2000

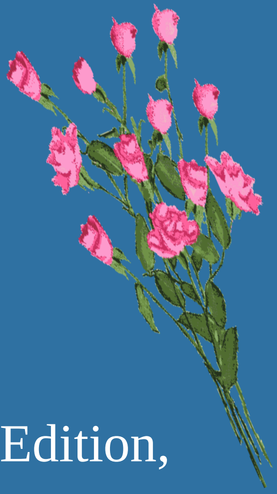
IARE

EDUCATION FOR LIBERATION

THERMODYNAMICS

B.TECH. III SEMESTER

MECHANICAL ENGINEERING



PREPARED BY:

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TEXT BOOKS

1. P. K. Nag, “Engineering Thermodynamics”, Tata McGraw Hill, 4th Edition, 2008.
2. Yunus Cengel, Michael A. Boles, “Thermodynamics-An Engineering Approach”, Tata McGraw Hill, 7th Edition, 2011

At the end of the unit students are able to:		
	Course Outcomes	Knowledge Level (Bloom's Taxonomy)
CO1	Recall the thermodynamic properties and discern the path and point functions through exact differentials.	Remember
CO2	Summarize working principles of energy conversions in physical systems by fundamental laws of thermodynamics.	Understand
CO3	Explain the various energy transfer mechanisms which leads to the ascertaining of properties involving thermodynamic cycles	Understand
CO4	Identify the laws of conservation of energy to yield the relationship between heat, work and change in internal energy.	Apply

INTRODUCTION

Basic Concepts: System, Control Volume, Surrounding, Boundaries, Universe, Types of Systems, Macroscopic and Microscopic viewpoints, Concept of Continuum, Thermodynamic Equilibrium, State, Property, Process, Cycle, Reversibility, Quasi static Process, Irreversible Process, Causes of Irreversibility, Various flow and non-flow processes ,Energy in State and in Transition, Types-Work and Heat, Point and Path function., Zeroth Law of Thermodynamics, Concept of quality of Temperature, Principles of Thermometry, Reference Points, Constant Volume gas Thermometer, Ideal Gas Scale, PMMI - Joule’s Experiments, First law of Thermodynamics, Corollaries First law applied to a Process, Applied to a flow system, Steady Flow Energy Equation.

Basic definitions

Definition of Thermodynamics

Thermodynamics is a branch of science ,phenomena of energy and related properties of matter, especially of laws of transformation of heat into other forms of energy and vice versa.

- **Macroscopic Approach**
- **Microscopic Approach**
- This approach considers that the system is made up of a very large numbers of the discrete particles known as molecules.
- These molecules have different velocities and energies.

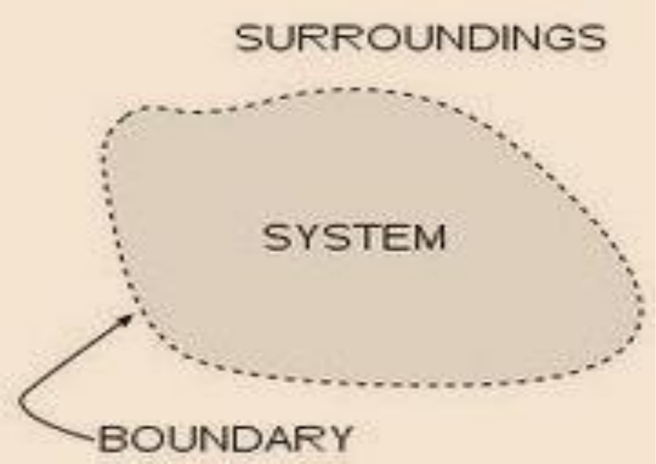
Difference between Microscopic and Macroscopic Approach

Sr. No.	Microscopic Approach	Macroscopic Approach
1	This approach considers that the system is made up of a very large numbers of the discrete particles known as molecules. These molecules have different velocities and energies.	In this approach, the behaviour of individual molecules is not considered but studies the properties of particular mass of the substances.
2	The behaviour of system is found by using statistical method as the number of molecules is very large.	The analysis of macroscopic system requires simple mathematical formulae.
3	The properties like velocity, momentum, impulse, kinetic energy etc, which describes the molecule cannot be easily measured by instruments.	The properties like temperatureand pressure are required to describe the system can be easily measured.
4	Large number of variables is needed to describe such a system. So approach is complicated.	Only few properties are needed to describe such a system.

Definitions of thermodynamics terminology

Thermodynamic systems: A thermodynamic system may be defined as the quantity of matter or definite region in space upon which some thermodynamic process is taking place.

Thermodynamic systems are defined by using a real or imaginary boundary. Anything beyond real or imaginary boundary is known as *surroundings*.



Surrounding: The space outside the thermodynamic system is known as surrounding.

Boundary: The line separating the system and surrounding is known as boundary.

2 Types boundaries are

Fixed and movable w.r.t volume

Adiabatic and w.r.t heat transfer.

Universe: The combination of system , surrounding and boundary is known as universe.

State of system:

A state is a macroscopic condition of a thermodynamic system as described by its particular thermodynamic parameters.

Some thermodynamic parameters are pressure,temperature, density, composition etc.

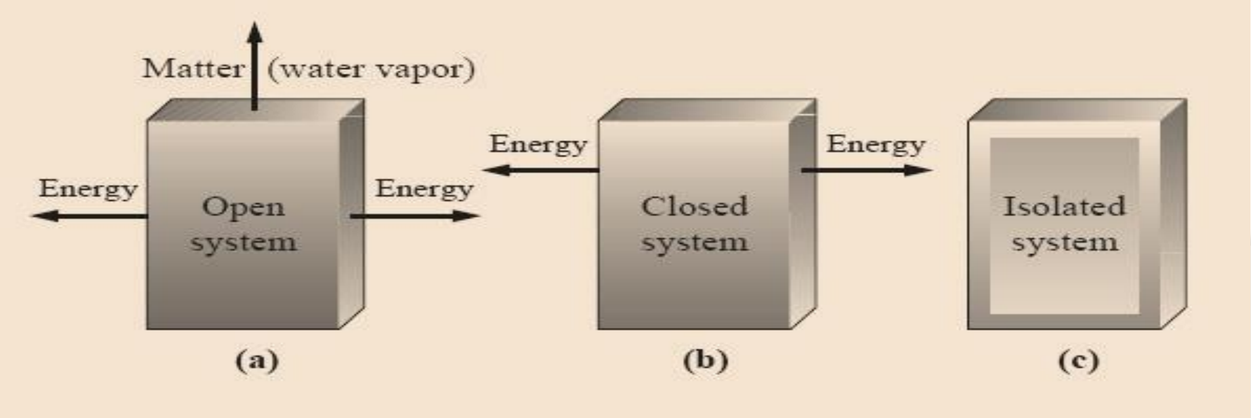
Classification of thermodynamic systems

Thermodynamic systems may be broadly classified in three categories:

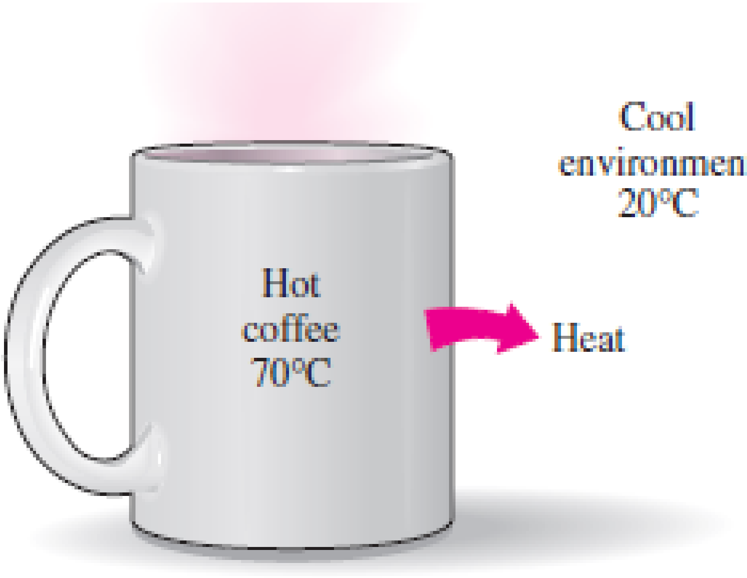
1. Open system
2. Closed system
3. Isolated system

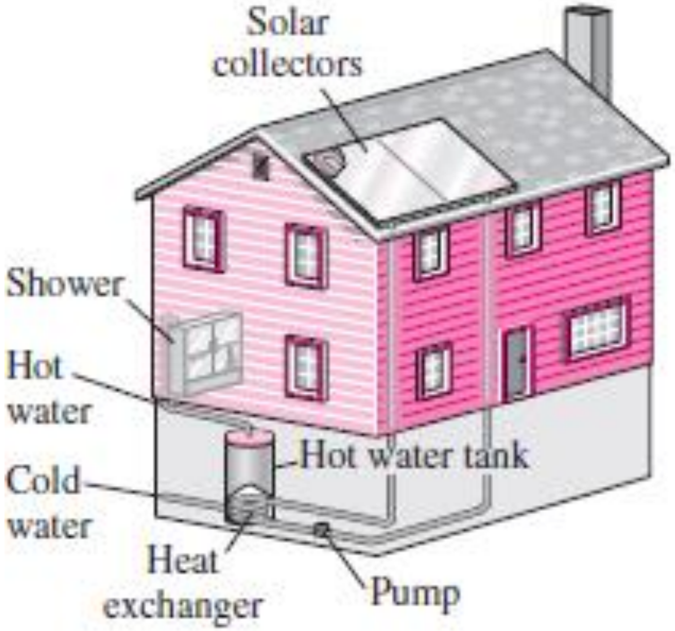
Open system: Open system is one in which matter (mass of working substance) as well as energy (heat and work) crosses the boundary of the system. energy as well as water vapour is coming out from the system.

Closed system: Closed system is one in which only energy (heat and work) crosses the boundary of the system without adding or losing of matter (mass of working substance). **Isolated system:** In an isolated system neither matter (mass of working substance) nor energy (heat and work) crosses the boundary of the system.



Examples of Thermodynamics





Examples of Thermodynamics

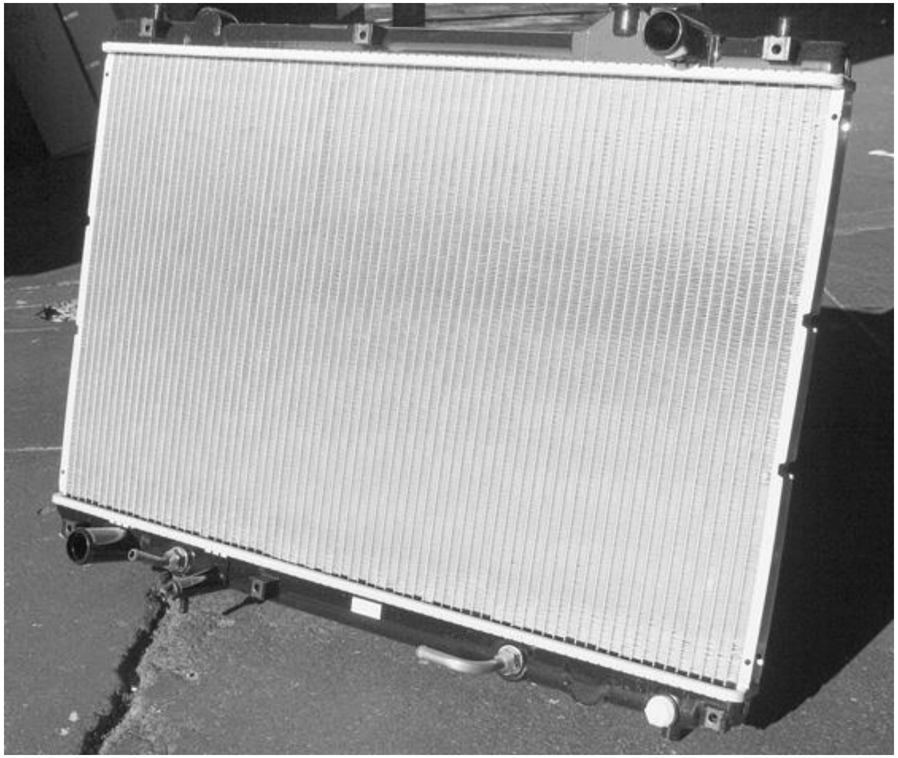
Human beings

Air conditioners

Refrigerators

Examples of Thermodynamics

Power Plant



Car radiator

THERMODYNAMIC EQUILIBRIUM

Equilibrium

Equilibrium indicates the state of balance. In an equilibrium state there are no unbalanced potentials within the system.

Equilibrium may be classified as:

- Chemical Equilibrium
- Mechanical Equilibrium
- Thermal Equilibrium

(i) **Chemical Equilibrium:** If there is no chemical reaction or diffusion of matter from one part of the system to another, the system is said to be in chemical equilibrium.

(ii) **Mechanical Equilibrium:** If there are no unbalanced forces in the system, the system is said to be in mechanical equilibrium.

(ii) **Thermal Equilibrium:** When a system is prevailing in chemical and mechanical equilibrium is separated from its surroundings by a diathermic wall and if no spontaneous change in any property of the system, the system is said to be in state of thermal equilibrium.

Thermodynamic Properties of a system

Properties are those characteristics of the system which can be used for defining the system. Such as volume, pressure, temperature, viscosity etc.

Classification of properties of a thermodynamic system

The thermodynamic properties may be classified into two categories:

1. Intensive property
2. Extensive property

1.Intensive property: Intensive properties are those properties which have same value for any part of the system or these are those properties that are independent of the mass of the system. Such as temperature, pressure and density.

2.Extensive property**:** Extensive properties are those properties which depend upon the mass of the system and do not maintain the same value for any path of the system. Such as mass, enthalpy, volume and energy etc

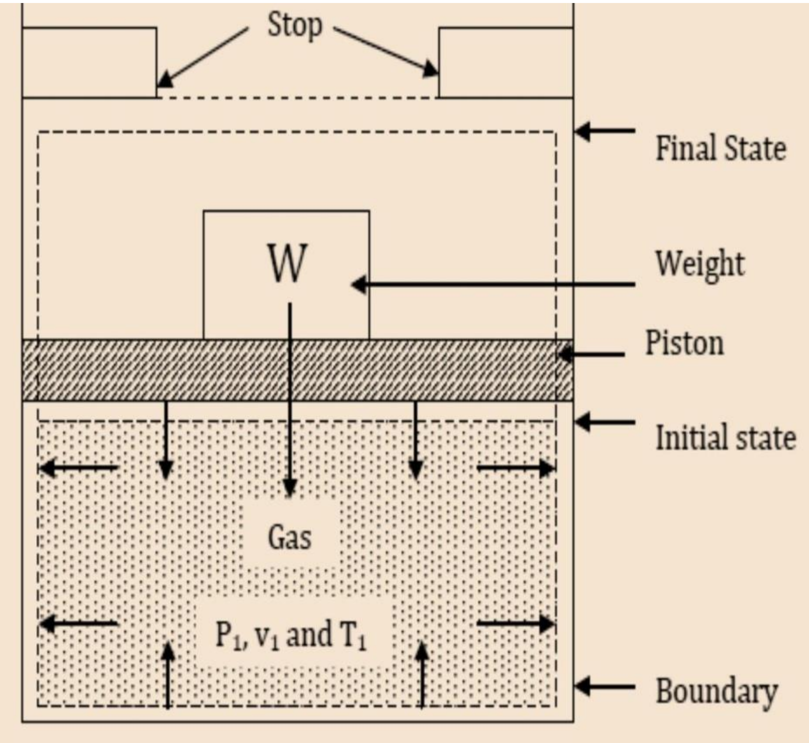
- Note: The ratio of extensive property of the system to the mass of the system gives the intensive property. Such as the ratio of total volume (V) of the system to its total mass (m) is known as v_s specific volume. = V/m …………it is an intensive property.

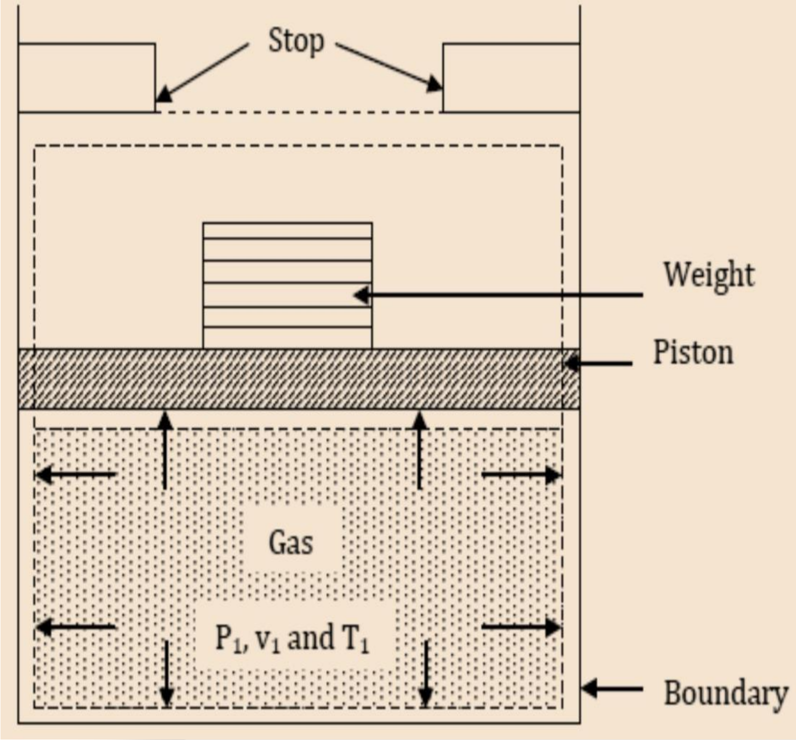
Path: If all the changes of states of the system are plotted, then line joining the change of states of the system is known as path.

- **cycle:** A thermodynamic cycle is defined as the series of state of changes such that the intial state is identical with the final state.

Quasi-Static Process

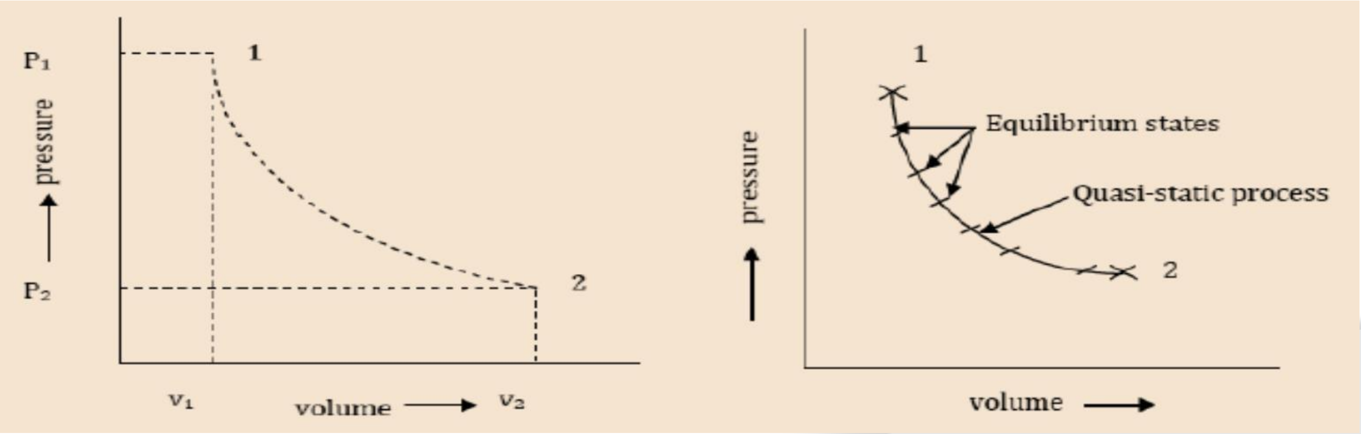
Consider a system which contained gas in a cylinder in fig. Initially it is in an equilibrium state, represents the properties P1, v1, T1. The weight on the piston just balance the force exerted by the gas. When weight is removed from the piston the system become unbalanced. The unbalanced force is between the system and the surrounding, and gas pressure will moves the piston in upward direction till it hits the stop.





The system again comes to an equilibrium states, being described by the properties P2, v2, T2. But the immediate states passed through by the system are non-equilibrium states which cannot be described by thermodynamic coordinates. Figure shows the points 1 and 2 as the initial and final equilibrium states joined by dotted line.

Now if the single weight on the piston is made up of many very small pieces of weights and these weights are removed one by one very slowly, at any instant of the upward travel of the piston, if the gas is isolated, the departure of the state of the system from thermodynamic equilibrium state will be infinitesimally small. So every state passed through by the system will be an equilibrium state.



Forms of Energy

1. Work
2. Heat

Work

Work is one of the basic modes of energy transfer.

In mechanics the action of a force on a moving body is identified as work. The work is done by a force as it acts upon a body moving in the direction of force.

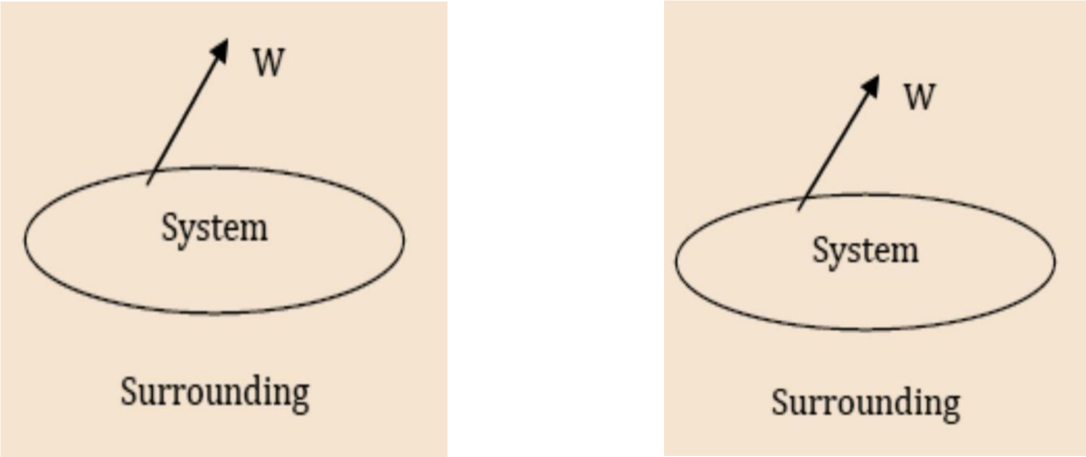
In thermodynamics, work transfer is considered as occurring between the system and the surroundings. Work is said to be done by a system if the sole effect on the things external to the system can be reduced to the raising of a weight.

The work is done by a system, it is taken to be positive, and when work is done on a system, it is taken to be negative.

Energy and its forms

Energy is defined as the capacity to do work or energy can also be defined as the capacity to exert a force in a given direction through a distance.

The unit of energy in SI (System international) system is Nm or Joule (J).



(a)Work is Positive (+ve)(b) Work is negative (-ve)

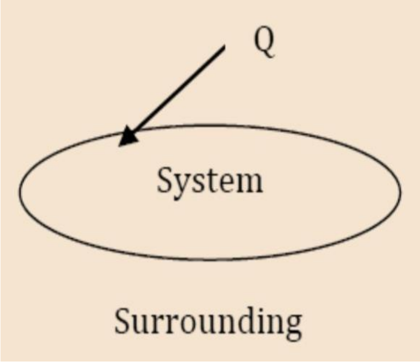
Power: The rate of energy transfer is known as power or the rate of work transfer is known as power. The unit of power is J/s or Watt.

Heat

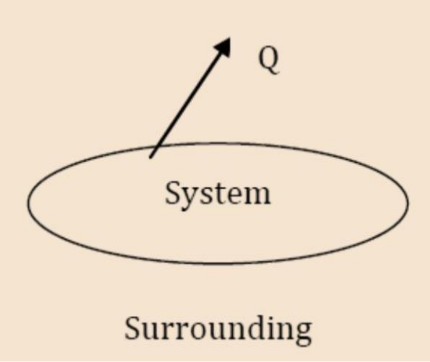
Heat is defined as the form of energy that is transferred across a boundary by virtue of a temperature difference. The temperature difference is the potential or force and heat transfer is the flux.

Heat flow into a system is taken to be positive, and heat flow out of a system is taken as negative.

A process in which no transfer of heat through boundary is known as adiabatic process.



(a)Heat transfer is Positive (+ve)



(b) Heat transfer is negative (-ve)

The symbol used for heat transfer is Q. The unit of heat transfer in SI (System international) system is Nm or Joule (J). The rate of heat transfer is given by W or kW.

Types of Heat

1. Specific Heat: Specific heat is defined as the amount of heat required to raise the temperature of a unit mass (1kg) of the substance by unit degree (1oC or 1K) change in temperature.

The quantity of heat absorbed or rejected by a system during heating or cooling is measured by the formula as given below:

$$Q=m\times c\times(T2-T1)$$

Where, Q= heat gainor loose by the system in kJ,

m= mass of the substance in kilograms (kg),

c= specific heat in kJ/kgK

(T2-T1)= Temperature rise or drop in degree Celsius or Kelvin

Types of specific heat: Basically there are two types of specific heats as given below:

(i) Specific heat at constant pressure (cp)

(ii) Specific heat at constant volume (cv)

(iii)Specific heat at constantpressure(cp): It is defined as the amount of heatrequired to raise the temperature of a unit mass (1kg) of the substance by unit degree(1oC or 1K) change in temperature when the pressure is constant. It is represented bycp. Its unit is kJ/kgK.

(ii) Specific heat at constant volume (cv): It is defined as theamount of heatrequired to raise the temperature of a unit mass (1kg) of the substance by unit degree(1oC or 1K) change in temperature when the volume is constant. It is represented by cv. Its unit is kJ/kgK.

Specific heat of water: c=4.186 kJ/kgK

Specific heats of air: cp=1.005 kJ/kgK cv=1.005 kJ/kgK

2.Latent heat of vaporization: Itis defined as the amount ofheat requiredto evaporated one kilogram of water at its saturation temperature (boiling point) without change of temperature. It is represented by hfg. Its unit is kJ/kg. The latent heat of vaporization of water or latent heat of steam is 2257 kJ/kg.

FIRST LAW OF THERMODYNAMICS

First law of thermodynamics

First law of thermodynamics also states that, “the energy can neither be created nor be destroyed it can only be transformed from one form to another.” According to this law, when a system undergoes a thermodynamic process, both heat and work transfer takes place. The net energy is stored within the system and is termed as stored energy or total energy of the system. Mathematically it is written as:

$$\delta Q - \delta W = dE$$

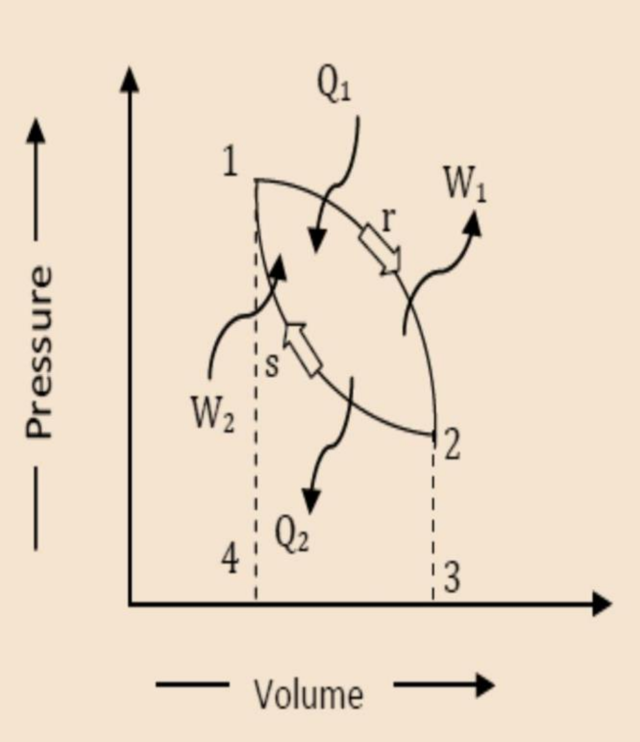
First law of thermodynamics for a cyclic process

A process is cyclic if the initial and final states of the system are identical. A system represented by state 1 undergoes a process 1-r-2 and returns to the initial state following the path 2-s-1. All the properties of the system are restored, when the initial and final state is reached. During the completion of these processes:

(a)Area 2-3-4-1-s-2 denotes the work done W1 by the system during expansion process 2-s-1.

(b)Area 4-3-1-s-4 denotes the work done W2 supplied to the system during the compression process 4-s-1.

(c) Area 1-r-2-s-1 denotes the net work done (W1-W2) delivered by the system.



Note: The total energy is the sum of potential energy, kinetic energy and internal energy of the system. It is mathematically written as:

$$E = P.E. + K.E. + U$$

$$E = mgz + \frac{mv^2}{2} + U$$

Where,

P.E. = Potential energy,

K.E. = Kinetic energy, U = Internal Energy.

Internal Energy: Internal energy of steam is define as the energy stored in the steam, above 0oC (freezing point) of water. It may be obtained by subtracting the work done during evaporation to the enthalpy of steam. It is represented by U. Mathematically it is written as,

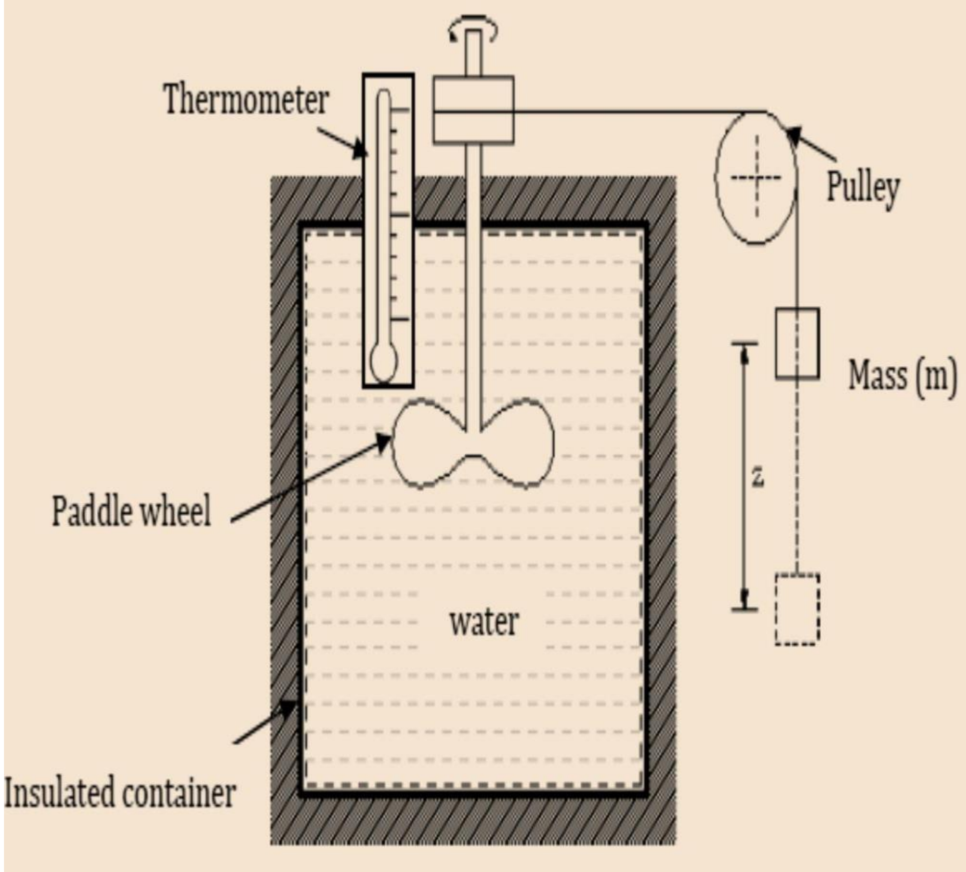
Internal energy of steam=Enthalpy of steam-Workdone during evaporation

Enthalpy: It is defined as the amount of heat absorbed by water from 0oC (freezing point) to saturation point (sensible heat) plus heat absorbed during evaporation (latent heat). It is represented by hg.

So that,

Enthalpy=sensible heat + latent heat

Joule’s experiment



TYPES OF PROCESSES

- **isobaric:** process done at constant pressure
- **isochoric:** process done at constant volume
- **isothermal:** process done at constant temperature
- **adiabatic:** process where $q=0$
- **cyclic:** process where initial state = final state

ISOBARIC PROCESS

- An **isobaric process** is a thermodynamic process in which the pressure stays constant.
- An example would be to have a movable piston in a cylinder, so that the pressure inside the cylinder is always at atmospheric pressure, although it is isolated from the atmosphere. In other words, the system is **dynamically connected**, by a movable boundary, to a constant-pressure reservoir.

An isochoric process

- also called a **constant-volume process**, an **iso volumetric process**, or an **isometric process**, It is a process during which the volume of the closed system undergoing such a process remains constant.
- An isochoric process is exemplified by the heating or the cooling of the contents of a sealed, inelastic container:

STEADY FLOW ENERGY EQUATION

Steady Flow Energy Equation (S.F.E.E.)

The fluid enters the control volume at point 1 with a average velocity V_1, pressure P_1, specific volume v_1 and internal energy U_1.The fluid exit the control volume at point 2 and the corresponding values are V_2, P_2, v_2, U_2. During the fluid flow from the two sections, heat Q and mechanical work W may also cross the control surface.

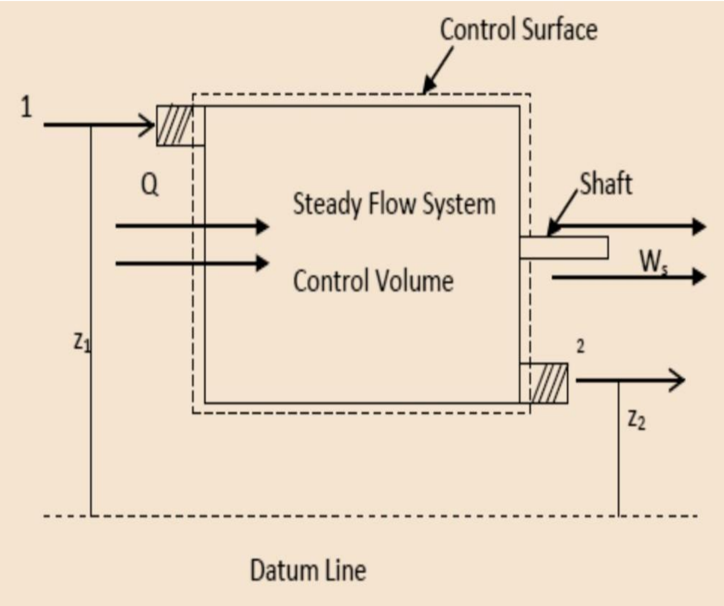
The following points are taken into consideration for energy balance equation:

(i) Internal energy

(ii) Kinetic and potential energies.

(iii) Flow work

(iv) Heat and mechanical work which cross the control volume.



From the law of conservation of energy, energy neither be created nor be destroyed we can write,

Total energy flow rate into the control volume = Total energy flow rate out of control volume

m(energy carried into the system)+m(flow work)+ rate of heat flow= m(energy carried out of the system)+m(flow work)+ rate of work transfer

m(I.E.+P.E.+K.E.)$_1$ +m(flow work)$_1$ +Q= m(I.E.+P.E.+K.E.)$_2$ +m(flow work)$_2$ +W

$$\text{Where, } Q = \frac{dQ}{dt} \, and \, W = \frac{dW}{dt}$$

$$m\left(U_1 + gz_1 + \frac{V_1^2}{2}\right) + m(P_1 v_1) + Q = m\left(U_2 + gz_2 + \frac{V_2^2}{2}\right) + m(P_2 v_2) + W$$

Arranging the equation,

$$m\left(U_1+P_1v_1+gz_1+\frac{V_1^2}{2}\right)+Q=m\left(U_2+P_2v_2+gz_2+\frac{V_2^2}{2}\right)+W$$

$$m\left((U_1+P_1v_1)+gz_1+\frac{V_1^2}{2}\right)+Q=m\left((U_2+P_2v_2)+gz_2+\frac{V_2^2}{2}\right)+W$$

Since $h = (U+Pv)$, so that $h_1 = (U_1+P_1v_1)$ and $h_2 = (U_2+P_2v_2)$

$$\boldsymbol{m\left(h_1+gz_1+\frac{V_1^2}{2}\right)+Q=m\left(h_2+gz_2+\frac{V_2^2}{2}\right)+W}$$

This equation is known as steady flow energy equation (SFEE).

If the mass of fluid is taken as unity then steady flow energy equation is reduces to,

$$\left(h_1+gz_1+\frac{V_1^2}{2}\right)+q_{1-2}=\left(h_2+gz_2+\frac{V_2^2}{2}\right)+w$$

All the terms represent energy flow per unit mass of fluid (J/kg).

