: (a) saturated vapour, 304.9°C ; (b) saturated liquid, 364.3°C

5. A piston-cylinder device contains 1 kg of water at temperature of 200°C and pressure of 0.8 MPa. The water undergoes an isobaric process until it becomes a saturated liquid. Find the total work done in the process. Is it work done on or by the system? Show the process on a T - v diagram.

Answer |Work done| = 207.80 kJ, work is done on the system

6. A person cooks a meal in a 30-cm-diameter pot that is covered with a well-fitting lid and lets the food cool to the room temperature of 20°C . The total mass of the food and the pot is 8 kg. Now the person tries to open the pan by lifting the lid up. Assuming no air has leaked into the pan during cooling, determine if the lid will open or the pan will move up together with the lid.

Answer: The weight of the pan and its contents is much less than the reaction force at the pan-lid interface. Therefore, the pan will move up with the lid when the person attempts to open by lifting the lid up.

7. 0.05 kg of steam at 15 bar is contained in a rigid vessel of volume 0.0076 m^3 . What is the temperature of the steam? If the vessel is cooled, at what temperature will the steam be just dry saturated? Cooling is continued until the pressure in the vessel is 11 bar; calculate the final dryness fraction of the steam, and the heat rejected between the initial and the final states.

Answer: 250°C , 191.4°C ; dryness fraction = 0.857, heat rejected = 18.5 kJ

SESSION 3-4: APPLICATION OF 1ST AND 2ND LAWS TO 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 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.

3-4.3 Efficiency

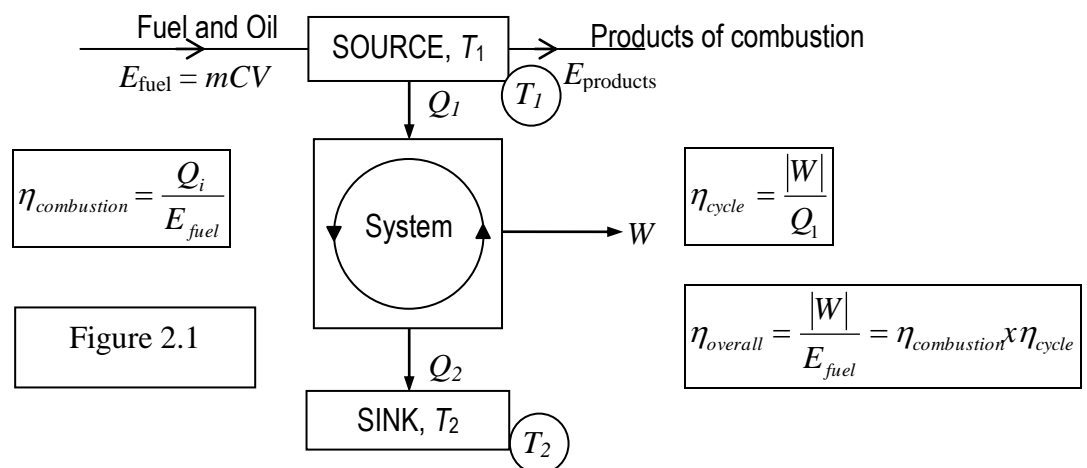


Figure 48: Essential features of a vapour power cycle

The essential features of a vapour power cycle are as illustrated in Fig. 48. The overall efficiency of a vapour power plant is suitably measured by the proportion of latent heat in the fuel, which is converted into useful mechanical work. The overall thermal efficiency can be expressed as a product of two efficiencies:

- i) **Combustion efficiency**: This expresses the proportion of the internal energy or latent energy in the fuel transferred as heat to the working fluid.
- ii) **Cycle efficiency**: This expresses the proportion of heat energy transferred to the working fluid and which is subsequently converted into mechanical work.

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

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

3-4.4 Process Efficiencies

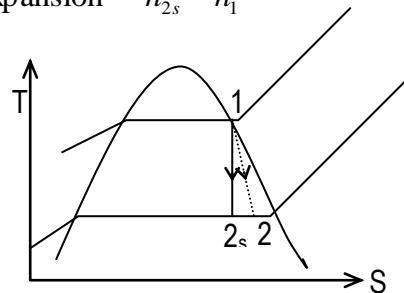
It is a measure of irreversibility and can be defined for a steady flow process as the ratio of isentropic to actual work or vice versa, depending on whether the process is a work producing process, or a work requiring process,

Turbine process (work producing device):

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

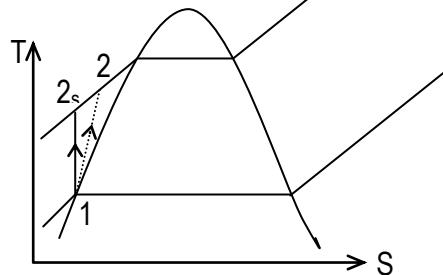
$$\text{Work producing} = \frac{\text{Actual}}{\text{Isentropic}}$$

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



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

Compressor or pump process (work requiring device):

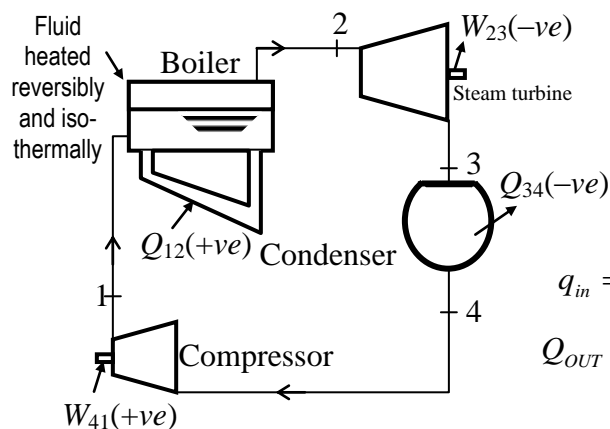


$$\eta_{\text{compressor, isentropic}} = \frac{\text{work required for isentropic compression}}{\text{work required for actual compression}} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

SESSION 4-4:

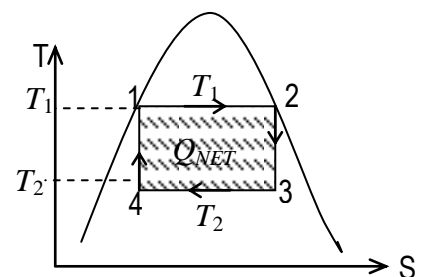
4-4.1 Carnot Cycle

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



$$q_{in} = h_{fg}$$

$$Q_{OUT} = \frac{T_2}{T_1} Q_{IN}$$



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

Figure 49: Carnot Cycle

Notes For a Cycle, from 1st Law

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

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

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

$$Q_{NET} = (T_1 - T_2)(S_2 - S_1)$$

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

Processes of the Carnot Cycle:

1-2: Saturated liquid in state 1 is evaporated in a boiler at constant pressure to form saturated steam in state 2.

Using the steady-state open flow energy equation

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

$$W_{12} = 0$$

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

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

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

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

$$m_t v_{av} = m_f v_f + m_g v_g$$

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

3-4: After expansion the wet steam is then partially condensed at constant pressure 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:

$s_1 = s_4$ and $s_{f,4}$, $s_{fg,4}$ 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.

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

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.

4-4.2 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. 49: 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. 50. The working fluid is water at the new state point 4 in Fig. 51, 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*.

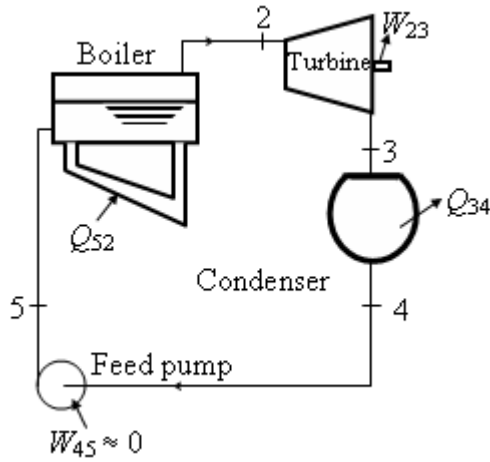


Figure 50: T-s diagram of the Rankine Cycle

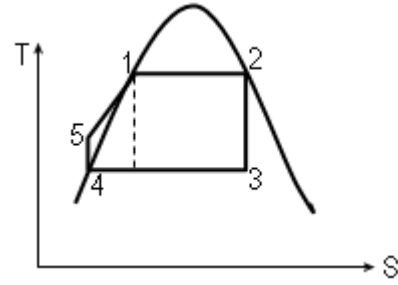


Figure 51: The Rankine Cycle without superheat

Feed pump work:

For a reversible process: $dq = du - dw$ (1st Law) (1)

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

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

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

$$dq = dh - vdp$$

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

Thus, $w_{45} = h_5 - h_4 = v_{f4}(P_5 - P_4)$ (4)

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

In general, for a steady state, for process 1-2, $\dot{m}(s_2 - s_1) - \frac{d\dot{Q}}{T} \geq 0$. But for an adiabatic process $dQ = 0$, hence $s_2 \geq s_1$. Thus, for an irreversible process $s_2 > s_1$ and the irreversibility in process in process 1-2 is accounted for by introducing the process efficiency. The actual expansion and compression processes are irreversible and are indicated by lines 1-2 and 3-4 in Fig. 52.

