THERMAL ENGINEERING- I

Semester: 3RD

STUDY MATERIAL

Thermal Engineering

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TH – 4
THERMAL ENGINEERING-I

Chapter -1
Thermodynamic concept & Terminology

Syllabus

1. Thermodynamic concept & Terminology

1.1 Thermodynamic Systems (closed, open, isolated)

1.2 Thermodynamic properties of a system (pressure, volume, temperature, entropy, enthalpy, Internal energy and units of measurement).

1.3 Intensive and extensive properties

1.4 Define thermodynamic processes, path, cycle, state, path function, point function.

1.5 Thermodynamic Equilibrium.

1.6 Quasi-static Process.

1.7 Conceptual explanation of energy and its sources

1.8 Work, heat and comparison between the two.

1.9 Mechanical Equivalent of Heat.

1.10 Work transfer, Displacement work

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Thermodynamics:

- Thermodynamics is a science dealing with Energy and its transformation and its effect on the physical properties of substances.
- It deals with equilibrium and feasibility of a process.
- Deals with the relationship between heat and work and the properties of systems in equilibrium.

Scope of Thermodynamics:

- Steam power plant
- Separation and Liquification Plant
- Refrigeration
- Air-conditioning and Heating Devices.
- Internal combustion engine
- Chemical power plants
- Turbines
- Compressors, etc

Thermodynamic System:

A thermodynamic system is defined as a definite quantity of matter or a region of space within a
prescribed boundary upon which attention is focussed in the analysis of a problem.

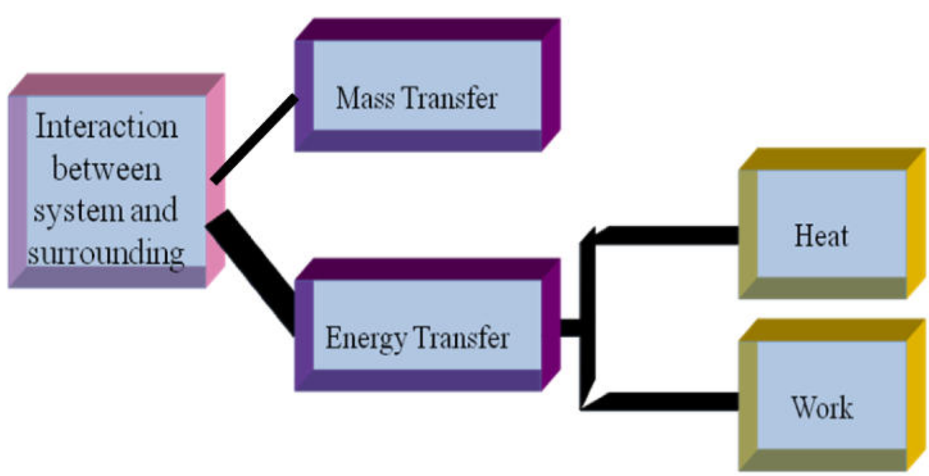
Surrounding: Everything external to the system is Surroundings.

Boundary:

- The surface which separates the system from the surrounding.
- System and surrounding interact through boundary in the form of Heat and Work.
- Boundary can be real (or) imaginary.
- Boundary can be fixed (or) moving.

System and Surrounding put together is known as **Universe**

Interaction between System and Surrounding



Based on the type of interaction, the systems are classified as
• **CLOSED SYSTEM**
• **OPEN SYSTEM**
• **ISOLATED SYSTEM**

CLOSED SYSTEM (Control Mass) : It is also termed as control mass or fixed mass analysis.

There is no mass transfer across the system boundary but energy in the form of Heat or Work
can cross the system boundary.

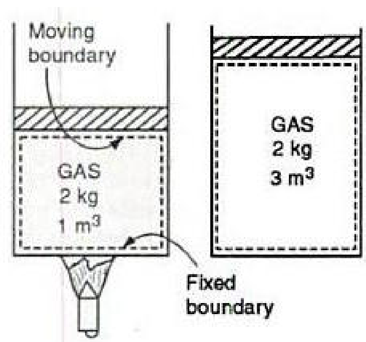
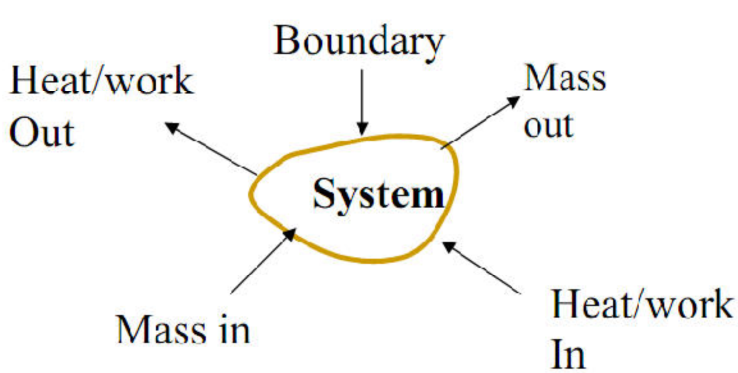


Fig-1.1

Eg. A certain amount of gas enclosed in a cylinder piston arrangement.

Open System(Control Volume): The open system is one in which both mass and energy can
cross the boundary of the system.
Open system is also termed as control volume analysis.



Concept of Control Volume:

A large engineering problem involves mass flow in and out of a system and therefore, is modeled as control volumes.

Control volume refers to a definite volume on which attention is focused for energy analysis.

Examples: Nozzles, Diffusers, Turbines, Compressors, Heat Exchanger, De-superheater, throttling valves, I.C engine etc.

Control Surface: The closed surface that surrounds the control volume is called **CONTROL SURFACE.** Mass as well as energy crosses the control surface. Control surface can be real or imaginary.

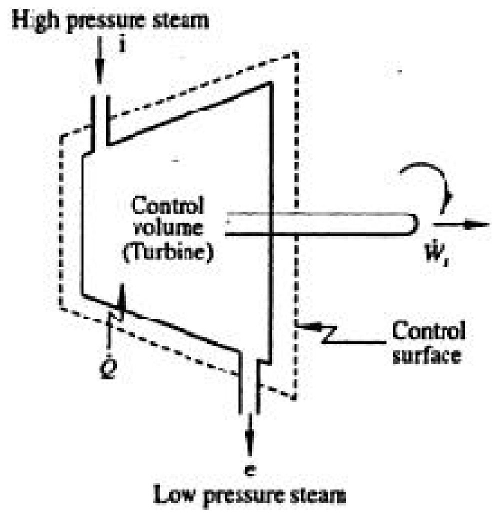
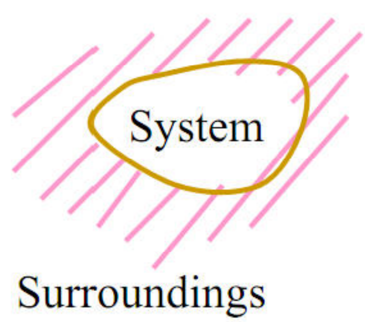


Fig-1.2

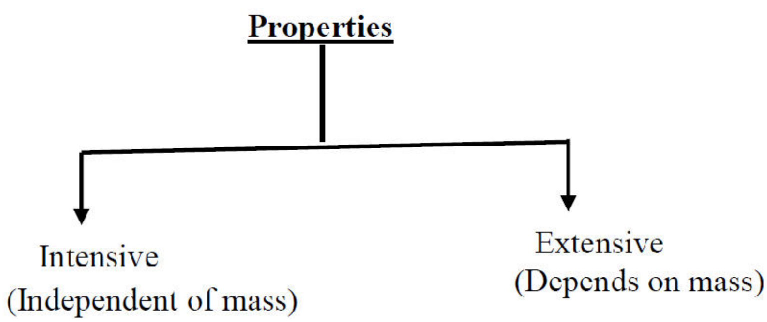
Isolated System: The isolated system is one in which there is no interaction between the system and the surroundings that neither the mass nor the energy interactions. Therefore it is of fixed mass and energy.



Mass Transfer	Energy Transfer	Type of System
No	Yes	Closed System
Yes	Yes	Open System
No	No	Isolated System

Property

Any observable characteristics required to describe the conditions or state of a system is known as Thermodynamic property of a system.



1) **Intensive properties:**

The properties which are independent on mass of the system is called as intensive properties. The properties of the system, whose value for the entire system is not equal to the sum of their values for individual parts of the system.

E.g. pressure, temperature, density etc

2) **Extensive properties:**

The properties of system which depend on mass of the system is called as extensive properties.

The properties of the system, whose value for the entire system is equal to the sum of their values for the individual parts of the systems, are called as extensive properties.

E.g. total volume, total mass, total energy, enthalpy, entropy, weight etc.

Differentiate Intensive and Extensive Property:

Extensive Property	**Intensive Property**
1. Extensive properties are dependent on the mass of a system.	1. Intensive properties are independent of the mass of a system.
2. Extensive properties are additive.	2. Intensive properties are not additive.
3. Its value for an overall system is	3. Its value remains the same whether one

the sum of its values for the parts into which the system is divided.	considers the whole system or only a part of it.
4.Example:mass(m),volume(V),Energy (E), Enthalpy(H) etc.	4.Example:Pressure(P),Temperature(T),Density etc.
5. Uppercase letters are used for extensive properties except mass.	5. Lowercase letters are used for intensive properties except pressure(P) and temp.(T)

Specific property= Extensive property/mass.
*Example: Specific volume (**v**) = Volume(**V**)/mass(**m**)*
*Specific enthalpy (**h**) = Enthalpy(**H**)/mass(**m**)*
*Specific entropy (**s**) = Entropy(**S**)/mass(**m**)*

State:

- It is the condition of a system as defined by the values of all it's properties.
- It gives a complete description of the system.
- Any operation in which one or more properties of a system change is called ***change of state*** .

Path and Process:

- The series of state through a system passes during a change of state is ***Path of the system***.
- If the path followed by the system during change of state is specified or defined completely, then it is called a process.

We can allow one of the properties to remain a constant during a process.