Applications of Steady flow energy equation

Steady flow energy equation is commonly used in flow processes in many engineering plants. Some commonly used engineering systems which works on steady flow energy equation (SFEE) are as follows:

(i) Compressor

(ii) Condenser

(iii) Boiler

(iv) Turbine

(v) Nozzle and

(vi) Pump

(i) Compressor: Compressor is a device which is used to compress the fluid (may be air) and deliver it at a high pressure and large flow rate. There are two types of compressors as follows:

(a) Rotary compressor

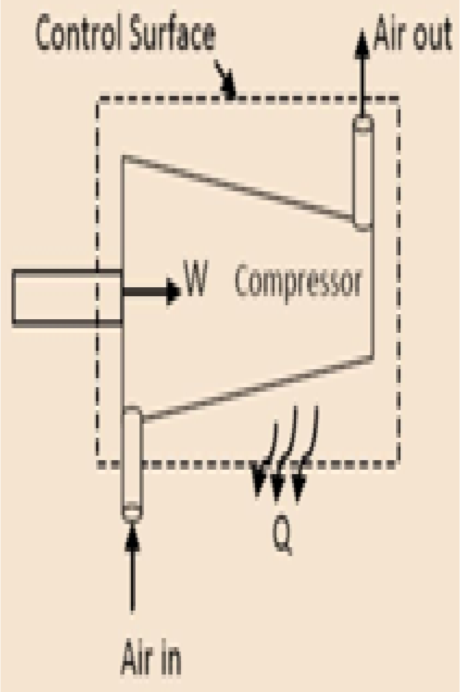
(b) Reciprocating compressor

(a) Rotary compressor: Rotary compressors are the devices which are used to develop high pressure and have a rotor as their primary element. The characteristic features of flow through a rotary compressor are:

- ☐ Work is done on the system so that W is negative.
- ☐ Negligible change in Potential energy.
- ☐ Heat is lost from the system so that Q is negative

Steady flow energy equation may be written as follows:

$$m\left(h_1+\frac{V_1^2}{2}\right)-Q=m\left(h_2+\frac{V_2^2}{2}\right)-W$$



Or

$$W=m\left(h_2+\frac{V_2^2}{2}\right)-m\left(h_1+\frac{V_1^2}{2}\right)+Q$$

If the change in velocity is negligible and the flow process is assumed as adiabatic (i.e. Q=0) due to very high flow rates, then

$$W=m(h_2-h_1)$$

Steady flow energy equation may be written as follows:

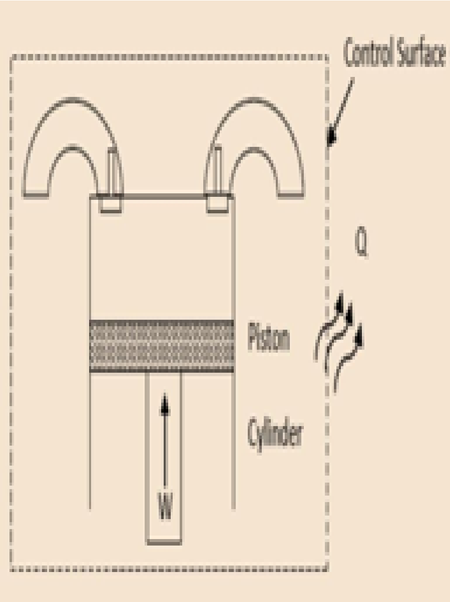
$$m\left(h_1+\frac{V_1^2}{2}\right)-Q=m\left(h_2+\frac{V_2^2}{2}\right)-W$$

Or

$$W=m\left(h_2+\frac{V_2^2}{2}\right)-m\left(h_1+\frac{V_1^2}{2}\right)+Q$$

If the change in velocity is negligible, then

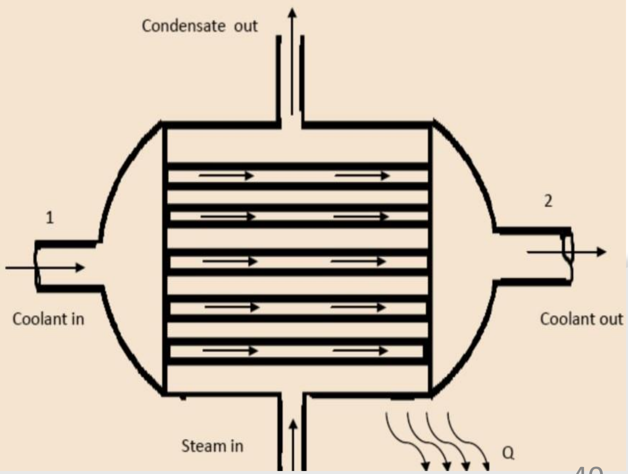
$$W=m(h_2-h_1)+Q$$



Condenser: Condenser is a type of heat exchanger. It is used to transfer heat from one fluid to another. The characteristic features of a condenser are as follows:

- No mechanical work (i.e., W=0).
- No change in kinetic and potential energies.
- No external heat interaction (Since it is perfectly insulated).
- Heat is absorbed by the one fluid (Steam) to the another fluid (coolant), so that heat is taken negative.
- Thus steady flow energy equation reduces to;

$$h_1 - Q = h_2$$
$$Q = h_1 - h_2$$

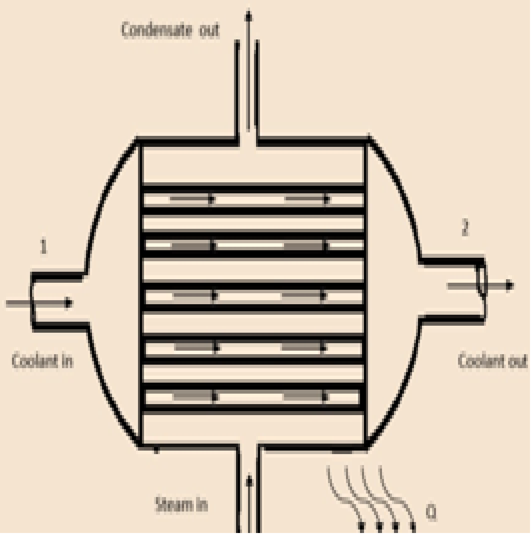


Thus steady flow energy equation reduces to;

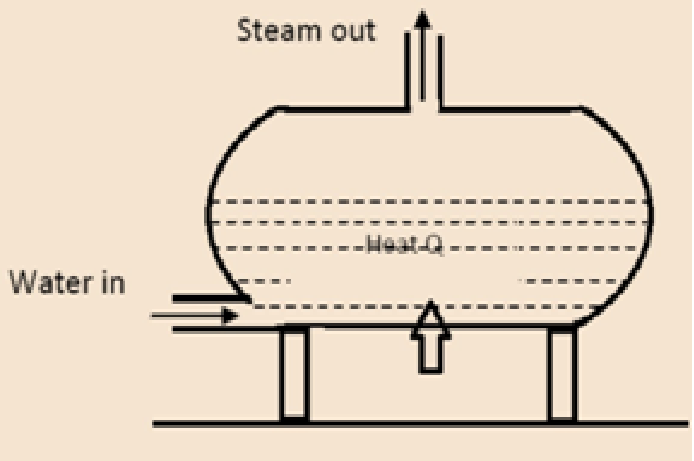
$$m\left(h_1+gz_1+\frac{V_1^2}{2}\right)+Q=m\left(h_2+gz_2+\frac{V_2^2}{2}\right)+W$$

$$h_1-Q=h_2$$

$$Q=h_1-h_2$$



(iii) Boiler: Boiler is an equipment used for generation of steam. Thermal energy released by combustion of fuel is transferred to water which vaporizes and gets converted into steam.



The characteristic features of a boiler are as follows:

- ☐ No mechanical work (i.e., W=0).
- ☐ No change in kinetic and potential energies
- ☐ Height change between inlet and exit point is negligible.

Thus steady flow energy equation reduces to;

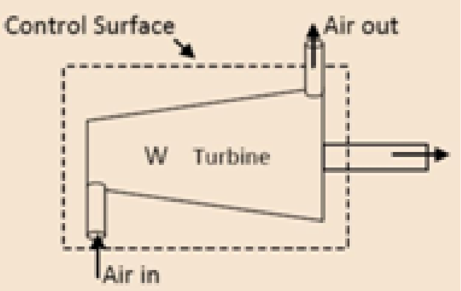
$$m\left(h_1 + gz_1 + \frac{V_1^2}{2}\right) + Q = m\left(h_2 + gz_2 + \frac{V_2^2}{2}\right) + W$$

$$h_1 + Q = h_2$$

$$Q = h_2 - h_1$$

(iv) Turbine: Turbine is a device which converts thermal energy into useful work. In turbine fluids expand from high pressure to a low pressure. The work output from the turbine may be used to drive a generator to produce electricity. The characteristic features of a turbine are as follows:

- ❑ Negligible change in velocity so that negligible change in kinetic energy.
- ❑ Negligible change in potential energy.
- ❑ Isentropic expansion takes place since the walls of turbine are thermally insulated.



Thus steady flow energy equation reduces to;

$$m\left(h_1 + gz_1 + \frac{V_1^2}{2}\right) + Q = m\left(h_2 + gz_2 + \frac{V_2^2}{2}\right) + W$$

$$W = m(h_2 - h_1)$$

(v) Nozzle: Nozzle is a device of varying cross-section used for increasing the velocity of a flowing stream at the expense of its pressure drop. In nozzle pressure energy of the fluid is converted into kinetic energy. It is used in turbines, fuel pumps and jet engines etc.

The characteristic features of a nozzle are as follows:

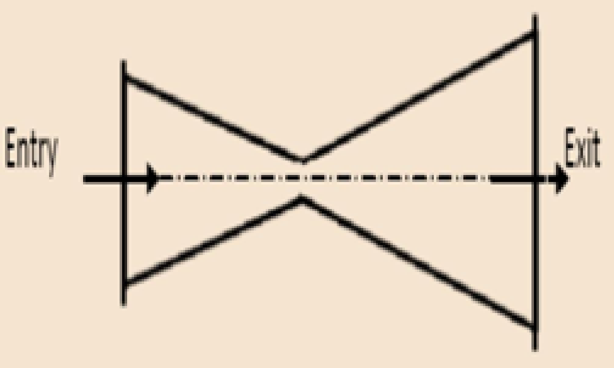
- No mechanical work (i.e. W=0)
- Flow is isentropic (i.e. Q=0)
- Change in height between entry and exit is negligible. (i.e. $z_1=z_2$)

Thus steady flow energy equation reduces to;

$$\left(h_1+\frac{V_1^2}{2}\right)=\left(h_2+\frac{V_2^2}{2}\right)$$

Let V_1 is known then,

$$V_2=\sqrt{2(h_1-h_2)+V_1^2}$$



(vi) Pump: A pump is a device which takes the fluid from a low level and delivers it to a high level. The characteristic features of a pump are as follows:

❑ No change in internal energy.

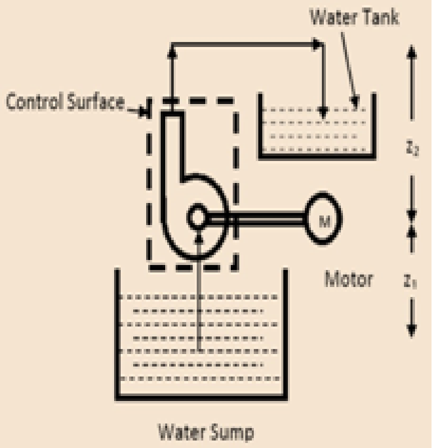
❑ Work is done on the system, so that work is taken negative.

Thus steady flow energy equation reduces to;

❑ Flow is assumed to be adiabatic (i.e. Q=0)

$$m\left(h_1 + gz_1 + \frac{V_1^2}{2}\right) + Q = m\left(h_2 + gz_2 + \frac{V_2^2}{2}\right) + W$$

$$m\left(gz_1 + \frac{V_1^2}{2}\right) = m\left(gz_2 + \frac{V_2^2}{2}\right) - W$$



UNIT – II

SECOND LAW OF THERMODYNAMICS

At the end of the unit students are able to:		
	Course Outcomes	Knowledge Level (Bloom's Taxonomy)
CO5	Contrast between various statements of purpose in heat to work conversion and notice that thermodynamic direction laws defining them are mutually complementary.	Understand
CO6	Relate various relations involving pressure, temperature and volume to discern the change in entropy generation in universe.	Understand

LIMITATIONS OF FIRST LAW

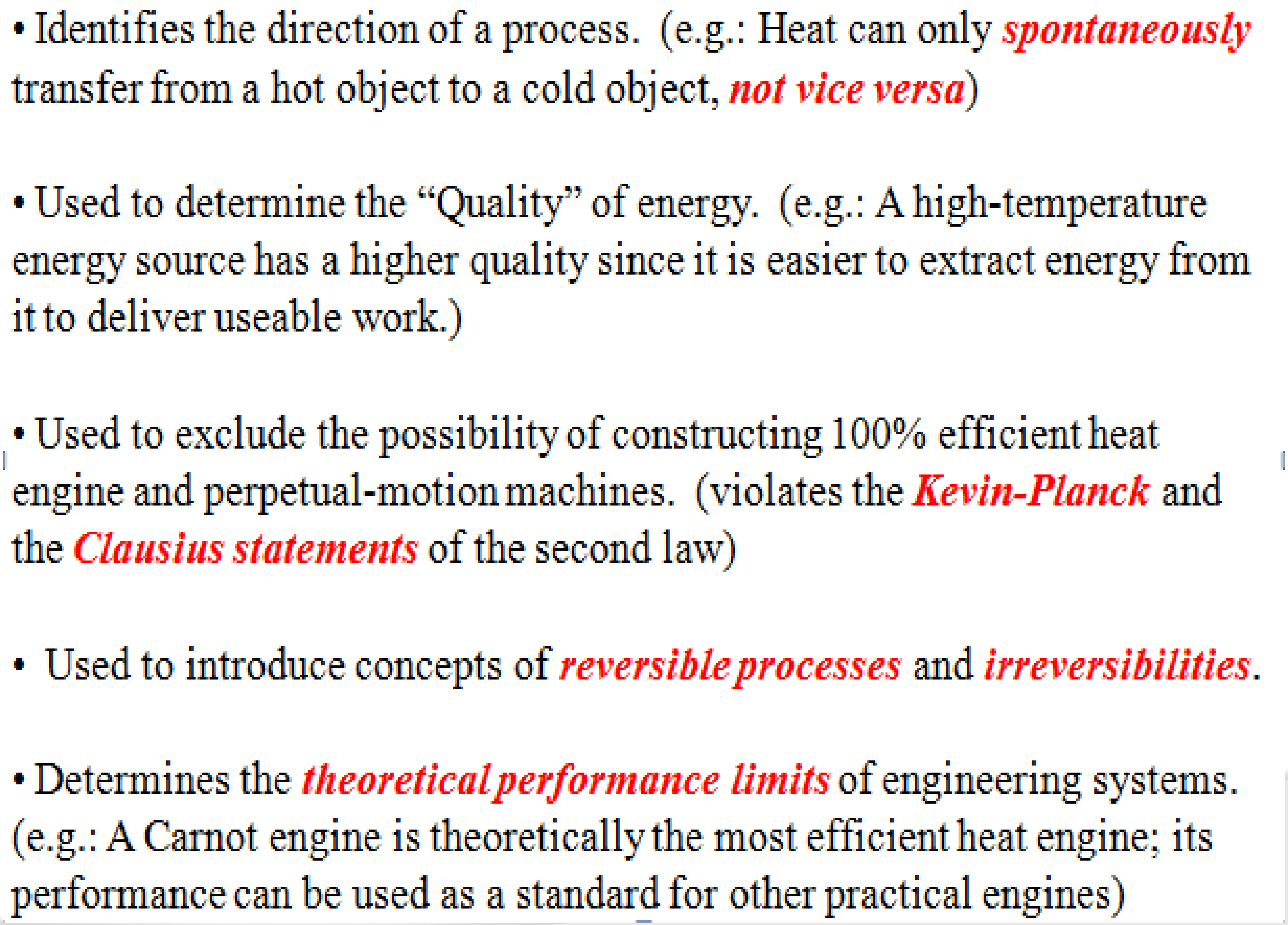
Thermal Reservoir, Heat Engine, Heat pump, Parameters of performance, Second Law of Thermodynamics, Kelvin Planck and Clausius Statements and their Equivalence / Corollaries, PMM of Second kind, Carnot's principle, Carnot cycle and its specialties, Thermodynamic scale of Temperature, Clausius Inequality, Entropy, Principle of Entropy Increase, Availability and Irreversibility, Thermodynamic Potentials, Gibbs and Helmholtz Functions, Maxwell Relations, Elementary Treatment of the Third Law of Thermodynamics

The problems arise from:

1. Classical thermodynamics is connected with states of equilibrium and various processes connecting them.
2. The exact process by which a system reaches the final state from its initial state is immaterial. i.e. the transition is independent of the particular path taken
3. The theory emphasizes reversible processes! Yet, real processes are irreversible!

Examples of processes which are not prohibited by the first law, but cannot happen in a real world.

- Transfer heat from cold to hot subject
- Gas expansion



- Identifies the direction of a process. (e.g.: Heat can only ***spontaneously*** transfer from a hot object to a cold object, ***not vice versa***)

- Used to determine the “Quality” of energy. (e.g.: A high-temperature energy source has a higher quality since it is easier to extract energy from it to deliver useable work.)

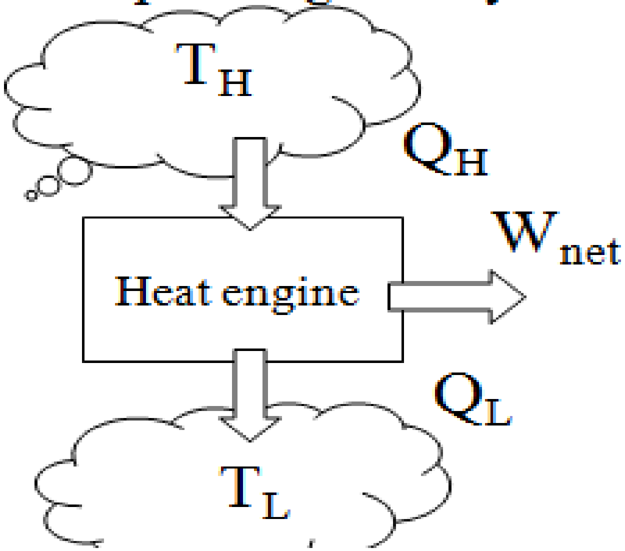
- Used to exclude the possibility of constructing 100% efficient heat engine and perpetual-motion machines. (violates the ***Kevin-Planck*** and the ***Clausius statements*** of the second law)

- Used to introduce concepts of ***reversible processes*** and ***irreversibilities***.

- Determines the ***theoretical performance limits*** of engineering systems. (e.g.: A Carnot engine is theoretically the most efficient heat engine; its performance can be used as a standard for other practical engines)

- A process can not happen unless it satisfies both the first and second laws of thermodynamics. The first law characterizes the balance of energy which defines the "quantity" of energy. The second law defines the direction which the process can take place and its "quality".

- Define a "Heat Engine": A device that converts heat into work while operating in a cycle.



$\Delta Q - W_{net} = \Delta U$ (since $\Delta U = 0$ for a cycle)
$\Rightarrow W_{net} = Q_H - Q_L$

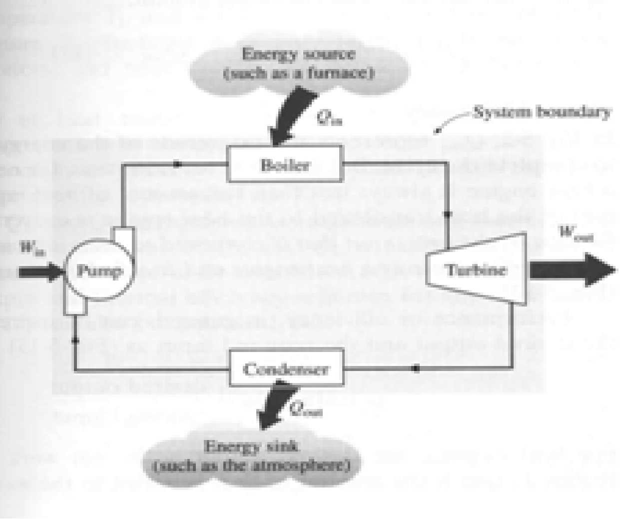
Thermal efficiency, η_{th} is defined as
$\eta_{th} = W_{net}/Q_H = (Q_H - Q_L)/Q_H$
$= 1 - (Q_L/Q_H)$

Question: Can we produce an 100% heat engine, i.e. a heat engine where $Q_L = 0$?

Steam Power Plant

- A ***steam power plant*** is a good example of a heat engine where the working fluid, water, undergoes a thermodynamic cycle

$W_{net} = W_{out} - W_{in} = Q_{in} - Q_{out}$
Q_{in} is the heat transferred from the high temp. reservoir, and is generally referred to as Q_H
Q_{out} is the heat transferred to the low temp. reservoir, and is generally referred to as Q_L



Thermal efficiency

$\eta_{th} = W_{net}/Q_H = (Q_H - Q_L)/Q_H = 1 - (Q_L/Q_H)$
Typical Efficiency of a large commercial steam power plant ≈ 40%

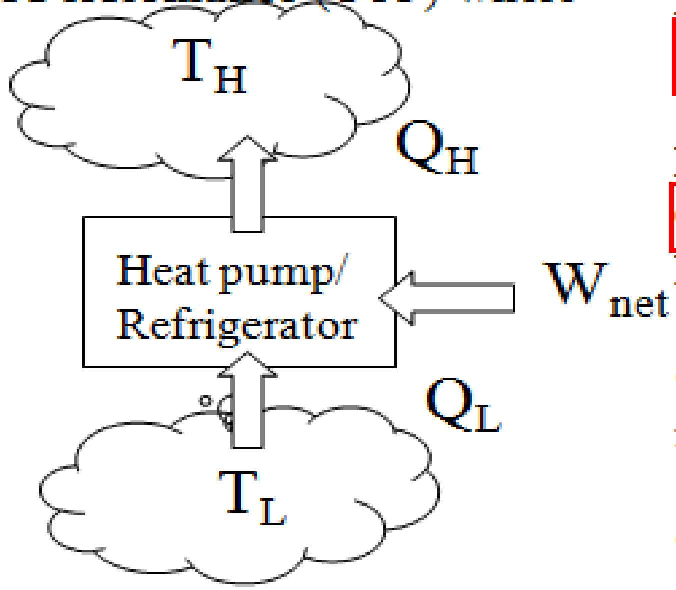
Thermal Reservoir

A hypothetical body with a very large thermal capacity (relative to the system beig examined) to/from which heat can be transferred without changing its temperature. E.g. the ocean, atmosphere, large lakes.

Back

Heat Pumps and Refrigerators

- A "heat pump" is defined as a device that transfers heat from a low-temperature source to a high-temperature one. E.g. a heat pump is used to extract energy from outside cold outdoor air into the warm indoors.
- A refrigerator performs the same function; the difference between the two is in the type of heat transfer that needs to be optimized.
- The efficiencies of heat pumps and refrigerators are denoted by the **Coefficient of Performance** (COP) where



For a Heat Pump:

$$\boxed{COP_{HP}=Q_H/W_{net}=Q_H/(Q_H-Q_L) = 1/(1-Q_L/Q_H)}$$

For a Refrigerator:

$$\boxed{COP_R=Q_L/W_{net}=Q_L/(Q_H-Q_L) = 1/(Q_H/Q_L-1)}$$

Note: $COP_{HP} = COP_R + 1$

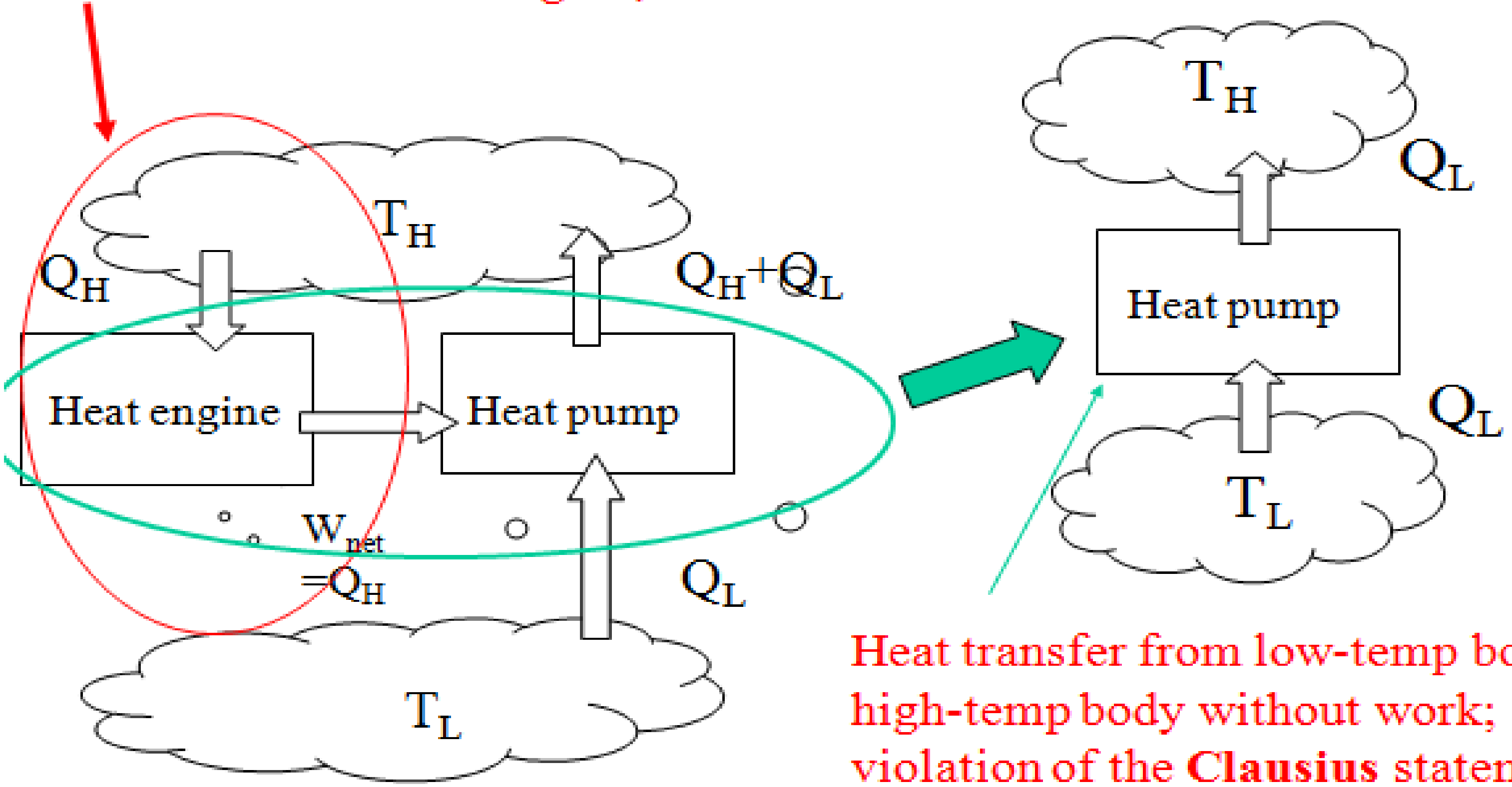
- $COP_{HP}>1$, ex: a typical heat pump has a COP in the order of 3

- **Question**: Can one build a heat pump operating $COP= \infty$, that is $W_{net}= 0$ and $Q_H=Q$?

Equivalence of the Two Statements

It can be shown that the violation of one statement leads to a violation of the other statement, i.e. they are equivalent.

A 100% efficient heat engine; violates **K-P** Statement



Heat transfer from low-temp body to high-temp body without work; A violation of the **Clausius** statement

Reversible Processes and Irreversibility's

- A reversible process is one that can be executed in the reverse direction with no net change in the system or the surroundings.
- At the end of a forwards and backwards reversible process, ***both system and the surroundings are returned to their initial states.***
- ***No real processes are reversible.***
- However, ***reversible processes are*** theoretically ***the most efficient*** processes.
- All real processes are irreversible due to ***irreversibilities***. Hence, real processes are less efficient than reversible processes.

Common Sources of Irreversibility:

  - Friction
  - Sudden Expansion and compression
  - Heat Transfer between bodies with a *finite temperature difference.*

- A **quasi-equilibrium process**, e.g. very slow, frictionless expansion or compression is a reversible process.

Reversible Processes and Irreversibilities (cont'd)

- A ***work-producing*** device which employs quasi-equlibrium or reversible processes ***produces the maximum amount of work*** theoretically possible.

- A ***work-consuming*** device which employs quasi-equilibrium or reversible processes ***requires the minimum amount of work*** theoretically possible.

- One of the most common idealized cycles that employs all reversible processes is called the ***Carnot Cycle*** proposed in 1824 by Sadi Carnot.

The Carnot Cycle

French military engineer Nicolas Sadi Carnot (1769-1832) was among the first to study the principles of the second law of thermodynamics. Carnot was the first to introduce the concept of cyclic operation and devised a reversible cycle that is composed of four reversible processes, two isothermal and two adiabatic.

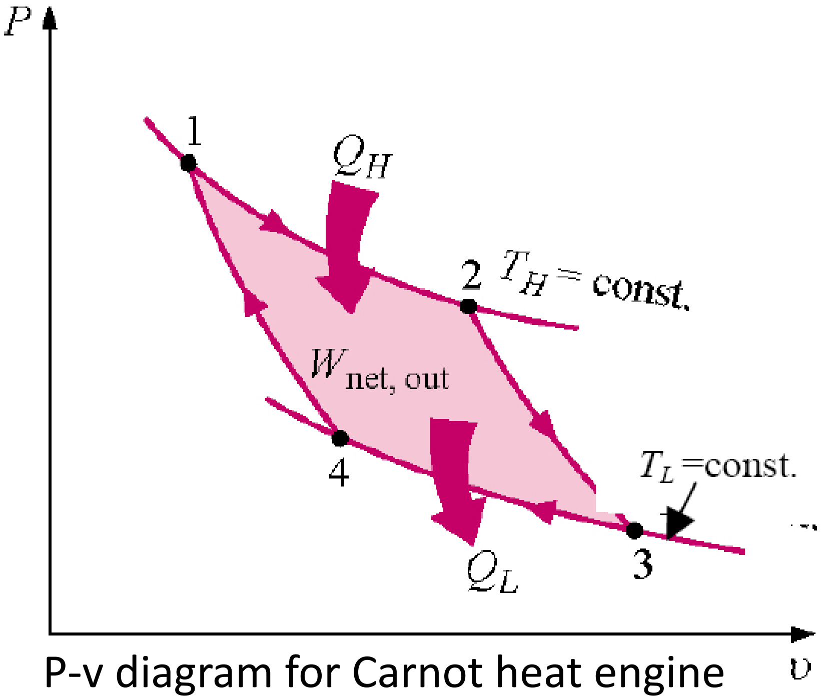
The Carnot Cycle

Process 1-2:Reversible isothermal heat addition at high temperature, $T_H > T_L$, to the working fluid in a piston-cylinder device that does some boundary work.

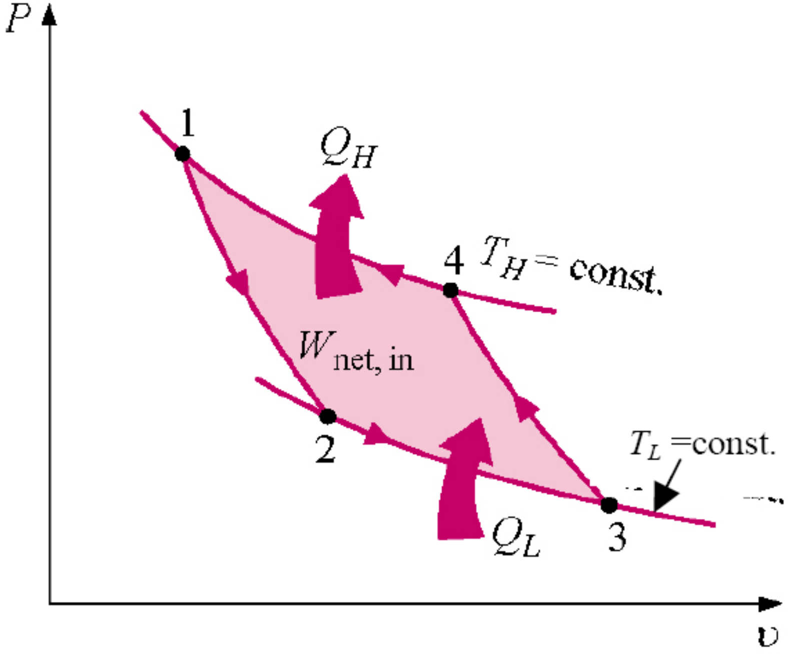
Process 2-3:Reversible adiabatic expansion during which the system does work as the working fluid temperature decreases from T_H to T_L.

Process 3-4:The system is brought in contact with a heat reservoir at $T_L < T_H$ and a reversible isothermal heat exchange takes place while work of compression is done on the system.

Process 4-1:A reversible adiabatic compression process increases the working fluid temperature from T_L to T_H



P-v diagram for Carnot heat engine



P-v diagram for Carnot refrigerator

You may have observed that power cycles operate in the clockwise direction when plotted on a process diagram. The Carnot cycle may be reversed, in which it operates as a refrigerator. The refrigeration cycle operates in the counterclockwise direction.

Carnot Principles

The second law of thermodynamics puts limits on the operation of cyclic devices as expressed by the Kelvin-Planck and Clausius statements. A heat engine cannot operate by exchanging heat with a single heat reservoir, and a refrigerator cannot operate without net work input from an external source.

Consider heat engines operating between two fixed temperature reservoirs at $T_H > T_L$. We draw two conclusions about the thermal efficiency of reversible and irreversible heat engines, known as the Carnot principles.

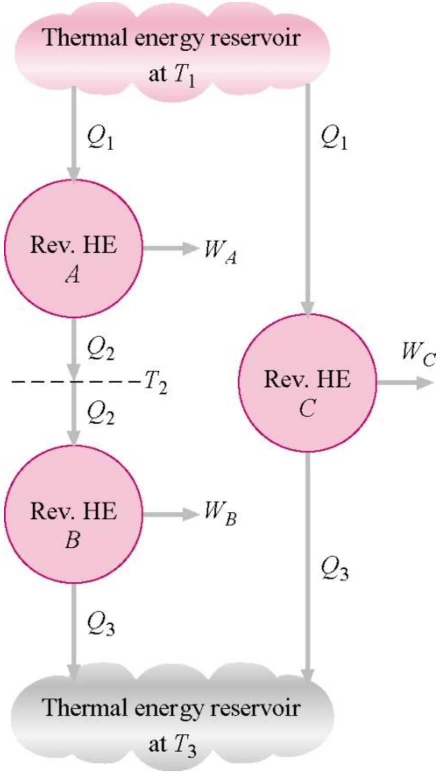
(a)The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

$$\eta_{th} < \eta_{th,\, Carnot}$$

(b) The efficiencies of all reversible heat engines operating between the same two constant-temperature heat reservoirs have the same efficiency.

As the result of the above, Lord Kelvin in 1848 used energy as a thermodynamic property to define temperature and devised a temperature scale that is independent of the thermodynamic substance.

The following is Lord Kelvin's Carnot heat engine arrangement.



Since the thermal efficiency in general is

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

For the Carnot engine, this can be written as

$$\eta_{th} = g(T_L, T_H) = 1 - f(T_L, T_H)$$

Considering engines A, B, and C

This looks like

$$\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2}\frac{Q_2}{Q_3}$$

$$f(T_1, T_3) = f(T_1, T_2)\, f(T_2, T_3)$$

One way to define the *f* function is

$$f(T_1, T_3) = \frac{\theta(T_2)}{\theta(T_1)}\frac{\theta(T_3)}{\theta(T_2)} = \frac{\theta(T_3)}{\theta(T_1)}$$

The simplest form of θ is the absolute temperature itself.

$$f(T_1, T_3) = \frac{T_3}{T_1}$$

The Carnot thermal efficiency becomes

$$\eta_{th,\, rev} = 1 - \frac{T_L}{T_H}$$

This is the maximum possible efficiency of a heat engine operating between two heat reservoirs at temperatures T_H and T_L. Note that the temperatures are absolute temperatures.

These statements form the basis for establishing an absolute temperature scale, also called the Kelvin scale, related to the heat transfers between a reversible device and the high- and low-temperature heat reservoirs by

$$\frac{Q_L}{Q_H} = \frac{T_L}{T_H}$$

Then the Q_H/Q_L ratio can be replaced by T_H/T_L for reversible devices, where T_H and T_L are the absolute temperatures of the high- and low-temperature heat reservoirs, respectively. This result is only valid for heat exchange across a heat engine operating between two constant temperature heat reservoirs. These results do not apply when the heat exchange is occurring with heat sources and sinks that do not have constant temperature.

The thermal efficiencies of actual and reversible heat engines operating between the same temperature limits compare as follows:

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

Reversed Carnot Device Coefficient of Performance

If the Carnot device is caused to operate in the reversed cycle, the reversible heat pump is created. The COP of reversible refrigerators and heat pumps are given in a similar manner to that of the Carnot heat engine as

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

$$= \frac{T_L}{T_H - T_L} = \frac{1}{\frac{T_H}{T_L} - 1}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{\frac{Q_H}{Q_L}}{\frac{Q_H}{Q_L} - 1}$$

$$= \frac{T_H}{T_H - T_L} = \frac{\frac{T_H}{T_L}}{\frac{T_H}{T_L} - 1}$$

Again, these are the maximum possible COPs for a refrigerator or a heat pump operating between the temperature limits of T_H and T_L.

The coefficients of performance of actual and reversible (such as Carnot) refrigerators operating between the same temperature limits compare as follows:

$$COP_R \begin{cases} < COP_{R,\,rev} & \text{irreversible refrigerator} \\ = COP_{R,\,rev} & \text{reversible refrigerator} \\ > COP_{R,\,rev} & \text{impossible refrigerator} \end{cases}$$

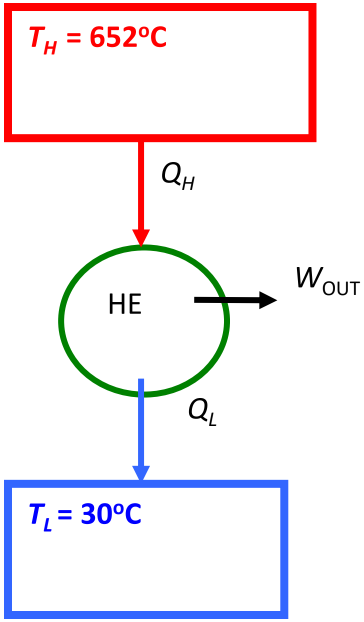
A similar relation can be obtained for heat pumps by replacing all values of COP_R by COP_{HP} in the above relation.

Example 6-2

A Carnot heat engine receives 500 kJ of heat per cycle from a high-temperature heat reservoir at 652°C and rejects heat to a low-temperature heat reservoir at 30°C. Determine

(a) The thermal efficiency of this Carnot engine.
(b) The amount of heat rejected to the low-temperature heat reservoir.

a.



$$\eta_{th,\,rev} = 1 - \frac{T_L}{T_H}$$

$$= 1 - \frac{(30+273)K}{(652+273)K}$$

$$= 0.672 \quad or \quad 67.2\%$$

b.

$$\frac{Q_L}{Q_H} = \frac{T_L}{T_H}$$

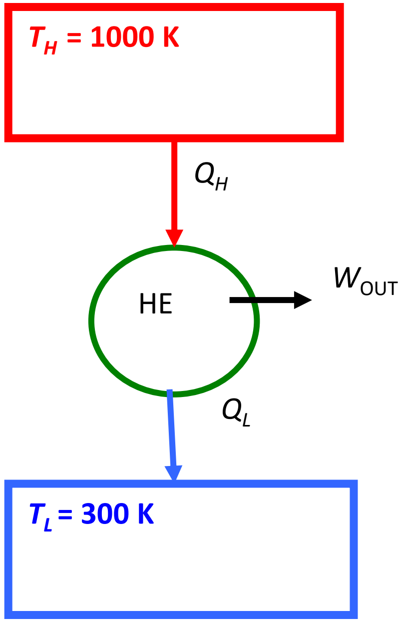
$$= \frac{(30+273)K}{(652+273)K} = 0.328$$

$$Q_L = 500\,kJ(0.328)$$

$$= 164\,kJ$$

Example 6-3

An inventor claims to have invented a heat engine that develops a thermal efficiency of 80 percent when operating between two heat reservoirs at 1000 K and 300 K. Evaluate his claim.



$$\eta_{th,\,rev} = 1 - \frac{T_L}{T_H}$$

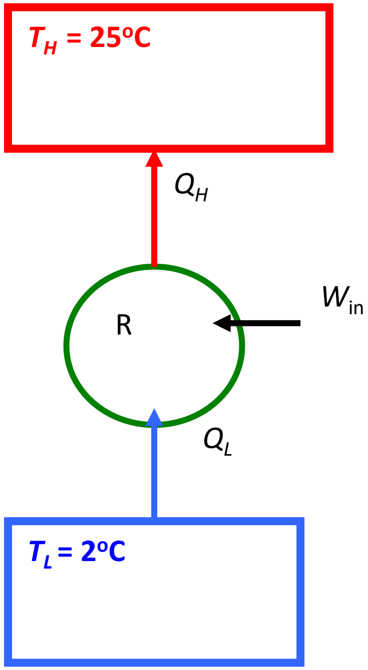
$$= 1 - \frac{300K}{1000K}$$

$$= 0.70 \quad or \quad 70\%$$

The claim is false since no heat engine may be more efficient than a Carnot engine operating between the heat reservoirs.