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

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

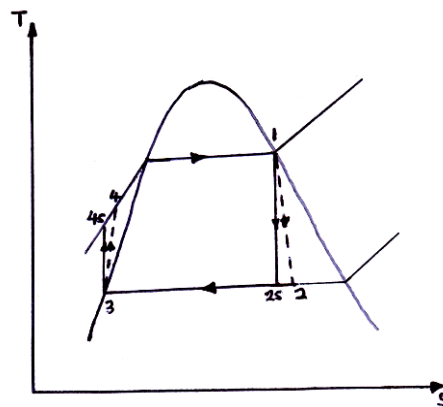


Figure 52: Rankine Cycle showing real processes on a T-s diagram

4-4.3 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. 53.

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

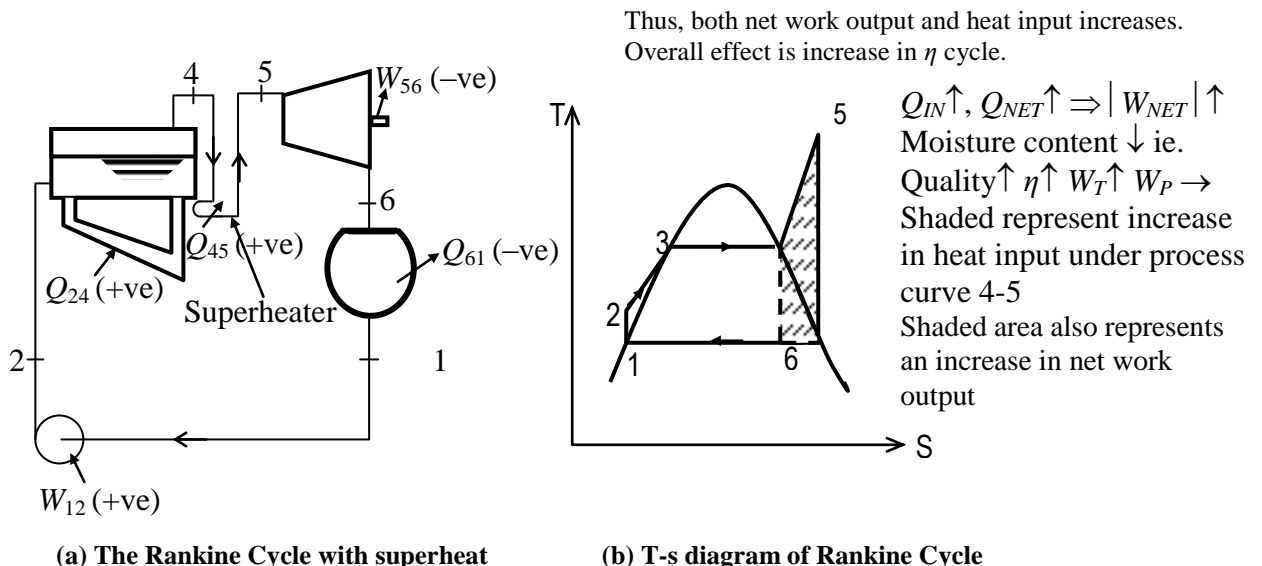


Figure 53: Rankine Cycle with superheat

The super-heater 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 super-heat increases continuously with pressure.
- ii) The work ratio does **not** change since the work ratio in un-super-heated 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 super-heater 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.

4-4.4 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 54. 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.*

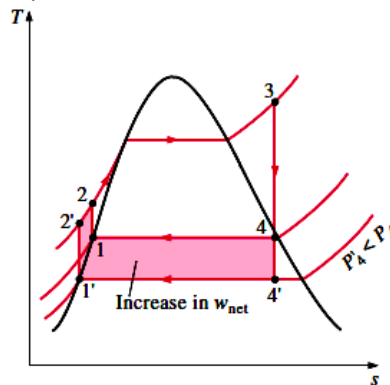


Figure 54: Effect of lowering condenser pressure on Rankine Cycle performance

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 Higher 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 55.

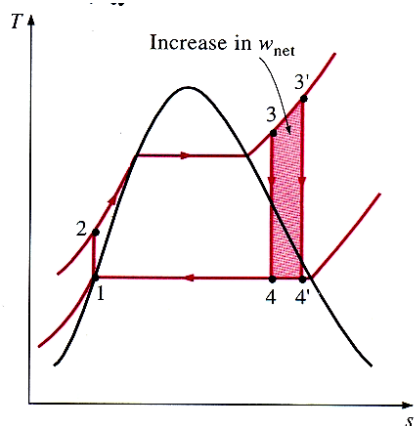


Figure 55: Effect of superheating on Rankine Cycle performance

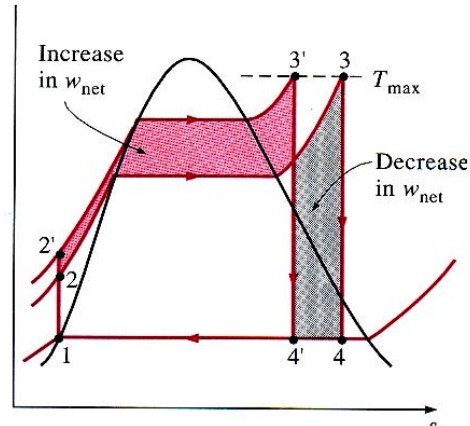


Figure 56: Effect of increasing boiler pressure on Rankine Cycle performance

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.

(b) 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 56.

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 ($P > 22.12\text{ MPa}$) 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.

Self Assessment 4-4

1. A steam power plant operates on the ideal Rankine cycle. The steam leaves the turbine at a pressure of 0.2 MPa and quality of 0.98. The turbine produces 1500 kW of power. If the mass flow rate is 1.5 kg/s, find the net power output and the cycle thermal efficiency.

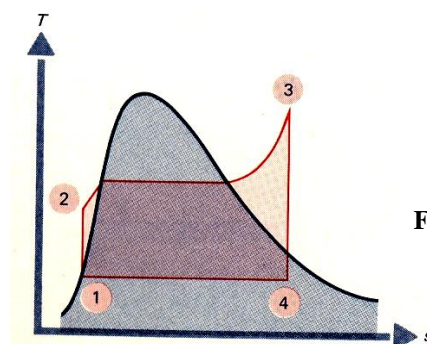


Fig. Q.1

2. Is it possible to maintain a pressure of 10 kPa in a condenser that is being cooled by river water entering at 20°C ?

Answer Tips

- 1. [1492 MW, 33.4 %]
- 2. yes

Appendices

Appendix 1: Tutorial problems Set 1

1. The temperature of a system rises by 15 °C during a heating process. Express this rise in temperature in Kelvin.

2. The water tank is pressurized by air, and the pressure is measured by a multi-fluid manometer as shown in Fig. Q.2. Determine the gage pressure of air in the tank if $h_1 = 0.2$ m, $h_2 = 0.3$ m, and $h_3 = 0.46$ m. Take the densities of water, oil and mercury to be 1000 kg/m³, 850 kg/m³, and 13,600 kg/m³, respectively.

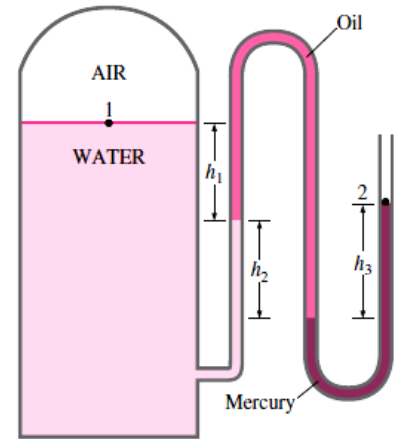


Fig. Q.2

4. The gage pressure in a liquid at a depth of 3 m is read to be 28 kPa. Determine the gage pressure in the same liquid at a depth of 9 m.
5. A gas is contained in a vertical, frictionless piston-cylinder device. The piston has a mass of 4 kg and a cross-sectional area of 35 cm². A compressed spring above the piston exerts a force of 60 N on the piston. If the atmospheric pressure is 95 kPa, determine the pressure inside the cylinder.

[123.4 kPa]

6. A mercury manometer ($\rho = 13,600$ kg/m³) is connected to an air duct to measure the pressure inside. The difference in the manometer levels is 15 mm, and the atmospheric pressure is 100 kPa. (a) Judging from Fig. Q.6, determine if the pressure in the duct is above or below the atmospheric pressure. (b) Determine the absolute pressure in the duct.