- ✓ Isothermal ⟹ Constant Temperature (**T**)
- ✓ Isobaric ⟹ Constant Pressure (**P**)
- ✓ Isochoric ⟹ Constant Volume (**V**)
- ✓ Isentropic ⟹ Constant Entropy (**s**)
- ✓ Isenthalpic ⟹ Constant Enthalpy (**h**)

Cycle: When a system in a given initial state undergoes a series of processes and returns to initial state at the end of process, then the system is said to have undergone a hermodynamic cycle.

Point Function:

- A Point function (also known as state function) is a function whose value depends on the final and initial states of the thermodynamic process, irrespective of the path followed by the process.
- They depend on the state only, and not on how a system reaches that state. All properties are point functions.

Example : density, enthalpy, internal energy, entropy etc.
Process A: $V_2 - V_1 = 3\ m^3$
Process B: $V_2 - V_1 = 3\ m^3$

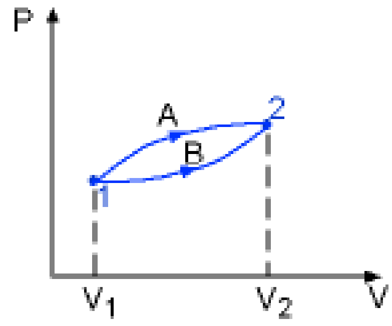


Fig-1.3

Path Function:

- There are certain quantities which cannot be located on a graph (Co-ordinate axis)

by a point but are given by the area or so, on that graph. In that case, the area on the graph, pertaining to the particular process, is a function of the path of the process, such quantities are called Path Functions.

- Their magnitudes depend on the path followed during a process as well as the end states. Work (W), heat (Q) are path functions.

Examples: Heat, Work, etc.
ProcessA: $W_A=10kJ$
Process b: $W_B = 7\ kJ$

Point Function	**Path Function**
1. Any quantity whose change is independent of the path is known as point function.	1. Any quantity, the value of which depends on the path followed during a change of state is known as path function.
2. The magnitude of such quantity in a process depends on the state.	2. The magnitude of such quantity in a process is equal to the area under the curve on a property diagram.
3. These are exact differential	3. These are inexact differential. Inexact differential is denoted by δ
4. Properties are the examples of point function like pressure(P), volume(V), Temp.(T),Energy etc.	4. Ex: Heat and work

Thermodynamic Equilibrium

A system is said to exist in a state of Thermodynamic Equilibrium when no changes in macroscopic property is observed if the system is isolated from its surrounding. At the state of equilibrium, the properties of the system are uniform and only one value can be assigned to it.

A system will be in a state of thermodynamic equilibrium, if the condition for following three types of equilibrium is satisfied.

Mechanical Equilibrium (Equality of Pressure):

In the absence of any unbalanced force within the system itself and also between the system and the surroundings, the system is said to be in a state of mechanical equilibrium.

- Mechanical equilibrium is related to pressure.
- A system is in mechanical equilibrium if there is no change in pressure at any point of the system .

Thermal Equilibrium (Equality of Temperature):

A state of thermal equilibrium can be described as one in which the temperature of the system is uniform.

Chemical Equilibrium (**Equality of chemical potential**):

- A system is in chemical equilibrium when its chemical composition does not change with time that is no chemical reaction occurs.
- It is related to chemical potential.

E.g. Let us suppose that there are two bodies at different temperatures, one hot and one cold. When these two bodies are brought in physical contact with each other, temperature of both the bodies will change. The hot body will tend to become colder while the cold body will tend to become hotter. Eventually both the bodies will achieve the same temperatures and they are said to be in thermodynamic equilibrium with each other.

Reversible Process:

Reversible process is one which is performed in such a way that at the end of the process both the system and surrounding may be restored to their initial state without producing any changes in rest of the Universe.

Reasons for studying Reversible Process:

1. They are easy to analyze.
2. They served as an idealized process to which actual process can be compared.
3. They are taken for consideration because work producing devices such as steam turbine, automobile engines etc delivers the maximum work and work consuming devices like compressors, pumps etc consumes the least work.

Characteristics of Reversible Process

- ✓ A Reversible process is carried out infinitely slowly with an infinitesimal gradient so that every state pass through by the system is in equilibrium.
- ✓ It is possible to execute the process in either of the direction.
- ✓ No dissipative effect such as friction, loss in a resistor, etc are present.

- ✓ Heat and work interactions of the system and the surroundings in the reverse process are equal and opposite in direction to the same in the forward process.

Examples:

1. Frictionless isothermal expansion or compression of a fluid.
2. Frictionless adiabatic expansion or compression of a fluid.
3. Elastic stretching of a solid.
4. Electric current with zero resistance.

Irreversible Process:

An irreversible process is one that is carried out in such a way that the system and surrounding cannot be exactly restored to their respective initial state at the end of the reverse process, that a net change occurs in the Universe.

- ☺ **Note**: In an irreversible the surrounding would always be affected by loss of work and gain of low temperature heat, which can be considered as waste heat for the surrounding.

Causes of Irreversibility:

The irreversibility of a process may be due to either one or both of the following.

(i) Lack of Equilibrium.

(ii) Involvement of Dissipative effects.

Characteristics of an Irreversible Process:

1. It can be carried out in one direction only.
2. It occurs at a finite rate.
3. During an irreversible process, the system is not in equilibrium.

An irreversible process cannot be reversed without causing permanent changes in the surroundings.

Lack of Equilibrium (Mechanical, Thermal, Chemical)

The lack of equilibrium between the system and the surroundings or between the two systems

causes a spontaneous change which makes the process irreversible.

Examples:

1. Heat transfer through a finite temperature difference.
2. Compression or Expansion through a finite pressure difference between the system and the surroundings.
3. Free expansion or unrestrained expansion.
4. Mixing of substances.

Dissipative Effects:

Dissipation results in the transformation of work into molecular energy of the system.

Examples:

1. Friction.
2. Flow of electricity through a resistor.
3. Paddle wheel work transfer .etc

Quasi-static process or quasi equilibrium process:

- When a process is carried out in such a way that ,at every instant, the system deviation form the thermodynamic equilibrium is infinitesimal then the process is known as Quasi-static process or quasi equilibrium processes.

- ***"Quasi"*** *means Almost slow or infinitely slow.*
- *Consider a system of gas contained in a cylinder fitted with a piston upon which many very small pieces of weights are placed as shown in Fig.1.4(a).*
- *The upward force exerted by the gas just balances the weights on the piston and the system is initially in equilibrium state identified by pressure P_1, volume V_1 and temperature T_1.*
- *When these weights are removed slowly, one at a time, the unbalanced potential is infinitesimally small.*
- *The piston will slowly move upwards and at any particular instant of piston travel, the system would be almost close to state of equilibrium.*
- *Every state passed by the system will be an equilibrium state.*

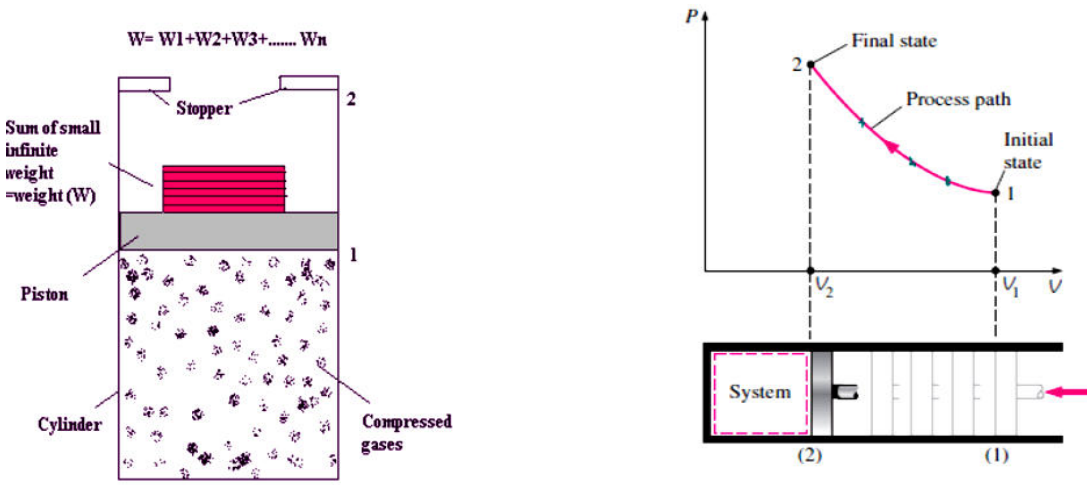


Fig. 1.4 (a) Quasi-Static Process (b) p-v diagram of a compression process

The locus of a series of such equilibrium states is called a "Quasi-Static or Quasi-equilibrium process."

- It should be pointed out that a quasi-equilibrium process is an idealized process and is not a true representation of an actual process. But many actual processes closely approximate it, and they can be modeled as quasi-equilibrium with negligible error.
- Engineers are interested in quasi-equilibrium processes for two reasons. First, they are easy to analyze; second, work-producing devices deliver the most work when they operate on quasi-equilibrium processes. Therefore, quasi-equilibrium processes serve as standards to which actual processes can be compared.
- Fig. 1.4(b) shows the p-v diagram of a compression process of a gas.

- ✓ A quasi-static process is also called a reversible process. This process is a succession of equilibrium states and ***infinite slowness*** is its characteristic feature.

Conceptual explanation of energy and its sources:

Energy:

The energy is defined as the capacity to do work.

Or

A system is said to possess energy when it is capable of doing work.

Source of Energy: A specific source which provides useful energy. The total energy of the system is conserved but it converts into a form which cannot be utilized again.

Types of Sources of Energy: These can be broken down into renewable and non-renewable energy sources.

Renewable Energy Source:

A renewable energy source is any natural resource that can replace it quickly and dependably. These energy sources are plentiful, sustainable, naturally replenished and good to the environment.

The major types or sources of renewable energy are:

- Solar energy from the sun
- Wind energy
- Geothermal energy from the heat inside the earth
- Hydropower from flowing water
- Ocean energy in the form of wave, tidal, current energy and ocean thermal energy.
- Biomass from plants

Non-renewable Energy Source:

A non-renewable energy source is a source with a limited supply that we can mine or extract from the earth, and it'll eventually run out.