Example 6-4

An inventor claims to have developed a refrigerator that maintains the refrigerated space at 2°C while operating in a room where the temperature is 25°C and has a COP of 13.5. Is there any truth to his claim?



$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L}$$

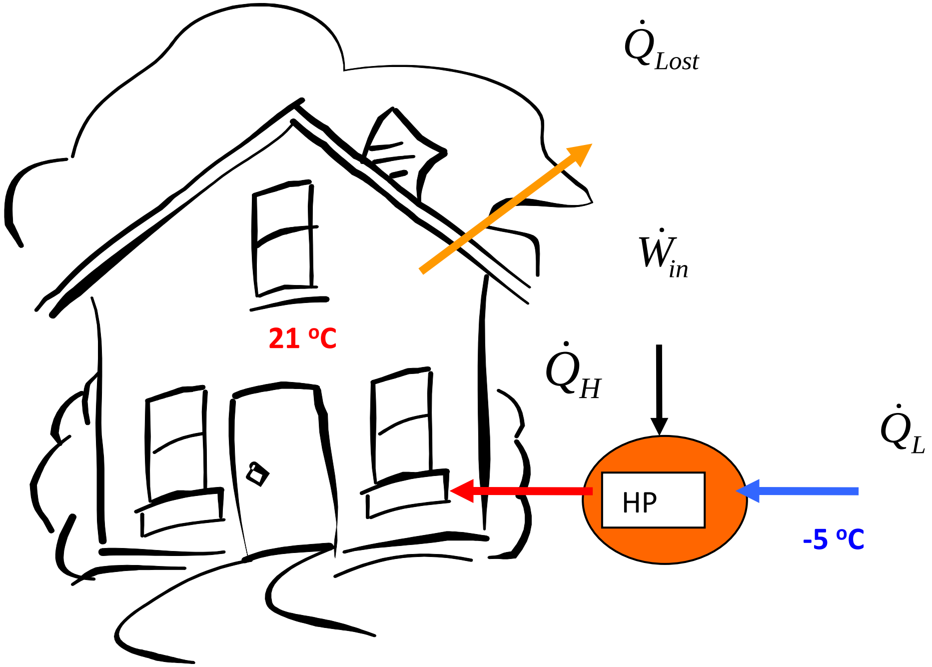
$$= \frac{(2+273)K}{(25-2)K}$$

$$= 11.96$$

The claim is false since no refrigerator may have a COP larger than the COP for the reversed Carnot device.

Example 6-5

A heat pump is to be used to heat a building during the winter. The building is to be maintained at 21°C at all times. The building is estimated to be losing heat at a rate of 135,000 kJ/h when the outside temperature drops to -5°C. Determine the minimum power required to drive the heat pump unit for this outside temperature.



The heat lost by the building has to be supplied by the heat pump.

$$\dot{Q}_H = \dot{Q}_{Lost} = 135000 \frac{kJ}{h}$$

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{Q}_H - \dot{Q}_L} = \frac{T_H}{T_H - T_L}$$

$$= \frac{(21+273)K}{(21-(-5))K}$$

$$= 11.31$$

Using the basic definition of the COP

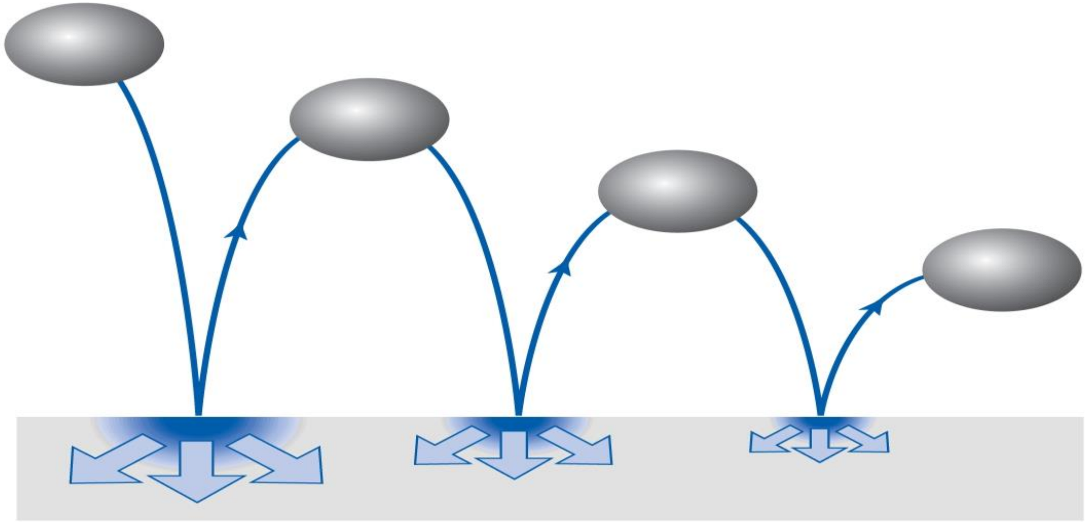
$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,\,in}}$$

$$\dot{W}_{net,\,in} = \frac{\dot{Q}_H}{COP_{HP}}$$

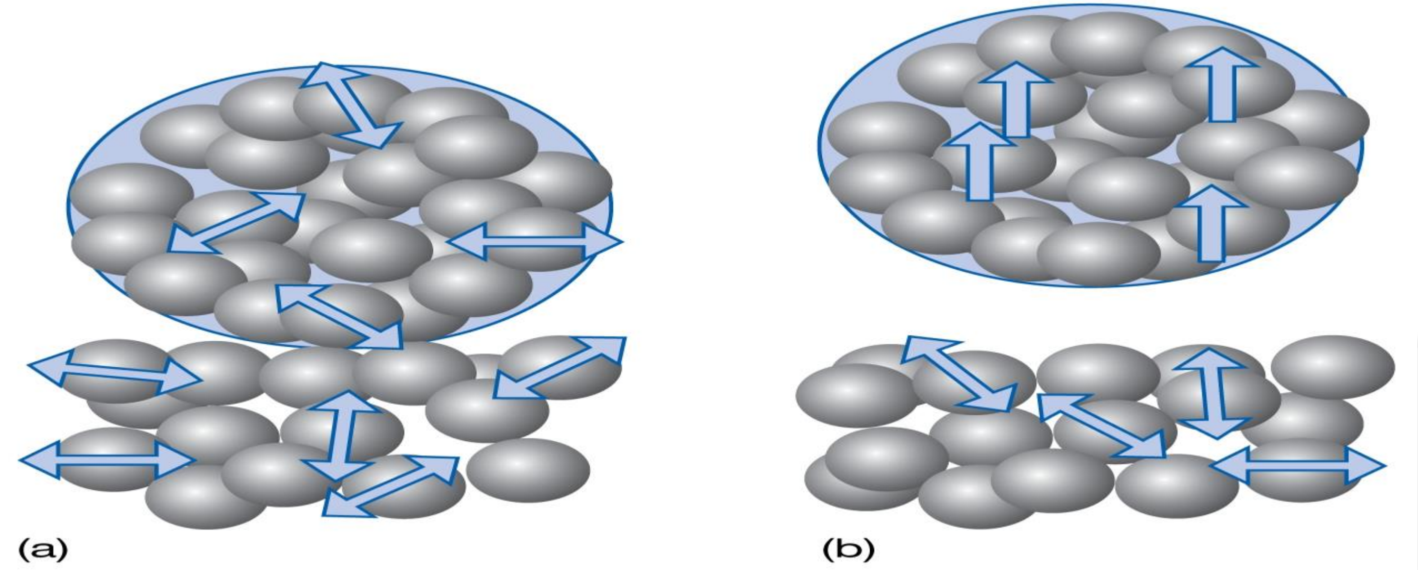
$$= \frac{135{,}000\,kJ/h}{11.31} \frac{1h}{3600s} \frac{1kW}{kJ/s}$$

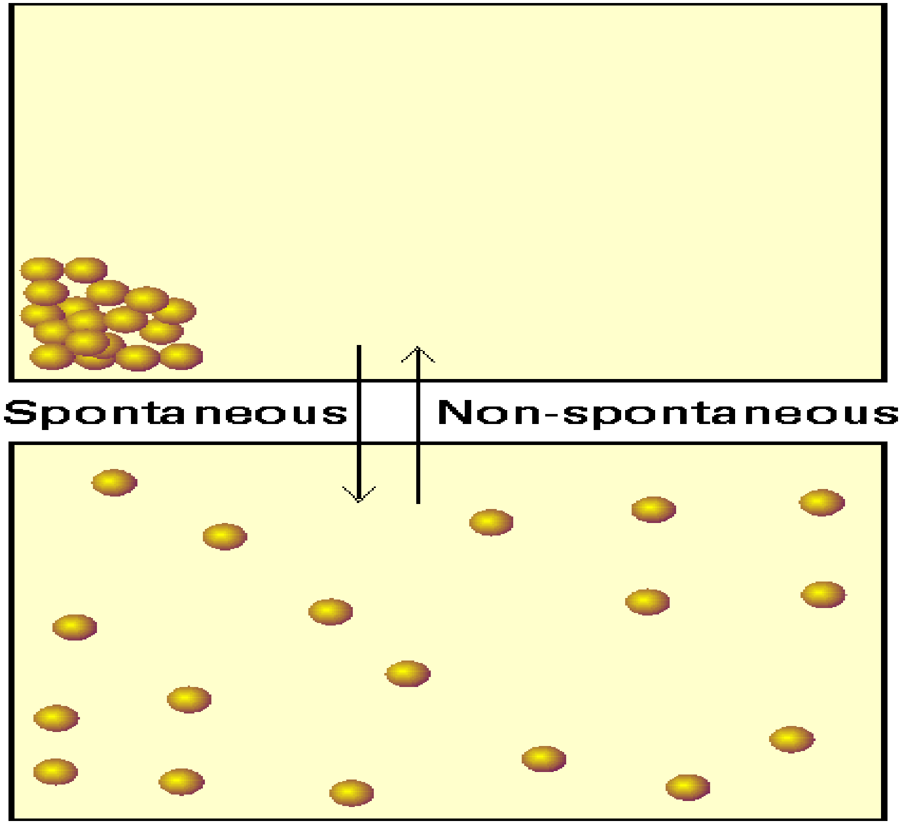
$$= 3.316\,kW$$

A ball bouncing on the floor



A ball resting on the warm surface.





Entropy is measure of randomness/ chaosness.

Total entropy of the system and its surroundings increases in the course of a spontaneous change.

20.2 Irreversible Processes and Entropy:

Examples to show the arrow of time…

Changes in energy within a closed system do not set the direction of irreversible processes.

Calling for another state variable to account for the arrow of time…

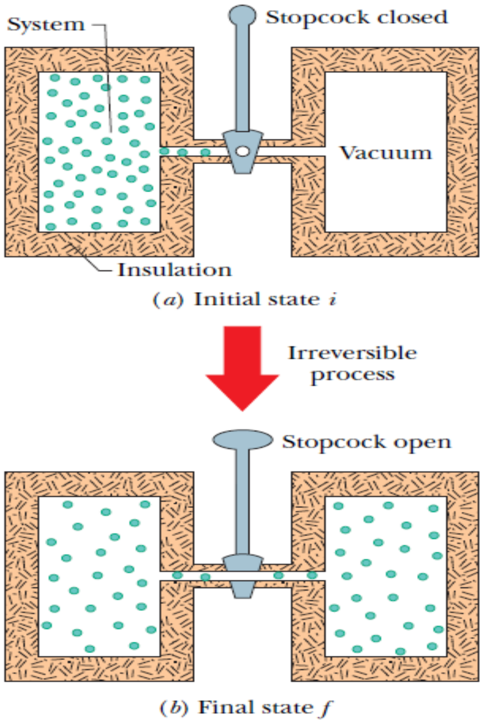
Entropy Postulate:

If an irreversible process occurs in a closed system, the entropy S of the system always increases; it never decreases.

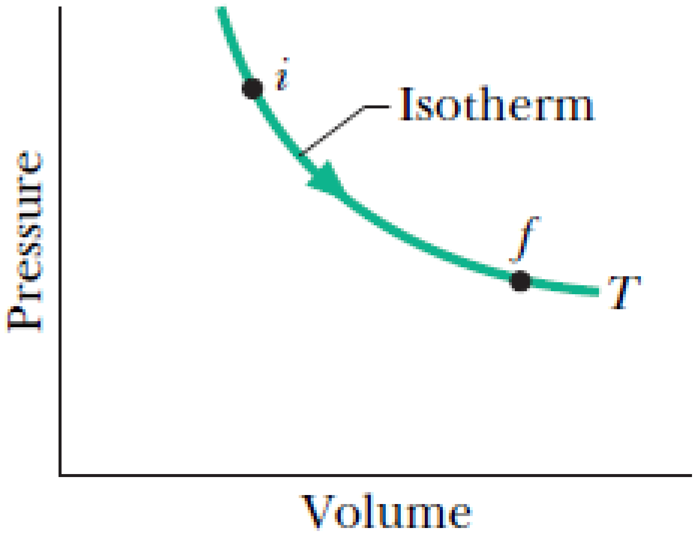
$$\Delta S = S_f - S_i = \int_i^f \frac{dQ}{T} \qquad \text{(change in entropy defined).}$$

Here *Q* is the energy transferred as heat to or from the system during the (reversible) process, and *T* is the temperature of the system in kelvins.

Entropy change of an irreversible process can be found with a reversible one connecting the initial and final states.

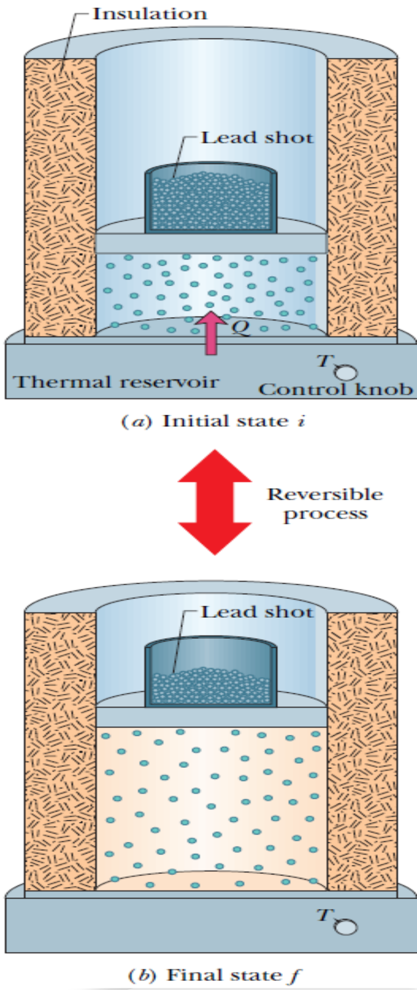


free expansion



$$\Delta S = S_f - S_i = \frac{1}{T}\int_i^f dQ.$$

$$\int dQ = Q,$$



an isothermal process

$$\Delta S = S_f - S_i = \frac{Q}{T} \qquad \text{(change in entropy, isothermal process).}$$

20.3 Change in Entropy: Entropy is a State Function

Suppose that an ideal gas is taken through a reversible process, with the gas in an equilibrium state at the end of each step.

For each small step, the energy transferred as heat to or from the gas is *dQ,* the work done by the gas i nge in internal energy is dE_{int}.

$$dE_{\text{int}} = dQ - dW.$$

We have:

Since the proc = *p dV* and $dE_{int} = nC_V\,dT$.

$$dQ = p\,dV + nC_V\,dT.$$

Therefore,

$$\frac{dQ}{T} = nR\frac{dV}{V} + nC_V\frac{dT}{T}.$$

Using ideal g

$$\int_i^f \frac{dQ}{T} = \int_i^f nR\frac{dV}{V} + \int_i^f nC_V\frac{dT}{T}.$$

Integratin

$$\Delta S = S_f - S_i = nR\ln\frac{V_f}{V_i} + nC_V\ln\frac{T_f}{T_i}.$$

Finally,

The change in entropy ΔS between the initial and final states of an ideal gas depends only on properties of the initial and final states; ΔS does not depend on how the gas changes between the two states.

Claussius inequality theorem

$$dS_{sys} + dS_{surr} \geq 0$$

$$dS_{sys} \geq -dS_{surr}$$

$$dS_{sys} \geq \frac{dq}{T}$$

If the system is isolated,

$$dq = 0$$

$$\Rightarrow dS_{sys} \geq 0$$

The entropy of an isolated system increases in the course of a spontaneous change.

Entropy change for a reversible process

$$dq_{sys} = -dq_{surr}$$

$$dS_{sys} = -dS_{surr}$$

$$\Rightarrow dS_{sys} + dS_{surr} = 0$$

Isothermal process for an ideal gas

Reversible process :

$$dS_{sys} = \frac{C_V dT}{T} + \left(\frac{\partial p}{\partial T}\right)_V dV$$

At constant Temperature,

$$dS_{sys} = \left(\frac{\partial p}{\partial T}\right)_V dV$$

$$dS_{sys} = \frac{nR}{V} dV$$

$$\Delta S_{sys} = nR \ln \frac{V_2}{V_1}$$

$$\Delta S_{surr} = -nR \ln \frac{V_2}{V_1}$$

For an irreversible process,

$$dS_{sys} = \frac{dq_{rev}}{T} = nR \ln \frac{V_2}{V_1} = \frac{-w_{rev}}{T}$$

$$dS_{surr} = \frac{dq_{surr}}{T} = \frac{-dq_{sys}}{T} = \frac{w}{T} = \frac{p_{ext}(V_2 - V_1)}{T}$$

Adiabatic Processes for an ideal gas

$$dS_{surr} = \frac{-dq_{sys}}{T}$$

Since, in an adiabatic process,

$$dq_{sys} = 0$$

$$\Delta S_{surr} = 0$$

(a) Reversible process :

$$dS_{sys} = \frac{dq_{sys,rev}}{T} = \frac{dq_{sys}}{T} = 0$$

(b) Irreversible process :

$$dS_{sys} = \frac{dq_{sys,rev}}{T} \neq \frac{dq_{sys}}{T}$$

For an ideal gas,

$$\Delta S_{sys} = R\ln\frac{V_f}{V_i} + C_{V,m}\ln\frac{T_{f,irrev}}{T_i}$$

$$\Delta S_{sys} = -C_{V,m}\ln\frac{T_{f,rev}}{T_i} + C_{V,m}\ln\frac{T_{f,irrev}}{T_i}$$

$$\Delta S_{sys} = C_{V,m}\ln\frac{T_{f,irrev}}{T_{f,rev}}$$

Spontaneous process

$$dS_{sys} + dS_{surr} \geq 0$$

$$dS_{sys} \geq -dS_{surr}$$

$$dS_{sys} \geq \frac{dq}{T}$$

$$dq - TdS \leq 0$$

At constant volume, no additional work

$$dq_v - TdS \leq 0$$

$$dU - TdS \leq 0$$

$$dS_{U,V} \geq 0 \quad \text{or}$$

$$dU_{S,V} \leq 0$$

At constant V and T

$$dU - TdS = dU - d(TS)$$

$$= d(U - TS)_{V,T} \leq 0$$

$$= d(A)_{V,T} \leq 0$$

A is called helmholtz free energy.

$$dS_{sys} + dS_{surr} \geq 0$$

$$dS_{sys} \geq -dS_{surr}$$

$$dS_{sys} \geq \frac{dq}{T}$$

$$dq - TdS \leq 0$$

At constant pressure, no additional work

$$dq_p - TdS \leq 0$$

$$dH - TdS \leq 0$$

$$dS_{H,p} \geq 0 \quad \text{or}$$

$$dH_{S,p} \leq 0$$

At constant P and T

$$dH - TdS = dH - d(TS)$$

$$= d(H - TS)_{P,T} \leq 0$$

$$= d(G)_{V,T} \leq 0$$

G is called Gibb's free energy.

Some thermodynamic properties can be measured directly, but many others cannot. Therefore, it is necessary to develop some relations between these two groups so that the properties that cannot be measured directly can be evaluated. The derivations are based on the fact that properties are point functions, and the state of a simple, compressible system is completely specified by any two independent, intensive properties.

Some Mathematical Preliminaries

Thermodynamic properties are continuous point functions and have exact differentials. A property of a single component system may be written as general mathematical function $z = z(x,y)$. For instance, this function may be the pressure $P = P(T,v)$. The total differential of z is written as

$$dz = \left(\frac{\partial z}{\partial x}\right)_y dx + \left(\frac{\partial z}{\partial y}\right)_x dy$$

$$dz = M\,dx + N\,dy$$

where

$$M = \left(\frac{\partial z}{\partial x}\right)_y \quad and \quad N = \left(\frac{\partial z}{\partial y}\right)_x$$

Taking the partial derivative of *M* with respect to *y* and of *N* with respect to *x* yields

$$\left(\frac{\partial M}{\partial y}\right)_x = \frac{\partial^2 z}{\partial x \partial y} \quad and \quad \left(\frac{\partial N}{\partial x}\right)_y = \frac{\partial^2 z}{\partial y \partial x}$$

Since properties are continuous point functions and have exact differentials, the following is true

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

The equations that relate the partial derivatives of properties *P, v, T,* and *s* of a simple compressible substance to each other are called the *Maxwell relations.* They are obtained from *the four Gibbs equations.* The first two of the Gibbs equations are those resulting from the internal energy *u* and the enthalpy *h*.

$$du = T\,ds - P\,dv$$

$$dh = T\,ds + v\,dP$$

The second two Gibbs equations result from the definitions of the Helmholtz function *a* and the Gibbs function *g* defined as

$$
\begin{aligned}
a &= u - Ts \\
da &= du - T\,ds - s\,dT \\
da &= -s\,dT - P\,dv
\end{aligned}
$$

$$
\begin{aligned}
g &= h - Ts \\
dg &= dh - T\,ds - s\,dT \\
dg &= -s\,dT + v\,dP
\end{aligned}
$$

Setting the second mixed partial derivatives equal for these four functions yields the *Maxwell relations*

$$
\begin{aligned}
\left(\frac{\partial T}{\partial v}\right)_s &= -\left(\frac{\partial P}{\partial s}\right)_v \\
\left(\frac{\partial T}{\partial P}\right)_s &= \left(\frac{\partial v}{\partial s}\right)_P \\
\left(\frac{\partial s}{\partial v}\right)_T &= \left(\frac{\partial P}{\partial T}\right)_v \\
\left(\frac{\partial s}{\partial P}\right)_T &= -\left(\frac{\partial v}{\partial T}\right)_P
\end{aligned}
$$

Now we develop two more important relations for partial derivatives—the reciprocity and the cyclic relations. Consider the function $z = z(x,y)$ expressed as $x = x(y,z)$. The total differential of x is

$$dx = \left(\frac{\partial x}{\partial y}\right)_z dy + \left(\frac{\partial x}{\partial z}\right)_y dz$$

Now combine the expressions for dx and dz.

$$dz = \left(\frac{\partial z}{\partial x}\right)_y \left[\left(\frac{\partial x}{\partial y}\right)_z dy + \left(\frac{\partial x}{\partial z}\right)_y dz\right]dx$$

$$+\left(\frac{\partial z}{\partial y}\right)_x dy$$

Rearranging,

$$\left[\left(\frac{\partial z}{\partial x}\right)_y \left(\frac{\partial x}{\partial y}\right)_z + \left(\frac{\partial z}{\partial y}\right)_x\right]dy =$$

$$\left[1 - \left(\frac{\partial x}{\partial z}\right)_y \left(\frac{\partial z}{\partial x}\right)_y\right]dz$$

Since *y* and *z* are independent of each other, the terms in each bracket must be zero. Thus, we obtain the reciprocity relation that shows that the inverse of a partial derivative is equal to its reciprocal.

$$1-\left(\frac{\partial x}{\partial z}\right)_y\left(\frac{\partial z}{\partial x}\right)_y=0$$

or

$$\left(\frac{\partial x}{\partial z}\right)_y=\frac{1}{\left(\frac{\partial z}{\partial x}\right)_y}$$

The second relation is called the cyclic relation.

$$\left(\frac{\partial z}{\partial x}\right)_y\left(\frac{\partial x}{\partial y}\right)_z+\left(\frac{\partial z}{\partial y}\right)_x=0$$

$$\left(\frac{\partial z}{\partial x}\right)_y\left(\frac{\partial x}{\partial y}\right)_z=-\left(\frac{\partial z}{\partial y}\right)_x$$

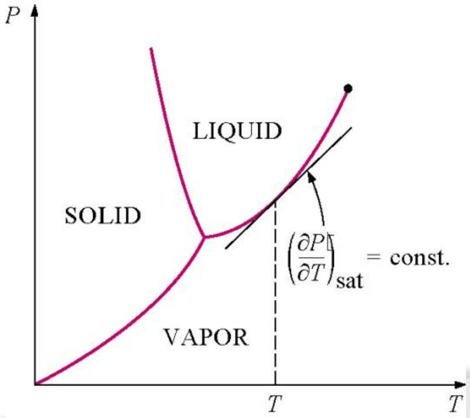
$$\left(\frac{\partial x}{\partial y}\right)_z\left(\frac{\partial y}{\partial z}\right)_x\left(\frac{\partial z}{\partial x}\right)_y=-1$$

Another way to write this last result is

$$\left(\frac{\partial x}{\partial y}\right)_z = -\frac{\left(\frac{\partial z}{\partial y}\right)_x}{\left(\frac{\partial z}{\partial x}\right)_y}$$

The Clapeyron Equation

The *Clapeyron equation* enables us to determine the enthalpy change associated with a phase change, h_{fg}, from knowledge of *P, v*, and *T* data alone.



Consider the third Maxwell relation

$$\left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial P}{\partial T}\right)_v$$

During phase change, the pressure is the saturation pressure, which depends on the temperature only and is independent of the specific volume. That is $P_{sat} = f(T_{sat})$. Therefore, the partial derivative $(\partial P/\partial T)_v$ an be expressed as a total derivative (dP/dT)sat, which is the slope of the saturation curve on a *P-T* diagram at a specified state. This slope is independent of the specific volume, and thus it can be treated as a constant during the integration of the third Maxwell relation between two saturation states at the same temperature. For an isothermal liquid-vapor phase-change process, the integration yields

$$\int_f^g ds = \int_f^g \left(\frac{\partial P}{\partial T}\right)_v dv$$

$$s_g - s_f = \left(\frac{dP}{dT}\right)_{sat} (v_g - v_f)$$

During the phase-change process, the pressure also remains constant. Therefore, from the enthalpy relation

$$dh = T\,\overset{0}{\cancel{ds}} + v\,dP$$

$$\int_f^g dh = \int_f^g T\,ds = T\int_f^g ds$$

$$h_g - h_f = h_{fg} = Ts_{fg}$$

Now we obtain the Clapeyron equation expressed as

$$\frac{h_{fg}}{T} = \left(\frac{dP}{dT}\right)_{sat} v_{fg}$$

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{fg}}{Tv_{fg}}$$

Example 12-1

Using only *P-v-T* data, estimate the enthalpy of vaporization of water at 45°C.

The enthalpy of vaporization is given by the Clapeyron equation as

$$h_{fg} = Tv_{fg}\left(\frac{dP}{dT}\right)_{sat}$$

Using *the P-v-T* data for water from Table A-4

$$v_{fg} = (v_g - v_f)_{@45^o C} = (15.251 - 0.001010)\frac{m^3}{kg}$$

$$= 15.250\frac{m^3}{kg}$$

$$\left(\frac{dP}{dT}\right)_{sat} \cong \left(\frac{\Delta P}{\Delta T}\right)_{sat,\,45^o C} = \frac{P_{sat@50^o C} - P_{sat@40^o C}}{50^o C - 40^o C}$$

$$= \frac{(12.35 - 7.385)kPa}{10^o K} = 0.4965\frac{kPa}{K}$$

$$h_{fg} = Tv_{fg}\left(\frac{dP}{dT}\right)_{sat}$$

$$= (40 + 273.15)K(15.250\frac{m^3}{kg})(0.4965\frac{kPa}{K})\frac{kJ}{m^3 kPa}$$

$$= 2371.1\frac{kJ}{kg}$$

The actual value of h_{fg} is 2394.0 kJ/kg. The Clapeyron equation approximation is low by about 1 percent due to the approximation of the slope of the saturation curve at 45°C.

Clapeyron-Clausius Equation

For liquid-vapor and solid-vapor phase-change processes at low pressures, an approximation to the Clapeyron equation can be obtained by treating the vapor phase as an ideal gas and neglecting the specific volume of the saturated liquid or solid phase compared to that of the vapor phase. At low pressures

$$v_g >> v_f$$

$$v_{fg} \cong v_g$$

$$v_g = \frac{RT}{P}$$

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{fg}}{Tv_{fg}}$$

$$= \frac{h_{fg}}{T\dfrac{RT}{P}} = \frac{Ph_{fg}}{RT^2}$$

$$\left(\frac{dP}{P}\right)_{sat} = \frac{h_{fg}}{R}\left(\frac{dT}{T^2}\right)_{sat}$$

For small temperature intervals, h_{fg} can be treated as a constant at some average value. Then integrating this equation between two saturation states yields

$$\ln\left(\frac{P_2}{P_1}\right)_{sat} \cong \frac{h_{fg}}{R}\left(\frac{T_2 - T_1}{T_1 T_2}\right)_{sat}$$

General Relations for *du*, *dh*, *ds*, C_v, and C_p

The changes in internal energy, enthalpy, and entropy of a simple, compressible substance can be expressed in terms of pressure, specific volume, temperature, and specific heats alone.

Consider internal energy expressed as a function of *T* and *v*.

$$du = \left(\frac{\partial u}{\partial T}\right)_v dT + \left(\frac{\partial u}{\partial v}\right)_T dv$$

Recall the definition of the specific heat at constant volume

$$C_V = \left(\frac{\partial u}{\partial T}\right)_v$$

Then *du* becomes

$$du = C_V\, dT + \left(\frac{\partial u}{\partial v}\right)_T dv$$

Now let's see if we can evaluate $(\partial u / \partial v)_T$ terms of *P-v-T* data only. Consider the entropy as a function of *T* and *v*; that is,

$$s = s(T, v)$$

$$ds = \left(\frac{\partial s}{\partial T}\right)_v dT + \left(\frac{\partial s}{\partial v}\right)_T dv$$

Now substitute *ds* into the *T ds* relation for *u*.

$$du = T\left[\left(\frac{\partial s}{\partial T}\right)_v dT + \left(\frac{\partial s}{\partial v}\right)_T dv\right] - P\,dv$$

$$= T\left(\frac{\partial s}{\partial T}\right)_v dT + \left[T\left(\frac{\partial s}{\partial v}\right)_T - P\right]dv$$

Comparing these two results for *du*, we see

$$C_V = T\left(\frac{\partial s}{\partial T}\right)_v \quad or \quad \left(\frac{\partial s}{\partial T}\right)_v = \frac{C_V}{T}$$

$$\left(\frac{\partial u}{\partial v}\right)_T = T\left(\frac{\partial s}{\partial v}\right)_T - P$$

Using the third Maxwell's relation

$$\left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial P}{\partial T}\right)_v$$

$$\left(\frac{\partial u}{\partial v}\right)_T = T\left(\frac{\partial P}{\partial T}\right)_v - P$$

Notice that the derivative $(\partial u / \partial v)_T$ a function of *P-v-T* only. Thus the total differential for *u* = *u*(*T*,*v*) is written as

$$du = C_v\, dT + \left[T\left(\frac{\partial P}{\partial T}\right)_v - P\right]dv$$

Example

Do you remember that we agreed that the internal energy of an ideal gas depended only on temperature? Let's evaluate the following partial derivative for an ideal gas.

$$\left(\frac{\partial u}{\partial v}\right)_T = T\left(\frac{\partial P}{\partial T}\right)_v - P$$

For ideal gases

$$P = \frac{RT}{v}$$

$$\left(\frac{\partial P}{\partial T}\right)_v = \frac{R}{v}$$

$$\left(\frac{\partial u}{\partial v}\right)_T = T\frac{R}{v} - P = P - P = 0$$

This result helps to show that the internal energy of an ideal gas does not depend upon specific volume. To completely show that internal energy of an ideal gas is independent of specific volume, we need to show that the specific heats of ideal gases are functions of temperature only. We will do this later.

We could also find the following relations for *dh* and *ds* where $h = h(T,P)$ and $s = s(T,v)$ or $s = s(T,P)$

$$dh = C_p\, dT + \left[v - T\left(\frac{\partial v}{\partial T}\right)_P\right] dP$$

$$ds = \frac{C_v}{T} dT + \left(\frac{\partial P}{\partial T}\right)_v dv$$

$$ds = \frac{C_p}{T} dT - \left(\frac{\partial v}{\partial T}\right)_P dP$$

Example

Determine an expression for the entropy change of an ideal gas when temperature and pressure data are known and the specific heats are constant.

$$s = s(T, P)$$

$$ds = \frac{C_p}{T} dT - \left(\frac{\partial v}{\partial T}\right)_P dP$$

$$\Delta s = \int_{T_1}^{T_2} \frac{C_p}{T} dT - \int_{P_1}^{P_2} \left(\frac{\partial v}{\partial T}\right)_P dP$$

For an ideal gas

$$v = \frac{P}{RT}$$

$$\left(\frac{\partial v}{\partial T}\right)_P = \frac{P}{R}$$

For constant specific heat this becomes

$$\Delta s = C_p \int_{T_1}^{T_2} \frac{dT}{T} - \int_{P_1}^{P_2} \frac{R}{P} dP$$

$$= C_P \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

Available and Unavailable Energy

- There are many forms in which an energy can exist. But even under ideal conditions all these forms cannot be converted completely into work. This indicates that energy has two parts :

  - *Available part*
  - *Unavailable part*

- ‘***Available energy***’ or ‘**Exergy’**: is the *maximum portion of energy which could be converted into useful work by ideal processes which reduce the system to a dead state* (a state in equilibrium with the earth and its atmosphere).

  - There can be only one value for maximum work which the system alone could do while descending to its dead state, therefore 'Available *energy’ is a property*

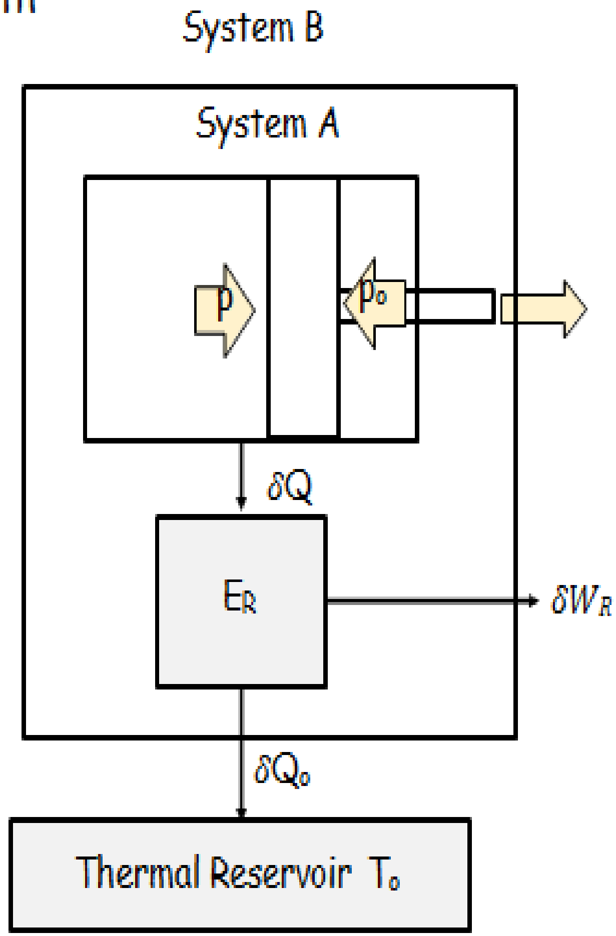
- ‘**U*navailable energy***’ or **Anergy’**: is the portion of energy which could not be converted into useful work and is rejected to the surroundings

- A system which has a pressure difference from that of surroundings, work can be obtained from an expansion process, and if the system has a different temperature, heat can be transferred to a cycle and work can be obtained. But when the temperature and pressure becomes equal to that of the earth, transfer of energy ceases, and although the system contains internal energy, this energy is ***unavailable***
- Summarily available energy denote, the latent capability of energy to do work, and in this sense it can be applied to energy in the system or in the surroundings.
- *The theoretical maximum amount of work which can be obtained from a system at any state* p_1 *and* T_1 *when operating with a reservoir at the constant pressure and temperature* p_0 *and* T_0 *is called* '**availability**'.