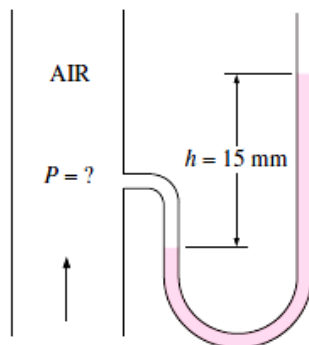


Fig. Q.6

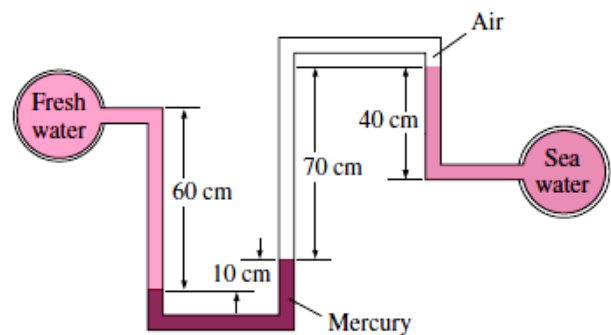


Fig. Q.7

7. Freshwater and seawater flowing in parallel horizontal pipelines are connected to each other by a double U-tube manometer, as shown in Fig. Q.7. Determine the pressure difference between the two pipelines. Take the density of sea water at that location to be $\rho = 1035 \text{ kg/m}^3$. Can the air column be ignored in the analysis? Assume the density of air, $\rho_{\text{air}} = 1.15 \text{ kg/m}^3$.
8. A multi-fluid container is connected to a U-tube, as shown in Fig. Q.8. For the given specific gravities and fluid column heights, determine the gage pressure at A. Also determine the height of a mercury column that would create the same pressure at A.
[0.471 kPa; 0.353 cm]

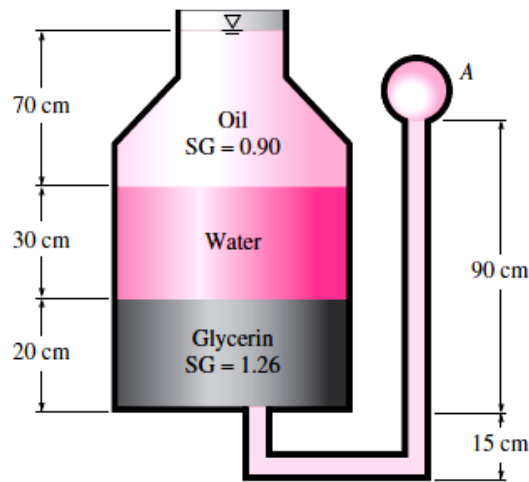


Fig. Q.8

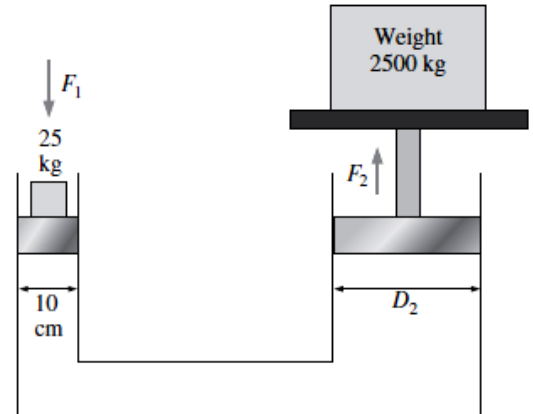


Fig. Q.9

9. A hydraulic lift is to be used to lift a 2500 kg weight by putting a weight of 25 kg on a piston with a diameter of 10 cm. Determine the diameter of the piston on which the weight is to be placed.
10. The pilot of an airplane reads the altitude 3000 m and the absolute pressure 58 kPa when flying over a city. Calculate the local atmospheric pressure in that city in kPa and in mmHg. Take the densities of air and mercury to be 1.15 kg/m^3 and $13,600 \text{ kg/m}^3$, respectively.



Fig. Q.10

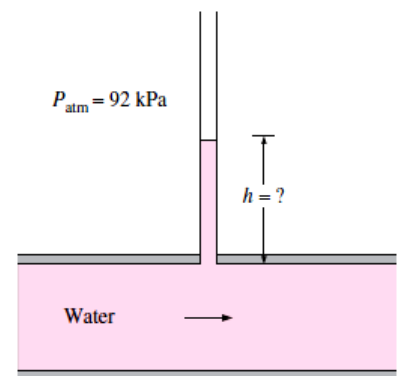


Fig. Q.11

11. A glass tube is attached to a water pipe, as shown in Fig. Q.11. If the water pressure at the bottom of the tube is 115 kPa and the local atmospheric pressure is 92 kPa, determine how high the water will rise in the tube, in m. Take the density of water to be 1000 kg/m^3 .

12. Intravenous infusions are usually driven by gravity by hanging the fluid bottle at sufficient height to counteract the blood pressure in the vein and to force the fluid into the body. The higher the bottle is raised, the higher the flow rate of the fluid will be. (a) If it is observed that the fluid and the blood pressure balance each other when the bottle is 1.2 m above the arm level, determine the gage pressure of the blood. (b) If the gage pressure of the fluid at the arm level needs to be 20 kPa for sufficient flow rate, determine how high the bottle must be placed. Take the density of the fluid to be 1020 kg/m^3 .

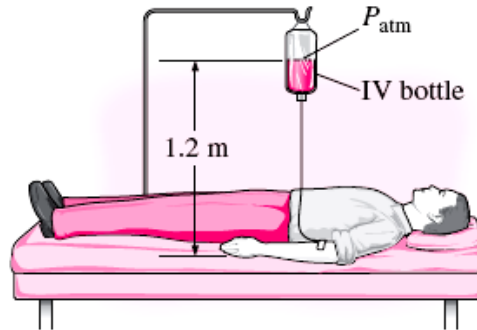


Fig. Q.12

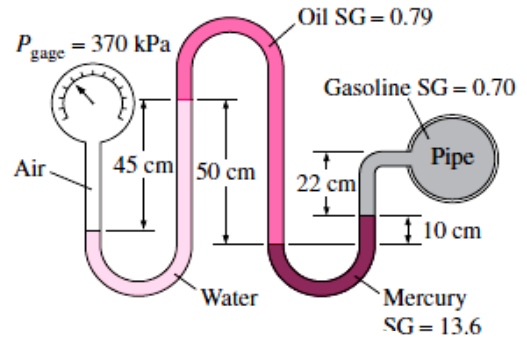


Fig. Q.13

13. A gasoline line is connected to a pressure gage through a double-U manometer, as shown in Fig. Q.13. If the reading of the pressure gage is 370 kPa, determine the gage pressure of the gasoline line.
14. A force of 3000 N is exerted uniformly over a plate of area 3 cm^2 at an angle of 30° to the normal. What is the pressure, in Pascal, exerted on the plate?
15. A person starts an outing at sea level where the pressure is 0.101 MPa. Calculate the final pressure for each of the following excursions:
- The person climbs to the top of Mt. Everest where the elevation is 8848 m. Take the average air density between sea level and the mountaintop to be 0.754 kg/m^3 .
 - The person dives to the bottom of a sea where the depth is 395 m. Take the water density to be 1000 kg/m^3 .
 - The person travels to the bottom of Death Valley where the elevation is 86 m below mean sea level. Take the air density to be 1.30 kg/m^3 .
- Neglect the fluid density variations and local gravity variations for each excursion.
16. If the density of H_2O in a container is 600 kg/m^3 , calculate the mass of the H_2O if the container has a total volume of 70 cm^3 .
17. What is the weight of H_2O occupying a volume of 0.85 m^3 if $\nu = 0.021 \text{ m}^3/\text{kg}$? The acceleration due to gravity is 9.807 m/s^2 .
18. A frictionless piston-cylinder device has a cross-sectional area of 100 cm^2 . Find the piston mass such that the absolute pressure in the cylinder is 1.0 MPa. Atmospheric pressure is 0.1 MPa, and the local acceleration of gravity is 9.807 m/s^2 .
19. A new absolute temperature scale is proposed. On this scale the ice point of water is 150°S and the steam point is 300°S . Determine the temperatures in $^\circ\text{C}$ that correspond to 100° and 400°S , respectively. What is the ratio of the size of the $^\circ\text{S}$ to the Kelvin?

Appendix 2: Tutorial problems 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 23.0 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 $V_1 = 0.09$ m³ to $V_2 = 0.03$ m³. 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 m³, 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 $V = 0.1$ m³ 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. Q.4. Initially, $p_1 = 100$ kPa, $V_1 = 2 \times 10^{-3}$ m³, 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 m². The air expands slowly until its volume is $V_2 = 3 \times 10^{-3}$ m³. 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.