These are formed over thousands of years from the buried remains of ancient sea plants and animals that lived millions of years ago. Most of these energy sources are "dirty" fossil fuels, which are generally bad for the environment.

The major types or sources of non-renewable energy are:

- Petroleum
- Hydrocarbon gas liquids
- Natural gas
- Coal
- Nuclear energy

DIFFERENT TYPES OF STORE ENERGY:

POTENTIAL ENERGY-The energy posed by a body by a virtue of its position or state of rest is known as potential energy

$$P.E = W \times h = mgh$$

W=weight of the body in N

M=mass of the body in kg
g=acceleration due to gravity
h=height in meter

KINETIC ENERGY-The energy posed by a body by virtue of its motion. Mathematically kinetic energy,

$$K.E=1/2\ mv^2$$

V=velocity of the body

INTERNAL ENERGY –The energy posed by a body or a system by virtue of its intermolecular arrangement and motions of molecules. The change in temperature causes the change in internal energy. It is usually denoted by U.

The sum of the above three energies is the total energy of the system

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

But when the system is stationary and the effect of gravity is neglected then P.E=0 and K.E=0. Thus $E = U$

- ☺ I.E the total energy is equal to the total energy of system.

Heat and Work

Energy can cross the boundary of a closed system in two distinct forms: heat and work. It is important to distinguish between these two forms of energy.

Heat

- ✓ "Heat is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference." Then it follows that there cannot be any heat transfer between two systems that are at the same temperature.
- ✓ The temperature difference is the driving potential for heat transfer.
- ✓ A process during which there is no heat transfer is called an adiabatic process. In an adiabatic process, energy content and the temperature of a system can be changed by other processes, such as work.
- ✓ All heat interaction need not to be result in temperature changes.
  *e.g. Evaporation and Condensation***.**

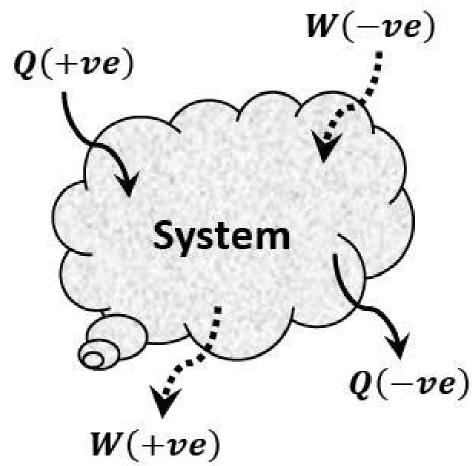
Work

- ✓ "An energy interaction between a system and its surroundings during a process can be considered as work transfer, if its sole effect on everything external to the system could have been to raise a weight."
- ✓ It is also a form of energy in transit like heat.

Sign Convention for Heat & Work

- ✓ Heat and Work are directional quantity, and its specification requires magnitude and direction both. Universally accepted sign convections for heat and work energy are shown in Fig

1. Heat transferred to a system (heat supply) and Work done by a system is considered **positive.**
2. Heat transferred from a system (heat rejection) and Work done on a system is considered **negative.**



Comparison Chart:

HEAT	WORK
Heat is a form of energy.	Work is the amount of energy transferred by force through a distance.
Heat Requires Temperature difference	**Work** Requires Force and Displacement
Q > 0; when the environment is at a higher temperature than the system. Energy is transfer to the system.	**W > 0** when gas is compressed. Energy is transfer into the system.
Q < 0; when the system is at a higher temperature than the environment. Energy is transferred out of the system.	**W < 0**; when a gas expands. Energy is transferred out of the **system.**
Heat is low-grade energy.	Work is high-grade energy.
The efficiency of the transfer of heat to work is lower.	The efficiency of the transfer of work to heat is higher.

Similarities

- Both are energy interactions.
- Both are transient phenomena.
- Both are boundary phenomena.
- Both represent energy crossing the boundary of the system.

- They are not the property of the system.
- Both are path functions.

Dissimilarities

- Heat transfer is the energy interaction due to temperature difference only while work is not.
- Heat is low-grade, while work is high-grade.
- Heat is thermal energy transfer, while work is mechanical energy transfer across the system boundary.

Mechanical Equivalent of Heat.

- Mechanical energy can be converted into heat, and heat can be converted into some mechanical energy. This important physical observation is known as the mechanical equivalent of heat.
- This means one can change the internal energy of a system by either doing work to the system, or adding heat to the system.
- This concept is fundamental to thermodynamics which applies the ideas of heat and work in order to create useful systems such as engines, power plants, and refrigerators.

Work transfer:

Different Forms of Work Transfer

1. Electrical work
2. Mechanical work
3. Moving boundary work
4. Flow work
5. Gravitational work
6. Acceleration work
7. Shaft work
8. Spring work

Some of the important forms of work transfer are discussed here

- ✓ ***Mechanical Work***
  - In mechanics work done by a system is expressed as a product of force (F) and– displacement (s).

$$W = F \times s$$

  - If the force is not constant, the work done is obtained by adding the differential– amounts of work,

$$W = \int_1^2 F ds$$

- The pressure difference is the driving force for mechanical work.–

Displacement work

- In many thermodynamic problems, mechanical work is the form of moving boundary work. The moving boundary work is associated with real engines and compressors.

Let consider the gas enclosed in a frictionless piston cylinder arrangement as shown above Fig. Let the initial gas pressure p_1 and volume V_1. The piston is the only boundary which moves due to gas pressure. Let the piston moves out to a new final position 2, specified by pressure $p_2$and volume V_2. At any intermediate point in the travel of the piston, let the pressure be p, volume V and piston cross sectional area is A. When the piston moves through and infinitesimal distance ds in a quasi- equilibrium manner, the force applied on piston is, $F = p \times F = p \times A$

– Then differential work transfer through a displacement of ds during this process,

- $\delta W = F \times ds = p \times A \times ds = p \times dV$

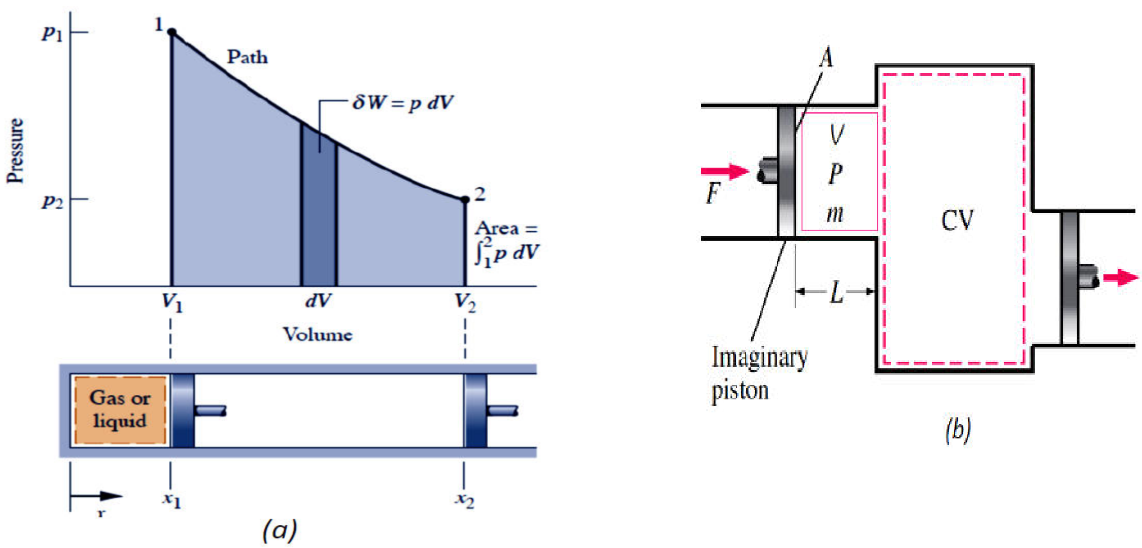


Fig. 1.5 (a) Displacement work and (b) Flow work

When piston moves out from initial state 1 to final state 2 with volume changing from V_1 to V_2, The total boundary work done by the system will be,

$$W_{1-2} = \int_{V_1}^{V_2} F ds \quad (kJ)$$

or

$$W_{1-2} = \int_{V_1}^{V_2} p dv \,(kJ/kg)$$

- ✓ This work transfer during a process is equal to the area under the curve on a $p - V$ diagram as shown in above fig.1.5(a)

Flow Work

- ✓ Flow energy or flow work refers to work required to push a certain mass of fluid into and out of the control volume. It is necessary for maintaining continuous flow through a control volume.
- ✓ Consider a fluid element of volume V, entering the control volume through a cross sectional area A as shown in fig.1.5 (b).
- ✓ If p is the fluid pressure acting uniformly at the imaginary piston at the entrance of the control volume, the force applied on the fluid element by imaginary piston is,

$$F = p \times A.$$

- ✓ If the fluid is pushed by a distance L, then the flow work will be,

$$W_f = p \times A \times L = p \times V$$

- ✓ Flow work at the entrance, $Wf_1 = p_1 V_1$
- ✓ Flow work at the exit, $Wf_2 = p_2 V_2$

Specific Heat

- ✓ "It is defined as heat energy required to change the temperature of the unit mass of a substance by one degree." It is designated as C and measured in kJ/kg-K.
- ✓ In general, the specific heat can be calculated as,

$$C = \frac{1}{m}\left(\frac{\delta Q}{dT}\right) = \frac{\delta q}{dT}$$

$$dQ = mcdT$$

- Gases have two specific heats, Cp and Cv but for liquids and solids, the specific volume is very small and its change with pressure and temperature is negligible, thus they have only one specific heat.
- Specific heat at constant volume, Cv :

$$dQ = m\, c_v\, dT$$

$$m\, c_v\, (T_2 - T_1)$$

and

- Specific heat at constant pressure, Cp:

$$dQ = m\,c_p\,dT$$
$$m\,c_p\,(T_2 - T_1)$$

Ratio of Specific Heats

- The ratio of specific heat at constant pressure to the specific heat at constant volume is given the symbol γ (gamma).

$$\gamma = \frac{C_p}{C_v}$$

Enthalpy

- One of the fundamental quantities which occur invariably in thermodynamics is the sum of internal energy (u) and pressure volume product (pv). This sum is called **Enthalpy** (h).

h = u + pv

INTERNAL ENERGY:

✓ It is the heat energy stored in a gas. If a certain amount of heat is supplied to a gas the result is that temperature of gas may increase or volume of gas may increase thereby doing some external work or both temperature and volume may increase.