- ***For stability of any system it is necessary and sufficient that, in all possible variations of the state of the system which do not alter its energy, the variation of entropy shall be negative***
- This can be stated mathematically as $\Delta \mathbf{S} < 0$
- It can be seen that the statements of equilibrium based on energy and entropy, namely $\Delta \boldsymbol{E} > 0$ and $\Delta \mathbf{S} < 0$

System A, which is a general system of constant composition in which the work output, δW, can be either shaft or displacement work, or a combination of both

Figure b, the workoutput is displacement work, $p\,\delta V$



- The expression **E - T_oS** is called the *Helmholtz energy* or *Helmholtz function.*
- In the absence of motion and gravitational effects the energy, E, may be replaced by the intrinsic internal energy, *U*, giving $\delta W_{net} = -d(U - T_oS)$
- The changes executed were considered to be reversible and δW_{net} was the net work obtained from System B (i.e. System A + heat engine E_R).Thus, δW_{net} must be the maximum quantity of work that can be obtained from the combined system
- The expression for δW is called the change in the Helmholtz energy, where the Helmholtz energy is defined as **F = U - TS**

  - Helmholtz energy is a property which has the units of energy, and indicates the maximum work that can be obtained from a system
  - It can be seen that this is less than the internal energy, **U**
  - Product TS is a measure of the unavailable energy

- The change in Helmholtz energy is the maximum work that can be obtained from a closed system undergoing a reversible process whilst remaining in temperature equilibrium with its surroundings
- **A** decrease in Helmholtz energy corresponds to an increase in entropy, hence the minimum value of the function signifies the equilibrium condition
- **A** decrease in entropy corresponds to an increase in F; hence the criterion $dF > 0$ is that for stability

-This criterion corresponds to work being done on the system

- For a constant volume system in which $W = 0$, $dF = 0$

- For reversible processes, $F_1 = F_2$; for all other processes there is a decrease in Helmholtz energy
- The minimum value of Helmholtz energy corresponds to the equilibrium condition

Gibbs energy (Gibbs Function)

System **A** could change its volume by δV, and while it is doing this it must perform work on the atmosphere equivalent to $p_o\,\delta V$, where p_o is the pressure of the atmosphere. This workdetracts from the work previously calculated and gives the maximum useful work, as $\mathbf{W_u} = \delta\mathbf{W_{net}} - P_o dV$

if the system is in pressure equilibrium withsurroundings.

$\delta W_u = -d(E - T_o S) - p_o dV$

$= -d(E + p_o V -$

$T_o S)$

because *po*= constant Hence

$\delta W_u = -d(H - T_o S)$

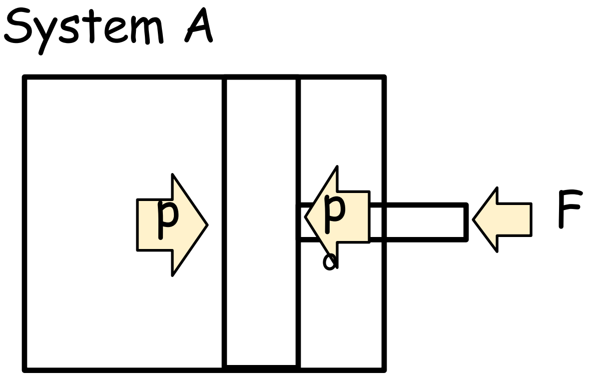
- The quantity $H - TS$ is called the *Gibbs energy*, *Gibbs potential*, or the *Gibbs function*, *G*

  Hence $G = H - TS$

  - Gibbs energy is a property which has the units ofenergy
  - Indicates the maximum useful work that can be obtained from a system
  - It can be seen that this is less than the enthalpy

Displacement Work

- The work done by a system can be considered to be made up of two parts: that done against a resisting force and that done against the environment.
- The pressure inside the system, p, is resisted by a force, F, and the pressure of the environment. Hence, for System **A,** which is in equilibrium with the surroundings $p.A = F + p_o.d$



If the piston moves distance dx, then work done by various components

$p.A.dx = F.dx + p_o.A.dx$

where $P.A.\,dx = p\,dV = \delta W$ = work done by the fluid in the system

$\boldsymbol{F}\,dx = \delta W$ = work done against the resisting force

$p_oA.dx = p_odV = \delta W$ = work done against the surroundings

Hence the work done by the system is not all converted into useful work, but some of it is used to do displacement work against the surroundings, i.e.

$$\delta W_{sym} = \delta W_{use} + \delta W_{surr}$$

which can be rearranged to give

$$\delta W_{use} = \delta W_{sys} - \delta W_{surr}$$

- ***A* is called the *non-flow availability function***

  - It is a combination of properties

  - A is not itself a property because it is defined in relation to the arbitrary datum values of p_o and T_o

  - It is not possible to tabulate values of A without defining both these datum levels

  - The datum levels are what differentiates A from Gibbs energy G

  - The maximum useful work achievable from a system changing state from 1 to 2 is given by $W_{max} = \Delta A = -(A_2 - A_l) = A_l - A_2$

  - The specific availability, *a* , i.e. the availability per unit mass is $a = u + p_o v - T_o s$

  - If the value of *a* were based on unit amount of substance (i.e. kmol) it would be referred to as the molar availability

- The change of specific (or molar) availability is

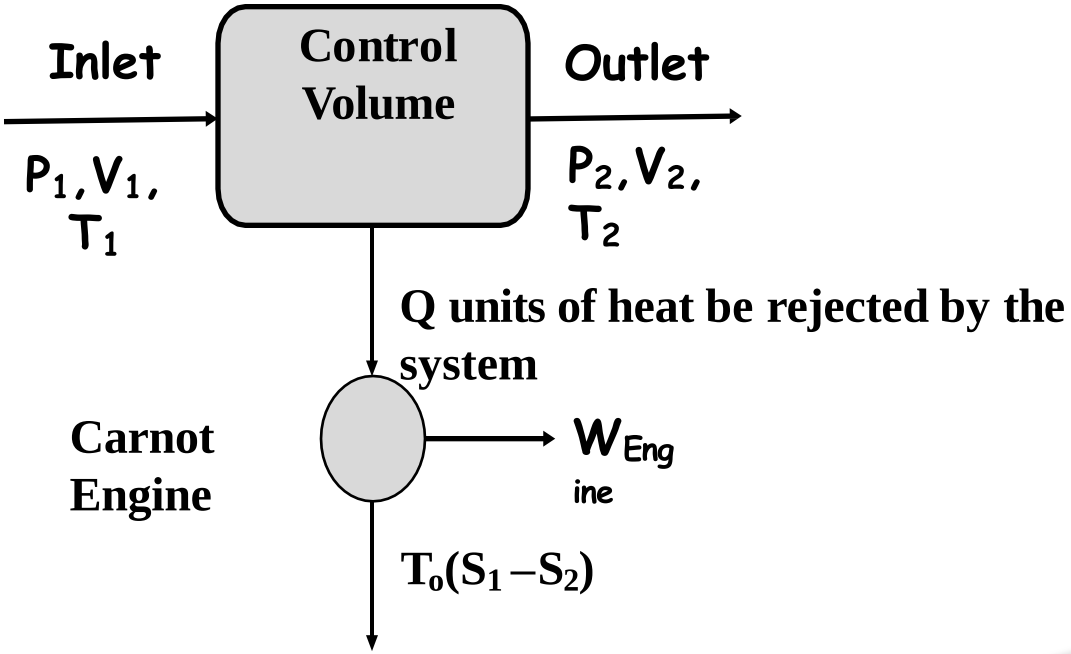
$$\Delta a = a_2 - a_1 = (u_2 + p_o v_2 - T_o s_2) - (u_1 + p_o v_1 - T_o s_1)$$

$$= (h_2 + v_2(P_o - P_2) - (h_1 + V_1(P_o - P_1)) - T_o(S_2 - S_1)$$

Availability of a Steady Flow System

- Consider a steady flow system and let it be assumed that the flowing fluid has the following properties and characteristics; Internal energy u, specific volume *v*, specific enthalpy h, pressure p, velocity c and location z

System delivers a work output W units



Inlet

P_1, V_1, T_1

Control Volume

Outlet

P_2, V_2, T_2

Q units of heat be rejected by the system

Carnot Engine

W_{Engine}

$T_o(S_1 - S_2)$

Normally, P_2 &T_2 ambient or state dead condition

$$U_1 + p_1 v_1 + \frac{V_1^2}{2} + gz_1 - Q = U_2 + p_2 v_2 + \frac{V_2^2}{2} + gz_2 + Ws$$

Neglecting the kinetic and potential energy changes

$$U_1 + p_1 v_1 - Q = U_2 + p_2 v_2 + Ws$$

$$H_1 - Q = H_2 + Ws$$

$$\text{Shaft work } Ws = (H_1 - H_2) - Q$$

Heat Q rejected by the system may be made to run a reversible heat engine, the output fro
engine equals

$$W_{engine} = Q\ (1 - \frac{\&}{c})$$

$$= Q - T_0 (S_1 - S_2)$$

Maximum available useful work or net work $W_{net} = W_s + W_{engine}$

$$= (H_1 - H_2) - Q + Q - To\ (S_1 - S_2)$$

$= (H_1 - H_2) - Q + Q - T_o (S_1 - S_2)$

$= (H_1 - T_o S_1) - (H_2 - T_o S_2)$

$= B_1 - B_2$ Steady flow availability function $H - T_o S$ or Darrieus function and the Keenam function

$dB = (B_1 - B_o) - (B_2 - B_o) = B_1 - B_2$

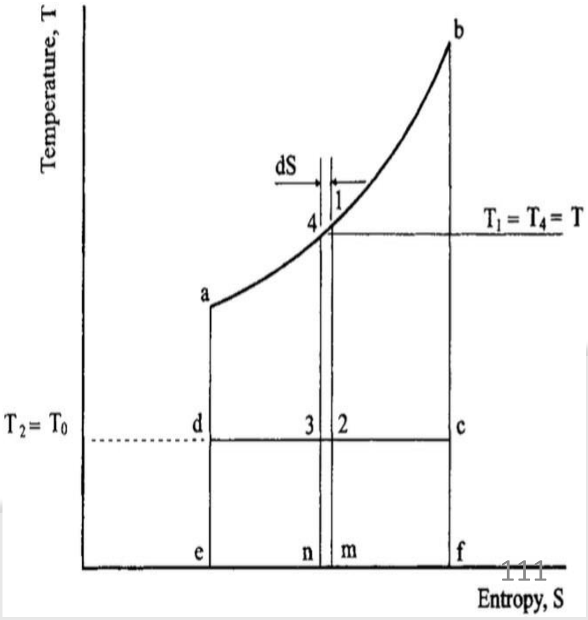
Clearly, the availability B is a state function in the strictest mathematical sense so the maximum (or minimum) work associated with any steady state process is also independent of the path

Availability: Yields the maximum work producing potential or the minimum work requirement of a process

- Allows evaluation and quantitative comparison of options in a sustainability context

Available & Unavailable Energy

- If a certain portion of energy is available then obviously another part is unavailable
  - the unavailable part is that which must be thrown away
  - Diagram indicates an internally reversible process from a to b
  - This can be considered to be made up of an infinite number of strips 1-m-n-4-1 where the temperature of energy transfer is essentially constant, i.e.
  - $\overline{T}_1 = \overline{T}_4$



The energy transfer obeys Where,

δQ = heat transferred to system and

δQ_o= heat rejected from system,

As in an engine (E_R) undergoing an infinitesimal Carnot cycle

- In reality δQ_0 is the minimum amount of heat that can be rejected because processes 1 to 2 and 3 to 4 are both isentropic, i.e. adiabatic and *reversible*

Hence the amount of energy that must be rejected is

$$E_{unav} = \int dQ_o = T_0 \Delta S$$

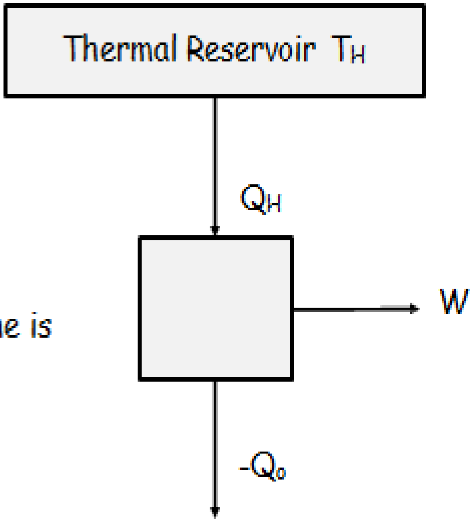
- Note that the quantity of energy, δQ, can be written as a definite integral because the process is an isentropic (reversible) one
- Then *E*, is the energy that is unavailable and is given by *cdefc*
- The available energy on this diagram is given by *abcda* and is given by
- $E_{av} = Q - E_{unav} = Q \quad - T.dS$ where Q is defined by the area *abfea*

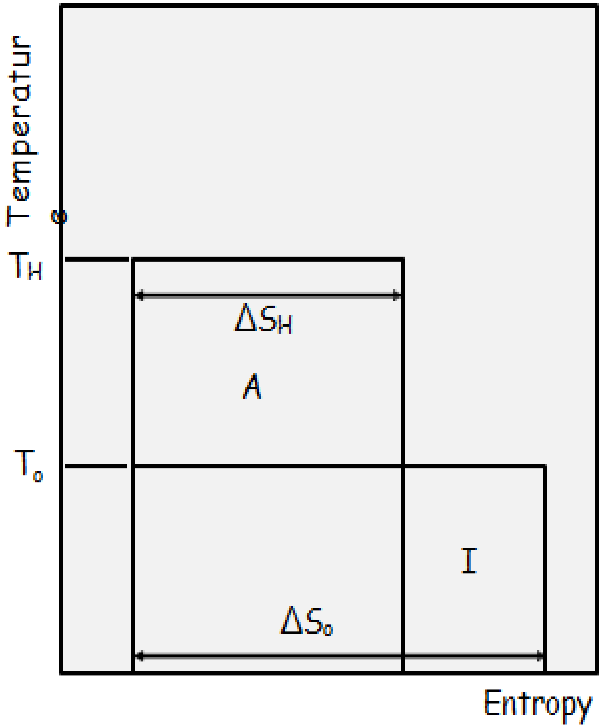
Graphical Representation of Available Energy, and Irreversibility

Consider the energy transfer from a high temperature reservoir at T_H through a heat engine (not necessarily reversible)

The available energy flow from the hot reservoir is
$E_H = Q_H - T_o \Delta S_H$

The work done by the engine is
$W = Q_H - Q_o$





The energy which is unavailable due to irreversibility is defined by

$$E_{irrev} = E_H - W = Q_H - T_o\,.\Delta S_H - W$$

$$= Q_H - T_o\,.\,\Delta S_H - (Q_H - Q_o) = Q_o - T_o\,.\Delta S_H$$

$$= T_o(\Delta S_0 - \Delta S_H)$$

In the case of a reversible engine $\sum \Delta S = 0$ because entropy flow is conserved, i.e. Hence the unavailable energy for a reversible engine is **To ΔS_H** while the irreversibility is zero However, for all other engines it is non-zero.

- The available energy is depicted by the area marked **'A',** while the energy 'lost' due to irreversibility **is** denoted **'I'** and is defined **E_{irrev} = $T_o(\Delta S_0 - \Delta S_H)$**

Irreversibility

- The entropy of a system plus its surroundings (i.e. an isolated system) can never decrease (2nd law).
- The second law states: $\Delta S_{system} + \Delta S_{surr.} = 0$

where, Δ = final - initial > 0 irreversible (real world)

= 0 reversible (frictionless, ideal)

- In an ideal case if Q is the heat supplied from a source at T, its availability or the maximum work it can deliver is $Q(1-T_0/T_1)$ where T_0 is the temperature of the surroundings.
  - Invariably it will be less than this value.
  - The difference is termed as irreversibility.
  - Availability = Maximum possible work -

Irreversibility $W_{useful} = W_{rev} - I$

- Irreversible Processes increase the entropy of the universe
- Reversible Processes do not effect the entropy of the universe
- Impossible Processes decrease the entropy of the universe

ΔS universe = 0

- Entropy Generation in the universe is a measure of lost work

$$\Delta S_{Universe} = \Delta S_{System} + \Delta S_{Surroundings}$$

- The losses will keep increasing
- The sin keeps accumulating and damage to environment keeps increasing
- When the entropy of the universe goes so high, then some one has to come and set it right

UNIT – III

PURE SUBSTANCES &GAS LAWS

PROPERTIES OF PURE SUBSTANCES

Phase Transformations, T-S and h-s diagrams, P-V-T- surfaces, Triple point at critical state properties during change of phase, Dryness Fraction, Mollier charts, Various Thermodynamic processes and energy Transfer, Steam Calorimeter

At the end of the unit students are able to:		
	Course Outcomes	Knowledge Level (Bloom's Taxonomy)
CO7	Interpret the properties of pure substances and steam to emit relevant inlet and exit conditions of thermodynamic work bearing systems..	Understand
CO8	Describe fundamental relationship between intensive properties in form of partial derivatives implemented for perfect gases	Understand

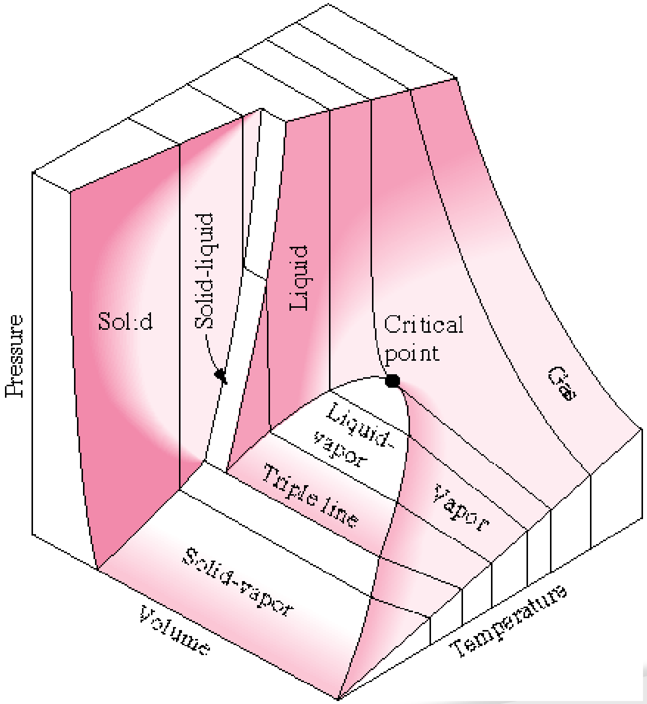
119

State Postulate

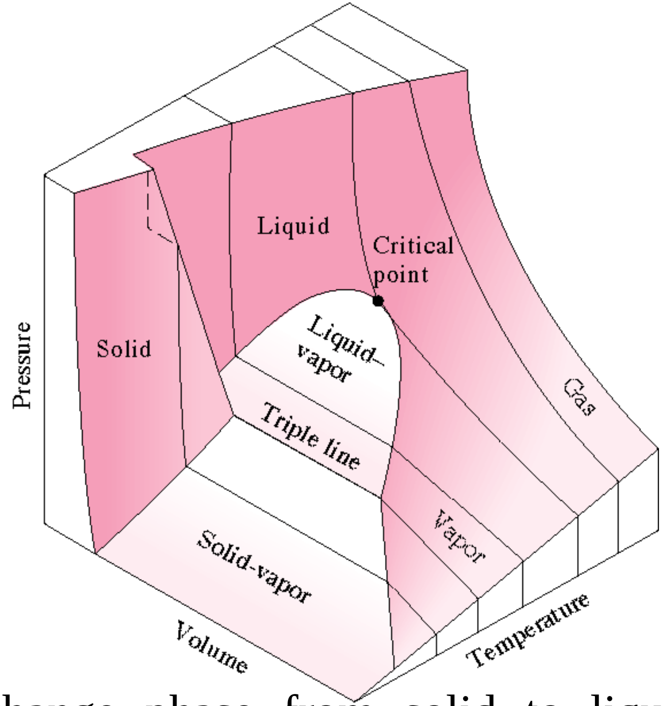
Again, the state postulate for a simple, pure substance states that the equilibrium state can be determined by specifying any two independent intensive properties.

The *P-V-T* Surface for a Real Substance

- ***P-V-T*** **Surface for a Substance that contracts upon freezing**



♦ *P-V-T* Surface for a Substance that expands upon freezing



Real substances that readily change phase from solid to liquid to gas such as water, refrigerant-134a, and ammonia cannot be treated as ideal gases in general. The pressure, volume, temperature relation, or equation of state for these substances is generally very complicated, and the thermodynamic properties are given in table form. The properties of these substances may be illustrated by the functional relation $F(P,v,T)=0$, called an equation of state. The above two figures illustrate the function for a substance that contracts on freezing and a substance that expands on freezing. Constant pressure curves on a temperature-volume diagram are shown

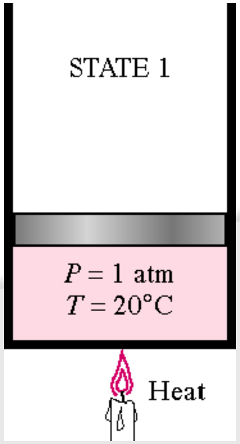
These figures show three regions where a substance like water may exist as a solid, liquid or gas (or vapor). Also these figures show that a substance may exist as a mixture of two phases during phase change, solid-vapor, solid-liquid, and liquid-vapor.

Water may exist in the compressed liquid region, a region where saturated liquid water and saturated water vapor are in equilibrium (called the saturation region), and the superheated vapor region (the solid or ice region is not shown).

Let's consider the results of heating liquid water from 20°C, 1 atm while keeping the pressure constant. We will follow the constant pressure process shown . First place liquid water in a piston-cylinder device where a fixed weight is placed on the piston to keep the pressure of the water constant at all times. As liquid water is heated while the pressure is held constant, the following events occur.

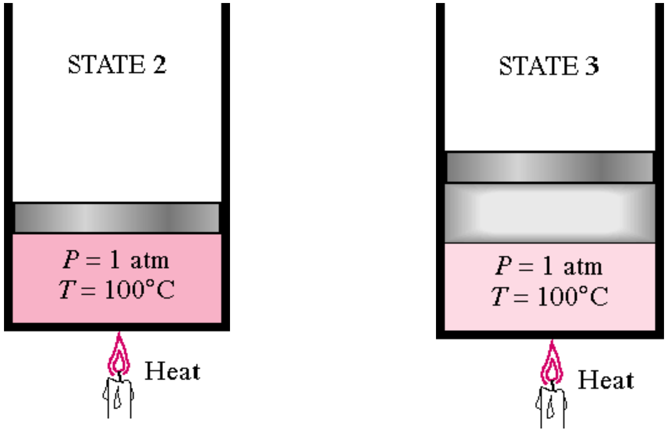
Process 1-2:

The temperature and specific volume will increase from the compressed liquid, or sub cooled liquid, state 1, to the saturated liquid state 2. In the compressed liquid region, the properties of the liquid are approximately equal to the properties of the saturated liquid state at the temperature.

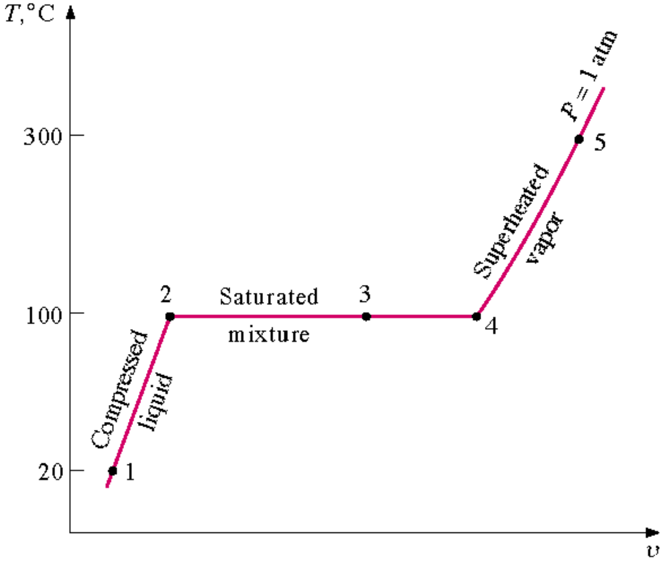


Process 2-3:

At state 2 the liquid has reached the temperature at which it begins to boil, called the saturation temperature, and is said to exist as a saturated liquid. Properties at the saturated liquid state are noted by the subscript **f** and $v_2 = v_f$. During the phase change both the temperature and pressure remain constant (according to the International Temperature Scale of 1990, ITS-90, water boils at 99.975°C ≅ 100°C when the pressure is 1 atm or 101.325 kPa). At state 3 the liquid and vapor phase are in equilibrium and any point on the line between states 2 and 3 has the same temperature and pressure.



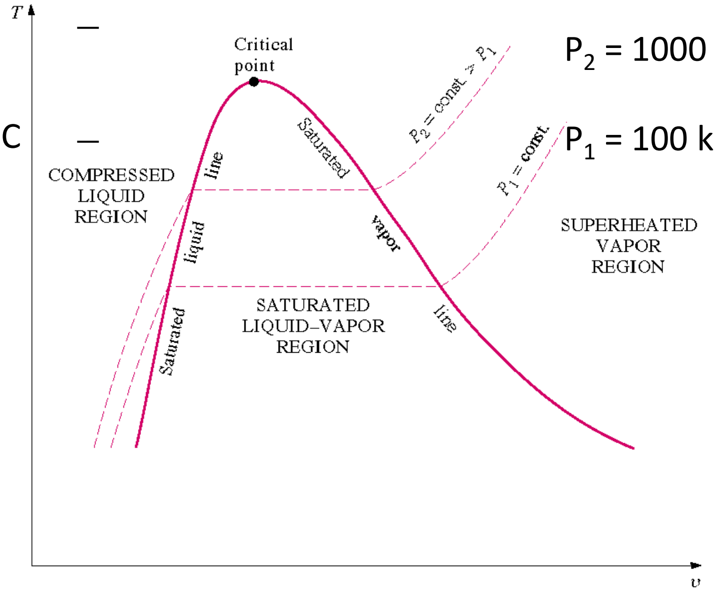
99.975 ≅



Consider repeating this process for other constant pressure lines as shown below.

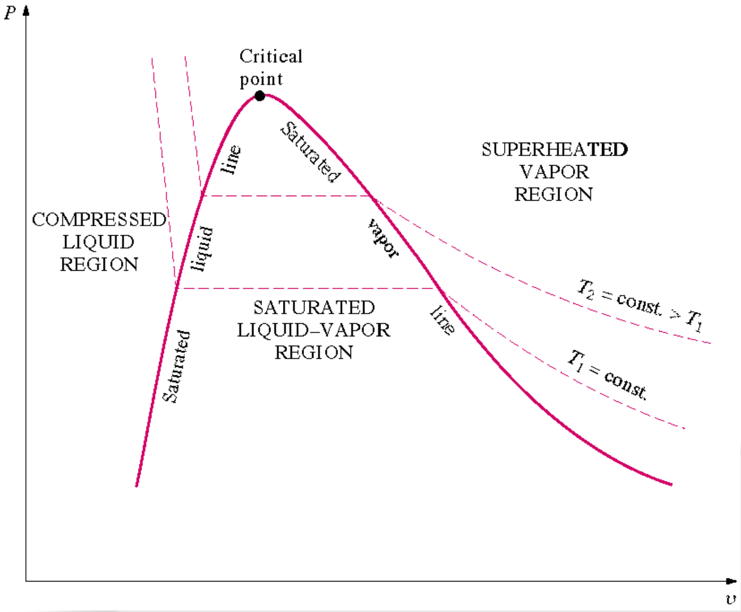
179.88°C

99.61°C



P_2 = 1000 kPa

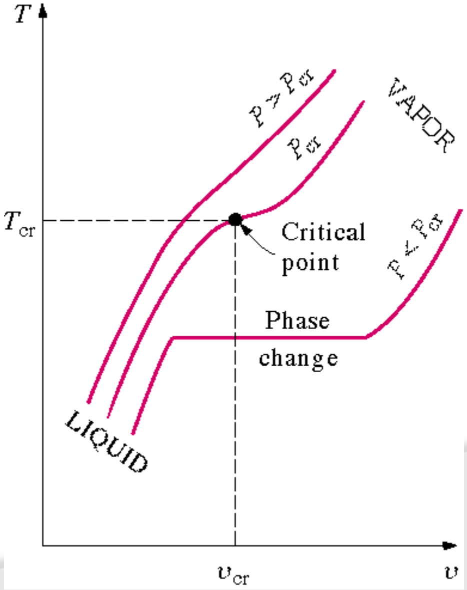
P_1 = 100 kPa



The region to the left of the saturated liquid line and below the critical temperature is called the compressed liquid region. The region to the right of the saturated vapor line and above the critical temperature is called the superheated region. for the critical point data for selected substances.

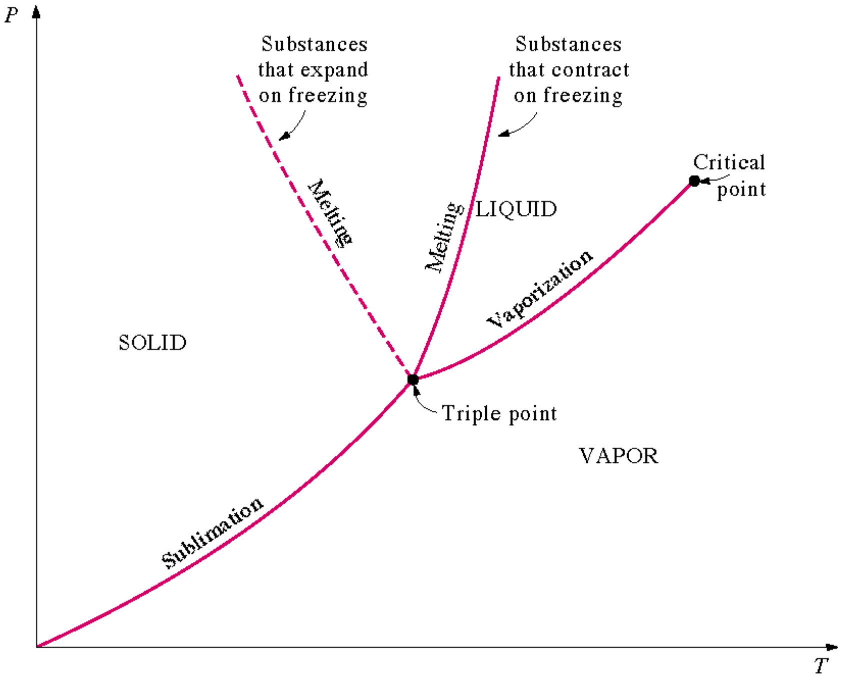
Review the *P*-*v* diagrams for substances that contract on freezing and those that expand on freezing given in Figure

At temperatures and pressures above the critical point, the phase transition from liquid to vapor is no longer discrete.



126

Figure shows the *P*-*T* diagram, often called the phase diagram, for pure substances that contract and expand upon freezing.

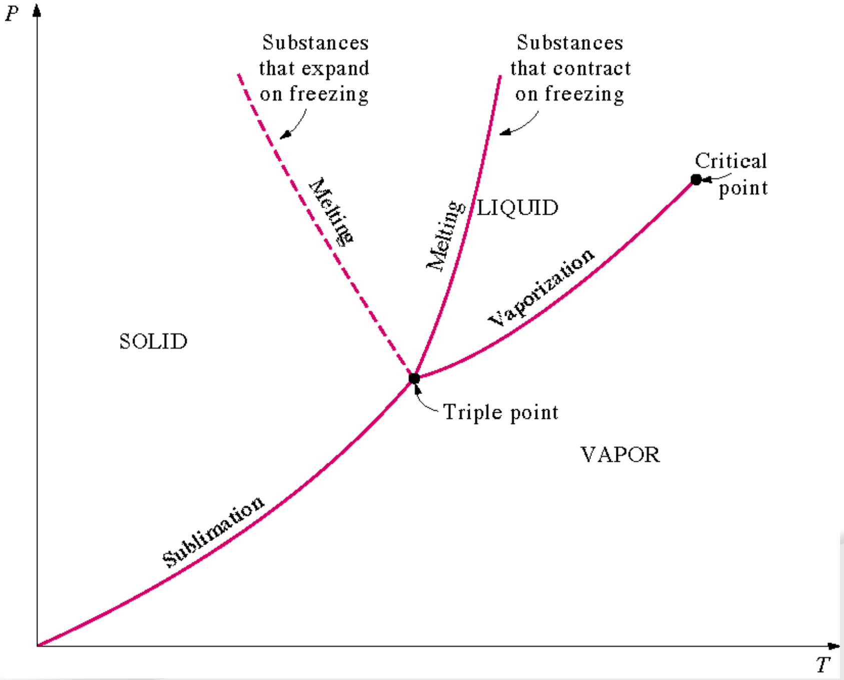


The triple point of water is 0.01^{o}C, 0.6117 kPa.

The critical point of water is 373.95^{o}C, 22.064 MPa

Plot the following processes on the *P*-*T* diagram for water (expands on freezing) and give examples of these processes from your personal experiences.

1. process a-b: liquid to vapor transition
2. process c-d: solid to liquid transition
3. process e-f: solid to vapor transition



Property Tables

In addition to the temperature, pressure, and volume data, Tables A-4 through A-8 contain the data for the specific internal energy *u* the specific enthalpy *h* and the specific entropy *s*. The enthalpy is a convenient grouping of the internal energy, pressure, and volume and is given by

$$H = U + PV$$

The enthalpy per unit mass is $$h = u + Pv$$

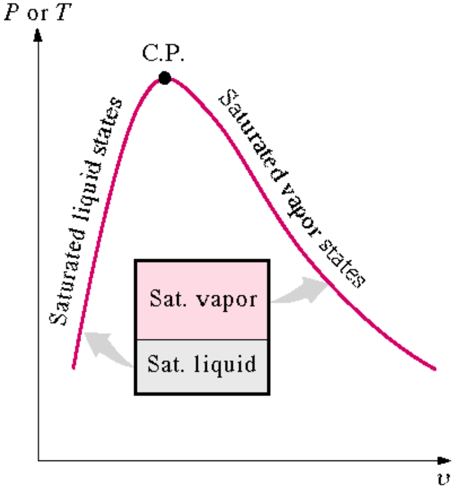
We will find that the enthalpy h is quite useful in calculating the energy of mass streams flowing into and out of control volumes. The enthalpy is also useful in the energy balance during a constant pressure process for a substance contained in a closed piston-cylinder device. The enthalpy has units of energy per unit mass, kJ/kg. The entropy s is a property defined by the second law of thermodynamics and is related to the heat transfer to a system divided by the system temperature; thus, the entropy has units of energy divided by temperature..

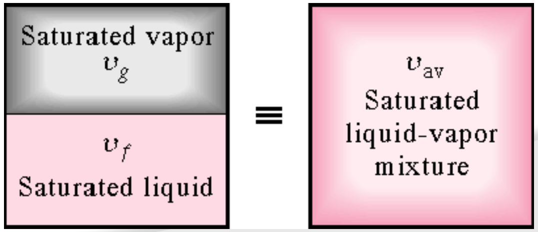
Quality and Saturated Liquid-Vapor Mixture

Now, let’s review the constant pressure heat addition process for water shown. Since state 3 is a mixture of saturated liquid and saturated vapor, how do we locate it on the T-v diagram? To establish the location of state 3 a new parameter called the quality *x* is defined as

$$x = \frac{mass_{saturated\ vapor}}{mass_{total}} = \frac{m_g}{m_f + m_g}$$

The quality is zero for the saturated liquid and one for the saturated vapor ($0 \le x \le 1$). The average specific volume at any state 3 is given in terms of the quality as follows. Consider a mixture of saturated liquid and saturated vapor. The liquid has a mass *mf* and occupies a volume V_f. The vapor has a mass *mg* and occupies a volume V_g.





$$V = V_f + V_g$$

$$m = m_f + m_g$$

$$V = mv, \quad V_f = m_f v_f, \quad V_g = m_g v_g$$

$$mv = m_f v_f + m_g v_g$$

$$v = \frac{m_f v_f}{m} + \frac{m_g v_g}{m}$$

Recall the definition of quality *x*

$$x = \frac{m_g}{m} = \frac{m_g}{m_f + m_g}$$

Then

$$\frac{m_f}{m} = \frac{m - m_g}{m} = 1 - x$$

Note, quantity 1- *x* is often given the name moisture. The specific volume of the saturated mixture becomes

$$v = (1 - x)v_f + xv_g$$

$$v = v_f + x(v_g - v_f)$$

It is noted that the value of any extensive property per unit mass in the saturation region is calculated from an equation having a form similar to that of the above equation. Let *Y* be any extensive property and let *y* be the corresponding intensive property, *Y/m*, then

$$y = \frac{Y}{m} = y_f + x(y_g - y_f)$$

$$= y_f + x\,y_{fg}$$

$$where \quad y_{fg} = y_g - y_f$$

The term y_{fg} is the difference between the saturated vapor and the saturated liquid values of the property *y*; *y* may be replaced by any of the variables *v, u, h*, or *s*.

We often use the above equation to determine the quality *x* of a saturated liquid-vapor state.

The following application is called the Lever Rule:

GAS LAWS

Equation of State, Specific and Universal Gas constants, Throttling and Free Expansion Processes, Deviations from perfect Gas Model, Vander Waals Equation of State.

Equations of State

The relationship among the state variables, temperature, pressure, and specific volume is called the equation of state. We now consider the equation of state for the vapor or gaseous phase of simple compressible substances.

$$F(P, T, v) \equiv 0$$

Ideal Gas

Based on our experience in chemistry and physics we recall that the combination of Boyle's and Charles' laws for gases at low pressure result in the equation of state for the ideal gas as

$$P = R\left(\frac{T}{v}\right)$$

where *R* is the constant of proportionality and is called the **gas constant** and takes on a different value for each gas. If a gas obeys this relation, it is called an ideal gas. We often write this equation as

$$Pv = RT$$

The gas constant for ideal gases is related to the universal gas constant valid for all substances through the molar mass (or molecular weight). Let R_u be the universal gas constant. Then,

$$R = \frac{R_u}{M}$$

The mass, *m*, is related to the moles, *N*, of substance through the molecular weight or molar mass, **M**, see Table A-1. The molar mass is the ratio of mass to moles and has the same value regardless of the system of units.

$$M_{air} = 28.97 \frac{g}{gmol} = 28.97 \frac{kg}{kmol} = 28.97 \frac{lbm}{lbmol}$$

Since 1 kmol = 1000 gmol or 1000 gram-mole and 1 kg = 1000 g, 1 kmol of air has a mass of 28.97 kg or 28,970 grams.

$$m = N\,M$$

The ideal gas equation of state may be written several ways.

$$Pv = RT$$

$$P\frac{V}{m} = RT$$

$$PV = mRT$$

$$PV = \frac{m}{M}(MR)T$$

$$PV = NR_uT$$

$$P\frac{V}{N} = R_uT$$

$$P\overline{v} = R_uT$$

Here

P = **absolute pressure** in MPa, or kPa
$\overline{v}$ = molar specific volume in m^3/kmol
T = **absolute temperature** in K
R_u = 8.314 kJ/(kmol·K)

Some values of the universal gas constant are

Universal Gas Constant, R_u
8.314 kJ/(kmol·K)
8.314 kPa·m^3/(kmol·K)
1.986 Btu/(lbmol·R)
1545 ft·lbf/(lbmol·R)
10.73 psia·ft^3/(lbmol·R)

The ideal gas equation of state can be derived from basic principles if one assumes

1. Intermolecular forces are small.
2. Volume occupied by the particles is small.

Example

Determine the particular gas constant for air and hydrogen.

$$R = \frac{R_u}{M}$$

$$R_{air} = \frac{8.314 \dfrac{kJ}{kmol - K}}{28.97 \dfrac{kg}{kmol}} = 0.287 \frac{kJ}{kg - K}$$

$$R_{hydrogen} = \frac{8.314 \dfrac{kJ}{kmol - K}}{2.016 \dfrac{kg}{kmol}} = 4.124 \frac{kJ}{kg - K}$$

The ideal gas equation of state is used when (1) the pressure is small compared to the critical pressure or (2) when the temperature is twice the critical temperature and the pressure is less than 10 times the critical pressure. The critical point is that state where there is an instantaneous change from the liquid phase to the vapor phase for a substance. Critical point data are given in Table A-1.