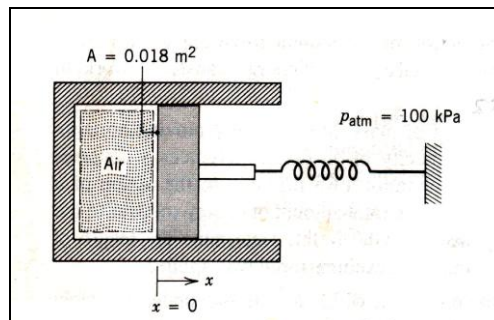


Figure Q.4: Piston-cylinder assembly in horizontal position

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 a closed system

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

6. Gas undergoes a thermodynamic cycle consisting of the following processes:
Process 1 – 2 constant pressure $p = 1.4$ bars, $V_1 = 0.028 \text{ m}^3$, $W_{12} = -10.5 \text{ kJ}$
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.
- Sketch the cycle on a $p - V$ diagram.
 - Calculate the net work for the cycle, in kJ.
 - Calculate the heat transfer for process 1 – 2, in kJ.
 - 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°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: $W_{23} = 0$, $Q_{31} = -150 \text{ kJ}$
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 m^3 . The tank is fitted with a paddle wheel that transfers energy to the air at a constant rate of 4 W for 20 min. The initial density of the air is 1.2 kg/m^3 . If no changes in kinetic or potential energy occur, determine
- The specific volume at the final state, in m^3/kg .
 - The change in specific internal energy of the air, in kJ/kg. [0.833 m^3/kg , 20 kJ/kg]
11. The mass flow rate into a steam turbine is 1.5 kg/s and heat transfer from the turbine is estimated at 8.5 kW. The properties of the steam at inlet and outlet of the turbine are as follows:

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

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

12. A cylinder-piston arrangement containing a gas has a spring, which makes contact with the piston. As the gas is heated the piston moves outward and compresses the spring such that the spring force is proportional to the displacement of the piston. The initial volume and pressure of the gas are 0.1 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 kJ, calculate the heat transferred during the process. [50 kJ]

13. A gas contained within a piston-cylinder assembly is shown in Fig. Q.13. Initially, the piston face is at $x = 0$, and the spring exerts no force on the piston. As a result of heat transfer, the gas expands, raising the piston until it hits the stops. At this point the piston face is located at $x = 0.05$ m, and the heat transfer ceases. The force exerted by the spring on the piston as the gas expands varies linearly with x according to $F = kx$ where $k = 10,000$ N/m. Friction between the piston and the cylinder wall can be neglected. The acceleration due to gravity is $g = 9.81$ m/s². Additional information is given on Fig. 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.

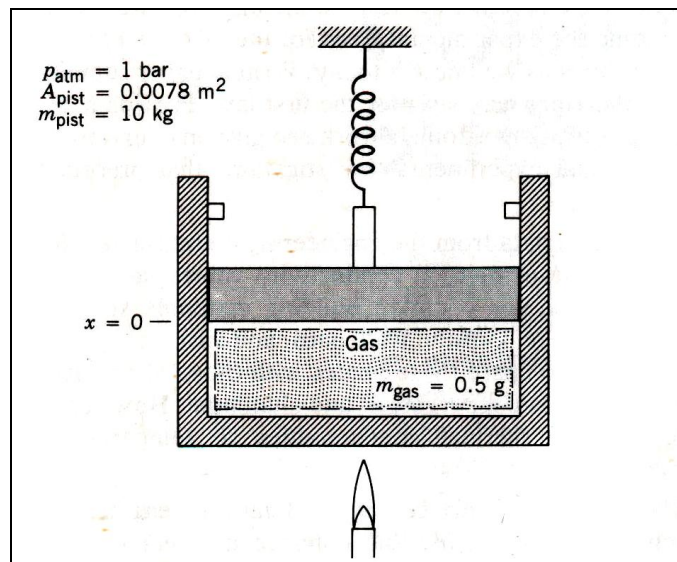


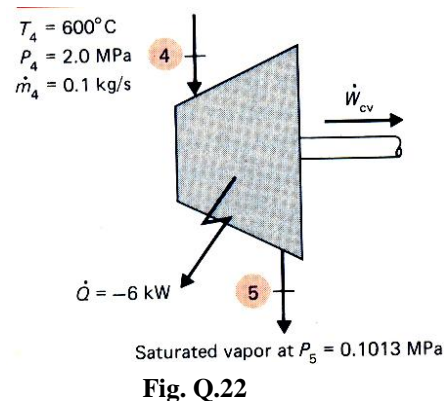
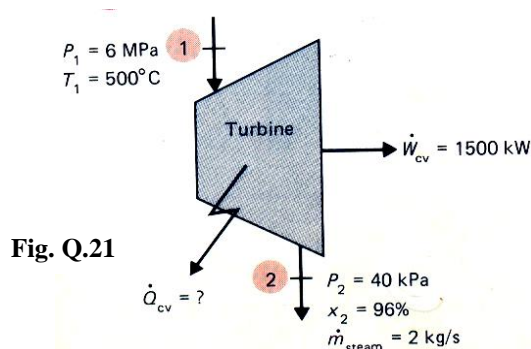
Figure Q.13: Piston-cylinder assembly in vertical position

- For a power cycle the total heat transfer to the cycle is, Q_{in} is 500 MJ. What is the net work delivered, in MJ, if the thermal efficiency is 30 %. **[150 MJ]**
- The coefficient of performance of a heat pump cycle is 3.5 and the net work input is 500 kJ. Determine the heat transfers Q_{in} and Q_{out} , in kJ. **[12,500 kJ; - 17,500 kJ]**
- A block of mass 10.0 kg is pushed along an incline a distance of 5.0 m as its centre of gravity is elevated by 3.0 m. The block is acted on by a constant force R parallel to the incline having a magnitude of 70 N and by the force of gravity. Assume frictionless surfaces and $g = 9.8$ m/s². 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 m/s² 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]**
- 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

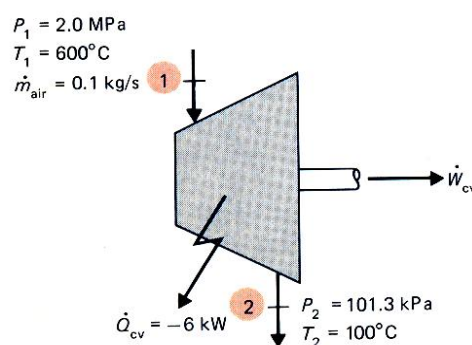
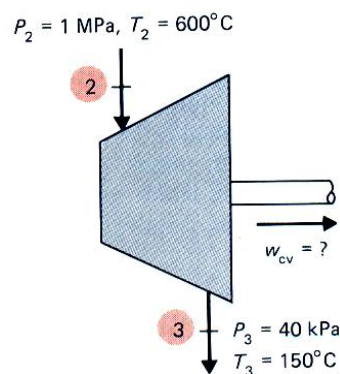
resistance, what is the magnitude of the velocity, in m/s, of the object just before it strikes the earth? The acceleration of gravity is $g = 9.81 \text{ m/s}^2$.

[109.4 m/s]

19. 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.
20. Steam enters a turbine at a temperature of 300°C and a pressure of 0.4 MPa. If it leaves as a saturated vapour at 0.03 MPa, what is the change in enthalpy between the two state points? [441.7 kJ/kg]
21. A non-adiabatic steam turbine operates as shown in Fig. Q.21. Determine the rate of heat transfer (kW). [-257.8 kJ/kg]



22. Determine the power (kW) output of the steam turbine operating as shown in Fig. Q.22.
23. Determine the work (kJ/kg) output of the adiabatic steam turbine operating as shown in Fig. Q.23. [917.7 kJ/kg]



24. Determine the power output (kW) of the air turbine operating as shown in Fig. Q.24 [44.26 kW]

25. Determine the work (kJ/kg) required to operate the adiabatic helium compressor operating as shown in Fig. Q.25. **[2077 kJ/kg]**

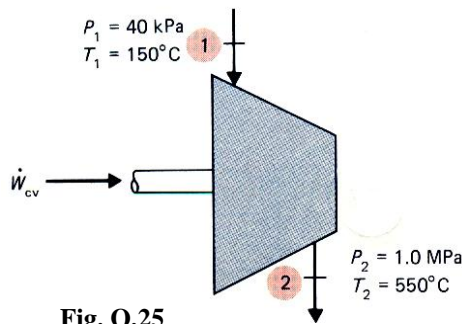


Fig. Q.25

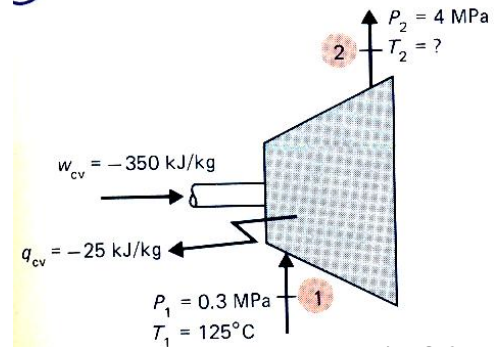


Fig. Q.27

26. Steam enters an isothermal compressor at 400 °C and 0.1013 MPa. If the exit pressure is 10 MPa, determine the change in enthalpy. **[-181.9 kJ/kg]**
27. A non-adiabatic air compressor operates as shown in Fig. Q.27. what is the exit temperature? **[448.3 °C]**
28. Consider the steady-state steady flow device shown in Fig. Q.28. The medium is steam. Calculate the shaft power. **[-8583 kW]**