Joules' Law:

✓ Joule's law of internal energy states that internal energy of a perfect gas is a function of temperature only. In other words, internal energy of a gas is dependent on the temperature change only and is not affected by the change in pressure and volume

MACROSCOPIC AND MICROSCOPIC APPROACH

1. Macroscopic approach—(Macro mean big or total)
   ✓ It is well known that every substance is composed of a large number of molecules. The properties of the substance depend on the behavior of these molecules.
2. Microscopic approach—(Micro means small)
   ✓ The behavior of a system may be investigated from either a microscopic (Micro means small) or macroscopic (Macro means big or total) point of view.

These approaches are discussed below in a comparative way:

S.No	Macroscopic Approach	Microscopic Approach
1	In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level. In other words this approach to thermodynamics is concerned with gross or overall behavior. ***This is known as classical thermodynamics.***	The approach considers that the system is made up of a very large number of discrete particles known as molecules. These molecules have different velocities and energies. ***This is known as statistical thermodynamics.***

2	The analysis of macroscopic system requires simple mathematical formulae	The behavior of the system is found by using statistical methods as the number of molecules is very large. So advanced statistical and mathematical methods are needed to explain the changes in the system.
3	The values of the properties of the system are their average values.	The properties like velocity, momentum, impulse, kinetic energy, force of impact etc. which describe the molecule cannot be easily measured by instruments
4	In order to describe a system only a few properties are needed.	Large numbers of variables are needed to describe a system. So the approach is Complicated.

PURE SUBSTANCE

- ✓ A pure substance is one that has a homogeneous and invariable chemical composition even though there is a change of phase.
- ✓ In other words, it is a system which is (a) **Homogeneous** in composition, (b) **homogeneous** in chemical aggregation.

  *Examples: Liquid, water, mixture of liquid water and steam, mixture of ice and water***.**
- ✓ **The** mixture of liquid air and gaseous air is not a pure substance.

Homogeneous System:

- ✓ A system which consists of a single phase is termed as homogeneous system.

Examples: Mixture of air and water vapour, water plus nitric acid and octane plus heptane.

Heterogeneous System:

- ✓ A system which consists of two or more phases is called a heterogeneous system.

Examples: Water plus steam, ice plus water and water plus oil.

Assignment work of Chapter-1

1. Define thermodynamics?
2. What are the scopes of thermodynamics?
3. What is thermodynamics system describing it?
4. What are thermodynamic properties?
5. What the difference between intensive properties and extensive properties?
6. What is the difference between point function and path function?
7. What is thermodynamically equilibrium and describe?
8. What is reversible and irreversible process?
9. What is Quasi-static equilibrium process and described it?
10. Write type of energy sources, what they are?
11. What are the different types of store energy?
12. What is the difference between heat and work?
13. What is displacement work?
14. What is enthalpy?
15. What is difference between macroscopic and microscopic approach?
16. What is pure substance?
17. What is internal energy and joules law?
18. What is ratio of specific heat?
19. What is specific heat?
20. What is Homogeneous System & Heterogeneous System?

OBJECTIVE TYPE QUESTIONS

1. A definite area or space where some thermodynamic process takes place is known as

(*a*) thermodynamic system (*b*) thermodynamic cycle

(*c*) thermodynamic process (*d*) thermodynamic law.

2. An open system is one in which

(*a*) heat and work cross the boundary of the system, but the mass of the working substance does not

(*b*) mass of working substance crosses the boundary of the system but the heat and work do not

(*c*) both the heat and work as well as mass of the working substances cross the boundary of the system

(*d*) neither the heat and work nor the mass of the working substances cross the boundary of the system.

3. An isolated system

(*a*) is a specified region where transfer of energy and/or mass take place

(*b*) is a region of constant mass and only energy is allowed to cross the boundaries

(*c*) cannot transfer either energy or mass to or from the surroundings (*d*) is one in which mass within the system is not necessarily constant

(*e*) none of the above.

4. In an extensive property of a thermodynamic system

(*a*) extensive heat is transferred (*b*) extensive work is done

(*c*) extensive energy is utilised (*d*) all of the above(*e*) none of the above.

5. Which of the following is an intensive property of a thermodynamic system ?

(*a*) Volume (*b*) Temperature (*c*) Mass (*d*) Energy.

6. Which of the following is the extensive property of a thermodynamic system?

(*a*) Pressure (*b*) Volume (*c*) Temperature (*d*) Density.

7. The condition for the reversibility of a cycle is

(*a*) the pressure and temperature of the working substance must not differ, appreciably, from those of the surroundings at any stage in the process

(*b*) all the processes, taking place in the cycle of operation, must be extremely slow

(*c*) the working parts of the engine must be friction free

(*d*) there should be no loss of energy during the cycle of operation

(*e*) all of the above (*f*) none of the above.

8. In an irreversible process, there is a

(*a*) loss of heat (*b*) no loss of heat

(*c*) gain of heat (*d*) no gain of heat.

9. The main cause of the irreversibility is

(*a*) mechanical and fluid friction (*b*) unrestricted expansion

(*c*) heat transfer with a finite temperature difference

(*d*) all of the above

TH - 4 THERMAL ENGINEERING-I

Chapter -2

Syllabus

2. Laws of Thermodynamics

2.1 State & explain Zeroth law of thermodynamics.

2.2 State & explain First law of thermodynamics.

2.3 Limitations of First law of thermodynamics

2.4Application of First law of Thermodynamics (steady flow energy equation and its application to turbine and compressor)

2.4 Second law of thermodynamics (Claucius & Kelvin Plank statements).

2.5 Application of second law in heat engine, heat pump, refrigerator & determination of efficiencies & C.O.P (solve simple numerical)

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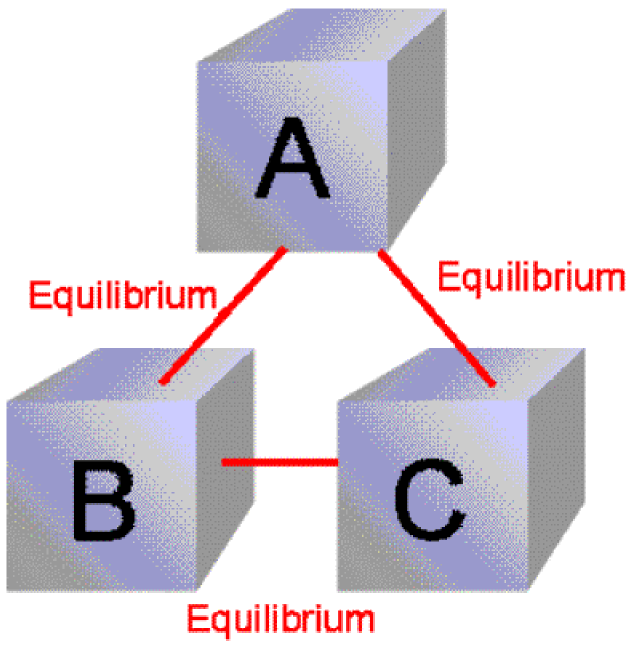
2.1 State & explain Zeroth law of thermodynamics: (Lect-1)

The Zeroth Law of Thermodynamics states that if two bodies are each in thermal equilibrium with some third body, then they are also in equilibrium with each other. Thermal equilibrium means that when two bodies are brought into contact with each other and separated by a barrier that is permeable to heat, there will be no transfer of heat from one to the other.



Example:

Body A is in contact with body B, which is in contact with body C. The temperature of A is more than B which is more than C. What is the correct direction of flow in accordance with the zeroth law of thermodynamics?

Solution:

Body having higher temperature will have higher heat and will transfer heat to low temperature bodies if it comes into contact with them. So, in this heat will flow from A to B to C and finally attain same temperature.

2.1.1 TEMPERATURE SCALES

Number of temperature measuring scales came up from time to time. The text ahead gives a brief idea of the different temperature scales used in thermometry. Different temperature scales have different names based on the names of persons who originated them and have different numerical values assigned to the reference states.

(*a*) Celsius Scale or Centigrade Scale

Anders Celsius gave this Celsius or Centigrade scale using ice point of 0°C as the lower fixed point and steam point of 100ºC as upper fixed point for developing the scale. It is denoted by letter *C*. Ice point refers to the temperature at which freezing of water takes place at standard atmospheric pressure. Steam point refers to the temperature of water at which its vaporization takes place at standard atmospheric pressure. The interval between the two fixed points was equally divided into 100 equal parts and each part represented 1ºC or 1 degree celsius.

(*b*) Fahrenheit Scale

Fahrenheit gave another temperature scale known as Fahrenheit scale and has the lower fixed point as 32 F and the upper fixed point as 212 F. The interval between these two is equally divided into 180 part. It is denoted by letter F. Each part represents 1 F.

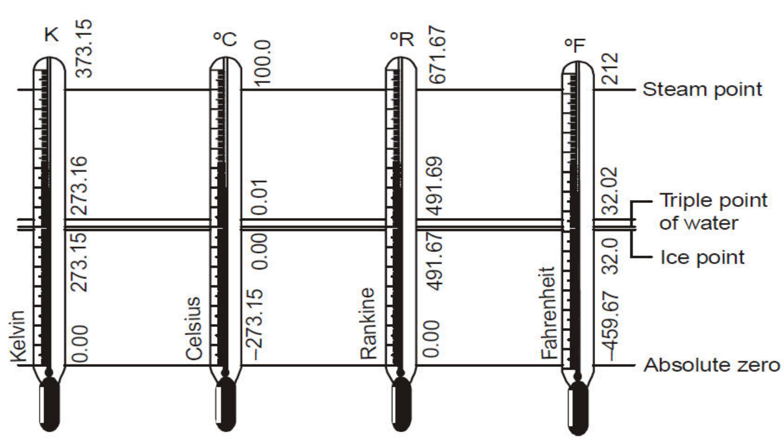
(*c*) Rankine Scale

Rankine scale was developed by William John MacQuorn Rankine, a Scottish engineer. It is denoted by letter *R*. It is related to Fahrenheit scale as given below.