Compressibility Factor

To understand the above criteria and to determine how much the ideal gas equation of state deviates from the actual gas behavior, we introduce the compressibility factor *Z* as follows.

or

$$P\bar{v} = Z\,R_u\,T$$

$$Z = \frac{P\bar{v}}{R_u\,T}$$

Useful Ideal Gas Relation: The Combined Gas Law

By writing the ideal gas equation twice for a fixed mass and simplifying, the properties of an ideal gas at two different states are related by

$$m_1 = m_2$$

or

$$\frac{P_1 V_1}{R\,T_1} = \frac{P_2 V_2}{R\,T_2}$$

But, the gas constant is_____________(fill in the blank), so

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Example 2-7

An ideal gas having an initial temperature of 25°C under goes the two processes described below. Determine the final temperature of the gas.

Process 1-2: The volume is held constant while the pressure doubles.
Process 2-3: The pressure is held constant while the volume is reduced to one-third of the original volume.

Boyle's Law: For a fixed amount of gas and constant temperature, PV = constant.

Charles's Law: at constant pressure the volume is linearly proportional to temperature. V/T = constant

Dalton's Law = the sum of the partial pressures of the gases in a mixture = the total pressure or $P = P_A + P_B + P_C + \ldots$where P_i = the partial pressure of component i.

Avagadro’s law for a fixed pressure and temperature, the volume of a gas is directly proportional to the number of moles of that gas. $V/n = k =$ constant.

UNIT – IV
GAS MIXTURES

At the end of the unit students are able to:

	Course Outcomes	Knowledge Level (Bloom’s Taxonomy)
CO9	Show the significance of partial pressure and temperature to table the performance parameters of gaseous mixtures.	Understand
CO10	Determine the properties of air-conditioning systems by practicing psychrometry chart and gas property tables.	Understand

145

GAS MIXTURES

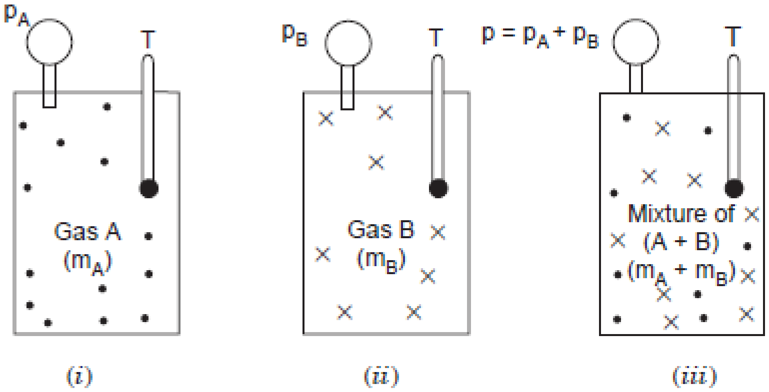
Mole Fraction, Mass friction, Gravimetric and volumetric Analysis, Volume fraction, Dalton’s Law of partial pressure, Avogadro’s Laws of additive volumes, and partial pressure, Equivalent Gas constant, Internal Energy, Enthalpy, sp. Heats and Entropy of Mixture of perfect Gases

Ideal-Gas Mixtures

$$\frac{P_i(T_m, V_m)}{P_m} = \frac{N_i R_u T_m / V_m}{N_m R_u T_m / V_m} = \frac{N_i}{N_m} = y_i$$

$$\frac{V_i(T_m, P_m)}{V_m} = \frac{N_i R_u T_m / P_m}{N_m R_u T_m / P_m} = \frac{N_i}{N_m} = y_i$$

$$\frac{P_i}{P_m} = \frac{V_i}{V_m} = \frac{N_i}{N_m} = y_i$$

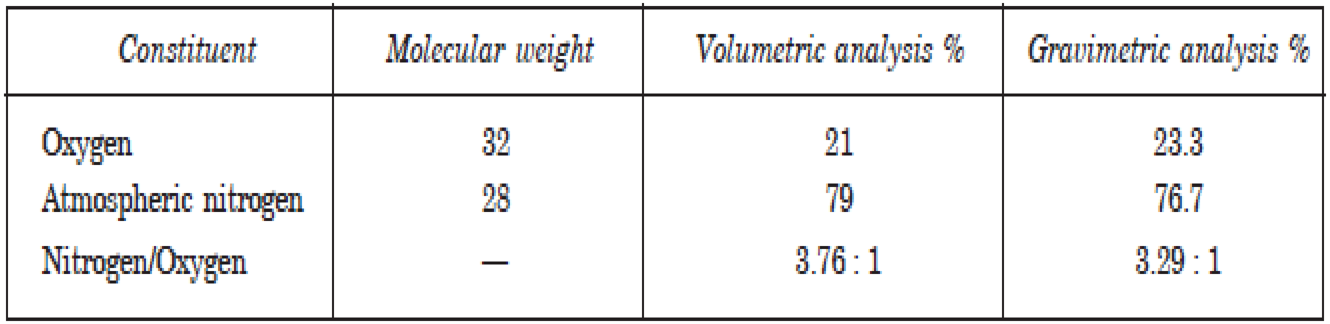


This equation is only valid for ideal-gas mixtures as it is derived by assuming ideal-gas behavior for the gas mixture and each of its components.

The quantity $P_{i/}\ P_m$ is called the **partial pressure** (identical to the *component pressure* for ideal gases), and the quantity $V_{i/}V_m$ is called the **partial volume** (identical to the *component volume* for ideal gases).

Note that for an ideal-gas mixture, the mole

The composition of an ideal-gas mixture (such as the exhaust gases leaving a combustion chamber) is frequently determined by a volumetric analysis



Constituent	*Molecular weight*	*Volumetric analysis %*	*Gravimetric analysis %*
Oxygen	32	21	23.3
Atmospheric nitrogen	28	79	76.7
Nitrogen/Oxygen	—	3.76 : 1	3.29 : 1

Volumetric analysis is the analysis by **volume**

gravimetric analysis is the analysis by **weight or mass**

Ex

A vessel of 0.35 m3 capacity contains 0.4 kg of carbon monoxide (molecular weight = 28) and 1 kg of air at 20°C. Calculate :

(i) The partial pressure of each constituent,

(ii) The total pressure in the vessel, and The gravimetric analysis of air is to be taken as 23.3% oxygen (molecular weight = 32) and 76.7% nitrogen (molecular weight = 28).

Mass of carbon monoxide = 0.4 kg
Mass of air = 1 kg
Temperature, T = 20°C or 293 K
Mass of oxygen present in 1 kg of air =23. 3/100=0.233 kg
Mass of nitrogen present in 1 kg of air =76.7/100.× 1 = 0.767 kg

Also, the characteristic gas equation is given by

$$pV = mRT$$

$$\therefore \quad pV = \frac{mR_0T}{M}$$

$$p = \frac{mR_0T}{MV}$$

Hence, for a constituent,

$$p_i = \frac{m_iR_0T}{M_iV}$$

Substituting the values, we get the partial pressures as follov

(*i*) **Partial pressures :**

For O_2, $$p_{O_2} = \frac{0.233 \times (8.314 \times 10^3) \times 293}{32 \times 0.35 \times 10^5} = \mathbf{0.5068\ bar.}$$

For N_2, $$p_{N_2} = \frac{0.767 \times (8.314 \times 10^3) \times 293}{28 \times 0.35 \times 10^5} = \mathbf{1.9065\ bar.}$$

For CO, $$p_{CO} = \frac{0.40 \times (8.314 \times 10^3) \times 293}{28 \times 0.35 \times 10^5} = \mathbf{0.9943\ bar.}$$

(*ii*) **Total pressure in the vessel, p :**

$$p = \Sigma p_i = p_{O_2} + p_{N_2} + p_{CO}$$

$$= 0.5068 + 1.9065 + 0.9943 = \mathbf{3.4076\ bar.}$$

The gravimetric analysis of air and other data are as follows :

Constituent	Percentage	Molecular weight
Oxygen	23.14	32
Nitrogen	75.53	28
Argon	1.28	40
Carbon dioxide	0.05	44

Calculate : (i) Gas constant for air ;
(ii) Apparent molecular weight.

Using the relation, $R = \dfrac{R_0}{M}$

$$R_{O_2} = \frac{8.314}{32} = 0.2598 \text{ kJ/kg K}$$

$$R_{N_2} = \frac{8.314}{28} = 0.2969 \text{ kJ/kg K}$$

$$R_{Ar} = \frac{8.314}{40} = 0.2078 \text{ kJ/kg K}$$

$$R_{CO_2} = \frac{8.314}{44} = 0.1889 \text{ kJ/kg K}$$

(*i*) **Gas constant for air :**

Now using the equation,

$$R = \sum \frac{m_i}{m} R_i, \text{ we have} \qquad ...(i$$

$$R = 0.2314 \times 0.2598 + 0.7553 \times 0.2969 + 0.0128 \times 0.2078 + 0.0005 \times 0.1889$$

$$= 0.0601 + 0.2242 + 0.00266 + 0.00009 = 0.2871 \text{ kJ/kg K}$$

(*ii*) **Apparent molecular weight :**

Now from eqn. (*i*), we have $M = \dfrac{8.314}{0.2871} =$

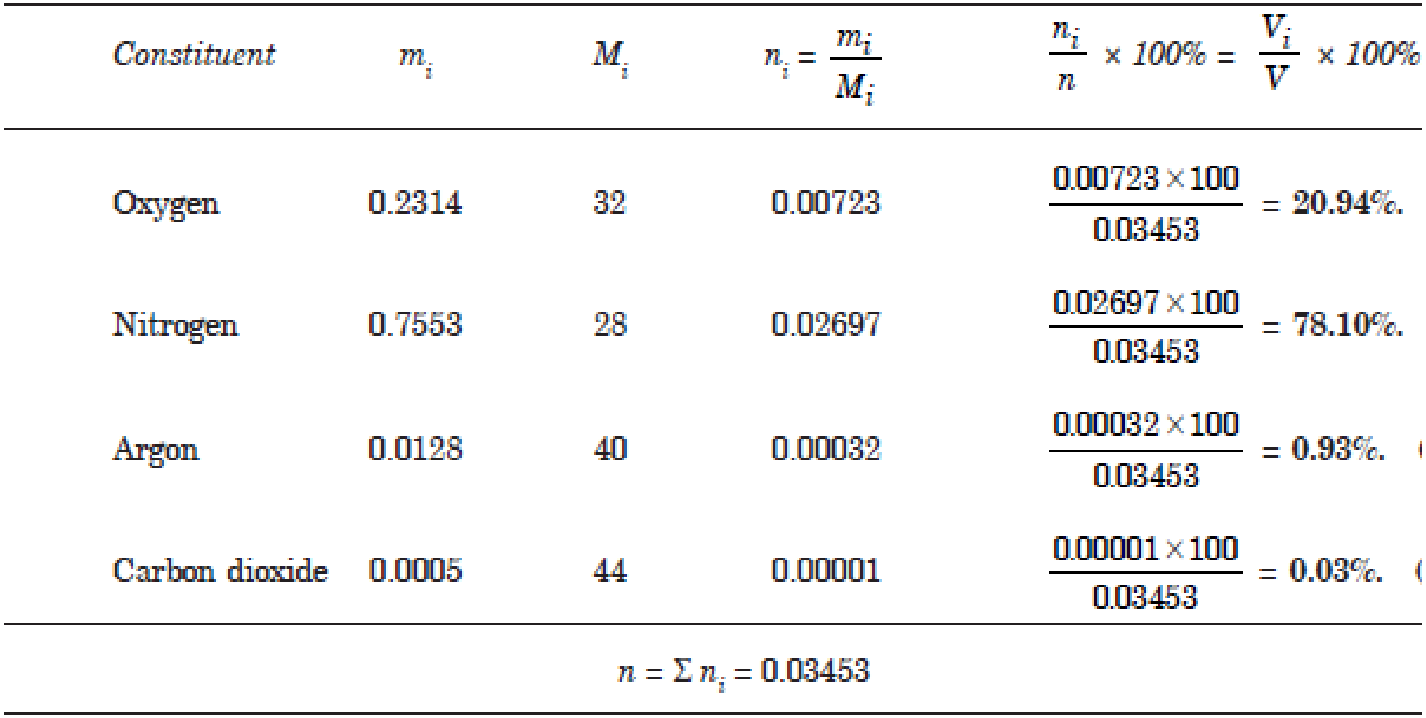
Hence apparent molecular weight = 28.96.

Ex

Following is the gravimetric analysis of air :

Constituent	Percentage
Oxygen	23.14
Nitrogen	75.53
Argon	1.28
Carbon dioxide	0.05

Calculate the analysis by volume and the partial pressure of each constituent when the total pressure is 1 bar.



Constituent	m_i	M_i	$n_i = \frac{m_i}{M_i}$	$\frac{n_i}{n} \times 100\% = \frac{V_i}{V} \times 100\%$
Oxygen	0.2314	32	0.00723	$\frac{0.00723 \times 100}{0.03453} = 20.94\%.$
Nitrogen	0.7553	28	0.02697	$\frac{0.02697 \times 100}{0.03453} = 78.10\%.$
Argon	0.0128	40	0.00032	$\frac{0.00032 \times 100}{0.03453} = 0.93\%.$
Carbon dioxide	0.0005	44	0.00001	$\frac{0.00001 \times 100}{0.03453} = 0.03\%.$
		$n = \Sigma n_i = 0.03453$		

Also, $$\frac{p_i}{p} = \frac{V_i}{V} = \frac{n_i}{n}$$

∴ $$p_i = \frac{n_i}{n} p \text{ hence}$$

For O_2, $P_{O_2} = 0.2094 \times 1 =$ **0.2094 bar.**

For N_2, $P_{N_2} = 0.7810 \times 1 =$ **0.7810 bar.**

For Ar, $P_{Ar} = 0.0093 \times 1 =$ **0.0093 bar.**

For CO_2, $P_{CO_2} = 0.0003 \times 1 =$ **0.0003 bar.**

PSYCHROMETRY

Psychrometric properties-Dry bulb temperature, wet bulb temperature, specific humidity, Relative humidity, saturated air, Degree of saturation-adiabatic saturation, carrier equation, psychrometric chart.

Psychrometry

The art of measuring the *moisture content of air is termed* “**psychrometry**”.

The science which investigates the thermal properties of moist air, considers the measurement and control of the moisture content of air, and studies the effect of atmospheric moisture on material and human comfort may properly be termed “**psychrometrics**

Dry air.

The term ‘*dry air*’ is used to indicate the *water free contents* of air having any degree of moisture.

Saturated air. Moist air is said to be saturated when its condition is such that it can co-exist in natural equilibrium with an associated condensed moisture phase presenting a flats surface to it. For *a given temperature, a given quantity of air can be saturated with a fixed quantity of moisture.*

At higher temperatures, it requires a larger quantity of moisture to saturate it. At saturation, vapour pressure of moisture in air corresponds to the saturation pressure given in steam tables corresponding to the given temperature of air.

Basic Terminology

Dry-bulb temperature (DBT)
It *is the temperature of air as registered by an ordinary thermometer* (t_{db}).

Wet-bulb temperature (WBT). *It is the temperature registered by a thermometer when the bulb is covered by a wetted wick and is exposed to a current of rapidly moving air* (t_{wb}).

Adiabatic saturation temperature. *It* is *the temperature at which the water or ice can saturate air by evaporating adiabatically into it*. It is numerically equivalent to the measured wet bulb temperature (as corrected, if necessary for radiation and conduction) (t_{wb}).

Wet bulb depression. It *is the difference between dry-bulb and wet bulb temperatures* ($t_{db} – t_{wb}$).

Dew point temperature (DPT). *It is the temperature to which air must be cooled at constant pressure in order to cause condensation of any of its water vapour*.
It is equal to steam table saturation temperature corresponding to the actual partial pressure of water vapour in the air (t_{dp}).

Dew point depression. *It is the difference between the dry bulb and dew point temperatures* ($t_{db} – t_{dp}$).

Specific humidity (Humidity ratio). *It is the ratio of the mass of water vapour per unit mass of dry air in the mixture of vapour and air*, it is generally expressed as grams of water per kg of dry air. For a given barometric pressure it is a function of dew point temperature alone.

Relative humidity (RH), (φ). *It is the ratio of the partial pressure of water vapour in the mixture to the saturated partial pressure at the dry bulb temperature, expressed as percentage.*

Sensible heat. *It is the heat that changes the temperature of a substance when added to or abstracted from it.*

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Psychrometric Relation

Dalton's law of partial pressure is employed to determine the pressure of a mixture of gases.

This law *states that the total pressure of a mixture of gases is equal to the sum of partial pressures which the component gases would exert if each existed alone in the mixture volume at the mixture temperature.*

For calculating partial pressure of water vapour in the air many equations have been proposed, probably Dr. arrier’s equation is most widely used.

$$p_v = (p_{vs})_{wb} - \frac{[pt - (p_{vs})_{wb}](t_{db} - t_{wb})}{1527.4 - 1.3\, t_{wb}}$$

p_v = Partial pressure of water vapour,
p_{vs} = Partial pressure of water vapour when air is fully saturated,
p_t = Total pressure of moist air,
t_{db} = Dry bulb temperature (ºC), and
t_{wb} = Wet bulb temperature (ºC).

Specific humidity W :

$$\text{Specific humidity} = \frac{\text{Mass of water vapour}}{\text{Mass of dry air}}$$

$$W = \frac{m_v}{m_a}$$

Also,
$$m_a = \frac{p_a V}{R_a T}$$

$$m_v = \frac{p_v \times V}{R_v \times T}$$

p_a = Partial pressure of dry air,
p_v = Partial pressure of water vapour,
V = Volume of mixture,
R_a = Characteristic gas constant for dry air, and
R_v = Characteristic gas constant for water vapour.

$$W = \frac{p_v \times V}{R_v \times T} \times \frac{R_a\,T}{p_a\,V} = \frac{R_a}{R_v} \times \frac{p_v}{p_a}$$

$$R_a = \frac{R_0}{M_a} \qquad \left(= \frac{8.3143}{28.97} = 0.287 \text{ kJ/kg K in SI units} \right)$$

$$R_v = \frac{R_0}{M_v} \qquad \left(= \frac{8.3143}{18} = 0.462 \text{ kJ/kg K in SI units} \right)$$

R_0 = Universal gas constant,

M_a = Molecular weight of air, and

M_v = Molecular weight of water vapour.

$$W = \frac{0.287}{0.462} \cdot \frac{p_v}{p_a} = 0.622 \frac{p_v}{p_t - p_v}$$

$$W = 0.622 \frac{p_v}{p_t - p_v}$$

Degree of saturation (μ)

$$\text{Degree of saturation} = \frac{\begin{array}{c}\text{Mass of water vapour associated}\\ \text{with unit mass of dry air}\end{array}}{\begin{array}{c}\text{Mass of water vapour associated with}\\ \text{saturated unit mass of dry saturated air}\end{array}}$$

$$\mu = \frac{W}{W_s}$$

W_s = Specific humidity of air when air is fully saturated

$$\mu = \frac{0.622\left(\dfrac{p_v}{p_t - p_v}\right)}{0.622\left(\dfrac{p_{vs}}{p_t - p_{vs}}\right)} = \frac{p_v(p_t - p_{vs})}{p_{vs}(p_t - p_v)}$$

$$= \frac{p_v}{p_s}\left[\frac{\left(1 - \dfrac{p_{vs}}{p_t}\right)}{\left(1 - \dfrac{p_v}{p_t}\right)}\right]$$

Relative humidity (RH), φ

$$\text{Relative humidity, } \phi = \frac{\text{Mass of water vapour in a given volume}}{\begin{array}{c}\text{Mass of water vapour in the same}\\ \text{volume if saturated at the same temp.}\end{array}}$$

$$= \frac{m}{m_{vs}} = \frac{\dfrac{p_v T}{R_v T}}{\dfrac{p_{vs} T}{R_v T}} = \frac{p_v}{p_{vs}}$$

Enthalpy of moist air

It is the sum of enthalpy of dry air and enthalpy of water vapour associated with dry air.

It is expressed in kJ/kg of dry air

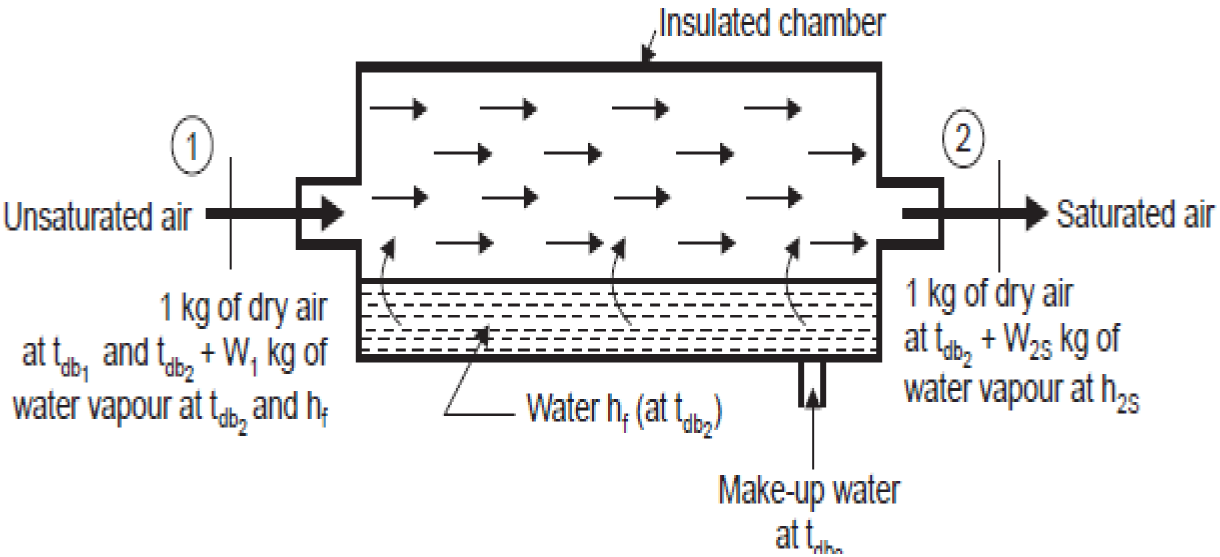
$h = h_{\text{air}} + W \,.\, h_{\text{vapour}}$

$= c_p t_{db} + W \,.\, h_{\text{vapour}}$

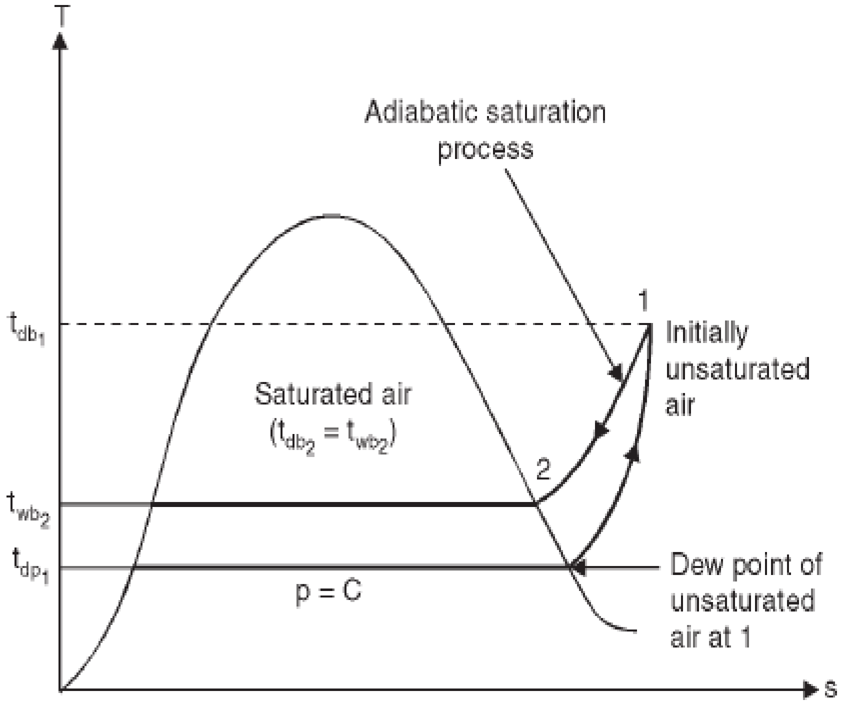
$$h_{\text{vapour}} = 2500 + 1.88 t_{db} \text{ kJ/kg of water vapour}$$

$$h = 1.005\ t_{db} + W(2500 + 1.88\ t_{db}) \text{ kJ/kg dry air.}$$

Adiabatic saturation process



Adiabatic cooling process



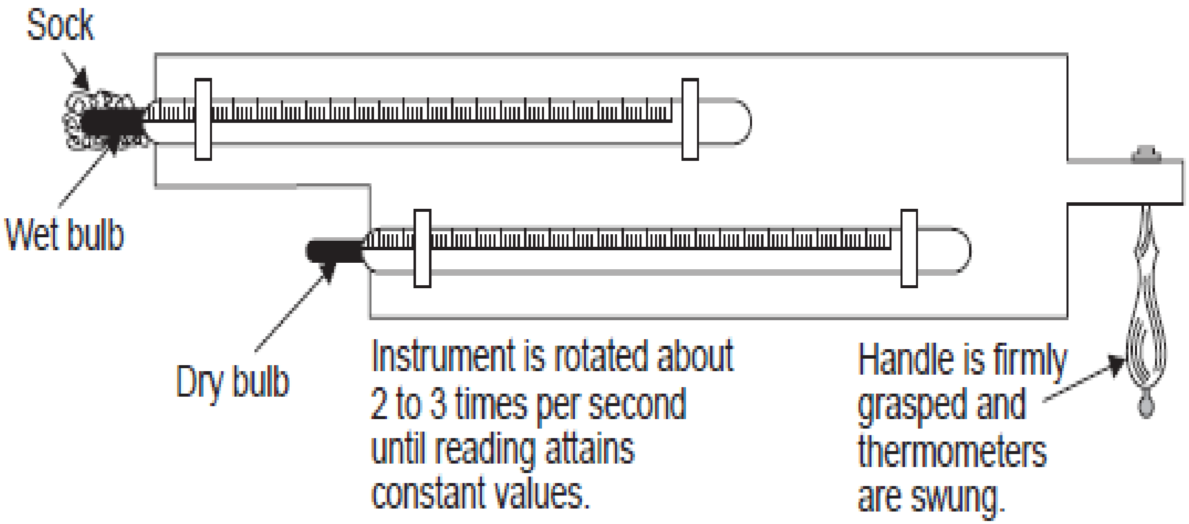
PSYCHROMETERS

The psychrometers may be classified as follows :

1. Laboratory psychrometer
2. Sling psychrometer
3. Aspirating psychrometer
4. Continuous recording psychrometer

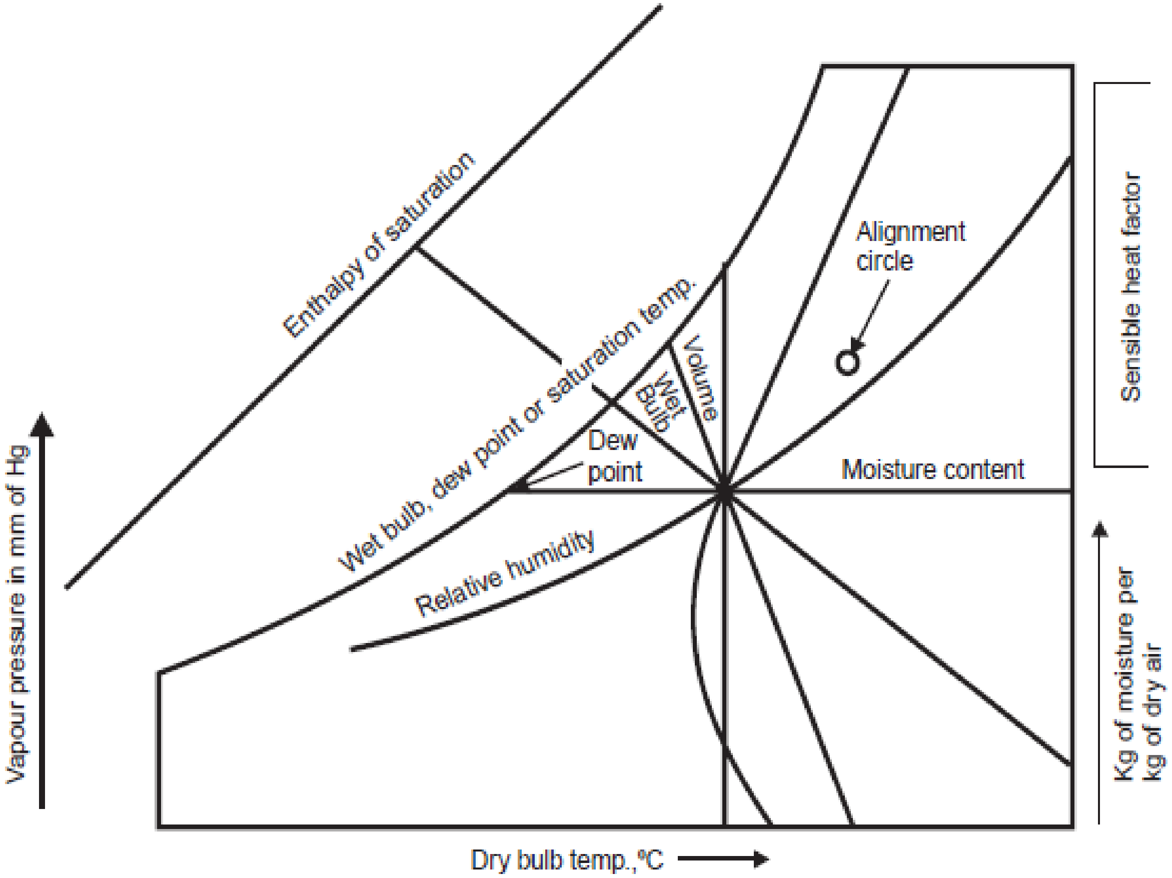
172

Sling psychrometer



173

PSYCHROMETRIC CHARTS



The dry bulb temperature (ºC) of unit mass of dry air for different humidity contents or humidity ratios are indicated by *vertical lines drawn parallel to the ordinate.*

Dew point temperatures are temperatures corresponding to the boiling points of water at low pressures of water vapour and are shown in the scale on the *upper curved line*. The dew points for different low pressures are read on *diagonal co-ordinates.*

Constant relative humidity lines in per cent are indicated by marking off vertical distances between the saturation line or the upper curved line and the base of the chart. The relative humidity curve depicts quantity (kg) of moisture actually present in the air as a percentage of the total amount possible at various dry bulb temperatures and masses of vapour.

Enthalpy or total heat at saturation temperature in kJ/kg of dry air is shown by a diagonal system of co-ordinates. The scale on the diagonal line is separate from the body of the chart and is indicated above the saturation line.

Wet bulb temperatures are shown on the diagonal co-ordinates coinciding with heat coordinates. The scale of wet bulb temperatures is shown on the saturation curve. The diagonals run downwards to the right at an angle of 30º to the horizontal

1.If dry bulb and wet bulb temperatures are known, the relative humidity can be read from the chart.

2. If the dry bulb and relative humidity are known, the wet bulb temperature can be determined.

3. If wet bulb temperature and relative humidity are known, the dry bulb temperature can be found.

4.If wet bulb and dry bulb temperatures are known, the dew point can be found.

5. If wet bulb and relative humidity are known, dew point can be read from the chart.

6. If dry-bulb and relative humidity are known, dew point can be found.

The quantity (kg) of moisture in air can be determined from any of the following combinations :

(*i*) Dry bulb temperature and relative humidity
(*ii*) Dry bulb temperature and dew point
(*iii*) Wet bulb temperature and relative humidity
(*iv*) Wet bulb temperature and dew point temperature
(*v*) Dry bulb temperature and wet bulb temperature and
(*vi*) Dew point temperature alone.

PSYCHROMETRIC PROCESSES

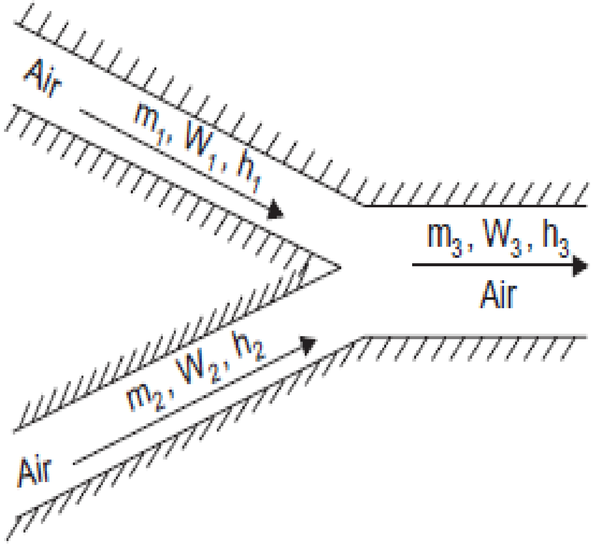
1. Mixing of air streams
2. Sensible heating
3. Sensible cooling
4. Cooling and dehumidification
5. Cooling and humidification
6. Heating and dehumidification
7. Heating and humidification.

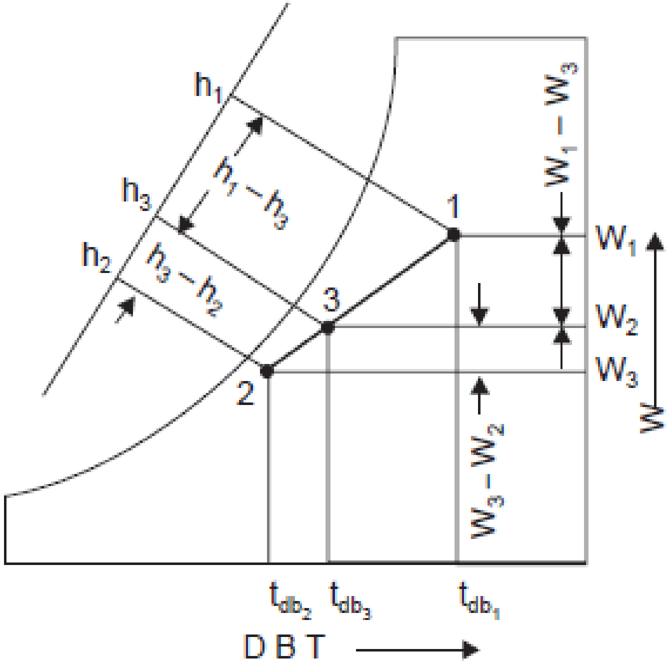
Mixing of Air Streams

$$m_1 + m_2 = m_3$$

$$m_1W_1 + m_2W_2 = m_3W_3$$

$$m_1h_1 + m_2h_2 = m_3h_3$$





$$\boxed{\frac{m_1}{m_2} = \frac{W_3 - W_2}{W_1 - W_3} = \frac{h_3 - h_2}{h_1 - h_3}}$$

Rearranging of last two equations gives the following :

$$m_1(W_1 - W_3) = m_2(W_3 - W_2)$$

$$m_1(h_1 - h_3) = m_2(h_3 - h_2)$$

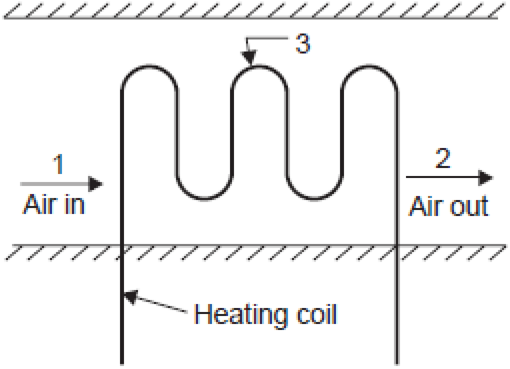
$$\frac{m_1}{m_2} = \frac{W_3 - W_2}{W_1 - W_3} = \frac{h_3 - h_2}{h_1 - h_3}$$

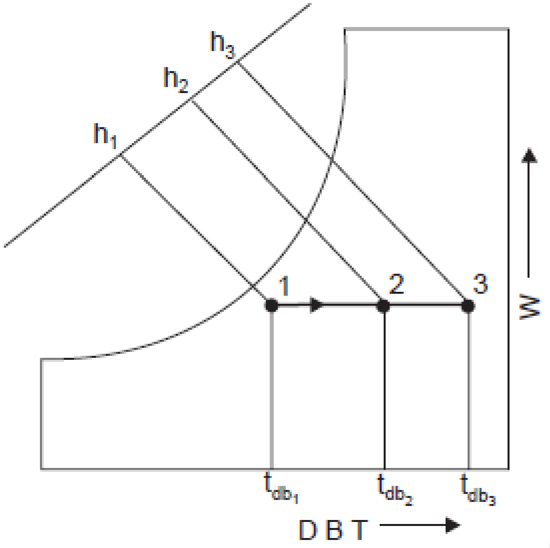
Sensible heating

The by-pass factor (BF) for the process is defined as the ratio of the difference between the mean surface temperature of the coil and leaving air temperature to the difference between the mean surface temperature and the entering air temperature

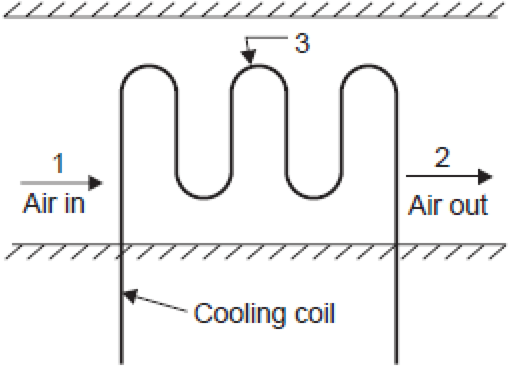
The by-pass factor is expressed as follows :

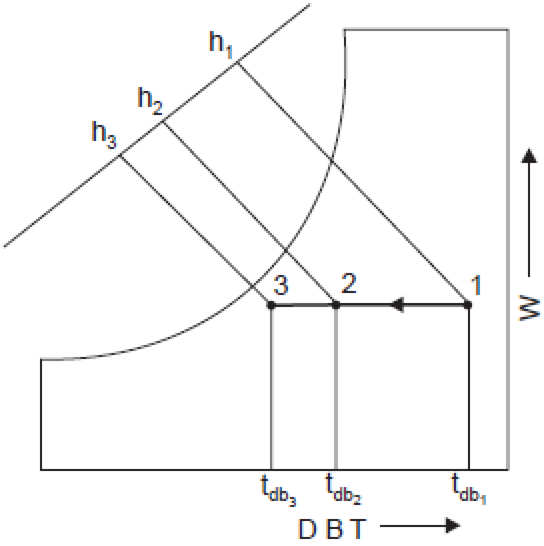
$$BF = \frac{t_{db_3} - t_{db_2}}{t_{db_3} - t_{db_1}}$$





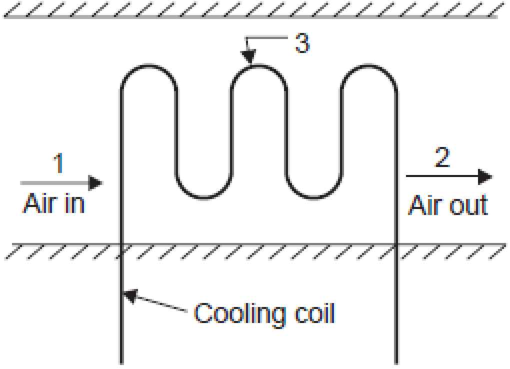
Sensible Cooling

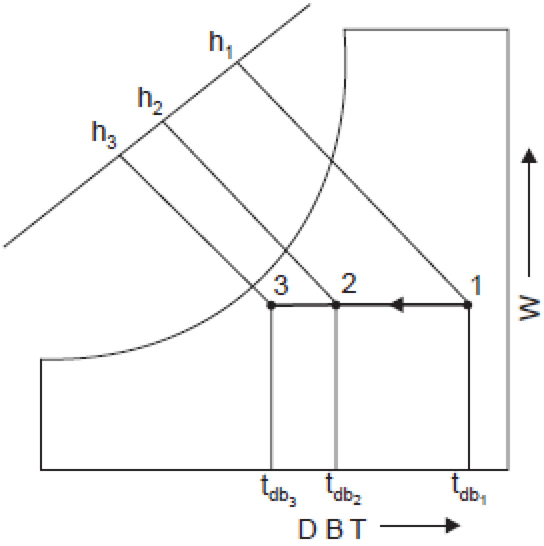




$$\text{By-pass factor BF} = \frac{t_{db_2} - t_{db_3}}{t_{db_1} - t_{db_3}}$$

Sensible Cooling





$$\text{By-pass factor BF} = \frac{t_{db_2} - t_{db_3}}{t_{db_1} - t_{db_3}}$$

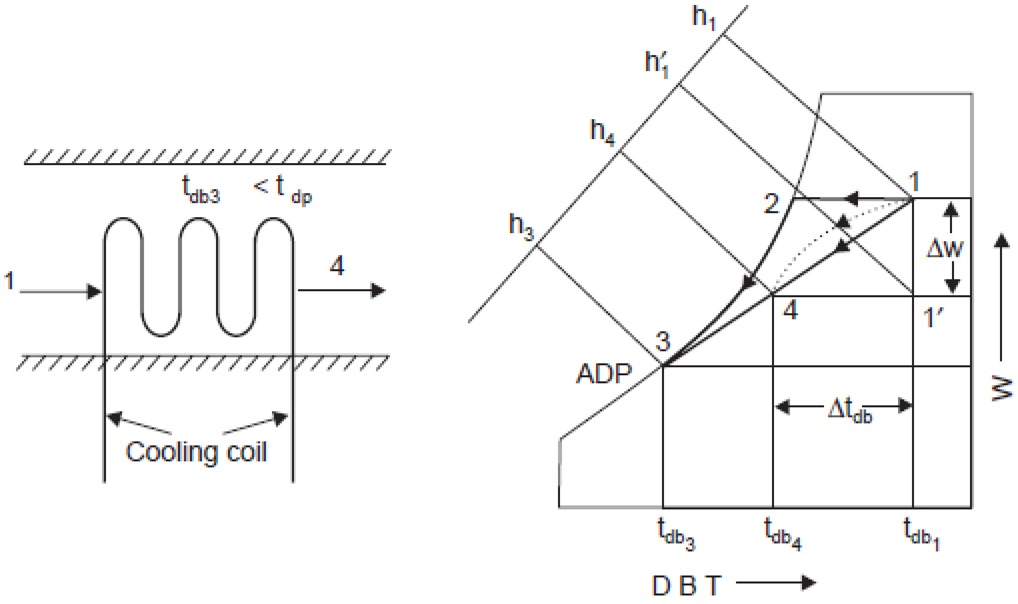
The heat removed from air can be obtained from the enthalpy difference ($h1 – h2$) or from humid specific heat multiplied by the temperature difference ($t_{db1} - t_{db2}$) .