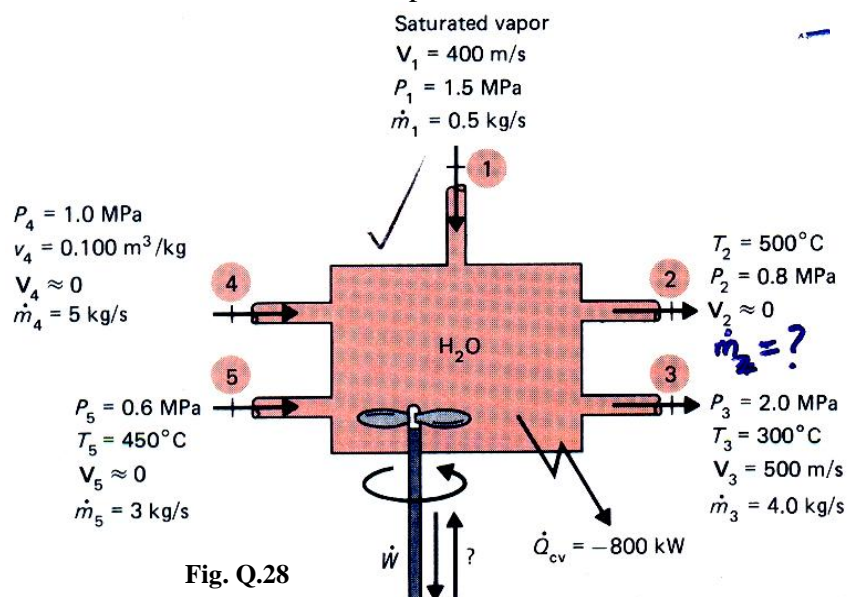


Fig. Q.28

29. Steam expands through the adiabatic steady-state steady flow nozzle shown in Fig. Q.29. For the given conditions, find the exit velocity V_2 . **[1082 m/s]**

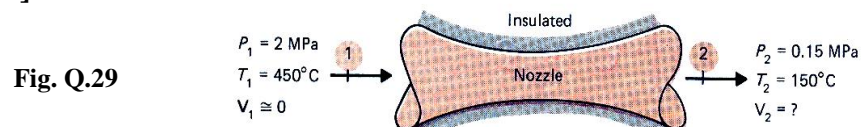


Fig. Q.29

30. Determine the exit velocity and exit area of the carbon dioxide nozzle shown in Fig. Q.30.

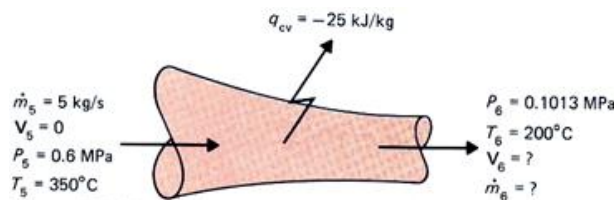


Fig. Q30

31. What is metabolism? What is basal metabolic rate? What is the value of basal metabolic rate for an average man?
32. For what is the energy released during metabolism in humans used?
33. Is the metabolizable energy content of a food the same as the energy released when it is burned in a bomb calorimeter? If not, how does it differ?
34. Is the number of prospective occupants an important consideration in the design of heating and cooling systems of classrooms? Explain.
35. What do you think of a diet program that allows for generous amounts of bread and rice provided that no butter or margarine is added?
36. Consider two identical 80-kg men who are eating identical meals and doing identical things except that one of them jogs for 30 min everyday while the other watches TV. Determine the weight difference between the two in a month. **[1.045 kg]**
37. A 55-kg man gives in to temptation and eats an entire 1-L box of ice cream. How long does this man need to jog to burn off the calories he consumed from the ice cream? **[2.52 h]**
38. Consider two identical 50-kg women, Candy and Wendy, who are doing identical things and eating identical food except that Candy eats her baked potato with four spoons of butter while Wendy eats hers plain every evening. Determine the difference in the weights of Candy and Wendy after one year. **[6.5 kg]**
39. A 60-kg man used to have an apple every day after dinner without losing or gaining any weight. He now eats a 200-ml serving of ice cream instead of an apple and walks 20 min every day. On this new diet, how much weight will he lose or gain per month? **[0.087-kg gain]**
40. The range of healthy weight for adults is usually expressed in terms of the *body mass index* (BMI), defined, in SI units as:

$$\text{BMI} = \frac{W \text{ (kg)}}{H^2 \text{ (m}^2\text{)}}$$

where W is the weight (actually, the mass) of the person in kg and H is the height in m, and the range of healthy weight is $19 \leq \text{BMI} \leq 25$. Convert the previous formula to English units such that the weight is in pounds and the height in inches. Also, calculate your own BMI, and if it is not in the healthy range, determine how many pounds (or kg) you need to gain or lose to be fit.

41. A reversible process for a piston-cylinder control mass is shown on the P-v and T-s diagrams in Figure Q41. Evaluate the change in internal energy per unit mass for the process.

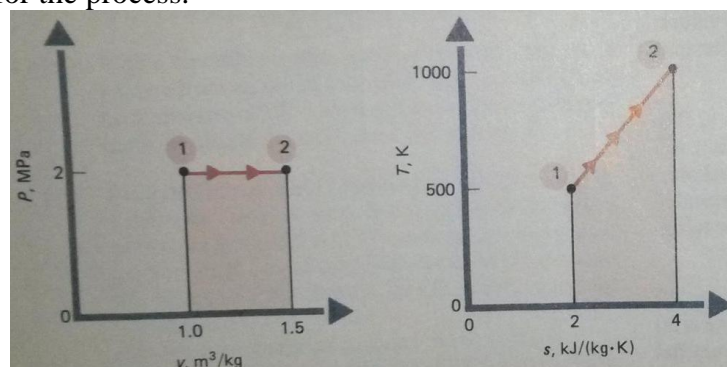


Figure Q41

Appendix 3: Tutorial problems Set 3

- 1 An inventor claims to have developed a car that runs on water instead of gasoline. What is your response to this claim?
- 2 Describe an imaginary process satisfies the first law but violates the second law of thermodynamics.
- 3 Describe an imaginary process that satisfies the second law but violates the first law.
- 4 Describe an imaginary process that violates both the first and the second laws of thermodynamics.
- 5 Does a heat engine that has a thermal efficiency of 100% necessarily violate (a) the first law and (b) the second law of thermodynamics?
- 6 In absence of any friction and other irreversibilities, can a heat engine have an efficiency of 100%? Explain.
- 7 Are the efficiencies of all the work producing devices, including hydroelectric power plants, limited by Kelvin-Planck statement of the second law?
- 8 A cold canned drink is left in a warmer room where its temperature rises as result of heat transfer. Is this a reversible process? Explain.
- 9 A hot baked potato is left on a table where it cools to the room temperature. Is this a reversible or irreversible process?
- 10 Why are engineers interested in reversible process even though they can never be achieved?
- 11 A refrigerator has a COP of 1.5. That is, the refrigerator receives 1.6 KWh of energy from the refrigerated space for each 1.5 kWh of electricity it consumes. Is this a violation of the first law of thermodynamics? Explain.
- 12 A household refrigerator with a COP of 1.8 removes heat from the refrigerated space at a rate of 90 kJ/min. Determine
 - a) the electric power consumed by the refrigerator and
 - b) the rate of heat transfer to the kitchen air

[a. 0.83 kW, b. 140 kJ/min]
- 13 An air conditioner removes heat steadily from a house at a rate of 750 kJ/min while drawing electric power at a rate of 5 kW. Determine
 - a) the COP of this air conditioner and
 - b) the rate of heat transfer to the outside air

[a. 2.08; b. 1110 kJ/min]
- 14 Determine the COP of a heat pump that supplies energy to a house at a rate of 8000 kJ/h for each kW of electric it draws. Also determine the rate of energy absorption from the outside air.

[2.22, 4400 kJ/h]
- 15 A Carnot heat engine receives 500 kJ of heat from a source of unknown temperature and rejects 200 kJ of it to a sink at 17°C. Determine
 - a) the temperature of the source and
 - b) the thermal efficiency of the heat engine
- 16 An air-conditioning system is used to maintain a house at a constant temperature of 20°C. The house is gaining heat from outdoors at rate of 20,000 kJ/h, and the heat generated in the house from the people, lights, and appliances amounts to 8000 kJ/h. For a COP of 2.5, determine the required power input to this air-conditioning system.
- 17 A power cycle operating between two reservoirs receives energy Q_H by heat transfer from a hot reservoir at $T_H = 2000\text{K}$ 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 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) $|W_{\text{cycle}}| = 400 \text{ kJ}$, $\text{COP}_R = 6$
- 19 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.