$TR = TF + 459.67$

(*d*) Kelvin Scale

Kelvin scale proposed by Lord Kelvin is very commonly used in thermodynamic analysis. It also defines the absolute zero temperature. Zero degree Kelvin or absolute zero temperature is taken as –273.15ºC. It is denoted by letter K.



2.2 State & explain First law of thermodynamics.

- *The heat and mechanical work are mutually convertible*: When a closed system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to net work done by the system on its surroundings. In other words, the cyclic integral of heat transfers is equal to the cyclic integral of work transfers.

Mathematically,

$$\oint \delta Q = \oint \delta W$$

First law of thermodynamics can't be proved but it is supported by a large number of experiments and no exceptions have been observed. It is therefore termed as the law of nature.

- *Energy can neither be created nor be destroyed through it can be transfer from one form to another form:* According To this law in the system undergoes a change of the state, then both heat transfer and work transfer takes place. The net energy transfer is stored within the system and is known as stored energy or total energy of the system.

  Mathematically,

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

Symbol of δ is used for quantity which is inexact differential and symbol d is used for a quantity for is in exact differential. The quantity E is extensive property and represents the total energy of the particular state

$$Q_{1-2} - W_{1-2} = E_2 - E_1$$

- ***For unit mass;***

$$q_{1-2} - w_{1-2} = e_2 - e_2$$

$$E_1 = PE_1 + KE_1 + U_1 = mgz_1 + \frac{mV_1^2}{2} + U_1$$

$$E_2 = PE_2 + KE_2 + U_2 = mgz_2 + \frac{mV_2^2}{2} + U_2$$

$$Q_{1-2} - W_{1-2} = E_2 - E_1$$

$$Q_{1-2} - W_{1-2} = \left(mgz_1 + \frac{mV_1^2}{2} + U_1 \right) - \left(mgz_2 + \frac{mV_2^2}{2} + U_2 \right)$$

$$Q_{1-2} - W_{1-2} = m\left(gZ_2 - gZ_1\right) + m\left(\frac{V_2^2}{2} - \frac{V_1^2}{2}\right) + \left(U_2 - U_1\right)$$

For unit mass

$$Q_{1-2} - W_{1-2} = m(gz_2 - gz_1) + m\left(\frac{V_2^2}{2} - \frac{V_1^2}{2}\right) + (u_2 - u_1)$$

- ***Case-1***
  When there are no changes in potential energy of the system (*i.e.* the height of the system from the datum label is same), then $PE_1 = PE_2$. Thus the above equation will be
  $$Q_{1-2} - W_{1-2} = (KE_2 + U_2) - (KE_1 + U_1)$$
  $$Q_{1-2} - W_{1-2} = (KE_2 - KE_1) + (U_2 - U_1)$$
- ***Case-2***
  When there is no change in PE_1 and also no flow of the mass into or out of the system then $PE_1 = PE_2$ and $KE_1 = KE_2$, thus the above equation written as,
  $$Q_{1-2} - W_{1-2} = (U_2 - U_1) = dU$$
- ***Case -3***
  For an isolated system for which $Q_{1-2} = W_{1-2} = 0$ so the above equation will be
  $$E_1 = E_2$$

Limitation of first law: (Lect-2)

There are two basic limitations of the first law of thermodynamics

I. First law does not differentiate between heat and work.
   It assumes complete inter-convertibility of the two. Though work being high grade energy can be fully converted into heat but heat cannot be completely converted to work.
II. It does not ensure whether the process is feasible or not.

III. It does not permit us to know the direction of energy transfer. We cannot ascertain whether heat will flow from a higher temperature body to a lower temperature body vice versa.

- *When a closed system undergoes a thermodynamic cycle, the net heat transfer is equal to the network transfer:* The statement does not specify the direction of flow of heat and work (i.e. weather the heat flows from a hot body to a cold body or from a body to the hot body). It also does not give the conditions under which these transfer takes place.
- *The heat and mechanical work are mutually convertible:* Through the mechanical work can be fully converted into heat energy, but only a part of heat energy can be converted into mechanical work this means that is the heat energy and mechanical work are not fully mutually convertible. In other words there is limitation of weight conversion of one form of energy into another form.
- A device that violates the First law of thermodynamics (by creating energy) is called a Perpetual Motion Machine of the first kind.
- The first device supplies continuously energy without receiving it. So this is a system creating energy and therefore violating the first law.
- Such machines will produce the energy by itself and as we know that according to the law of energy conservation, energy could not be created or destroyed but could be converted from one form of energy to other form of energy.

First Law Applied to a Cyclic Process – Joule's Experiment

- **Cyclic Process:** *"A process is cyclic if the initial and final states of the system executing the process are identical."*
- A system represented by a state point 1 undergoes a process 1-a-2, and comes back to initial state following the path 2-b-1.
- All properties of the system are restored, when the initial state is reached.
- During the execution of these processes:
  i. Area 1-a-2-3-4-1 represents the work done by the system ($W1$) during expansion process 1-a-2.
  ii. Similarly area 2-3-4-1-b-2 gives work supplied to the system ($W2$) during compression process 2-b-1.
  iii. Area 1-a-2-b-1 represents the net work ($W1 - W2$) delivered by the system.
- Since the system regains its initial state, there is no change in the energy stored by the system.
- For a cyclic process, the First Law of Thermodynamics can be stated as follows :

  "When a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to net work done by the system on its surroundings."

Mathematically,

$$\oint \delta Q = \oint \delta W$$

JOULE'S EXPERIMENT

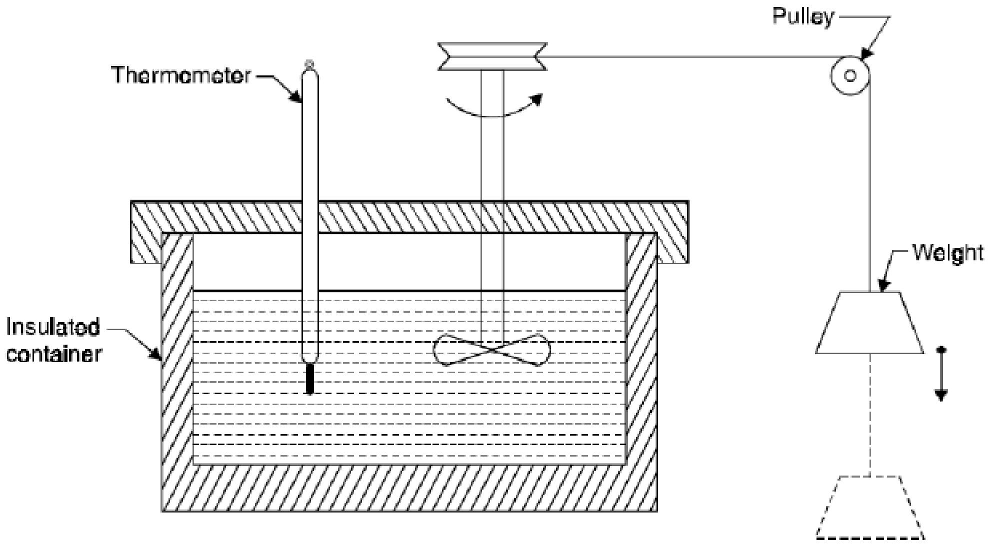


Fig. Joule's paddle-wheel experiment

- ✓ A known mass of water is taken into a rigid and well insulated container provided with a paddle wheel.
- ✓ The insulation is provided to prevent any heat interaction with surroundings.
- ✓ The work input to the paddle wheel is measured by the fall of weight while the corresponding temperature rise of the liquid in the insulated container is measured by the thermometer.

✓ Joule conducted a number of experiments involving different types of work interactions and found that the work expended was proportional to increase in thermal energy, i.e.

$$Q \propto W$$
$$\therefore \quad Q = \frac{W}{J}$$
$$\therefore \quad W = JQ$$

Where, J = Joule's equivalent or mechanical equivalent of heat.

In SI system of units, both heat and work are measured in Joules.

First Law Applied to a Process

- ✓ The first law of thermodynamics is often applied to a process as the system changes from one state to another.
- ✓ According to first law of thermodynamics,

$$\Delta E = Q - W$$

Where,

$\Delta E = \Delta U + \Delta KE + \Delta PE + other\ forms\ of\ energy$ = Net change in total energy of the system.

- ✓ If a ***closed system*** undergoes a change of state during which both heat and work transfer are involved, the net energy transfer will be stored or accumulated within the system. If Q is the heat transfer to the system and W is the work transferred from the system during process, the net energy transfer $(Q - W)$ will be stored in the system. Energy in storage is neither heat nor work and is given the name "***Internal Energy***" or "***Stored Energy***" of the system.

$$\therefore Q - W = \Delta U$$

- ✓ Most closed systems in practice are stationary, i.e. they do not involve kinetic energy and potential energy during the process. Thus the stationary systems are called non-flow systems and the first law of thermodynamics is reduced to above equation.
- ✓ In differential form first law of thermodynamics for a process can be written as,

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

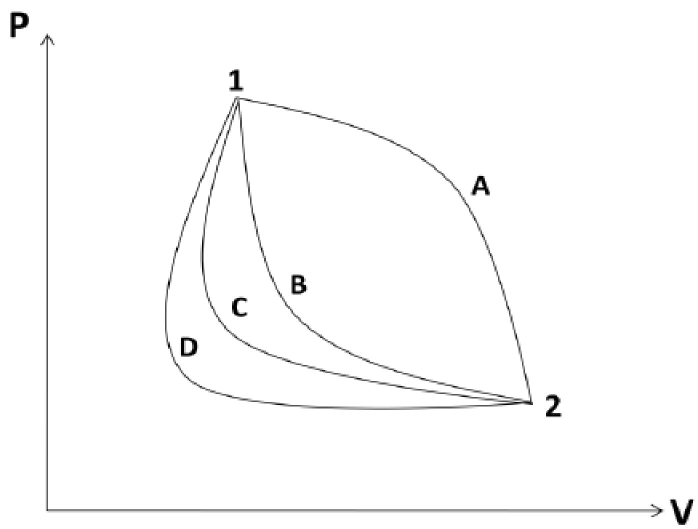
- ✓ Also for a ***cyclic process*** $\Delta U = 0$, as the system regains its original state hence,

$$Q - W = 0$$
$$\therefore Q = W$$

Internal Energy: A Property of the System

Consider a closed system which changes from state 1 to state 2 by path A and returns back to original state 1 by one of the following path as shown in below Fig.