During the process, *the specific humidity remains constant* and *dry bulb temperature decreases*, approaching the mean effective surface temperature.

On a psychrometric chart the process will appear as a horizontal line 1–2 where point 3 represents the effective surface temperature.

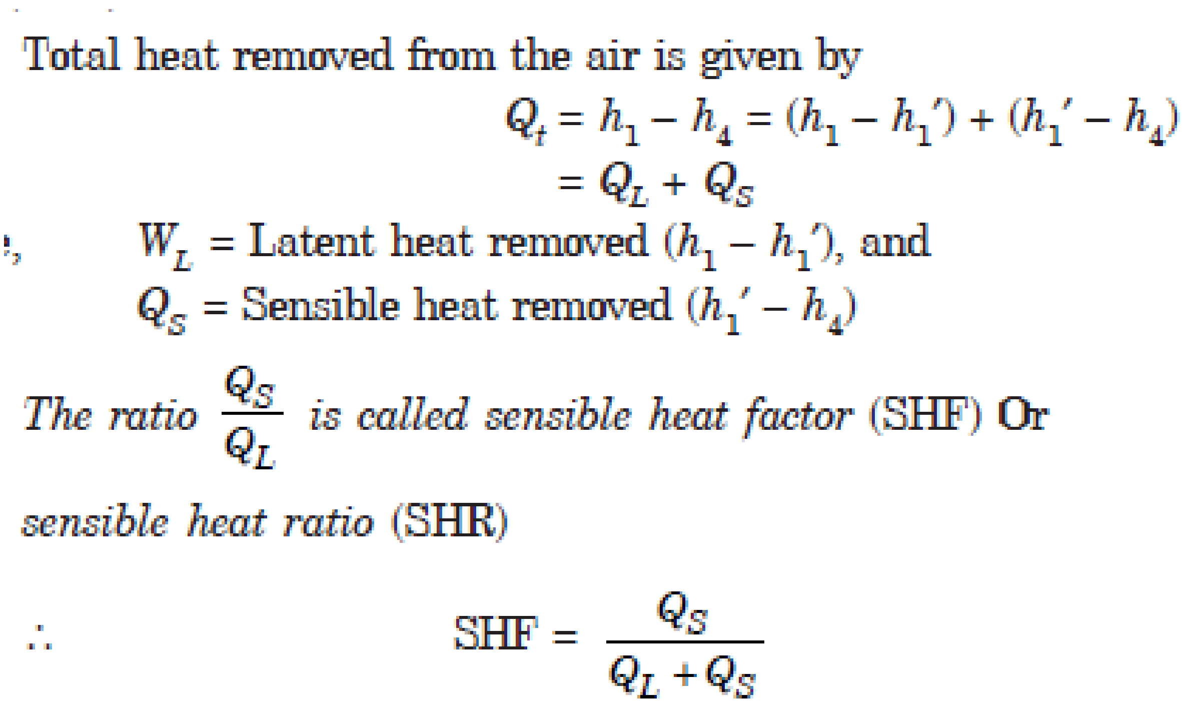
Cooling and Dehumidification

Whenever air is made to pass over a surface or through a spray of water that is at a *temperature less than the dew point temperature of the air, condensation of some of the water vapour in air will occur simultaneously with the sensible cooling process.*



by pass factor equal to
length 3 – 4/length 3 -1

.



Total heat removed from the air is given by

$$Q_t = h_1 - h_4 = (h_1 - h_1') + (h_1' - h_4)$$
$$= Q_L + Q_S$$

W_L = Latent heat removed $(h_1 - h_1')$, and

Q_S = Sensible heat removed $(h_1' - h_4)$

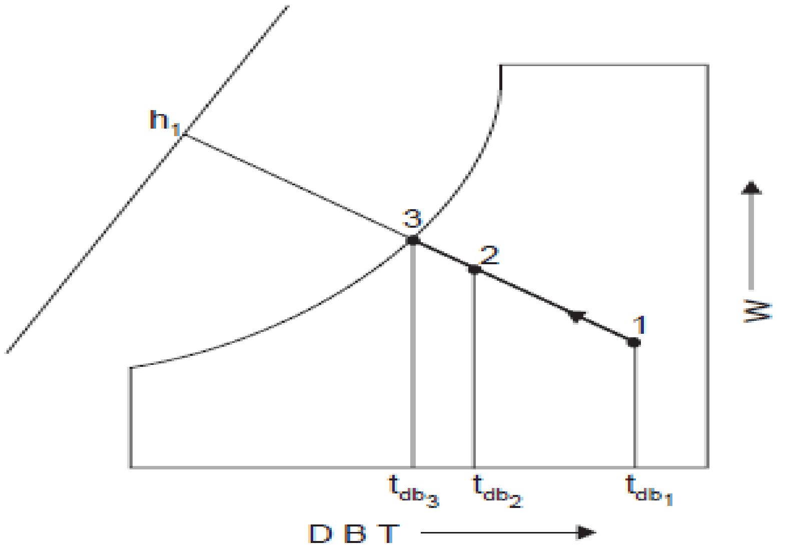
The ratio $\dfrac{Q_S}{Q_L}$ *is called sensible heat factor* (SHF) Or *sensible heat ratio* (SHR)

$$\therefore \qquad \text{SHF} = \frac{Q_S}{Q_L + Q_S}$$

Cooling and Humidification

If unsaturated air is passed through a spray of continuously recirculated water, the specific humidity will increase while the dry bulb temperature decreases. This is the process of ***adiabatic saturation* or *evaporative cooling*.** This process is one of constant adiabatic-saturation temperature and for all practical purposes, one of constant wet bulb temperature.

The ratio of dry-bulb temperature decrease to the entering wet bulb depression usually expressed as percentage---humidifying efficiency.

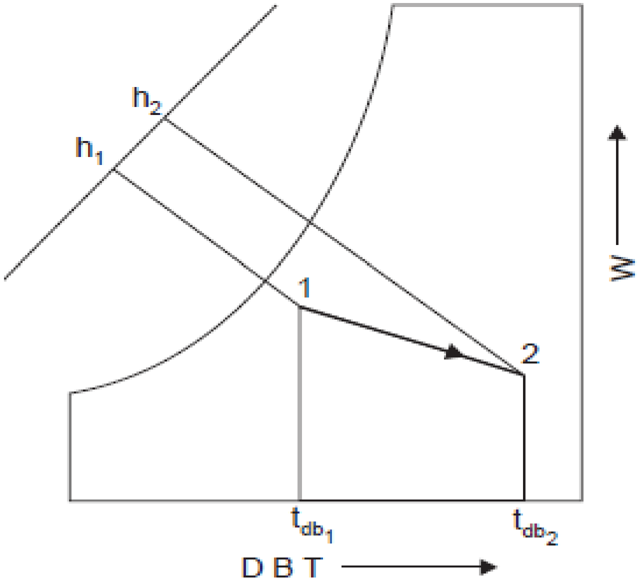


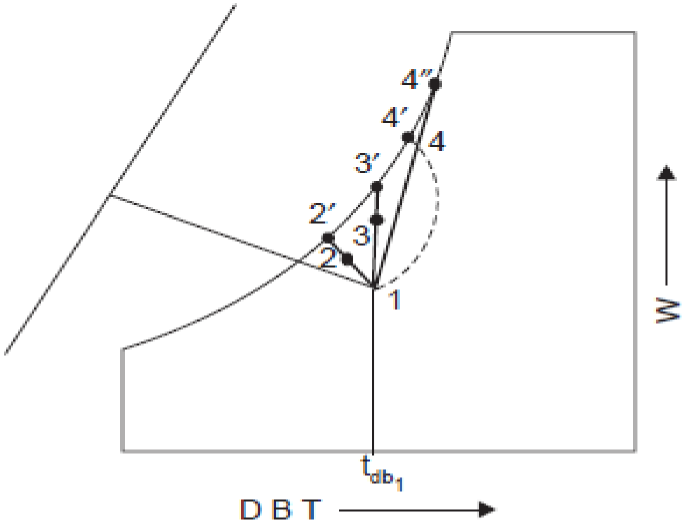
Heating and Dehumidification

If air is passed over a solid absorbent surface or through a liquid absorbent spray simultaneous heating and dehumidification is accompanied. In either case the dehumidification results from adsorbent or absorbent having a lower water vapour pressure than air.

Moisture is condensed out of the air, and consequently the latent heat of condensation is liberated, causing sensible heating of air. If these were the only energies involved, the process would be the inverse of the adiabatic saturation process.

There is, however, **an additional energy absorbed or liberated by the active material, termed the *heat of adsorption* or *absorption***. For the solid adsorbents used commercially, such as **silica gel or activated alumina,** and for the more common liquid absorbents, such as solutions of **organic salts or inorganic compounds like ethylene, glycol,** heat is involved and results in additional sensible heating.





Process 1-2 : It denotes the cases in which the temperature of the heated spray water is less than the air DBT.

Process 1-3 : It denotes the cases in which the temperature is *equal to the air DBT.*

Process 1-4 : It denotes the cases in which a spray temperature is *greater than air DBT.*

Ex

The atmospheric conditions are ; 20°C and specific humidity of 0.0095 kg/kg of dry air. Calculate the following :

(i) Partial pressure of vapour (ii) Relative humidity

(iii) Dew point temperature

Dry bulb temperature, *tdb* = 20ºC

Specific humidity, *W* = 0.0095 kg/kg of dry air

(*i*) **Partial pressure of vapour, pv :**

The specific humidity is given by

$$W = \frac{0.622\, p_v}{p_t - p_v}$$

(*ii*) **Relative humidity φ :**

Corresponding to 20ºC, from steam tables,

p_{vs} = 0.0234 bar

Relative humidity, $$\phi = \frac{p_v}{p_{vs}} = \frac{0.01524}{0.0234} = \mathbf{0.65}$$

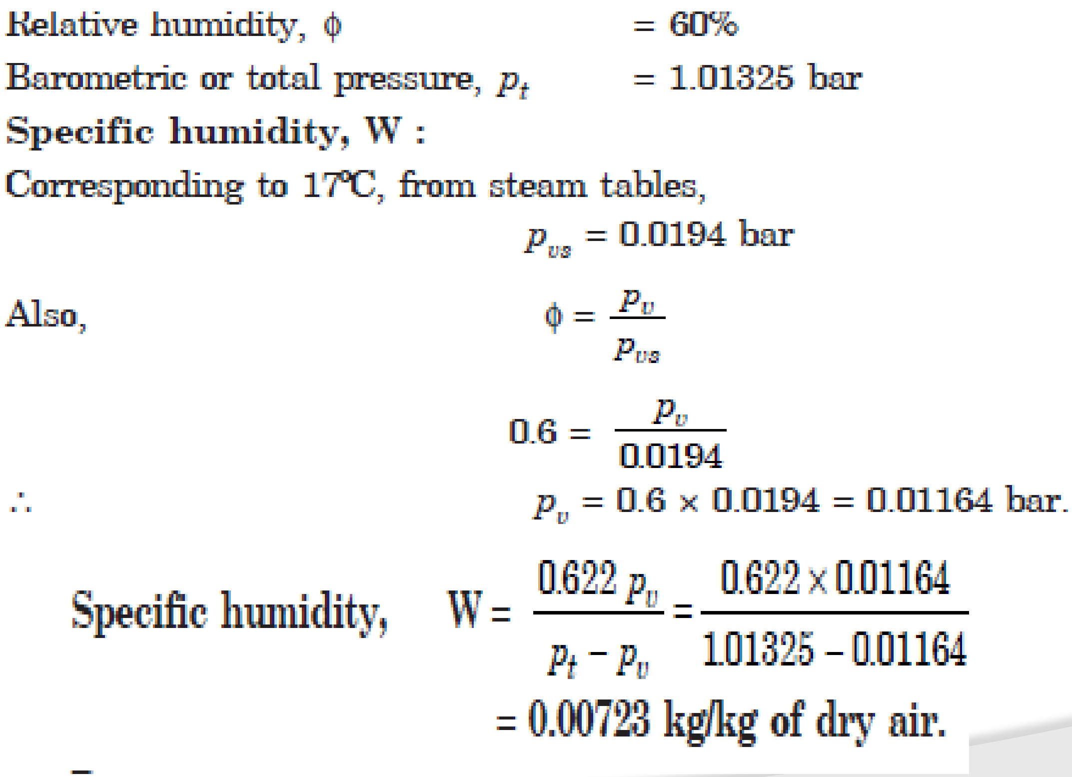
(*iii*) **Dew point temperature, t_{dp} :**

The dew point temperature is the saturation temperature of water vapour at a pressure of 0.01524 bar,

t_{dp} [from steam tables by interpolation]

$$= 13 + \frac{(14 - 13)}{(0.01598 - 0.0150)} \times [0.01524 - 0.0150]$$

The air supplied to a room of a building in winter is to be at 17°C and have a relative humidity of 60%. If the barometric pressure is 1.01325 bar, find : (i) The specific humidity ; (ii) The dew point under these conditions.



Relative humidity, ϕ = 60%

Barometric or total pressure, p_t = 1.01325 bar

Specific humidity, W :

Corresponding to 17°C, from steam tables,

$$p_{vs} = 0.0194 \text{ bar}$$

Also, $$\phi = \frac{p_v}{p_{vs}}$$

$$0.6 = \frac{p_v}{0.0194}$$

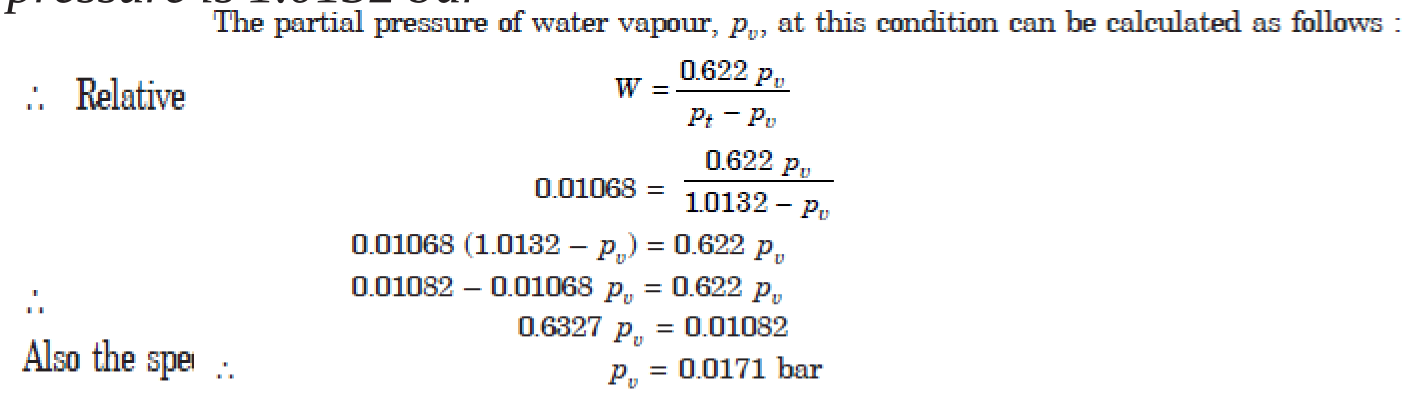
$$\therefore \quad p_v = 0.6 \times 0.0194 = 0.01164 \text{ bar.}$$

Specific humidity, $$W = \frac{0.622\, p_v}{p_t - p_v} = \frac{0.622 \times 0.01164}{1.01325 - 0.01164}$$

$$= 0.00723 \text{ kg/kg of dry air.}$$

0.004 kg of water vapour per kg of atmospheric air is removed and temperature of air after removing the water vapour becomes 20°C. Determine :(*i*) *Relative humidity* (*ii*) *Dew point temperature.*

Assume that condition of atmospheric air is 30°C and 55% R.H. and pressure is 1.0132 bar



The partial pressure of water vapour, p_v, at this condition can be calculated as follows :

∴ Relative

$$W = \frac{0.622\, p_v}{p_t - p_v}$$

$$0.01068 = \frac{0.622\, p_v}{1.0132 - p_v}$$

$$0.01068\,(1.0132 - p_v) = 0.622\, p_v$$

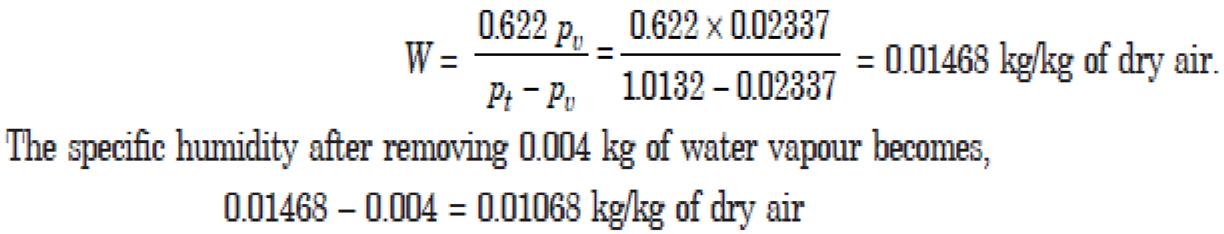
∴

$$0.01082 - 0.01068\, p_v = 0.622\, p_v$$

$$0.6327\, p_v = 0.01082$$

Also the spe ∴

$$p_v = 0.0171 \text{ bar}$$



$$W = \frac{0.622\, p_v}{p_t - p_v} = \frac{0.622 \times 0.02337}{1.0132 - 0.02337} = 0.01468 \text{ kg/kg of dry air.}$$

The specific humidity after removing 0.004 kg of water vapour becomes,

$$0.01468 - 0.004 = 0.01068 \text{ kg/kg of dry air}$$

The partial pressure of water vapour, p_v, at this condition can be calculated as follows :

$$W = \frac{0.622\, p_v}{p_t - p_v}$$

$$0.01068 = \frac{0.622\, p_v}{1.0132 - p_v}$$

$$0.01068\,(1.0132 - p_v) = 0.622\, p_v$$

$$0.01082 - 0.01068\, p_v = 0.622\, p_v$$

$$0.6327\, p_v = 0.01082$$

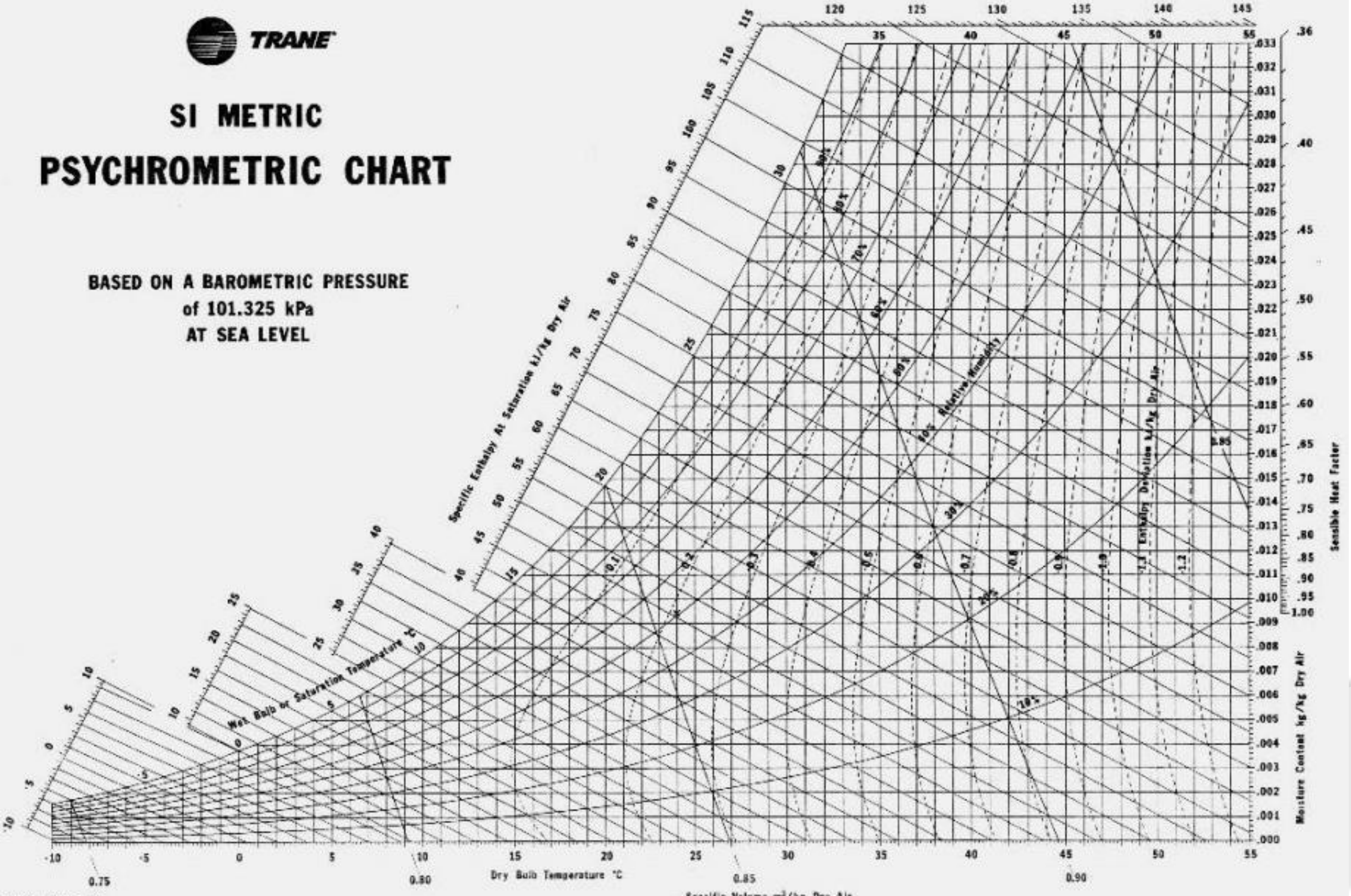
$$\therefore \quad p_v = 0.0171 \text{ bar}$$

(*i*) **Relative humidity,** $\phi = \dfrac{p_v}{p_{vs}} = \dfrac{0.0171}{0.0234}$ **= 0.73 or 73%.**

(*ii*) **Dew point temperature,** $\mathbf{t_{dp}}$ **:**

Corresponding to 0.0171 bar, from steam tables, t_{dp} = 15°C.

PSYCHROMETRIC CHARTS



UNIT – V
POWER CYCLES

At the end of the unit students are able to:

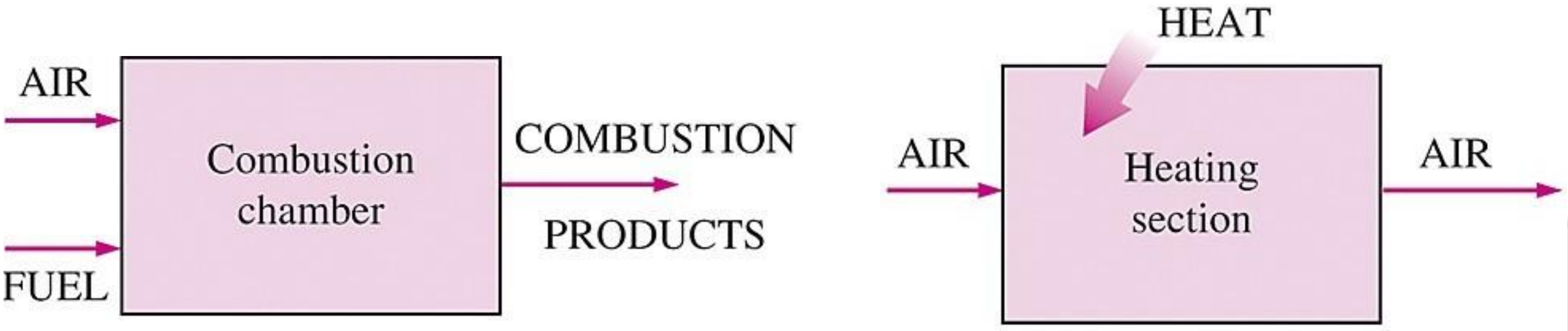
	Course Outcomes	Knowledge Level (Bloom’s Taxonomy)
CO11	Illustrate the working of various air standard cycles and work out the performance characteristics..	Understand
CO12	Infer the performance of power and refrigerant cycles, and their significance in real world systems	Understand

UNIT -V

POWER CYCLES: Otto, Diesel, Dual Combustion cycles, Description and representation on P-V and T-S diagram, Thermal Efficiency, Mean Effective Pressures on Air standard basis, comparison of Cycles, Introduction to Brayton cycle and Bell Coleman cycle

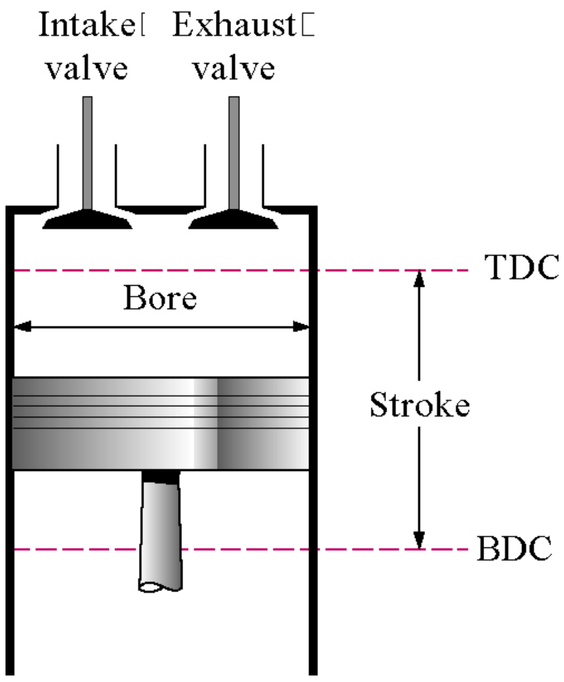
Air-Standard Assumptions

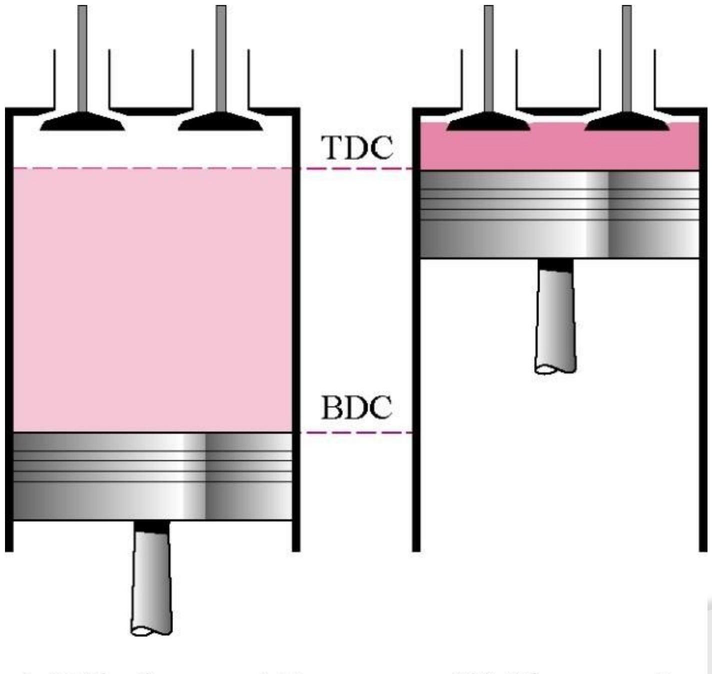
- Air continuously circulates in a closed loop.
- Always behaves as an ideal gas.
- All the processes that make up the cycle are internally reversible.
- The combustion process is replaced by a heat-addition
- process from an external source.



Terminology for Reciprocating Devices

Top dead center (TDC), bottom dead center (BDC), stroke, bore, intake valve, exhaust valve, clearance volume, displacement volume, compression ratio, and mean effective pressure





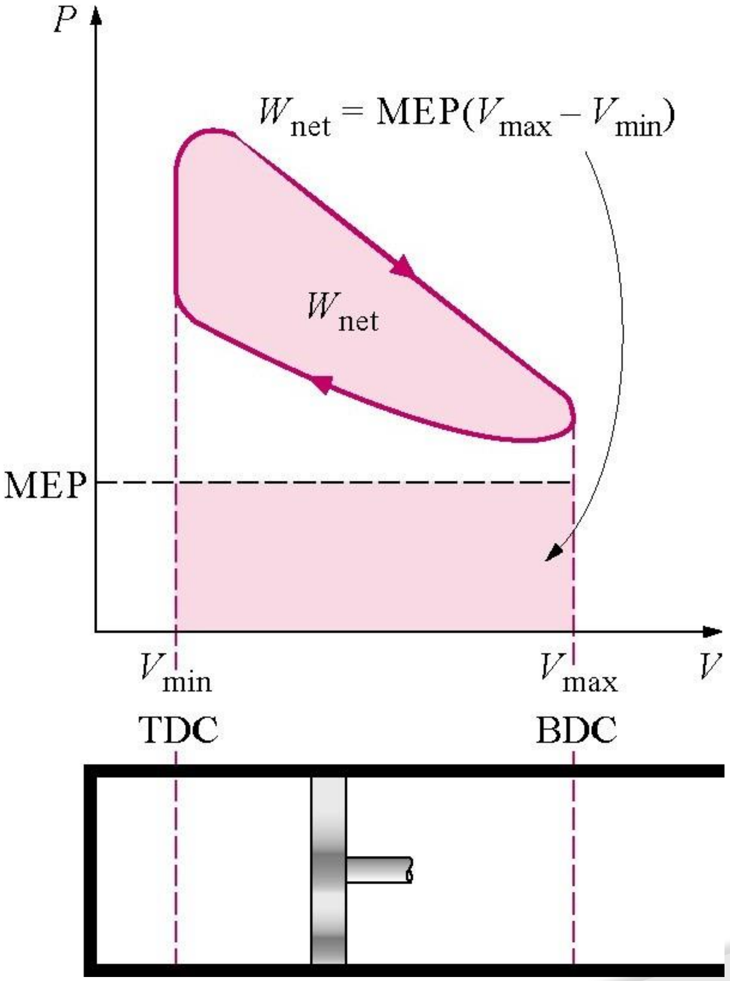
(*a*) Displacement volume

(*b*) Clearance volume

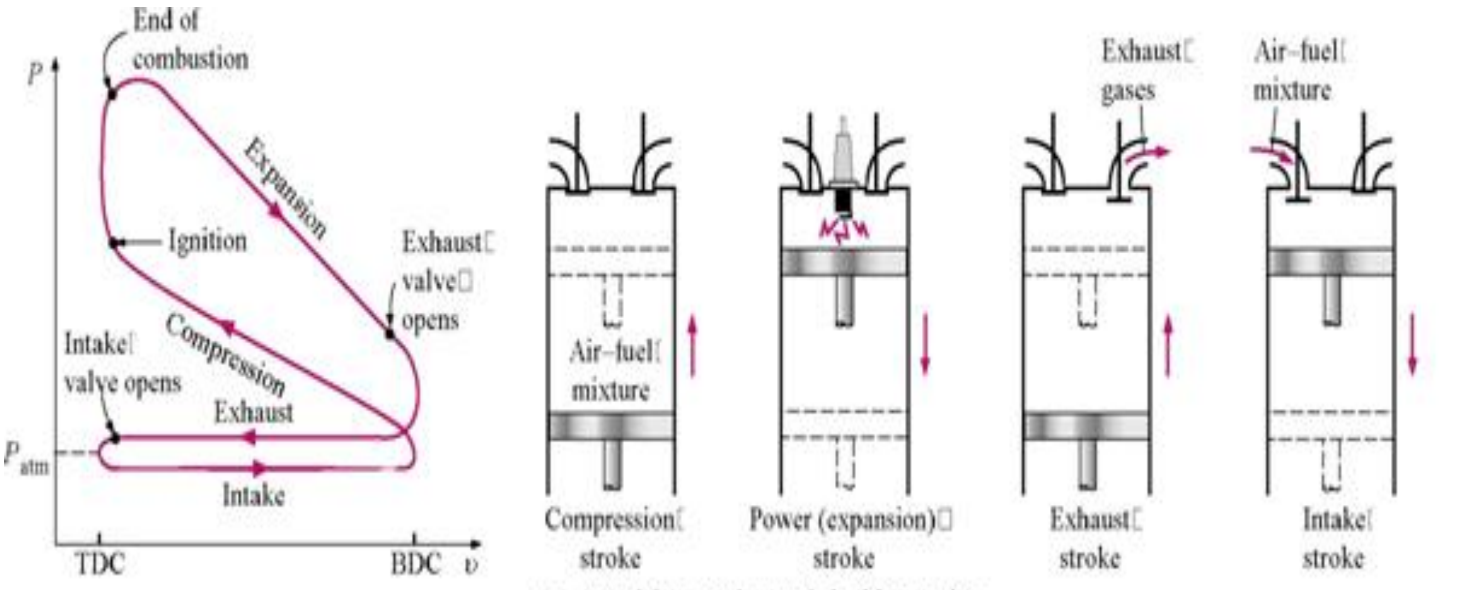
The compression ratio *r* of an engine is defined as

$$r = \frac{V\max}{V\min} = \frac{V_{BDC}}{V_{TDC}}$$

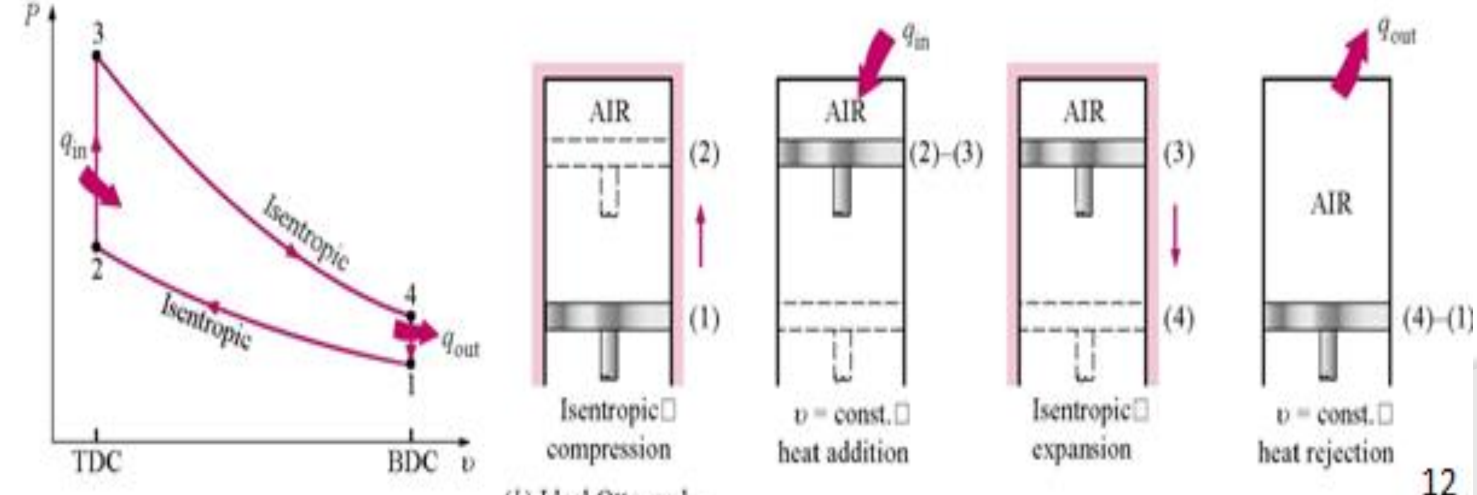
The mean effective pressure (**MEP**) is a fictitious pressure that, if it operated on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle.