20. An engine operates on the Carnot cycle. The engine efficiency is 60 percent when 20 kJ/kg per engine cycle of thermal energy is rejected to a low-temperature reservoir at $T_L = 27^\circ\text{C}$, and has a specific net work output of magnitude 30 kJ/kg per cycle.
- (a) How much energy is transferred to the engine from the high-temperature reservoir per cycle (kJ/kg)?
 (b) At what temperature T_H is the high-temperature reservoir?
[50 kJ/kg; 477 °C]
21. An engine operates on the Carnot cycle. The engine takes 50 kJ/kg per cycle of energy from a high-temperature reservoir with a heat transfer to a low-temperature reservoir at $T_L = 27^\circ\text{C}$, and has a specific work output of 10 kJ/kg per cycle.
- (a) How much energy is transferred from the engine to the low-temperature reservoir per cycle (kJ/kg)?
 (b) At what temperature T_H is the high-temperature reservoir?
 (c) What is the heat engine efficiency?
22. A heat engine operates between a higher temperature of T_H and a lower temperature of $T_L = 60^\circ\text{C}$. The efficiency of the engine is said to be 45 percent.
- (a) What is the minimum value of T_H ($^\circ\text{C}$) for which the proposed efficiency is possible?
 (b) If this engine operates on a Carnot cycle, how much heat transfer *to* the engine must occur for each kilojoule that is rejected at T_L ?
 (c) If the engine does not operate on a reversible cycle, would the heat transfer *to* the engine be greater or smaller than that found in part (b) for each kilojoule rejected at T_L ? Explain your answer.
[332 °C; 1.82 kJ; smaller]
23. Two Carnot heat engines are connected in series as shown in Fig. Q.23 so that the waste thermal energy at constant temperature T_M from engine 1 is the thermal energy source for engine 2. The high-temperature reservoir for

engine 1 is at T_H . The low-temperature reservoir for engine 2 is at $T_L = 27^\circ\text{C}$, and $T_L \leq T_M \leq T_H$. The total work output $|w_1| + |w_2|$ from this combined engine is 1.167 kJ/kg when the energy rejected from engine 1 (and used as input to engine 2) is $|q_M| = 1 \text{ kJ/kg}$. This occurs when $T_M = 327^\circ\text{C}$.

- What is the value of $|w_2|$ in (kJ/kg)?
- What is the value of $|w_1|$ in (kJ/kg)?
- What is the value of $|q_H|$ and T_H in (kJ/kg) and ($^\circ\text{C}$) respectively?

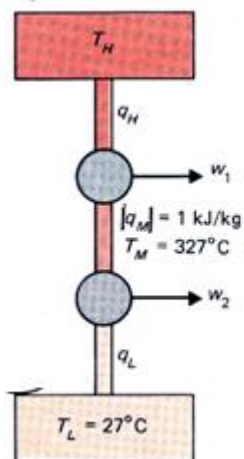


Fig. Q.23

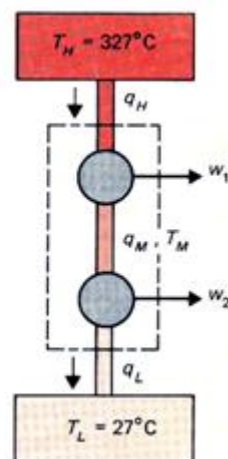


Fig. Q.24

- Two Carnot engines are hooked in series as shown in Fig. Q.24, so that the waste thermal energy at constant temperature T_M from engine 1 is used as the thermal energy source for engine 2. The high-temperature reservoir for engine 1 is at $T_H = 327^\circ\text{C}$. The low-temperature reservoir for engine 2 is at $T_L = 27^\circ\text{C}$, and $T_L \leq T_M \leq T_H$. What value of T_M ($^\circ\text{C}$) will provide the greatest total work output $|w_1 + w_2|$ for this combined engine? (Prove your answer)
- The thermal reservoirs to a Carnot engine are constant-pressure steam lines at $T_H = 300^\circ\text{C}$ and $T_L = 25^\circ\text{C}$, respectively. As heat transfer occurs from the high-temperature steam line, saturated vapour passing through the line at a mass flow rate of 3 kg/s is condensed to an exit quality of 95 percent.
 - If the steam line entering the low-temperature reservoir carries saturated liquid at a mass flow rate of 2.5 kg/s , what is the exit quality of the steam?
 - What is the power output of the Carnot engine in (kW)?

[0.018; 101.2 kW]

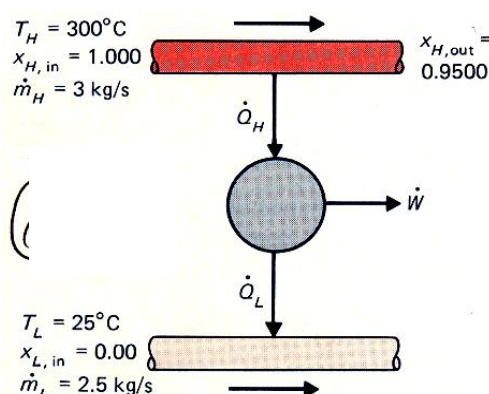


Fig. Q.25

- An electric utility company has a plant with a capacity of 1000 MW of electricity for sale to its customers. The overall thermal efficiency of the plant

- is 25 percent, and the oil (the fuel) costs 25 cents per gallon. The heating value of the oil is 4.56×10^6 kJ/kg, and there is 3.4 kg of oil per gallon. What is the cost of running at maximum capacity for one week? **[\$ 38,200]**
27. A Carnot heat pump delivers a heat transfer of 3×10^4 kJ at 50°C . The evaporator is at 15°C . Calculate W_{net} and the coefficient of performance for this Carnot heat pump. **[3.25 x 10³ kJ; 9.229]**
28. A steam power plant is constructed such that it produces 75 kW of power while rejecting 190.0 kJ/s to a low-temperature reservoir. (a) Find \dot{Q}_H . (b) Find η_{th} . **[266 kW; 28.2 %]**
29. A retired engineer living in Arizona is attempting to heat his home by using a heat pump. He has determined the minimum heat transfer rate needed to heat his home to be 50.8 kJ/h. He has the chance to buy a heat pump which has a coefficient of performance of 5 and which requires 2.75 W of electric power to run. Assuming the power requirement does not present a problem, should the heat pump be bought? **[No]**
30. A farmer buys a small heat engine from Carnot Products Co., Ottumwa, Iowa, to drive an irrigation pump. The engine takes a heat transfer from a nearby solar pond that is kept at $T_H = 73^\circ\text{C}$. The pump is 70 percent efficient and pumps 1 kg/s of water at 27°C from a well. The water undergoes a pressure change of 2 MPa in the pump. The water leaving the pump is used as the reservoir for the heat transfer from the so-called Carnot engine.
- Sketch the system.
 - Calculate the rate of heat transfer from the solar pond.
 - State your assumptions.
31. A reversible heat engine operates between a high-temperature thermal reservoir at 400°C and low-temperature thermal reservoir at 40°C . Calculate the ratio of the absolute temperatures of the two reservoirs. **[2.15]**
32. A Carnot refrigerator rejects a heat transfer of 2.5×10^3 kJ at 80°C . If W_{net} for this refrigerator is 1.1×10^3 kJ, find the heat transferred, the low temperature in the cycle, and the coefficient of performance. **[1.4 x 10³ kJ; - 75.3 °C; 1.27]**
33. A Carnot engine rejects a heat transfer of 230 kJ at 24°C . The net work for the cycle is 370 kJ. Find the thermal efficiency and T_H . **[61.7 %; 501.8 °C]**
34. An inventor claims she has a steam engine that operates between the temperature extremes of 700 and 10°C and produces 200 kJ of work while rejecting a heat transfer of 100 kJ. Is her heat engine possible? **[Possible]**
35. A Carnot cycle refrigerator operates in a room which has a temperature of 21°C . It must reject 75 kW to the room in order to maintain the refrigerated space at 10°C . What size motor (hp) is required? **[10.6 hp]**
36. A Carnot heat pump is designed to heat an apartment complex in an area where the expected winter temperature may be as low as -35°C . The expected COP_{HP} is 1.25. To what temperature could this unit conceivably heat the complex? Is this adequate? **[1190 K]**

Appendix 4: Tutorial problems Set 4

- Is iced water a pure substance? Why?
- 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 and 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/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/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/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/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 cm². 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 m³ 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. **[140.6 °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.