(i) 2-B-1 (ii) 2- C-1 (iii) 2-D-1



- ✓ Applying the 1st law for the cyclic process 1-A-2-**B**-1,

$$\oint (\delta Q - \delta W) = 0$$

$$\therefore \int_{1,\ via\ A}^{2} (\delta Q - \delta W) + \int_{2,\ via\ B}^{1} (\delta Q - \delta W) = 0$$

Similarly,

- ✓ Applying the 1st law for the cyclic process 1-A-2-**C**-1,

$$\therefore \int_{1,\ via\ A}^{2} (\delta Q - \delta W) + \int_{2,\ via\ C}^{1} (\delta Q - \delta W) = 0$$

And,

- ✓ Applying the 1st law for the cyclic process 1-A-2-**D**-1,

$$\therefore \int_{1,\ via\ A}^{2} (\delta Q - \delta W) + \int_{2,\ via\ D}^{1} (\delta Q - \delta W) = 0$$

- ✓ Comparing equations above equation, we get,

$$\therefore \int_{2,\ via\ B}^{1} (\delta Q - \delta W) + \int_{2,\ via\ C}^{1} (\delta Q - \delta W) = \int_{2,\ via\ D}^{1} (\delta Q - \delta W)$$

Since B, C and D represents arbitrary paths between the state point 2 and state point 1, it can be concluded that the integral $\int_2^1 (\delta Q - \delta W)$

(i) Remains the same irrespective of the path along which the system proceeds,

(ii) Is solely dependent on the initial and final states of the system; ***is a point function and hence property***.

The integral $\int_2^1 (\delta Q - \delta W)$ is called energy of the system and is given by a symbol E.

- ✓ Further the energy is a property of the system; its differential is exact and is denoted by dE.
- ✓ Thus for a process,

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

- ✓ The energy, E is an extensive property.
- ✓ The specific energy ($e = \frac{E}{m}$) is an intensive property.

First Law Applied to Steady Flow Processes

Conservation of Mass Principle – Continuity Equation

- ✓ Conservation of mass is one of the most fundamental principles for flow systems. ***"It states that the mass of a system can neither be created nor destroyed but its amount remains constant during any process. It only changes its form (phase)."***
- ✓ The conservation of mass principle for a control volume (CV) can be expressed as, *Total mass entering CV – Total mass leaving CV = Net change in mass within CV.*
- ✓ The amount of mass flowing through a cross-section per unit time is called the ***mass flow rate*** and it is calculated as, $\dot{m} = \frac{AV}{v}$

Where,
$\dot{m}$ = Mass flow rate in kg/sec,
A = Cross-sectional area of flow in m2,
v = Specific volume of fluid in m3/kg,
V = Fluid velocity in m/sec.
Further,

$$Specific\ volume = \frac{1}{Density}$$

$$\therefore v = \frac{1}{\rho}$$

So,Equation can be expressed as,

$$\dot{m} = \rho A V$$

- ✓ The volume flow rate through a cross-sectional area per unit time is called fluid ***discharge*** rate (Q),

$$Q = AV$$

- ✓ For a ***steady flow***,

$$\dot{m} = Constant = \rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

Steady and Un-steady Flow Process

- ✓ A flow process is said to be steady when the fluid parameters (P) at any point of the control volume remains constant with respect to time; the parameters may, however, be different at different cross-section of the flow passage.

$$\therefore \frac{\partial P}{\partial t} = 0$$

- ✓ A flow process is un-steady when the conditions vary with respect to time.

$$\therefore \frac{\partial P}{\partial t} \neq 0$$

Steady Flow Energy Equation (SFEE): (Lect-3)

Assumptions

The following assumptions are made in the steady flow system analysis:

a) The mass flow through the system remains constant.

b) Fluid is uniform in composition.

c) The only interaction between the system and surroundings are work and heat.

d) The state of fluid at any point remains constant with time.

e) In the analysis only potential, kinetic and flow energies are considered.

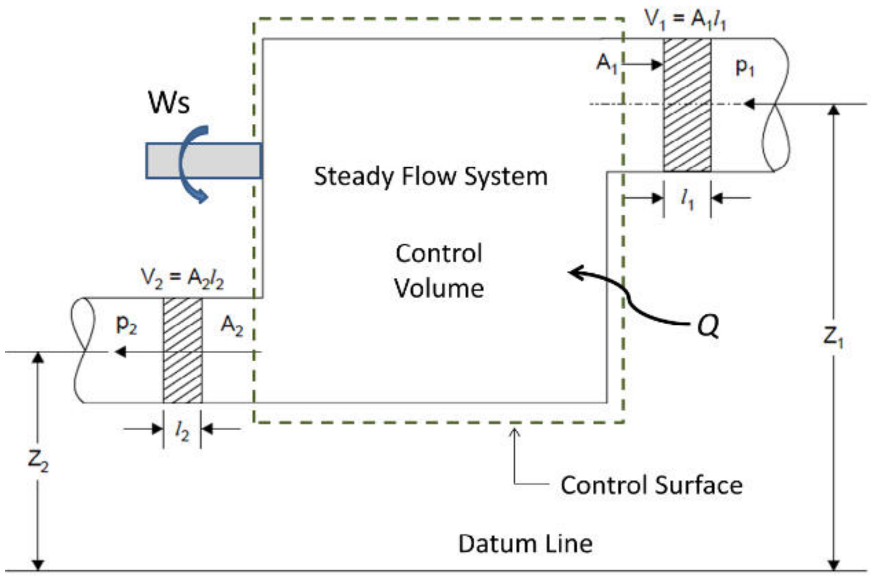


Fig. Schematic flow process for an open system

- Consider a flow of fluid through an open system as shown in above Fig.
- During a small time interval dt there occurs a flow of mass and energy into the fixed control volume; entry is at section 1 and exit occurs at section 2.
- The fluid enters the control volume at section 1 with average velocity V_1, Pressure P_1, Specific volume v_1, and Specific internal energy u_1.
- The corresponding values at the exit section 2 are V_2, P_2, v_2 *and* u_2.
- Further during, the fluid flow between the two selected sections, heat (Q) and mechanical or shaft work (Ws) may also cross the control surface.
- The following species of energy are taken into account while drawing up the energy balance:

  A. Internal energy stored by the fluid = U

  B. Kinetic energy = $\frac{1}{2}mV^2$

  C. Potential energy = mgZ

  D. Flow work = $P1V1$

  E. Heat interaction = Q

  F. Work interaction i.e. shaft work = Ws

According to 1st law of thermodynamics, energy balance in the symbolic form may be written as,

(Mass flow rate)$_{in}$=(Mass flow rate)$_{out}$

Σ Energy$_{in}$ = Σ Energy$_{out}$

$$u_1 + P_1v_1 + \frac{V_1^2}{2}m_1 + m_1gZ_1 + Q = u_2 + P_2v_2 + \frac{V_2^2}{2}m_2 + m_2gZ_2 + W_s$$

$$m_1\left(u_1 + P_1v_1 + \frac{V_1^2}{2} + gZ_1\right) + Q = m_2\left(u_2 + P_2v_2 + \frac{V_2^2}{2} + gZ_2\right) + W_s$$

Above Equation is the general steady flow energy equation (SFEE) and is equally applicable to compressible and incompressible; ideal and real fluids, liquids and gases.

- But according to assumption (1),

$$m = m_1 = m_2$$

Also enthalpy

$$h = u + Pv$$

So

$$m\left(h_1 + \frac{V_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{V_2^2}{2} + gZ_2\right) + W_s$$

$$m\left(u_1 + P_1v_1 + \frac{V_1^2}{2} + gZ_1\right) + Q = m\left(u_2 + P_2v_2 + \frac{V_2^2}{2} + gZ_2\right) + W_s \quad \because h = u + pv$$

$$m\left(h_1 + \frac{V_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{V_2^2}{2} + gZ_2\right) + W_s \quad \because m = m_1 = m_2$$

$$\left(h_1 + \frac{V_1^2}{2} + gZ_1\right) + Q = \left(h_2 + \frac{V_2^2}{2} + gZ_2\right) + W_s$$

SFEE on unit mass basis

$$h_1 + \frac{V_1^2}{2} + gZ_1 + q = h_2 + \frac{V_2^2}{2} + gZ_2 + W_s$$

Here, all the terms represents energy flow per unit mass of the fluid (J/kg).

SFEE Applied to Engineering Applications: (Lect-4&5)

- The SFEE applies to flow processes in many of the engineering applications, such as Turbines, Compressors, Pumps, Heat exchangers and flows through nozzles and diffusers.
- In certain flow processes, some of the energy terms in SFEE are negligibly small and can be omitted without much error.

1. Nozzles and Diffusers

- A nozzle is a device for increasing the velocity of a steadily flowing steam at the expense of its pressure and hence enthalpy.
- A diffuser is a device that increases the pressure of a fluid by slowing it down. That is nozzles and diffusers perform opposite task.
- Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses. Figure shows a commonly used convergent-divergent nozzle.