$$MEP = \frac{W_{net}}{V_{max} - V_{min}} = \frac{w_{net}}{v_{max} - v_{min}}$$



(*a*) Actual four-stroke spark-ignition engine



(*b*) Ideal Otto cycle

The processes in the Otto cycle are as per following:

Process	*Description*
1-2	Isentropic compression
2-3	Constant volume heat addition
3-4	Isentropic expansion
4-1	Constant volume heat rejection

Related formula based on basic thermodynamics:

Process	***Description***	***Related formula***
1-2	Isentropic compression	$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n = \left(\frac{T_1}{T_2}\right)^{\frac{n}{n-1}}$
2-3	Constant volume heat addition	$Q_{in} = mC_v(T_3 - T_2)$
3-4	Isentropic expansion	$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n = \left(\frac{T_1}{T_2}\right)^{\frac{n}{n-1}}$
4-1	Constant volume heat rejection	$Q_{out} = mC_v(T_4 - T_1)$

206

Thermal efficiency of the Otto cycle:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = \boxed{1 - \frac{Q_{out}}{Q_{in}}}$$

Apply first law closed system to process 2-3, V = constant.

$$Q_{net,23} - W_{net,23} = \Delta U_{23}$$

$$W_{net,23} = W_{other,23} + W_{b,23} = 0 + \int_2^3 PdV = 0$$

Thus, for constant specific heats

$$Q_{net,23} = \Delta U_{23}$$

$$\boxed{Q_{net,23} = Q_{in} = mC_v(T_3 - T_2)}$$

Apply first law closed system to process 4-1, *V* = constant.

$$Q_{net,41} - W_{net,41} = \Delta U_{41}$$

$$W_{net,41} = W_{other,41} + W_{b,41} = 0 + \int_4^1 PdV = 0$$

Thus, for constant specific heats,

$$Q_{net,41} = \Delta U_{41}$$

$$Q_{net,41} = -Q_{out} = mC_v(T_1 - T_4)$$

$$\boxed{Q_{out} = -mC_v(T_1 - T_4) = mC_v(T_4 - T_1)}$$

The thermal efficiency becomes

$$\eta_{th,\,Otto} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$= 1 - \frac{mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)}$$

$$\eta_{th,\,Otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

$$= 1 - \frac{T_1(T_4 / T_1 - 1)}{T_2(T_3 / T_2 - 1)}$$

Recall processes 1-2 and 3-4 are isentropic, so

$$\boxed{\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} \quad and \quad \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{k-1}}$$

Since $V_3 = V_2$ and $V_4 = V_1$,

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \quad or \quad \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

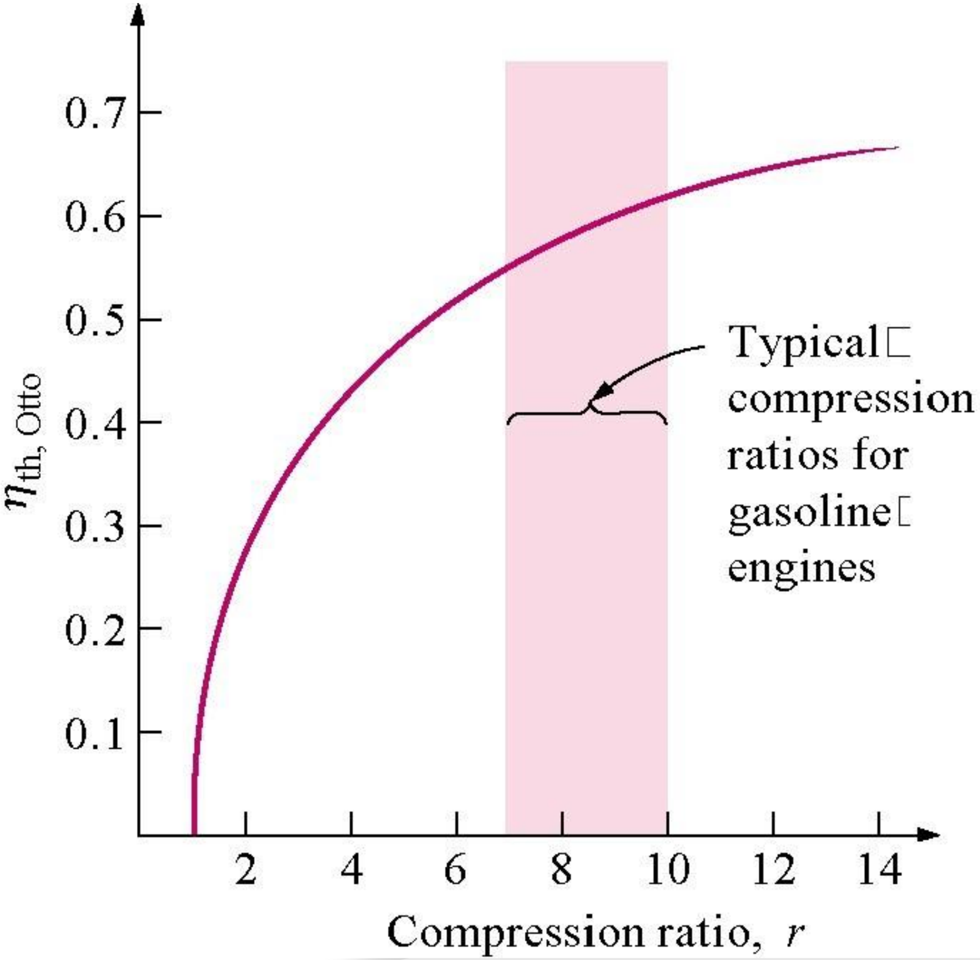
The Otto cycle efficiency becomes

$$\eta_{th,\,Otto} = 1 - \frac{T_1}{T_2}$$

Since process 1-2 is isentropic,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$$

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{k-1} = \left(\frac{1}{r}\right)^{k-1}$$



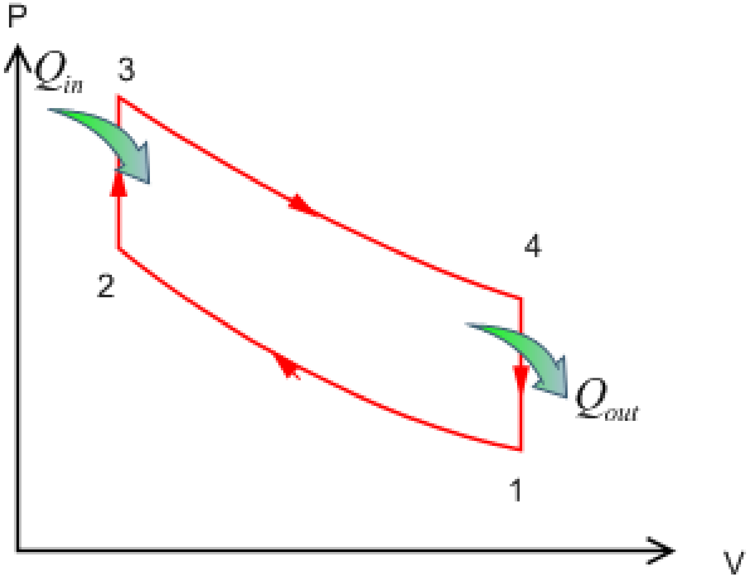
where the compression ratio is $r = V_1/V_2$ and

$$\boxed{\eta_{th,\,Otto} = 1 - \frac{1}{r^{k-1}}}$$

Example 5.1

An Otto cycle having a compression ratio of 9:1 uses air as the working fluid. Initially P_1 = 95 kPa, T_1 = 17°C, and V_1 = 3.8 liters. During the heat addition process, 7.5 kJ of heat are added. Determine all T's, P's, $\square_{th}$, the back work ratio and the mean effective pressure.

Solution:



Data given:

$$T_1 = 290K$$

$$V_1 / V_2 = 9$$

$$Q_{23} = 7.5kJ$$

$$P_1 = 95kPa$$

$$V_1 = 3.8Litres$$

Process 1 – 2 (isentropic compression)

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} \Rightarrow T_2 = 290(9)^{0.4} = 698.4K$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{k-1} \Rightarrow P_2 = 95(9)^{1.4} = 2059kPa$$

Process 2 – 3 (Const. volume heat addition)

$$1^{st}\ law : Q_{net} - \cancel{W_{net}}^{0} = \Delta U$$

$$Q_{23} = mC_v\left(T_3 - T_2\right)$$

$$IGL : \quad P_1 v_1 = RT_1 \Rightarrow v_1 = \frac{0.2871(290)}{95} = 0.875 \tfrac{m^3}{kg}$$

$$q_{23} = \frac{Q_{23}}{m} = Q_{23}\frac{v_1}{V_1} = 1727 \tfrac{kJ}{kg}$$

Example 5.1

$Back\ to\ IGL:$

$$q_{23} = C_v(T_3 - T_2)$$

$$= 0.718(T_3 - 698.4)$$

$$T_3 = 3103.7K$$

$But\ V_3 = V_2$

$$\frac{P_3}{T_3} = \frac{P_2}{T_2}$$

$$P_3 = 9.15\,MPa$$

$\boxed{\mathrm{Process}\ 3-4\ (isentropic\ expansion)}$

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{k-1} \Rightarrow T_4 = T_3(1/9)^{0.4} = 1288.8\,K$$

$$\frac{P_4}{P_3} = \left(\frac{V_3}{V_4}\right)^{k} \Rightarrow P_4 = P_3(1/9)^{1.4} = 422\,kPa$$

Example 5.1

$$\boxed{\text{Process } 4-1\left(\textit{Const.volume heat rejection}\right)}$$

$$Q_{41} = mC_v\left(T_4 - T_1\right)$$

$$q_{41} = C_v\left(T_4 - T_1\right)$$

$$= 0.718\left(1288.8 - 290\right)$$

$$= 717.1\,\frac{kJ}{kg}$$

Then:

$$W_{net} = q_{in} - q_{ou}$$

$$= q_{23} - \overset{t}{q}_{41}$$

$$= 1009.6\,\frac{kJ}{kg}$$

$$\eta_{th,Otto} = \frac{W_{net}}{q_{in}} = \underline{\underline{0.585\left(58.5\%\right)}}$$

Example 5.1

What else?

$$MEP = \frac{W_{net}}{V_{\max} - V_{\min}} = \frac{w_{net}}{v_{\max} - v_{\min}}$$

$$= \frac{w_{net}}{v_1 - v_2} = \frac{w_{net}}{v_1\left(1 - v_2/v_1\right)}$$

$$= \frac{w_{net}}{v_1\left(1 - \frac{1}{r}\right)} = \frac{1009.6}{0.875\left(1 - 1/9\right)} = \underline{\underline{1298\,kPa}}$$

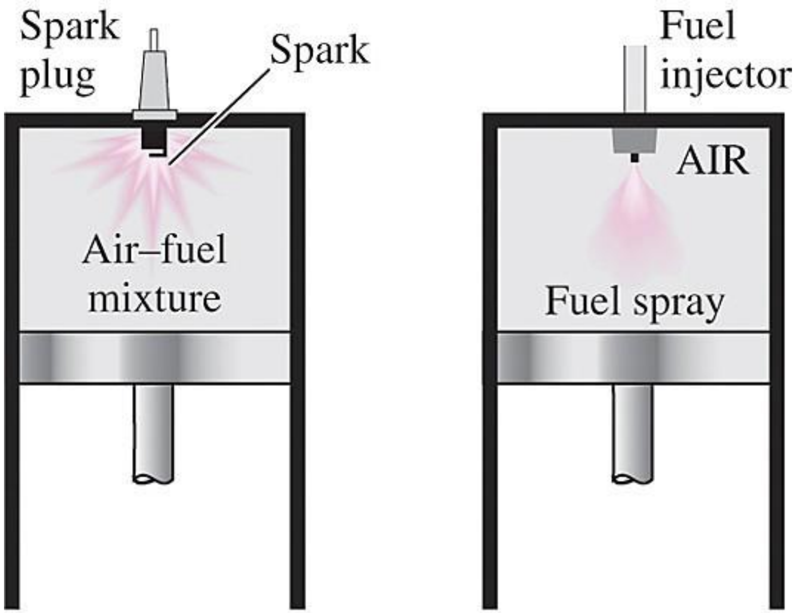
$$r_{bw} = \frac{w_{compr}}{w_{expans}} = \frac{\Delta u_{12}}{-\Delta u_{34}} = \frac{\cancel{C_v}\left(T_2 - T_1\right)}{\cancel{C_v}\left(T_3 - T_4\right)}$$

$$= \underline{\underline{0.225\left(22.5\%\right)}}$$

Diesel Cycle

The processes in the Diesel cycle are as per following:

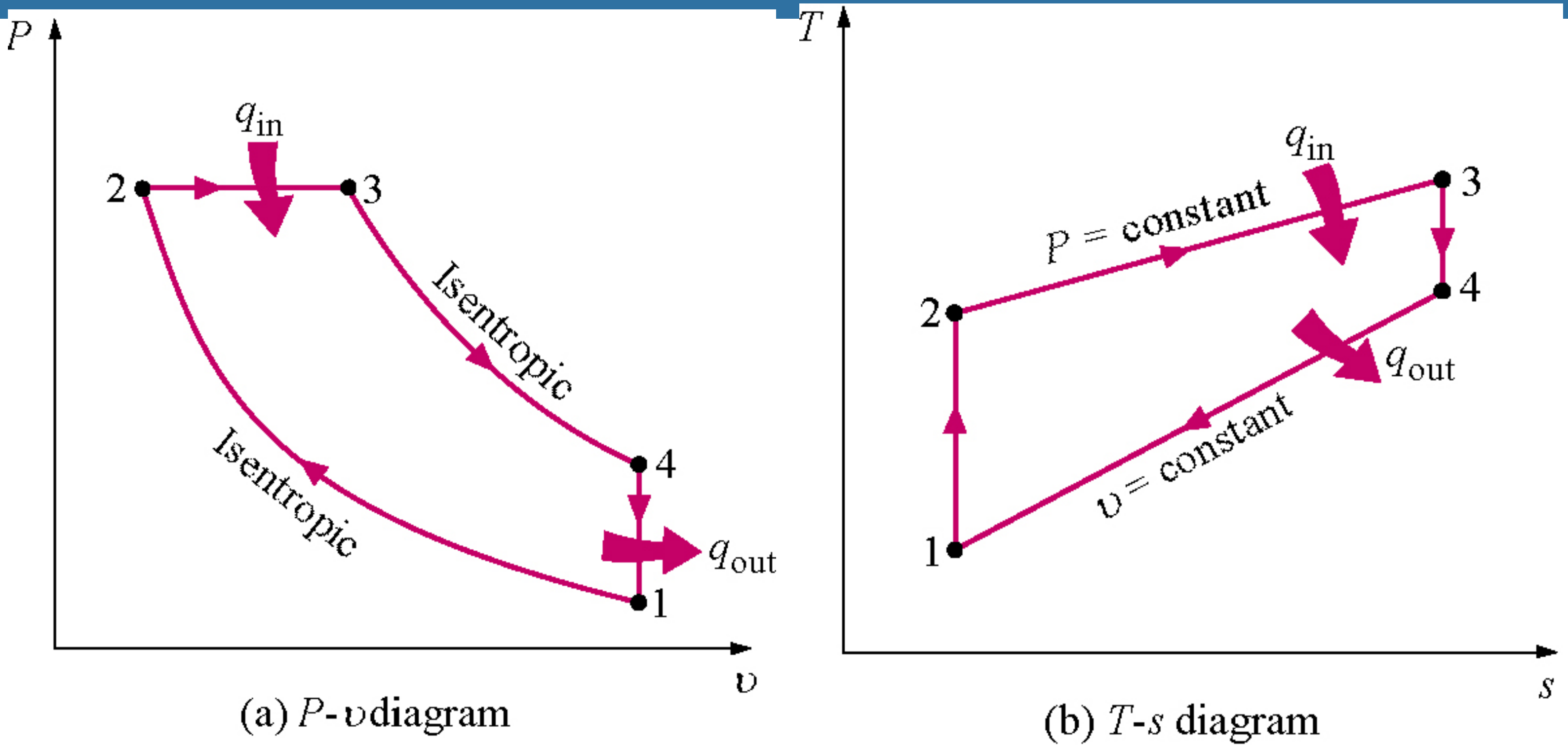
Process	***Description***
1-2	Isentropic compression
2-3	Constant pressure heat addition
3-4	Isentropic expansion
4-1	Constant volume heat rejection



Gasoline engine

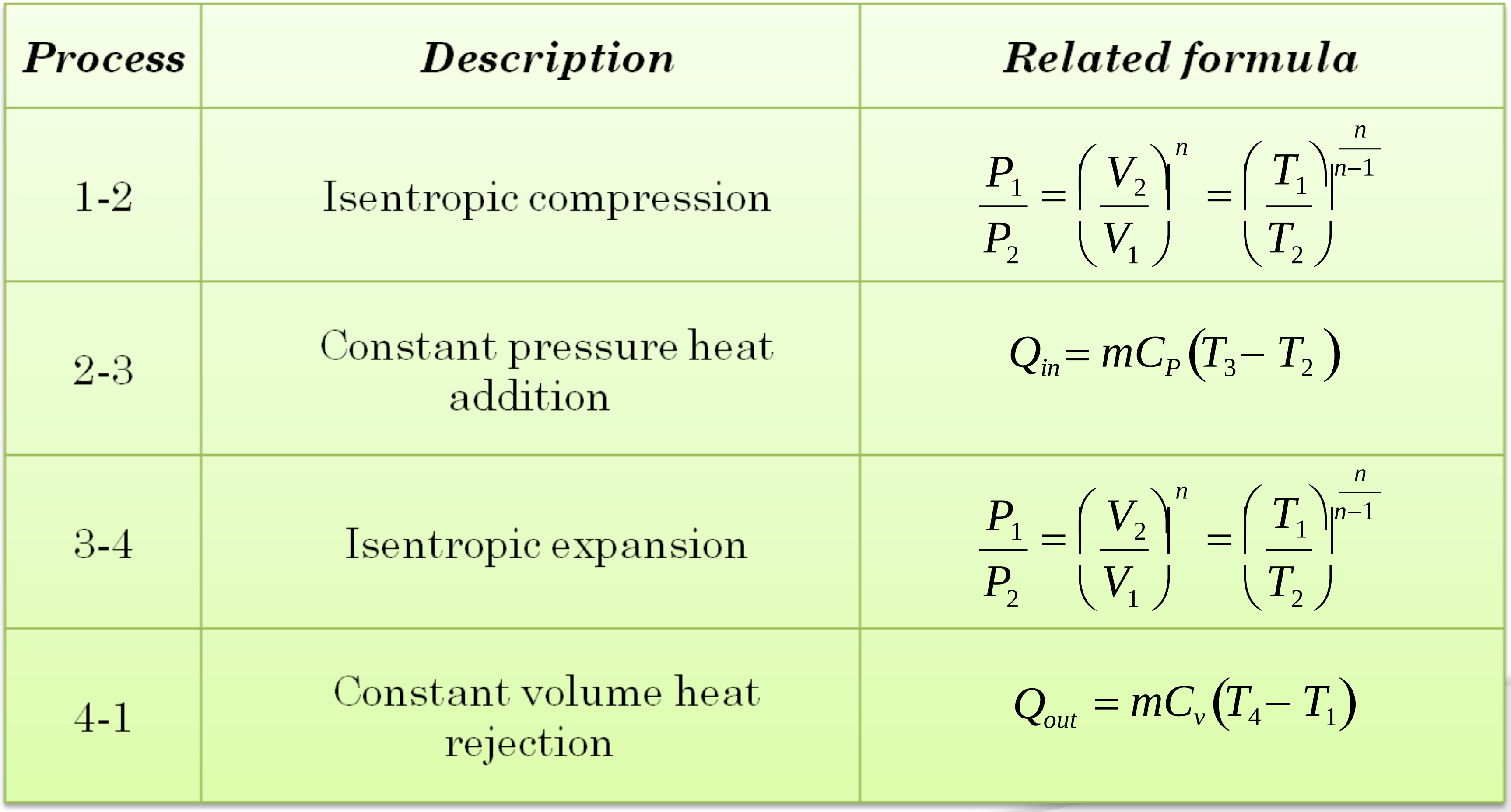
Diesel engine

DIESEL CYCLE



$$\frac{v_1}{v_2} = Compression\ ratio, r_v \quad and \quad \frac{v_3}{v_2} = Cut-off\ \ ratio, r_c$$

Related formula based on basic thermodynamics**:**



Process	***Description***	***Related formula***
1-2	Isentropic compression	$\frac{P_1}{P_2}=\left(\frac{V_2}{V_1}\right)^n=\left(\frac{T_1}{T_2}\right)^{\frac{n}{n-1}}$
2-3	Constant pressure heat addition	$Q_{in}=mC_P\left(T_3-T_2\right)$
3-4	Isentropic expansion	$\frac{P_1}{P_2}=\left(\frac{V_2}{V_1}\right)^n=\left(\frac{T_1}{T_2}\right)^{\frac{n}{n-1}}$
4-1	Constant volume heat rejection	$Q_{out}=mC_v\left(T_4-T_1\right)$

Thermal efficiency of the Diesel cycle

$$\eta_{th,\ Diesel} = \frac{W_{net}}{Q_{in}} = \boxed{1 - \frac{Q_{out}}{Q_{in}}}$$

Apply the first law closed system to process 2-3, P = constant.

$$Q_{net,23} - W_{net,23} = \Delta U_{23}$$

$$W_{net,23} = W_{other,23} + W_{b,23} = 0 + \int_2^3 P dV = 0$$

$$= P_2 (V_3 - V_2)$$

Thus, for constant specific heats

$$Q_{net,\,23} = \Delta U_{23} + P_2(V_3 - V_2)$$

$$Q_{net,\,23} = Q_{in} = mC_v(T_3 - T_2) + mR(T_3 - T_2)$$

$$\boxed{Q_{in} = mC_p(T_3 - T_2)}$$

Apply the first law closed system to process 4-1, V = constant

$$Q_{net,41} - W_{net,41} = \Delta U_{41}$$

$$W_{net,41} = W_{other,41} + W_{b,41} = 0 + \int_4^1 PdV = 0$$

Thus, for constant specific heats

$$Q_{net,41} = \Delta U_{41}$$

$$Q_{net,41} = -Q_{out} = mC_v(T_1 - T_4)$$

$$\boxed{Q_{out} = -mC_v(T_1 - T_4) = mC_v(T_4 - T_1)}$$

The thermal efficiency becomes

$$\eta_{th,\ Diesel} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$= 1 - \frac{mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)}$$

$$\frac{P_4V_4}{T_4} = \frac{P_1V_1}{T_1} \quad \text{where } V_4 = V_1$$

$$\frac{T_4}{T_1} = \frac{P_4}{P_1}$$

Recall processes 1-2 and 3-4 are isentropic, so

$$\boxed{P_1V_1^k = P_2V_2^k \quad \text{and} \quad P_4V_4^k = P_3V_3^k}$$

Since $V_4 = V_1$ and $P_3 = P_2$, we divide the second equation by the first equation and obtain

$$\frac{P_4}{T_4} = \left(\frac{V_3}{V_2}\right)^k = r_c^{\,k}$$

Therefore,

$$\boxed{\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}}\frac{r_c^{\,k} - 1}{k\left(r_c - 1\right)}}$$

Example 5.2

An air-standard Diesel cycle has a compression ratio of 18 and a cut-off ratio of 2.5. The state at the beginning of compression is fixed by P = 0.9 bar ant T = 300K. Calculate:

i. the thermal efficiency of the cycle,

ii. the maximum pressure, $P_{max,}$ and

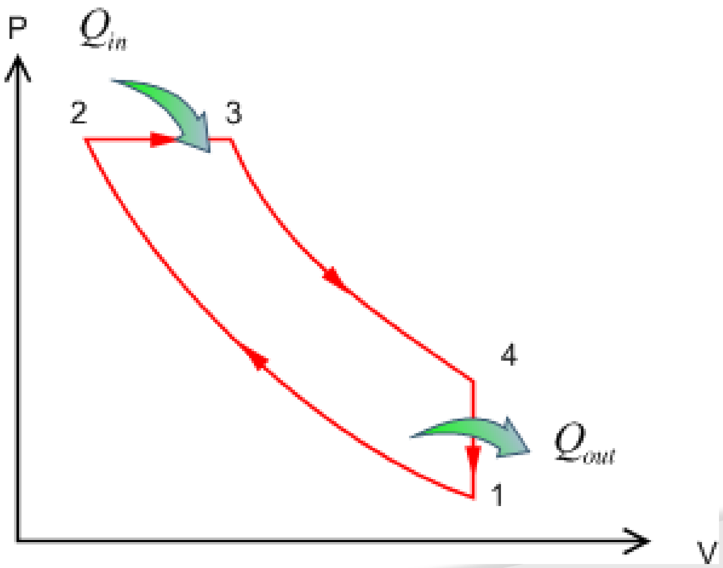
iii. The mean effective pressure.

Solution:

Data given:

$$\frac{V_1}{V_2} = 18$$

$$\frac{V_3}{V_2} = 2.5$$



222

Example 5.2

Process 1–2 (*isentropic compression*)

$$\frac{T_2}{T_1}=\left(\frac{V_1}{V_2}\right)^{k-1} \Rightarrow T_2 = 300(18)^{0.4} = 953.3K$$

Process 2 – 3 (*Const. pressure heat addition*)

$$P_2 = P_3 \Rightarrow \frac{V_2}{T_2} = \frac{V_3}{T_3} \Rightarrow T_3 = T_2\left(\frac{V_3}{V_2}\right) = 2383.3K$$

Process 3 – 4 (*isentropic expansion*)

$$\frac{V_4}{V_3} = \frac{V_1}{V_2}\cdot\frac{V_2}{V_3} = 18(1/2.5) = 7.2$$

$$\frac{T_4}{T_3}=\left(\frac{V_3}{V_4}\right)^{k-1} \Rightarrow T_4 = 2383.3(1/7.2)^{0.4} = 1082K$$

Example 5.2

$$Q_{in} = Q_{23} = mC_P\left(T_3 - T_2\right) \Rightarrow q_{in} = C_p\left(T_3 - T_2\right) = 1437.15\,\tfrac{kJ}{kg}$$

$$Q_{out} = Q_{41} = mC_P\left(T_4 - T_1\right) \Rightarrow q_{out} = C_p\left(T_4 - T_1\right) = 561.48\,\tfrac{kJ}{kg}$$

$$w_{net} = q_{in} - q_{out} = 875.67\,\tfrac{kJ}{kg}$$

What we need?

$$(i)\ \eta_{th,diesel} = \frac{w_{net}}{q_{in}} = \underline{\underline{0.6093\left(60.93\%\right)}}$$

$$(ii)\ P_{\max} = P_2 = P_3$$

$$\left(\frac{P_2}{P_1}\right) = \left(\frac{T_2}{T_1}\right)^{\frac{k-1}{k}} \Rightarrow P_2 = \underline{\underline{5148\,kPa\left(P_{\max}\right)}}$$

$$(iii)\ MEP = \frac{w_{net}}{V_1\left(1-1/r\right)} = \frac{875.67}{0.9566\left(1-1/18\right)} = \underline{\underline{969.1\,kPa}}$$

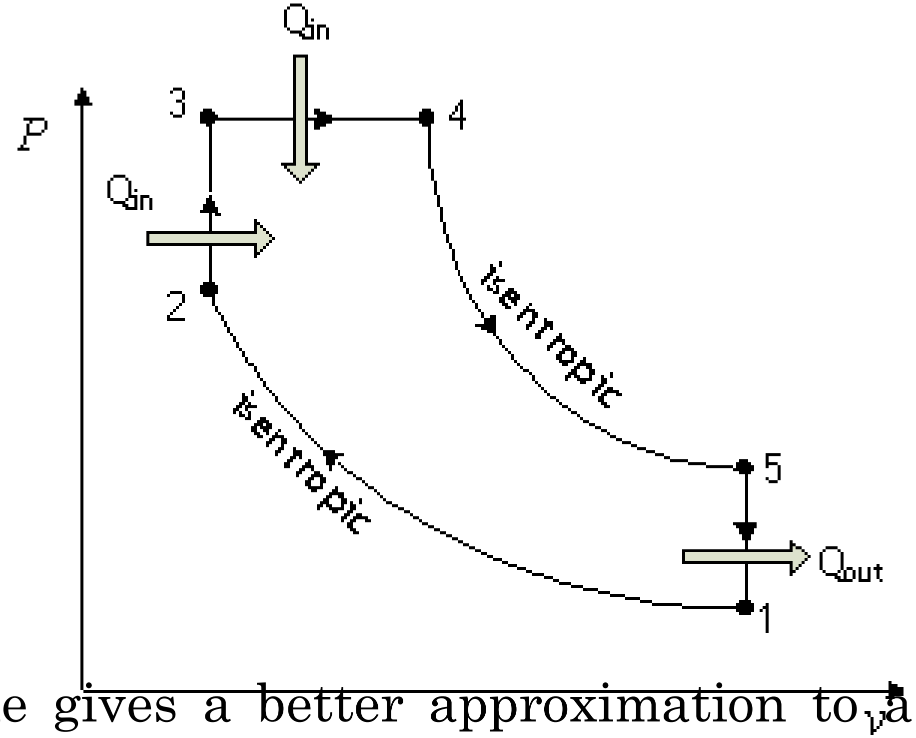
Supplementary Problems 5.2

1. An ideal diesel engine has a compression ratio of 20 and uses air as the working fluid. The state of air at the beginning of the compression process is 95 kPa and 20°C. If the maximum temperature in the cycle is not to exceed 2200 K, determine (a) the thermal efficiency and (b) the mean effective pressure. Assume constant specific heats for air at room temperature.

   [(a) 63.5 percent, (b) 933 kPa]

2. An ideal diesel cycle has a compression ratio of 16 to 1. The maximum cycle temperature is 1700°C and the minimum cycle temperature is 15°C. Calculate:
   1. the specific heat transfer to the cycle
   2. the specific work of the cycle
   3. the thermal efficiency of the cycle

Dual Cycle



Dual cycle gives a better approximation to a real engine. The heat addition process is partly done at a constant volume and partly at constant pressure. From the P-v diagram, it looks like the heat addition process is a combination of both Otto and Diesel cycles.

Dual Cycle

Process	*Description*
1-2	Isentropic compression
2-3	Constant volume heat addition
3-4	Constant pressure heat addition
4-5	Isentropic expansion
5-1	Constant volume heat rejection

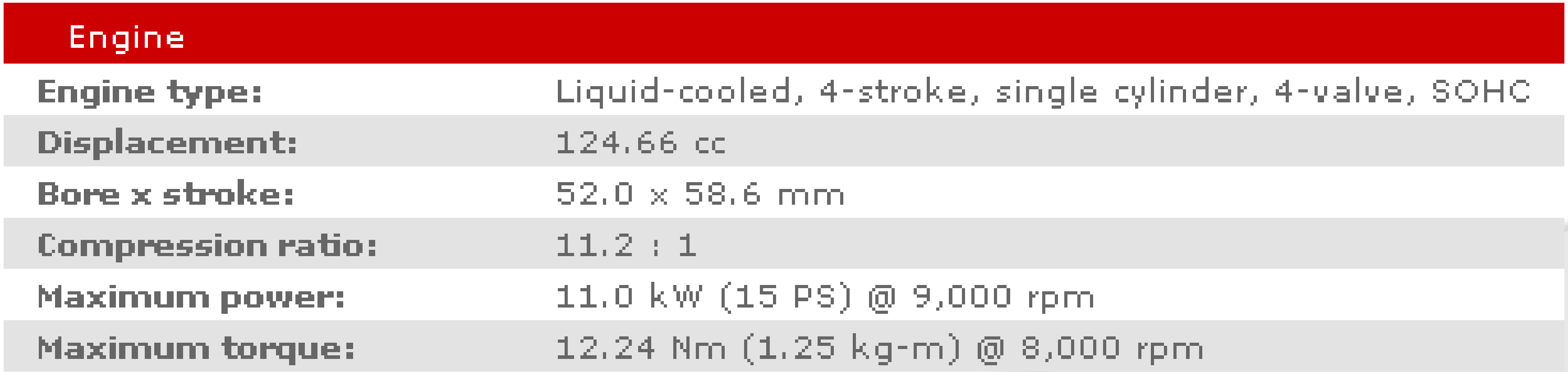
The same procedure as to Otto and Diesel cycles can be applied to Dual cycle. Upon substitutions, the thermal efficiency of Dual cycle becomes

$$\boxed{\eta_{th} = 1 - \frac{r_p r_c{}^k - 1}{\left[\left(r_p - 1\right) + k c_p \left(r_c - 1\right)\right] r_v{}^{k-1}}}$$

Real Case

$$IP = \frac{p_i LANn}{2}$$

$$bp = 2\pi N\tau$$



Engine	
Engine type:	Liquid-cooled, 4-stroke, single cylinder, 4-valve, SOHC
Displacement:	124.66 cc
Bore x stroke:	52.0 x 58.6 mm
Compression ratio:	11.2 : 1
Maximum power:	11.0 kW (15 PS) @ 9,000 rpm
Maximum torque:	12.24 Nm (1.25 kg-m) @ 8,000 rpm

CARNOT CYCLE

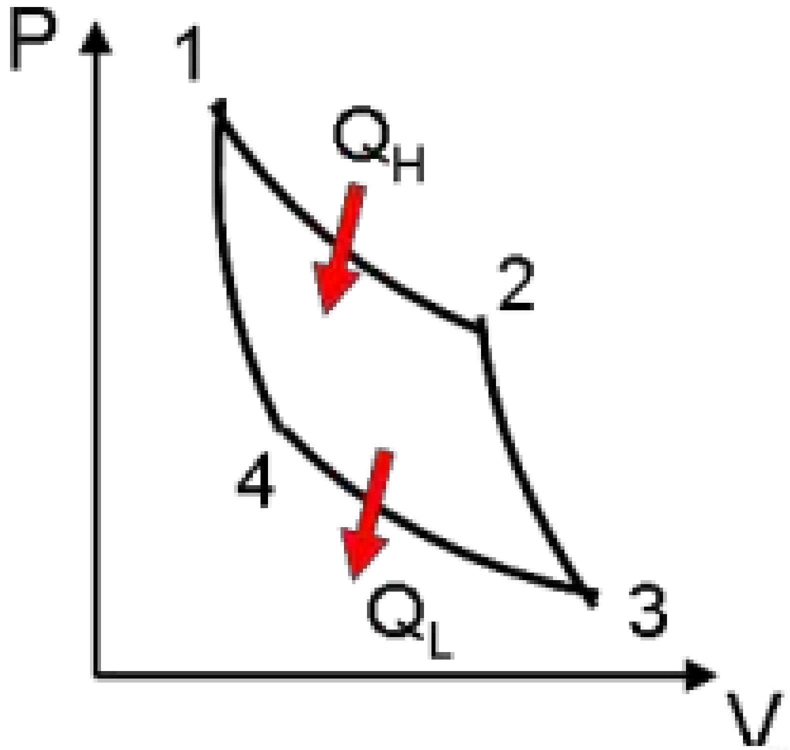
- This cycle is a hypothetical cycle having highest possible efficiency
- Consists of four simple operations namely:

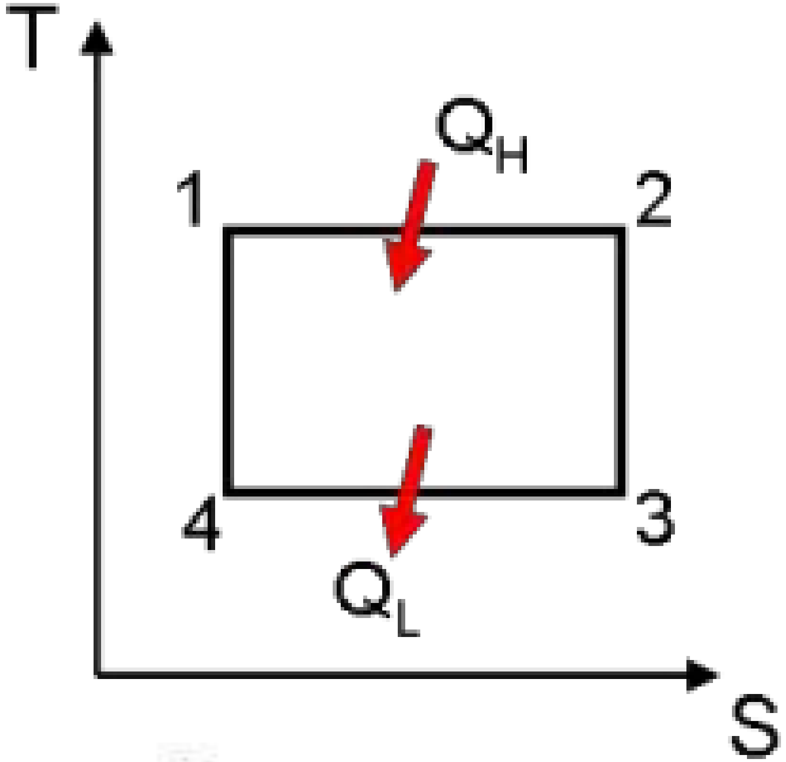
1. Isothermal expansion
2. Adiabatic expansion
3. Isothermal compression
4. Adiabatic compression