- What is the mass of the water?
- What is the final temperature?
- Determine the total enthalpy change
- 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]

23. Given an ideal gas with the following data, determine the molecular weight of the gas.

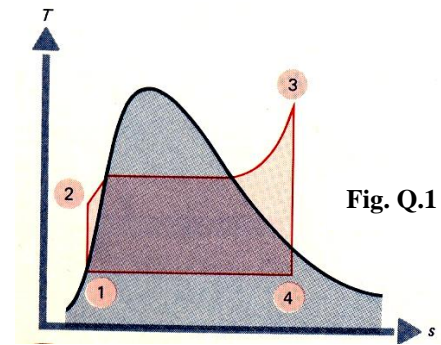
$$P = 2.1 \text{ MPa} \qquad T = 40 \text{ }^{\circ}\text{C} \qquad v = 0.0946 \text{ m}^3/\text{kg}$$

24. In a rigid tank 1.0 m³ of O₂ is heated from an initial pressure of 0.25 MPa and temperature of 50 °C to a final temperature of 325 °C. Determine the mass of the gas and its final pressure.
25. Air occupies a rigid container at the conditions shown below. Determine the temperature in Kelvin and the total volume of the container.
- $$P = 0.1 \text{ MPa} \qquad \rho = 1.00 \text{ kg/m}^3 \qquad m = 453.6 \text{ kg}$$
26. A piston-cylinder device contains 1 kg of water at temperature of 200 °C and pressure of 0.8 MPa. The water undergoes an isobaric process until it becomes a saturated liquid. Find the total work done in the process. Is work done on or by the system? Show the process on a T-v diagram.
27. A person cooks a meal in a 30-cm-diameter pot that is covered with a well-fitting lid and lets the food cool to the room temperature of 20 °C. The total mass of the food and the pot is 8 kg. Now the person tries to open the pan by lifting the lid up. Assuming no air has leaked into the pan during cooling, determine if the lid will open or the pan will move up together with the lid.
28. 0.05 kg of steam at 15 bar is contained in a rigid vessel of volume 0.0076 m³. What is the temperature of the steam? If the vessel is cooled, at what temperature will the steam be just dry saturated? Cooling is continued until the pressure in the vessel is 11 bar; calculate the final dryness fraction of the steam, and the heat rejected between the initial and the final states.

[250 °C; 191.4 °C; 0.857; 18.5 kJ]

Appendix 5: Tutorial problems Set 5

1. A steam power plant operates on the ideal Rankine cycle. The turbine inlet pressure is 4.0 MPa. The steam leaves the turbine at a pressure of 0.2 MPa and quality of 0.98. The turbine produces 1500 kW of power. If the mass flow rate is 1.5 kg/s, find the net power output and the cycle thermal efficiency.



2. Is it possible to maintain a pressure of 10 kPa in a condenser that is being cooled by river water entering at 20 °C?
3. An ideal Rankine cycle operates with a high pressure of 6 MPa and a low pressure of 40 kPa. The quality of the steam leaving the turbine is 0.83. If $\dot{m} = 0.25$ kg/s, find w_p , q_H , w_t , \dot{W}_{net} (hp), and q_L .
4. The condenser of an ideal Rankine cycle power plant operates at 20 kPa, and steam exits the boiler at 525 °C and 2.0 MPa. Compare the thermal efficiency of this power plant to that of a Carnot engine operating between the same temperature extremes. Do not neglect pump work.
5. Water enters the pump in an ideal Rankine cycle at $P = 0.1$ MPa. The H₂O exits the pump at 3 MPa. The maximum temperature in the cycle is 450 °C, and $\dot{m} = 0.3$ kg/s. Find w_p , q_H , w_t , \dot{W}_{net} (hp), and q_L .
6. Consider a 210-MW steam power plant that operates on a simple ideal Rankine cycle. Steam enters the turbine at 10 MPa and 500 °C and is cooled in the condenser at a pressure of 10 kPa. Show the cycle on a T - s diagram with respect to saturation lines, and determine (a) the quality of the steam at the turbine exit, (b) the thermal efficiency of the cycle, and (c) the mass flow rate of the steam. **[0.793; 40.2%; 165 kg/s]**
7. A steam power plant operates on the simple ideal Rankine cycle between the pressure limits of 10 kPa and 10 MPa, with a turbine inlet temperature of 600°C. The rate of heat transfer in the boiler is 800 kJ/s. Disregarding the pump work, calculate the power output of this plant. **[335 kW]**
8. How do the following quantities change when the basic ideal Rankine cycle is modified with superheating? Assuming the mass flow rate, the boiler pressure and condenser pressure are maintained the same.

Pump work input	(a) increases	(b) decreases	(c) remains the same
Turbine work output	(a) increases	(b) decreases	(c) remains the same
Heat supplied	(a) increases	(b) decreases	(c) remains the same
Heat rejected	(a) increases	(b) decreases	(c) remains the same
Moisture content at turbine exit	(a) increases	(b) decreases	(c) remains the same

SAMPLE OF SECTION A TYPE QUESTIONS IN ME 266

- Q1.** Consider a fish swimming 5 m below the free surface of water. The increase in the pressure exerted on the fish when it dives to a depth of 45 m below the free surface is
(a) 392 Pa (b) 9800 Pa (c) 50,000 Pa (d) 392,400 Pa (e) 441,000 Pa
- Q2.** 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. If the density of air is 1.0 kg/m^3 , the height of the building is (a) 17 m (b) 20 m (c) 170 m (d) 204 m (e) 252 m
- Q3.** An apple loses 4.5 kJ of heat as it cools per $^{\circ}\text{C}$ drop in its temperature. The amount of heat loss from the apple per $^{\circ}\text{F}$ drop in its temperature is
(a) 1.25 kJ (b) 2.50 kJ (c) 5.0 kJ (d) 8.1 kJ (e) 4.1 kJ
- Q4.** 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
- Q5.** During a heating process, the temperature of an object rises by 20°C . This temperature rise is equivalent to a temperature rise of
(a) 20°F (b) 52°F (c) 36 K (d) 36 R (e) 293 K
- Q6.** Air ($c_p = 1.005 \text{ kJ/kg} \cdot \text{K}$) is to be heated steadily by an 8-kW electric resistance heater as it flows through an insulated duct. If the air enters at 50°C at a rate of 2 kg/s, the exit temperature of air will be
(a) 46.0°C (b) 50.0°C (c) 54.0°C (d) 55.4°C (e) 58.0°C
- Q7.** A heat engine receives heat from a source at 1000°C and rejects the waste heat to a sink at 50°C . If heat is supplied to this engine at a rate of 100 kJ/s, the maximum power this heat engine can produce is
(a) 25.4 kW (b) 55.4 kW (c) 74.6 kW (d) 95.0 kW (e) 100.0 kW
- Q8.** Steam expands in an adiabatic turbine from 8 MPa and 500°C to 0.1 MPa at a rate of 3 kg/s. If steam leaves the turbine as a saturated vapour, the power output of the turbine is
(a) 2174 kW (b) 698 kW (c) 2881 kW (d) 1674 kW (e) 3240 kW
- Q9.** Air at 15°C is compressed steadily and isothermally from 100 kPa to 700 kPa at a rate of 0.12 kg/s. The minimum power input to the compressor is
(a) 1.0 kW (b) 11.2 kW (c) 25.8 kW (d) 19.3 kW (e) 161 kW
- Q10.** Steam enters an adiabatic turbine steadily at 400°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 a liquid is
(a) 5 % (b) 10 % (c) 15 % (d) 20 % (e) 0 %
- Q11.** A 2-kW electric resistance heater in a room is turned on and kept on for 30 min. The amount of energy transferred to the room by the heater is
(a) 1 kJ (b) 60 kJ (c) 1800 kJ (d) 3600 kJ (e) 7200 kJ
- Q12.** In a hot summer day, the air in a well-sealed room is circulated by a 0.373 kW (shaft) fan driven by a 65 % efficient motor. (Note that the motor delivers 0.373 kW of net shaft power to the fan). The rate of energy supply from the fan-motor assembly to the room is
(a) 0.769 kJ/s (b) 0.325 kJ/s (c) 0.574 kJ/s (d) 0.373 kJ/s (e) 0.242 kJ/s
- Q13.** A fan is to accelerate quiescent air to a velocity to 12 m/s at a rate of $3 \text{ m}^3/\text{min}$. If the density of air is 1.15 kg/m^3 , the minimum power that must be supplied to the fan is
(a) 248 W (b) 72 W (c) 497 W (d) 216 W (e) 162 W