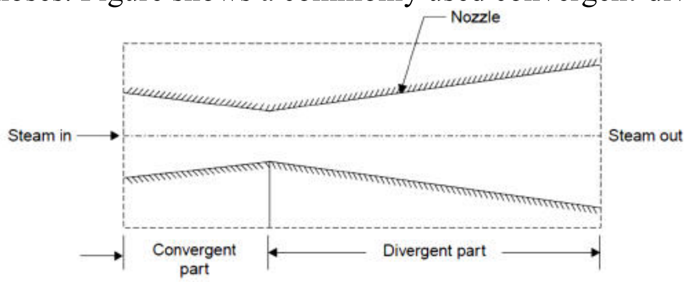


Fig. A convergent-divergent nozzle

Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1+\frac{V_1^2}{2}+gZ_1\right)+Q=m\left(h_2+\frac{V_2^2}{2}+gZ_2\right)+W_s$$

- The characteristic features of the flow through a ***nozzle*** are:
  No shaft work; $Ws = 0$
  If walls are thermally insulated; $Q = 0$
  Nozzle is horizontal i.e No elevation difference between inlet and exit; $Z_1 = Z_2$
- Hence, the SFEE is reduced to

$$\Rightarrow m\left(h_1+\frac{V_1^2}{2}+gZ_1\right)+Q=m\left(h_2+\frac{V_2^2}{2}+gZ_2\right)+W_s$$

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

$$\Rightarrow h_1+\frac{V_1^2}{2}=h_2+\frac{V_2^2}{2}$$

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

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

$$\Rightarrow (V_2^2-V_1^2)=2(h_1-h_2)$$

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

If $V_1 <<< V_2$, then

$$\Rightarrow V_2=\sqrt{2(h_1+h_2)}$$

- Similar way SFEE can be reduced for diffusers also.

2. Heat Exchangers

- Condensers and Evaporators are the main types of heat exchangers.
- These are the devices where the objective is to transfer heat energy between hot and cold fluids. Therefore the heat transfer rate cannot be taken as zero.
- These devices are widely used in refrigeration system, air conditioning system, thermal power plant and various industries.
- A ***steam condenser*** is also a heat exchanger in which steam losses heat as it passes over the tubes through which cold fluid is flowing.
- An ***evaporator*** is also a heat exchanger and is used to extract heat from the cold places or fluids.
- **Boiler** is a type of evaporator and hence heat exchanger; used for the generation of steam.
- Thermal energy released by combustion of fuel is transferred to water which vaporizes and gets converted into steam at the desired pressure and temperature.

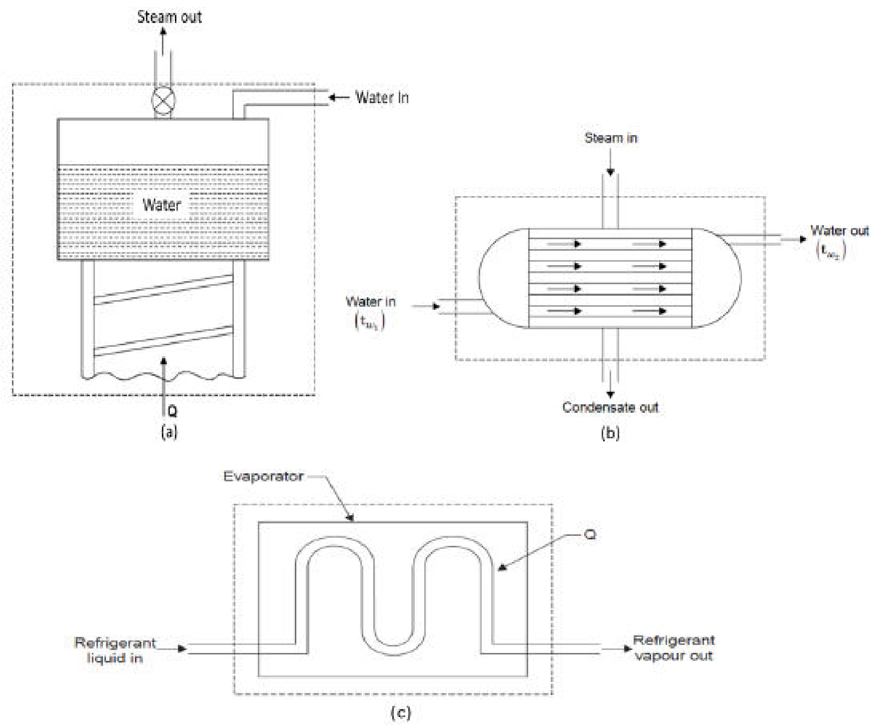


Fig. Schematic diagram of (a) Boiler (b) Condenser (c) Evaporator

Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1+\frac{V_1^2}{2}+gZ_1\right)+Q=m\left(h_2+\frac{V_2^2}{2}+gZ_2\right)+W_s$$

- The characteristic features of the flow through a ***heat exchangers*** are:
  No shaft work; $W_s = 0$
  Heat transfer, $Q \neq 0$ (Compulsory)
- Change in kinetic energy is negligible (compare to change in enthalpy);

$$\frac{V_2^2}{2}-\frac{V_1^2}{2}=0$$

- Change in potential energy is negligible (i.e. No elevation difference between inlet and exit); $Z_1 = Z_2$
- Hence, SFEE is reduced to,

$$m□_1 + Q = m□_2$$
$$\therefore Q = (□_2 - □_1)$$

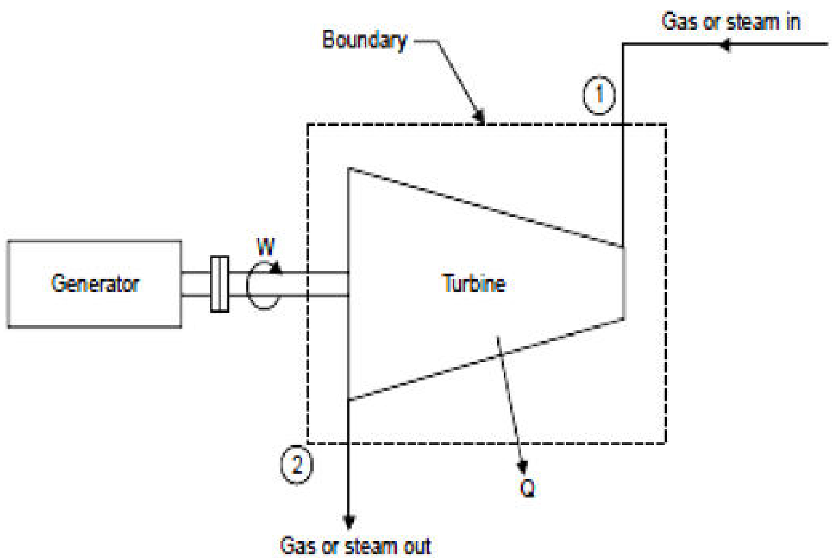
- For condenser and evaporator, from energy balance equation,

$$Heat\ lost\ by\ t□e\ steam = Heat\ gained\ by\ t□e\ cooling\ water$$
$$m_s(□_{si} - □_{so}) = m_w(□_{wo} - □_{wi})$$

  Where,
  m_s = Mass flow of steam
  m_w = Mass flow of cooling water

Steam or Gas Turbine

- A turbine is a device for obtaining work from a flow of fluid expanding from high pressure to low pressure.



- Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1 + \frac{V_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{V_2^2}{2} + gZ_2\right) + W_s$$

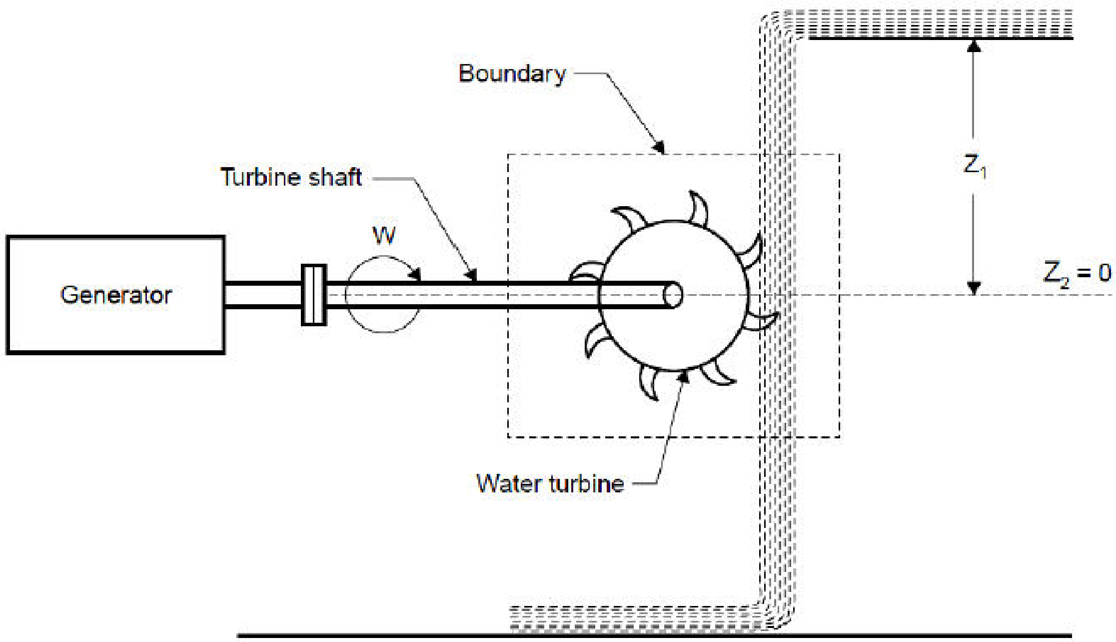
The characteristic features of flow through a ***steam or gas turbine*** are:

- Shaft work produced; $W_s = +ve$
- Negligible velocity change in the flow of fluid; $V_1 = V_2$
- Negligible potential energy change; $Z_1 = Z_2$
- No transfer of heat as its walls are thermally insulated; $Q = 0$
- Hence, SFEE is reduced to,
  $(□_1) + 0 = (□_1) + W_s$
  $W_s = (□_1 - □_2)$
- Apparently work is done at the expense of enthalpy.