229

ASSUMPTIONS MADE IN CARNOT CYCLE

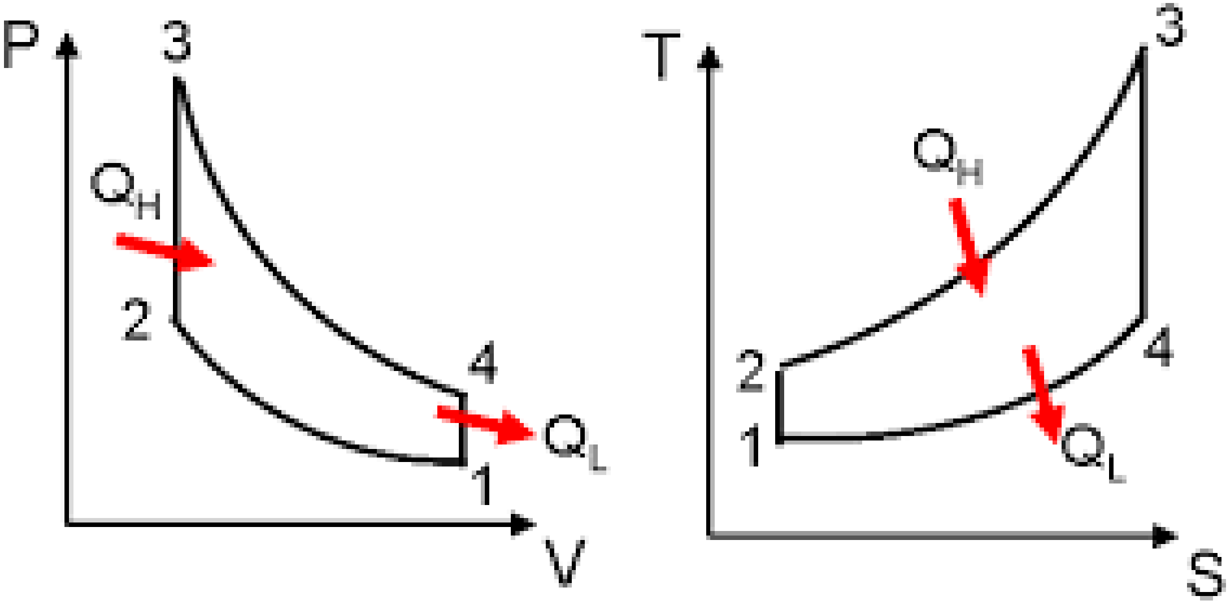
- The piston moving in the cylinder does not produce any friction during motion
- The cylinder head is arranged such a way that it can be perfect heat conductor or insulator
- The walls of cylinder and piston are considered as perfect insulators of heat
- Heat transfer does not affect the temperature of source or sink
- Compression and expansion processes are reversible
- Working medium is a perfect gas and has constant specific heat





$$\eta_{th} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}$$

OTTO CYCLE(CONSTANT VOLUME CYCLE)



Process 1-2: Reversible adiabatic compression

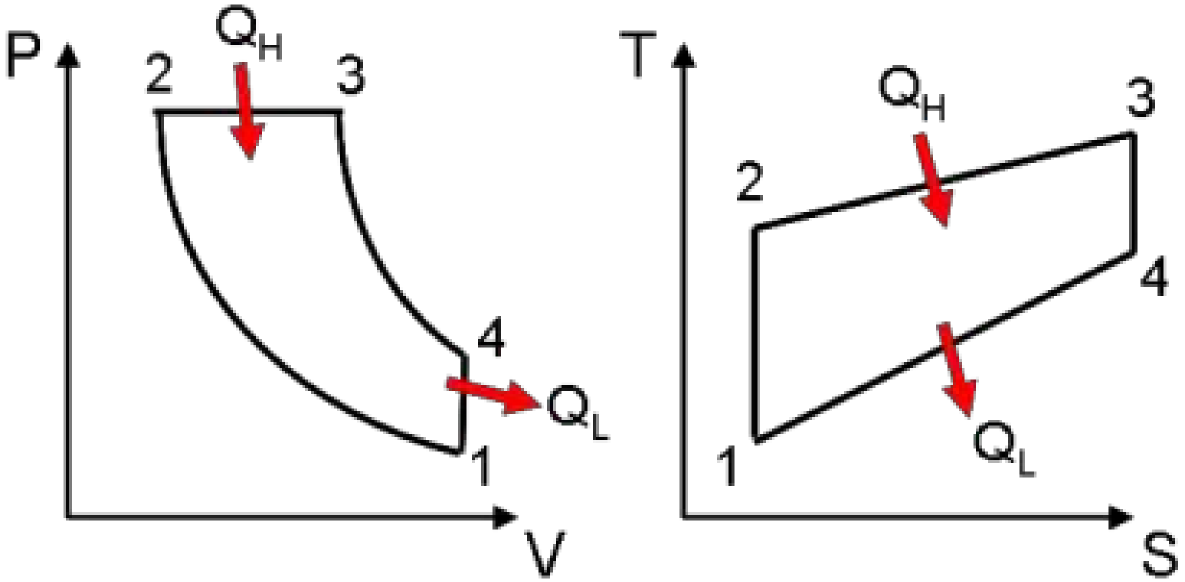
Process 2-3: Addition of heat at constant volume

Process 3-4: Reversible adiabatic expansion

Process 4-1: Rejection of heat at constant volume

$$\eta = 1 - \left(\frac{1}{r^{(\gamma-1)}}\right)$$

DIESEL CYCLE(CONSTANT PRESSURE CYCLE)

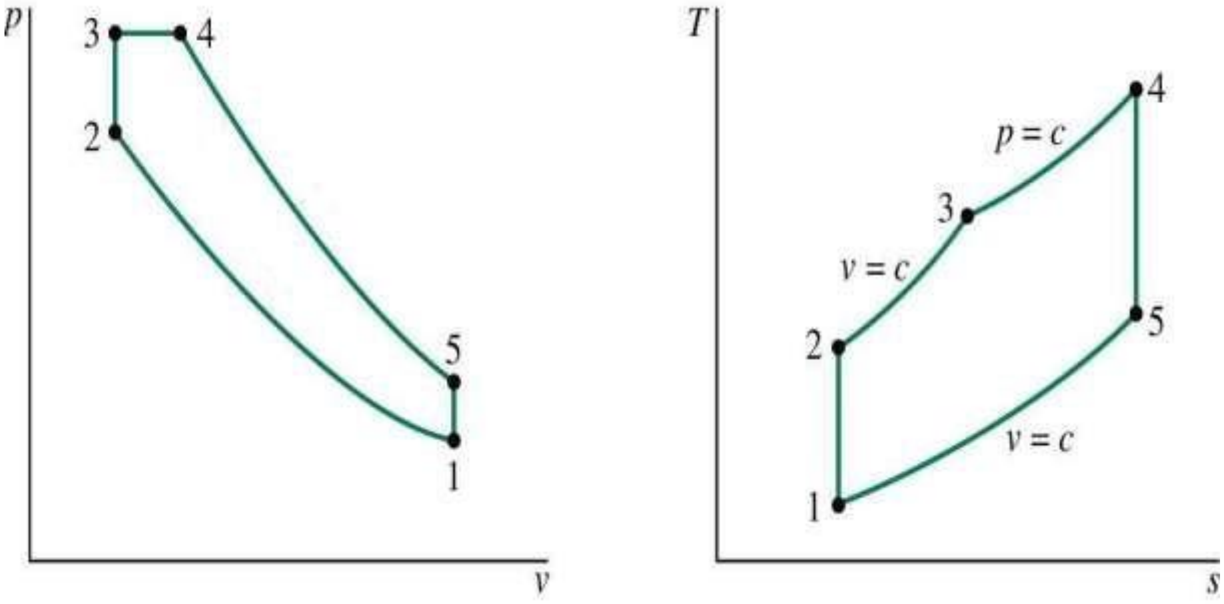


Process 1-2: Reversible adiabatic compression
Process 2-3: Addition of heat at constant pressure
Process 3-4: Reversible adiabatic expansion
Process 4-1: Rejection of heat at constant volume

Point 3: Cut-off point

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}}\left(\frac{\alpha^{\gamma}-1}{\gamma(\alpha-1)}\right)$$

DUAL CYCLE



Process 1-2: Reversible adiabatic compression
Process 2-3: Addition of heat at constant volume
Process 3-4: Addition of heat at constant pressure
Process 4-5: Reversible adiabatic expansion
Process 5-1: Rejection of heat at constant volume

$$\eta_{\underset{const\, c_v}{Dual}} = 1 - \frac{1}{r^{k-1}}\left[\frac{\alpha r_c^{k} - 1}{(\alpha - 1) + \alpha k (r_c - 1)}\right]$$

COMPARISON OF OTTO, DIESEL AND DUAL CYCLE

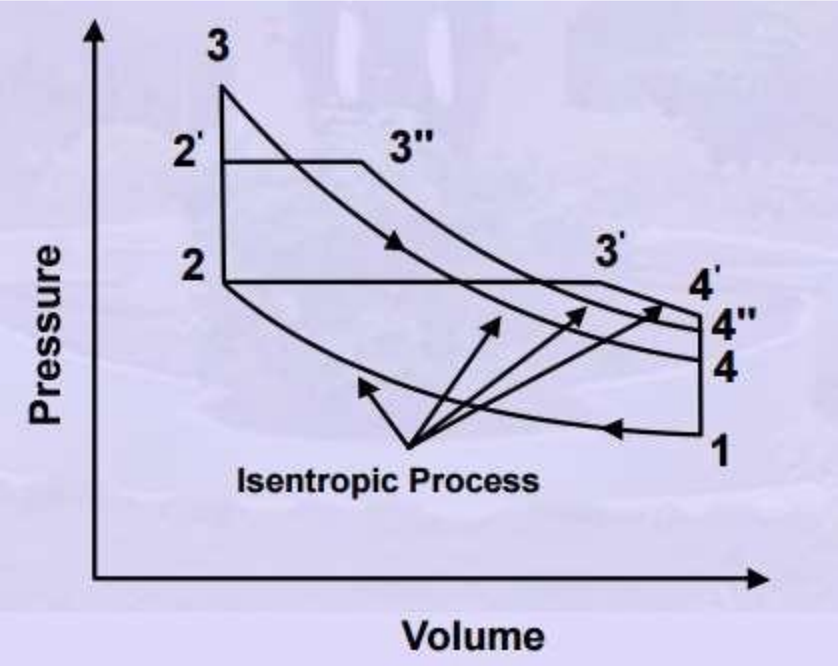
- Following are the important variable factors which are used for comparison of these cycles:

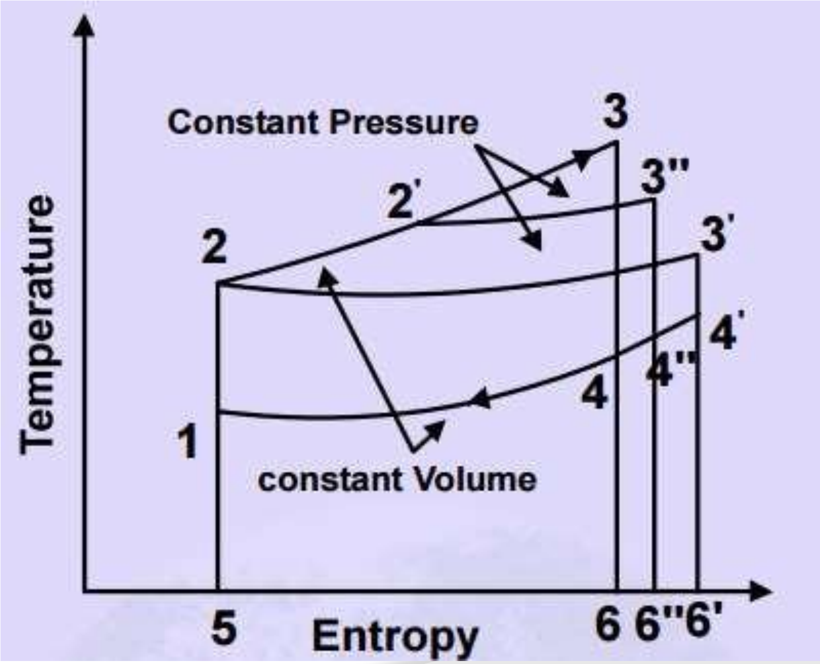
1. Compression ratio
2. Maximum pressure
3. Heat supplied
4. Heat rejected
5. Net work

1. Efficiency versus compression ratio

For a given compression ratio, Otto cycle is the most efficient while the diesel cycle is the least efficient

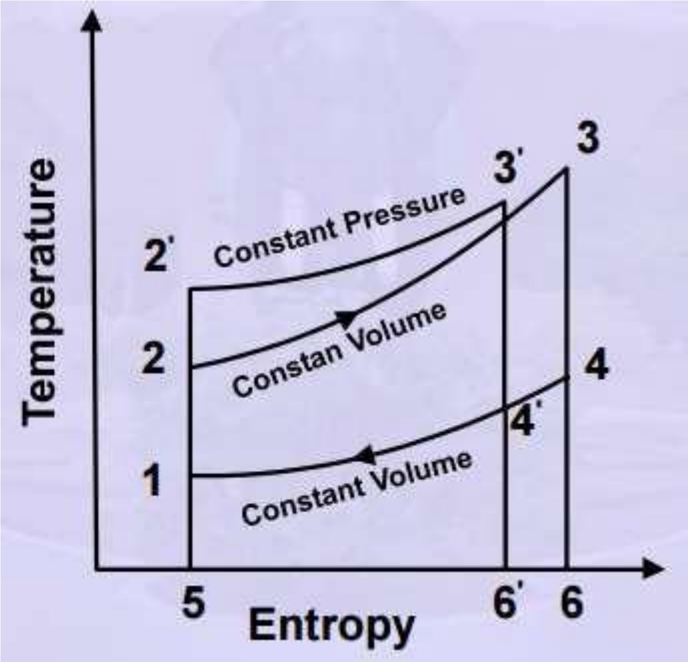
2. For the same compression ratio and the same heat input

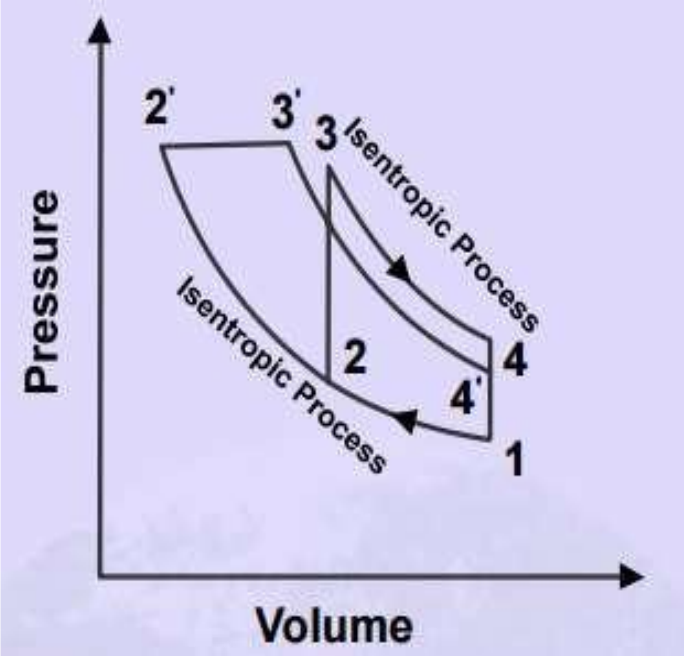




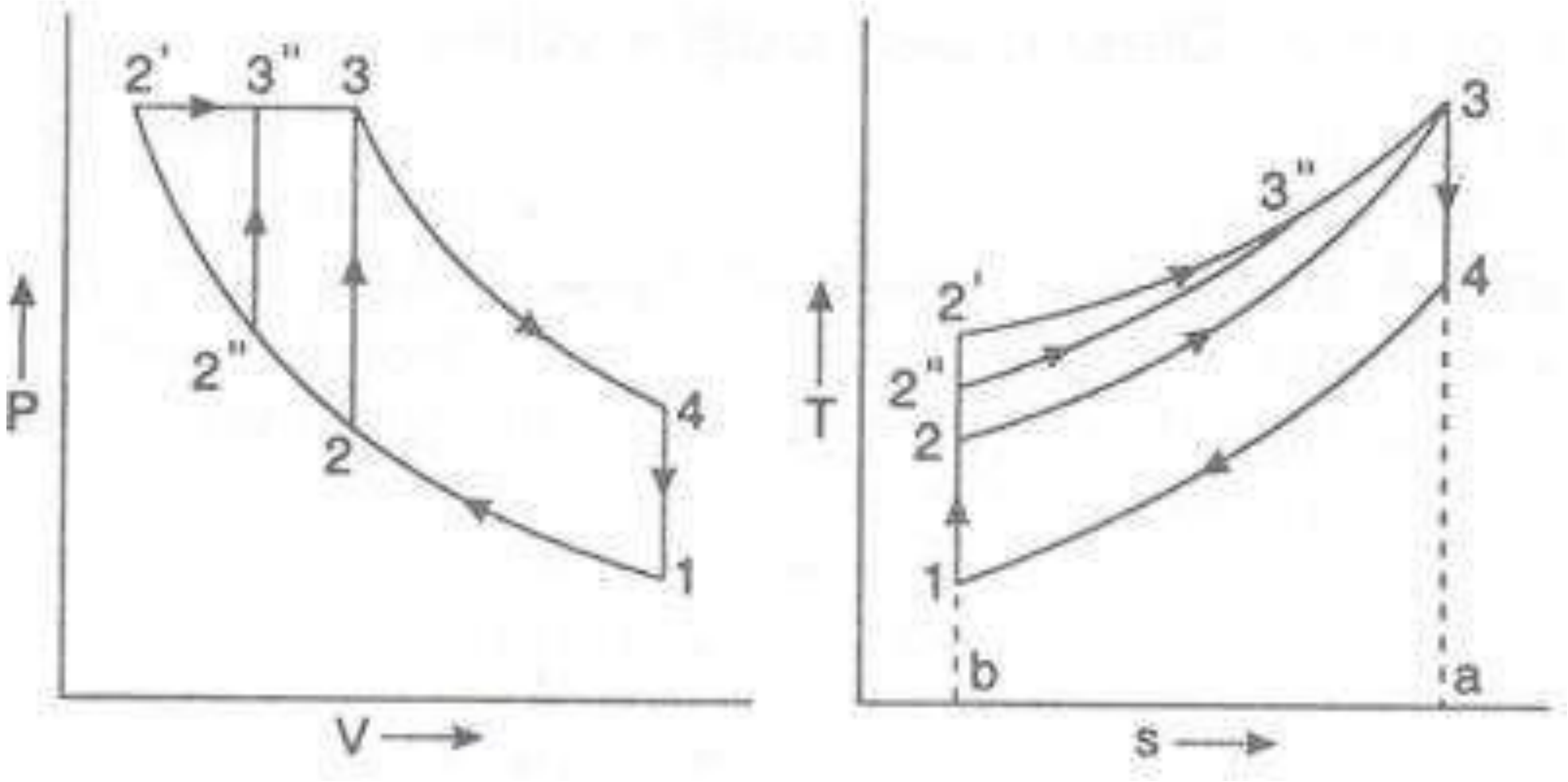
236

3. For constant maximum pressure and heat supplied

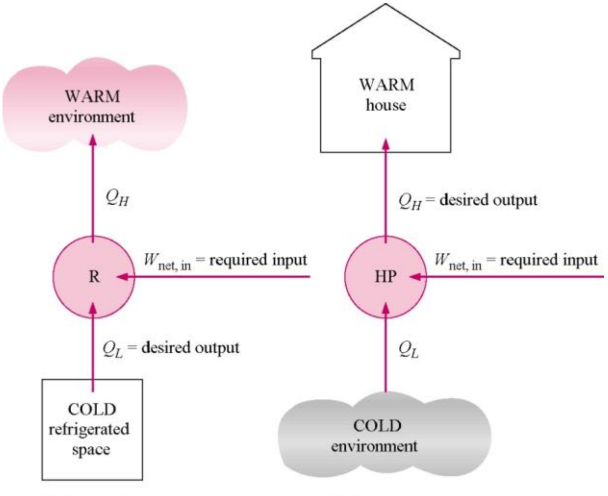




4. For the same maximum pressure and maximum temperature



The vapor compression refrigeration cycle is a common method for transferring heat from a low temperature to a high temperature.



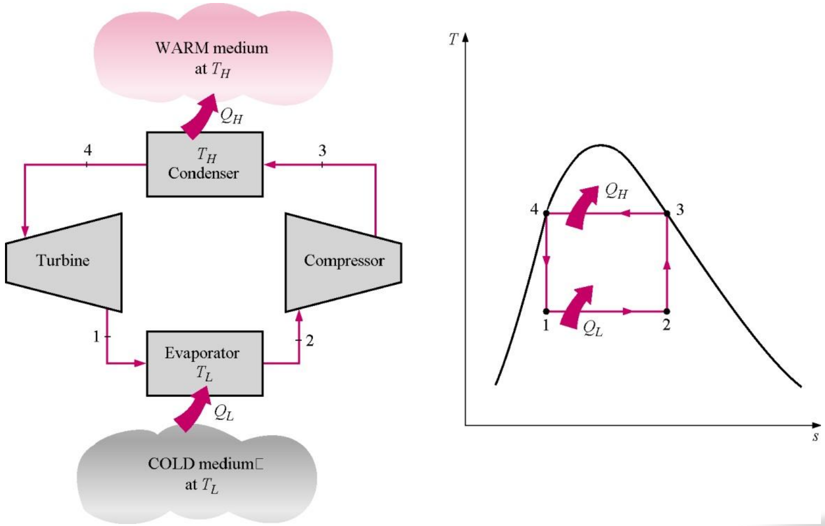
(*a*) Refrigerator (*b*) Heat pump

The above figure shows the objectives of refrigerators and heat pumps. The purpose of a refrigerator is the removal of heat, called the cooling load, from a low-temperature medium. The purpose of a heat pump is the transfer of heat to a high-temperature medium, called the heating load. When we are interested in the heat energy removed from a low-temperature space, the device is called a refrigerator. When we are interested in the heat energy supplied to the high-temperature space, the device is called a heat pump.

Refrigeration systems are also rated in terms of tons of refrigeration. One ton of refrigeration is equivalent to 12,000 Btu/hr or 211 kJ/min. How did the term “ton of cooling” originate?

Reversed Carnot Refrigerator and Heat Pump

Shown below are the cyclic refrigeration device operating between two constant temperature reservoirs and the *T*-*s* diagram for the working fluid when the reversed Carnot cycle is used. Recall that in the Carnot cycle heat transfers take place at constant temperature. If our interest is the cooling load, the cycle is called the Carnot refrigerator. If our interest is the heat load, the cycle is called the Carnot heat pump.



The standard of comparison for refrigeration cycles is the *reversed Carnot cycle*. A refrigerator or heat pump that operates on the reversed Carnot cycle is called a *Carnot refrigerator* or a *Carnot heat pump*, and their COPs are

$$COP_{R,Carnot} = \frac{1}{T_H / T_L - 1} = \frac{T_L}{T_H - T_L}$$

$$COP_{HP,Carnot} = \frac{1}{1 - T_L / T_H} = \frac{T_H}{T_H - T_L}$$

Notice that a turbine is used for the expansion process between the high and low-temperatures. While the work interactions for the cycle are not indicated on the figure, the work produced by the turbine helps supply some of the work required by the compressor from external sources.

Why not use the reversed Carnot refrigeration cycle?
- Easier to compress vapor only and not liquid-vapor mixture.
- Cheaper to have irreversible expansion through an expansion valve.

What problems result from using the turbine instead of the expansion valve?

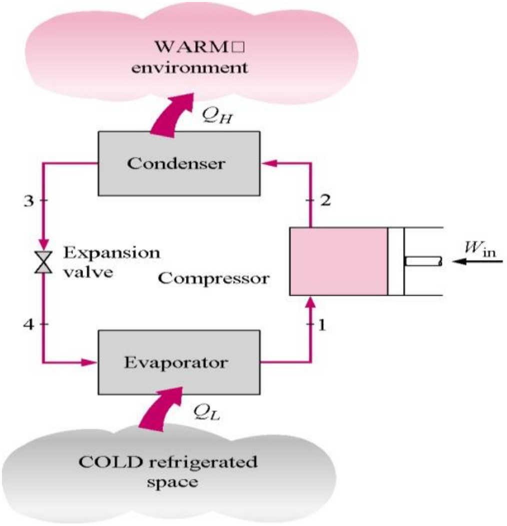
The Vapor-Compression Refrigeration Cycle

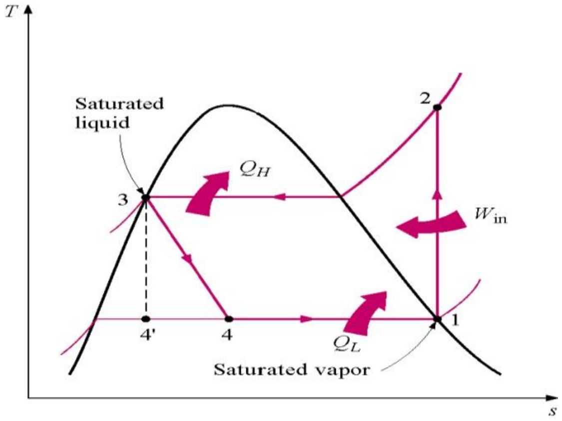
The vapor-compression refrigeration cycle has four components: evaporator, compressor, condenser, and expansion (or throttle) valve. The most widely used refrigeration cycle is the *vapor-compression refrigeration cycle*. In an ideal vapor-compression refrigeration cycle, the refrigerant enters the compressor as a saturated vapor and is cooled to the saturated liquid state in the condenser. It is then throttled to the evaporator pressure and vaporizes as it absorbs heat from the refrigerated space.

The ideal vapor-compression cycle consists of four processes.

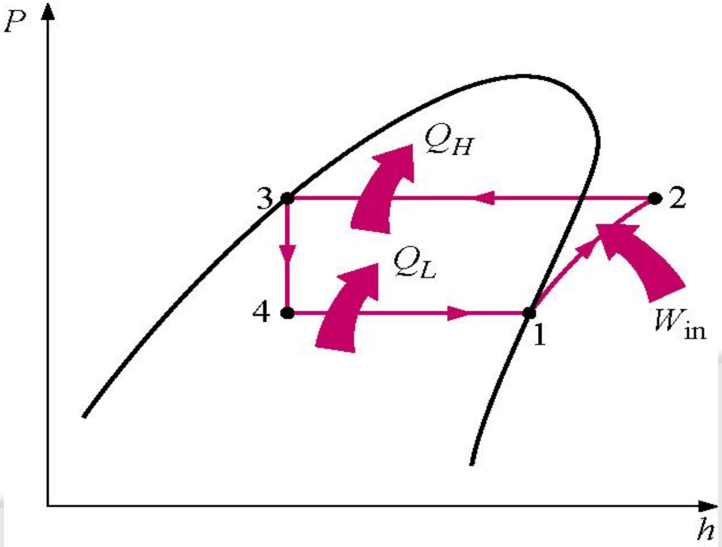
Ideal Vapor-Compression Refrigeration Cycle

Process	Description
1-2	Isentropic compression
2-3	Constant pressure heat rejection in the condenser
3-4	Throttling in an expansion valve
4-1	Constant pressure heat addition in the evaporator

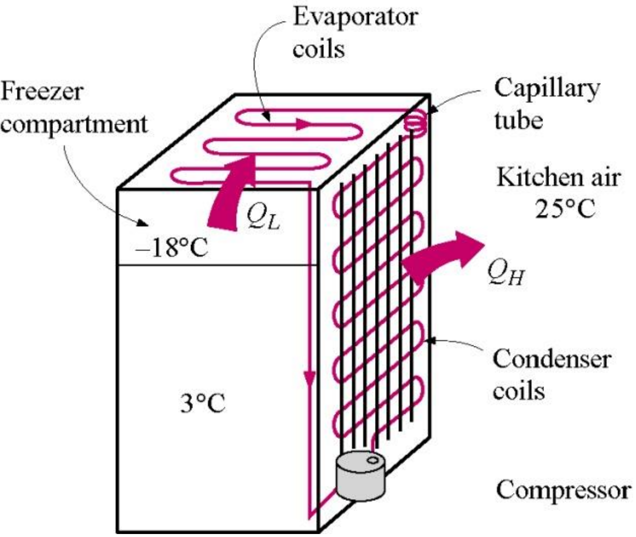




The *P-h* diagram is another convenient diagram often used to illustrate the refrigeration cycle.



The ordinary household refrigerator is a good example of the application of this cycle.



Results of First and Second Law Analysis for Steady-Flow

Component	Process	First Law Result
Compressor	$s = \text{const.}$	$\dot{W}_{in} = \dot{m}(h_2 - h_1)$
Condenser	$P = \text{const.}$	$\dot{Q}_H = \dot{m}(h_2 - h_3)$
Throttle Valve	$\Delta s > 0$ $\dot{W}_{net} = 0$ $\dot{Q}_{net} = 0$	$h_4 = h_3$
Evaporator	$P = \text{const.}$	$\dot{Q}_L = \dot{m}(h_1 - h_4)$

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

Example 11-1

Refrigerant-134a is the working fluid in an ideal compression refrigeration cycle. The refrigerant leaves the evaporator at -20°C and has a condenser pressure of 0.9 MPa. The mass flow rate is 3 kg/min. Find COP_R and $COP_{R,\ Carnot}$ for the same T_{max} and T_{min}, and the tons of refrigeration.

Using the Refrigerant-134a Tables, we have

$$\left.\begin{array}{l} State\,1 \\ Compressor\ \ inlet \\ T_1 = -20^o C \\ x_1 = 1.0 \end{array}\right\} \left\{\begin{array}{l} h_1 = 238.41\dfrac{kJ}{kg} \\ s_1 = 0.9456\dfrac{kJ}{kg\cdot K} \end{array}\right.$$

$$\left.\begin{array}{l} State\,2 \\ Compressor\ \ exit \\ P_{2s} = P_2 = 900\,kPa \\ s_{2s} = s_1 = 0.9456\dfrac{kJ}{kg\cdot K} \end{array}\right\} \left\{\begin{array}{l} h_{2s} = 278.23\dfrac{kJ}{kg} \\ T_{2s} = 43.79^o C \end{array}\right.$$

$$\left.\begin{array}{l} State\,3 \\ Condenser\ \ exit \\ P_3 = 900\,kPa \\ x_3 = 0.0 \end{array}\right\} \left\{\begin{array}{l} h_3 = 101.61\dfrac{kJ}{kg} \\ s_3 = 0.3738\dfrac{kJ}{kg\cdot K} \end{array}\right.$$

$$\left.\begin{array}{l} State\,4 \\ Throttle\ \ exit \\ T_4 = T_1 = -20^o C \\ h_4 = h_3 \end{array}\right\} \left\{\begin{array}{l} x_4 = 0.358 \\ s_4 = 0.4053\dfrac{kJ}{kg\cdot K} \end{array}\right.$$

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{\dot{m}(h_1 - h_4)}{\dot{m}(h_2 - h_1)} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$= \frac{(238.41 - 101.61)\dfrac{kJ}{kg}}{(278.23 - 238.41)\dfrac{kJ}{kg}}$$

$$= 3.44$$

The tons of refrigeration, often called the cooling load or refrigeration effect, are

$$\dot{Q}_L = \dot{m}(h_1 - h_4)$$

$$= 3\frac{kg}{\min}(238.41 - 101.61)\frac{kJ}{kg}\frac{1Ton}{211\dfrac{kJ}{\min}}$$

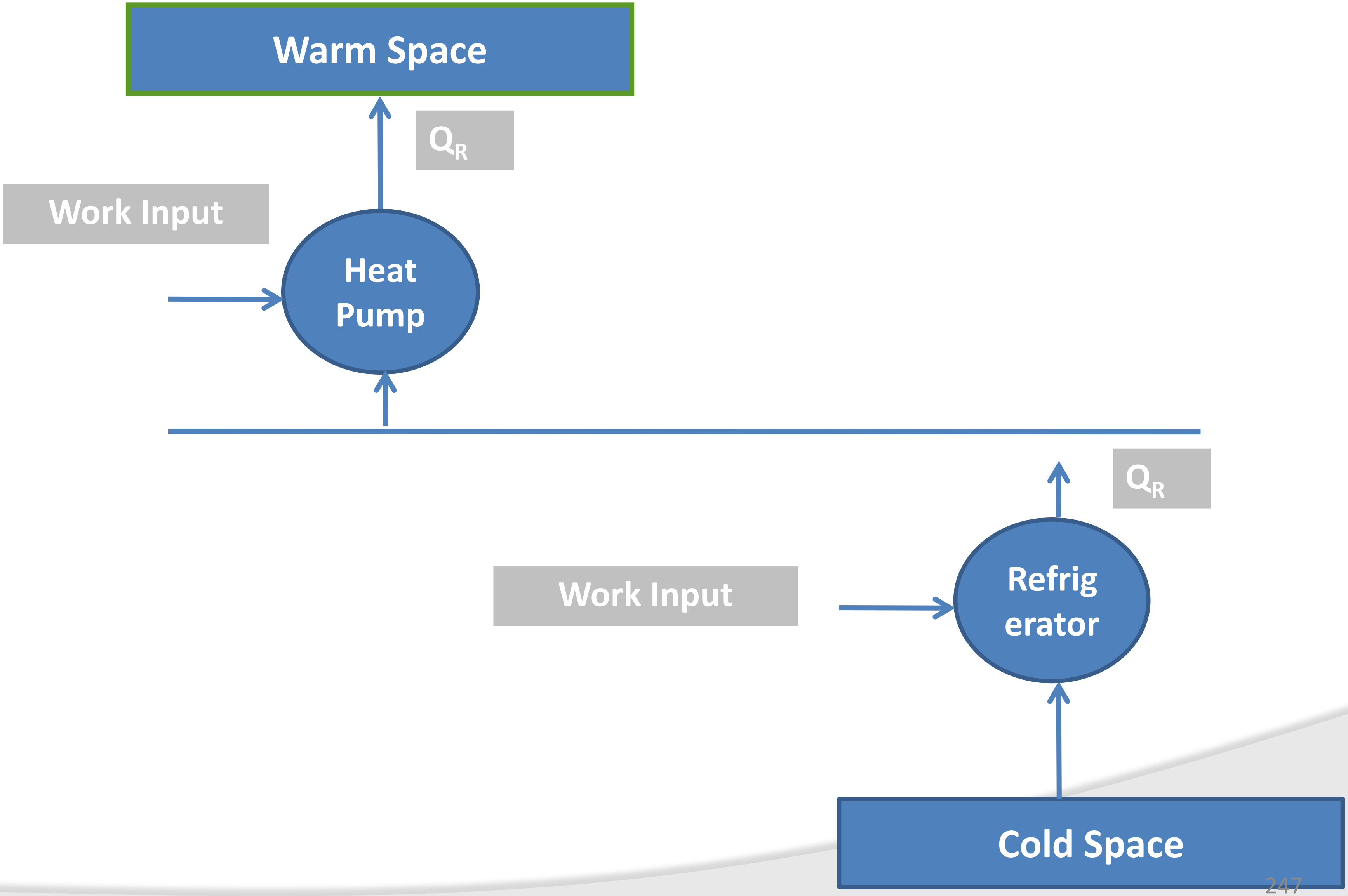
$$= 1.94\,Ton$$

$$COP_{R,\,Carnot} = \frac{T_L}{T_H - T_L}$$

$$= \frac{(-20 + 273)\,K}{(43.79 - (-20))K}$$

$$= 3.97$$

Refrigerator and Heat pump



Warm Space

Q_R

Work Input

Heat Pump

Q_R

Work Input

Refrigerator

Cold Space

Terminologies of Refrigeration

Refrigerating Effect (N): It is defined as the quantity of heat extracted from a cold body or space to be cooled in a given time.

N= Heat extracted from the cold space

Specific Heat of water and ice : It is the quantity of heat required to raise or lower the temperature of one kg of water (or ice), through one kelvin or (1^0 c) in one second.

Specific heat of water, $C_{pw} = 4.19$ kJ/kg K

Specific heat of ice, $C_{pice} = 2.1$ kJ/kg K.

Terminologies of Refrigeration

Capacity of a Refrigeration Unit :

- Capacity of a refrigerating machines are expressed by their cooling capacity.
- The standard unit used for expressing the capacity of refrigerating machine is ton of refrigeration.
- One ton of refrigeration is defined as, “the quantity of heat abstracted (refrigerating effect) to freeze one ton of water into one ton of ice in a duration of 24 hours at 0^o c”.

Heat extracted from at 0^o c = latent heat of ice

Latent heat of ice = 336 kJ/kg

i.e., 336 kJ of heat should be extracted from one kg of water at 0^o C to convert it into ice.

Terminologies of Refrigeration

One ton of refrigeration = 336x1000 kJ/24 hrs.

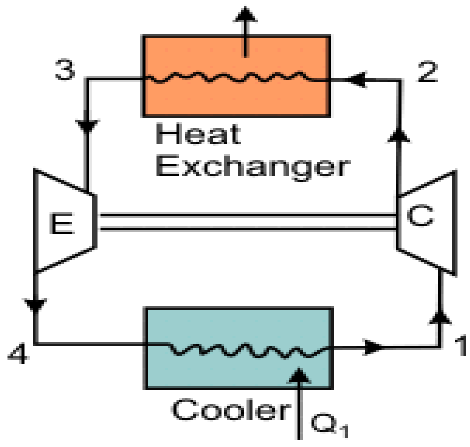
$$= \frac{336\text{x}1000 \text{ kJ/min}}{24\text{x}60}$$

One ton of refrigeration = 233.333 kJ/min

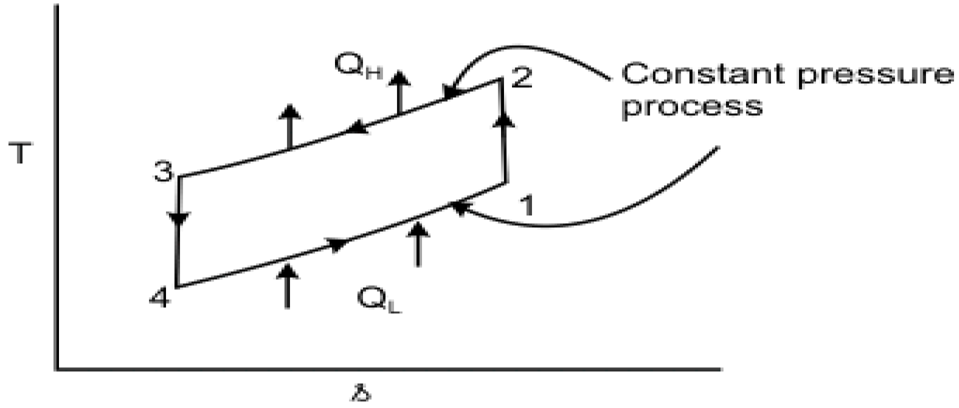
= 3.8889 kJ/sec

250

Brayton cycle and processes



(a)



(b)

THANK YOU