- Q14.** A 900-kg car cruising at a constant speed of 60 km/h is to accelerate to 100 km/h in 6 s. The additional power needed to achieve this acceleration is
(a) 41 kW (b) 222 kW (c) 1.7 kW (d) 26 kW (e) 37 kW
- Q15.** The elevator of a large building is to raise a net mass of 400 kg at a constant speed of 12 m/s using an electric motor. Minimum power rating of the motor should be
(a) 0 kW (b) 4.8 kW (c) 47 kW (d) 12 kW (e) 36 kW
- Q16.** Electric power is to be generated in a hydroelectric power plant that receives water at a rate of $70 \text{ m}^3/\text{s}$ from an elevation of 65 m using a turbine-generator with an efficiency of 85 percent. When frictional losses in piping are disregarded, the electric power output of this plant is
(a) 3.9 MW (b) 38 MW (c) 45 MW (d) 53 MW (e) 65 MW
- Q17.** A 56 kW (shaft) compressor in a facility that operates at full load for 2500 hours a year is powered by an electric motor that has an efficiency of 88 percent. If the unit cost of electricity is \$0.06/kWh, the annual electricity cost of this compressor is (a) \$7382 (b) \$9900 (c) \$12,780 (d) \$9533 (e) \$8389
- Q18.** Consider a refrigerator that consumes 320 W of electric power when it is running. If the refrigerator runs only one quarter of the time and the unit cost of electricity is \$0.09/kWh, the electricity cost of this refrigerator per month (30 days) is (a) \$3.56 (b) \$5.18 (c) \$8.54 (d) \$9.28 (e) \$20.74
- Q19.** A 2-kW pump is used to pump kerosene ($\rho = 0.820 \text{ kg/L}$) from a tank on the ground to a tank at a higher elevation. Both tanks are open to the atmosphere, and the elevation difference between the free surfaces of the tanks is 30 m. The maximum volume flow rate of kerosene is
(a) 8.3 L/s (b) 7.2 L/s (c) 6.8 L/s (d) 12.1 L/s (e) 17.8 L/s
- Q20.** A glycerin pump is powered by a 5-kW electric motor. The pressure differential between the outlet and the inlet of the pump at full load is measured to be 211 kPa. If the flow rate through the pump is 18 L/s and the changes in elevation and the flow velocity across the pump are negligible, the overall efficiency of the pump is (a) 69 % (b) 72 % (c) 76 % (d) 79 % (e) 82%
- Q21.** A 300-m^3 rigid tank is filled with saturated liquid-vapour mixture of water at 200 kPa. If 25 % of the mass is liquid and the 75 % of the mass is vapour, the total mass in the tank is
(a) 451 kg (b) 556 kg (c) 300 kg (d) 331 kg (e) 195 kg
- Q22.** A 3-m^3 rigid vessel contains steam at 10 MPa and 500 °C. The mass of the steam is (a) 3.0 kg (b) 19 kg (c) 84 kg (d) 91 kg (e) 130 kg
- Q23.** A 3-m^3 rigid tank contains nitrogen gas at 500 kPa and 300 K. Now heat is transferred to the nitrogen in the tank and the pressure of nitrogen rises to 800 kPa. The work done during this process is
(a) 500 kJ (b) 1500 kJ (c) 0 kJ (d) 900 kJ (e) 2400 kJ
- Q24.** A 0.8-m^3 cylinder contains nitrogen gas at 600 kPa and 300 K. Now the gas is compressed isothermally to a volume of 0.1 m^3 . The work done on the gas during this compression process is
(a) 746 kJ (b) 0 kJ (c) 420 kJ (d) 998 kJ (e) 1890 kJ
- Q25.** A piston-cylinder device contains 5 kg of air at 400 kPa and 30 °C. During a quasi-equilibrium isothermal expansion process, 15 kJ of boundary work is done by the system, and 3 kJ of 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) 3.5 kJ (e) 60 kJ

- Q26.** A 2-kW electric resistance heater submerged in 5-kg water is turned on and kept on for 10 min. During the process, 300 kJ of heat is lost from the water. The temperature rise of water is
(a) 0.4 °C (b) 43.1 °C (c) 57.4 °C (d) 71.8 °C (e) 180.0 °C

Use the information below to answer questions 27-29

Saturated steam vapour is contained in a piston–cylinder device. While heat is added to the steam, the piston is held stationary, and the pressure and temperature become 1.2 MPa and 700 °C, respectively. Additional heat is added to the steam until the temperature rises to 1200 °C, and the piston moves to maintain a constant pressure.

- Q27.** The initial pressure of the steam is most nearly
(a) 250 kPa (b) 500 kPa (c) 750 kPa (d) 1000 kPa (e) 1250 kPa
- Q28.** The work done by the steam on the piston is most nearly
(a) 230 kJ/kg (b) 1100 kJ/kg (c) 2140 kJ/kg (d) 2340 kJ/kg (e) 840 kJ/kg
- Q29.** The total heat transferred to the steam is most nearly
(a) 230 kJ/kg (b) 1100 kJ/kg (c) 2140 kJ/kg (d) 2340 kJ/kg (e) 840 kJ/kg
- Q30.** A Carnot refrigerator removes heat from a refrigerated space at –5 °C at a rate of 0.35 kJ/s and rejects it to an environment at 20 °C. The required power input is
(a) 30 W (b) 33 W (c) 56 W (d) 124 W (e) 350 W
- Q31.** Consider a Carnot refrigerator and a Carnot heat pump operating between the same two thermal energy reservoirs. If the COP of the refrigerator is 3.4, the COP of the heat pump is
(a) 1.7 (b) 2.4 (c) 3.4 (d) 4.4 (e) 5.0
- Q32.** Steam is condensed at a constant temperature of 30 °C as it flows through the condenser of a power plant by rejecting heat at a rate of 55 MW. The rate of entropy change of steam as it flows through the condenser is
(a) –1.83 MW/K (b) –0.18 MW/K (c) 0 MW/K (d) 0.56 MW/K (e) 1.22 MW/K
- Q33.** Which of the following properties is an example of an extensive property?
(a) Temperature (b) Energy (c) Pressure (d) Density
- Q34.** The non flow energy equation is applicable to which type of system?
(a) Open (b) Closed (c) Isolated (d) Adiabatic (e) Isothermal
- Q35.** The steady flow energy equation is applicable to which type of system?
(a) Open (b) Closed (c) Isolated (d) Adiabatic (e) Isothermal
- Q36.** Which of the following is an example of an isolated system?
(a) Automobile engine (b) Car radiator (c) Thermos flask (d) Turbine
- Q37.** The boundary of a thermodynamic system can be permeable. This means that it allows the transfer of which of the following to occur
(a) Heat (b) Work (c) Entropy (d) Mass (d) Temperature
- Q38.** A process that proceeds in such a manner that at any instance the system is only infinitesimally displaced from the equilibrium with the surroundings is known as
(a) Adiabatic process (b) Quasi-Static process (c) Isothermal process
(d) Reversible process
- Q39.** Which of the following is not a law in thermodynamics?
(a) Zeroth Law (b) First Law (c) Second Law (d) Hooke's Law
- Q40.** For a closed system undergoing a constant pressure process, the heat energy transfer during the process is equal to the change in
(a) Internal energy (b) Enthalpy (c) Entropy (d) Exergy
- Q41.** For a closed system undergoing a constant volume process, the heat energy transfer during the process is equal to the change in
(a) Internal energy (b) Enthalpy (c) Entropy (d) Exergy

- Q42.** For an adiabatic closed system, the work energy transfer during the process is equal to the change in
(a) Internal energy (b) Enthalpy (c) Entropy (d) Exergy
- Q43.** A perfectly thermal insulated cylinder undergoes a reversible process. Which of the following properties remains constant during the process?
(a) Enthalpy (b) Entropy (c) Internal Energy (d) Exergy
- Q44.** Which of the following laws of thermodynamics deals with quantity of energy?
(a) First Law (b) Second Law (c) Zeroth Law (d) Third Law
- Q45.** Which of the following laws of thermodynamics deals with quality of energy?
(a) First Law (b) Second Law (c) Zeroth Law (d) Third Law
- Q46.** Which of the following efficiencies expresses the proportion of the latent energy in the fuel that is transferred as heat to the working fluid?
(a) Relative efficiency (b) Cycle efficiency (c) Combustion efficiency
(d) Adiabatic efficiency
- Q47.** Which of the following efficiencies expresses the proportion of the heat energy transferred to the working fluid which is subsequently converted into useful mechanical work?
(a) Relative efficiency (b) Cycle efficiency (c) Combustion efficiency
(d) Adiabatic efficiency
- Q48.** All the following properties are intensive properties except
(a) Density (b) Volume (c) Temperature (d) Specific volume
- Q49.** When the basic ideal Rankine cycle is modified with superheating while maintaining the condenser and boiler pressures, the moisture content at the exit of the turbine
(a) Decreases (b) Increases (c) Remains constant (d) Becomes infinite
- Q50.** When the basic ideal Rankine cycle is modified with superheating while maintaining the condenser and boiler pressures, the work output of the turbine
(a) Decreases (b) Increases (c) Remains constant (d) Becomes infinite

SOLUTION TO SECTION A TYPE QUESTIONS

Q1	D	Q11	D	Q21	A	Q31	D	Q41	A
Q2	D	Q12	C	Q22	D	Q32	B	Q42	A
Q3	B	Q13	A	Q23	B	Q33	B	Q43	B
Q4	B	Q14	E	Q24	D	Q34	B	Q44	A
Q5	D	Q15	C	Q25	A	Q35	A	Q45	B
Q6	C	Q16	B	Q26	B	Q36	C	Q46	C
Q7	C	Q17	D	Q27	B	Q37	D	Q47	B
Q8	A	Q18	B	Q28	A	Q38	B	Q48	B
Q9	D	Q19	A	Q29	C	Q39	D	Q49	A
Q10	B	Q20	C	Q30	B	Q40	B	Q50	B