Hydraulic Turbine

A hydraulic turbine or water turbine is a device which takes in water from a height.

The water enters into the turbine, a part of its potential energy is converted into useful work (shaft work), which is used to generate electric power in a generator.



Applying Steady Flow Energy Equation (SFEE),

$$m_1\left(u_1 + P_1 v_1 + \frac{V_1^2}{2} + gZ_1\right) + Q = m_2\left(u_2 + P_2 v_2 + \frac{V_2^2}{2} + gZ_2\right) + W_s$$

The characteristic features of flow through a ***hydraulic turbine*** are:

- Shaft work produced; $W_s = +ve$
- Negligible change in temperature of water so,
- Heat transfer rate from turbine; $Q = 0$
- Change in specific internal energy; $\Delta u = u_2 - u_1 = 0$
- As water is an incompressible fluid, its specific volume and hence density will remain constant; $v_1 = v_2 = v$
- Hence, SFEE is reduced to,

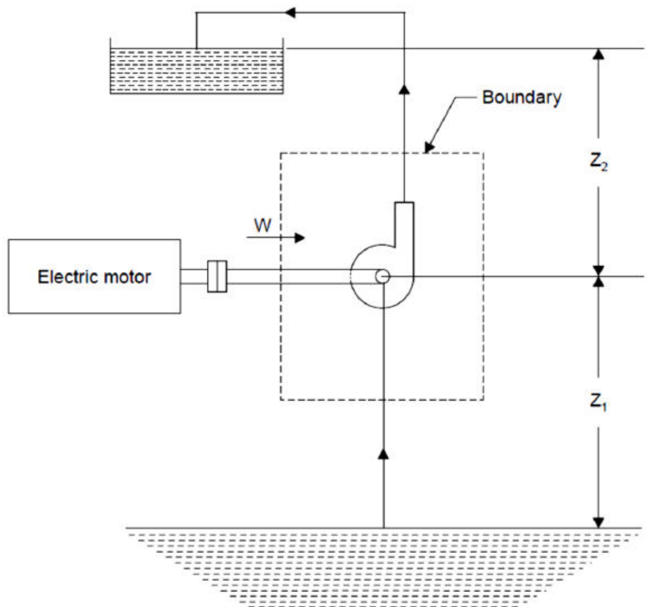
$$W_s = m\left[\left(P_1 v_1 - P_2 v_2\right) + \left(\frac{V_1^2}{2} - \frac{V_2^2}{2}\right) + g\left(Z_1 - Z_2\right)\right]$$

Centrifugal Water Pump

A centrifugal water pump is a device that transfers the mechanical energy of a motor or an engine into the pressure energy of incompressible fluid like water.

The characteristic features of flow through a ***centrifugal water pump*** are:

- Shaft work required; $W_s = -ve$
- Negligible change in temperature of water so,
    - Heat transfer rate from turbine; $Q = 0$
    - Change in specific internal energy; $\Delta u = u_2 - u_1 = 0$



Applying Steady Flow Energy Equation (SFEE),

$$m_1\left(u_1+P_1v_1+\frac{V_1^2}{2}+gZ_1\right)+Q=m_2\left(u_2+P_2v_2+\frac{V_2^2}{2}+gZ_2\right)+W_s$$

- As water is incompressible fluid, its specific volume and hence density willremain constant; $v_1 = v_2 = v$

Hence, SFEE is reduced to,

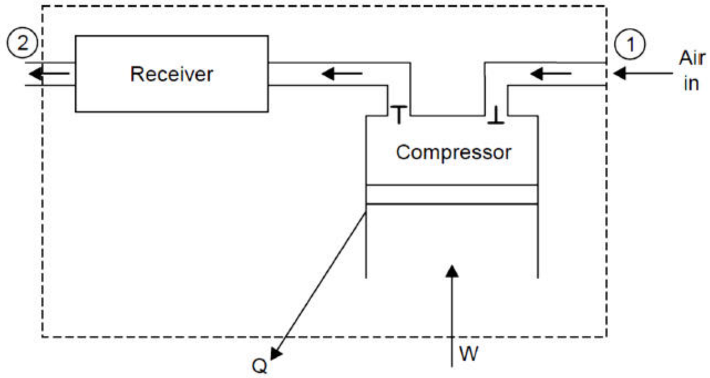
$$m_1\left(P_1v_1+\frac{V_1^2}{2}+gZ_1\right)=m_2\left(P_2v_2+\frac{V_2^2}{2}+gZ_2\right)-W_s$$

$$W_s=m\left[\left(P_1v_1-P_2v_2\right)+\left(\frac{V_1^2}{2}-\frac{V_2^2}{2}\right)\left(gZ_1-Z_2\right)\right]$$

Reciprocating Compressor

- A reciprocating compressor is used for increasing the pressure of a fluid and has a piston cylinder mechanism as the primary element.
- The unit sucks in definite quantity of fluid, compresses through a required pressure ratio and then delivers the compressed air/gas to a receiver.
- Reciprocating compressors are used when small quantity of fluid with high pressure is required.
- Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1+\frac{V_1^2}{2}+gZ_1\right)+Q=m\left(h_2+\frac{V_2^2}{2}+gZ_2\right)+W_s$$



- The characteristic features of flow through a ***reciprocating compressor*** are:

- ✓ Shaft work required; $W_s = -ve$
- ✓ Negligible velocity change in the flow of fluid; $C_1 = C_2$
- ✓ Negligible potential energy change; $Z_1 = Z_2$
- ✓ Appreciable amount of heat transfer is involved; heat is lost from the system as it gets sufficient time to interact with surrounding because of low speed;
  $Q \neq 0$ and $Q = -ve$
- Hence, SFEE is reduced to,

$$mh_1 - Q = mh_2 - W_s$$

$$\therefore W_s = Q + (h_2 - h_1)$$

Rotary Compressor

- Rotary compressors are used for increasing the pressure of a fluid and have a rotor as the primary element.
- Rotary compressors are employed where high efficiency, medium pressure rise and large flow rate are the primary considerations.

Applying Steady Flow Energy Equation (SFEE),

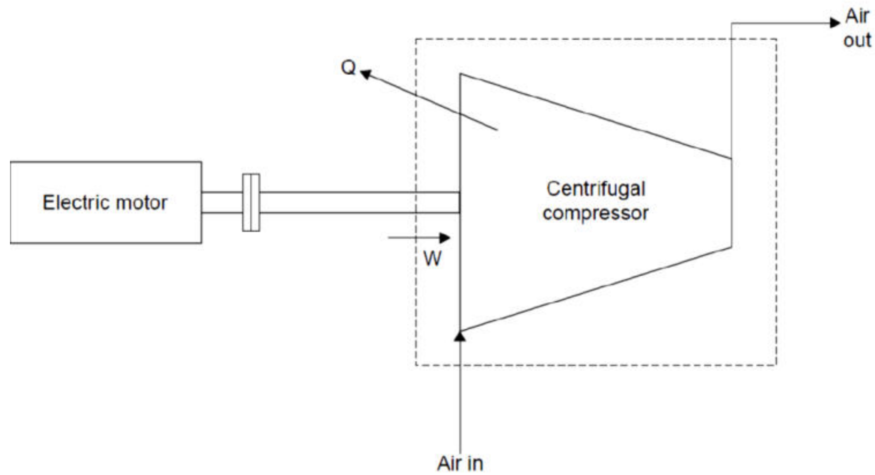
$$m\left(h_1 + \frac{V_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{V_2^2}{2} + gZ_2\right) + W_s$$

- The characteristic features of flow through a ***rotary compressor*** are:
  Shaft work required; $W_s = -ve$
  Negligible velocity change in the flow of fluid; $V_1 = V_2$
  Negligible potential energy changes; $Z_1 = Z_2$
  Flow process is treated as adiabatic due to vary high flow rates; $Q = 0$

- Hence, SFEE is reduced to,

$$mh_1 = mh_2 - W_s$$

$$Ws = (h_2 - h_1)$$

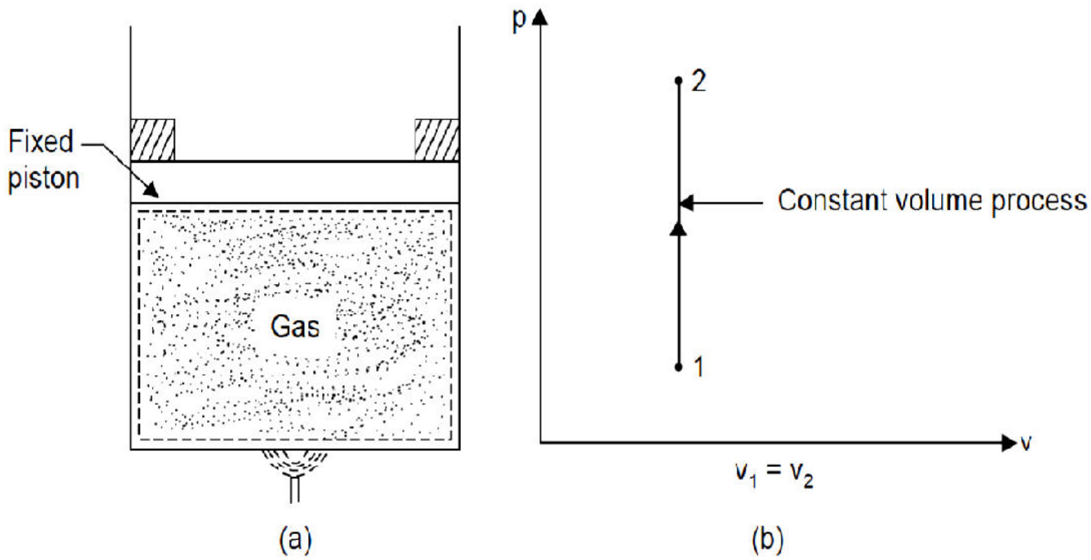

Air
out
Q
Electric motor
Centrifugal
compressor
W
Air in

First Law Applied to Non Flow Processes (Lect-6)

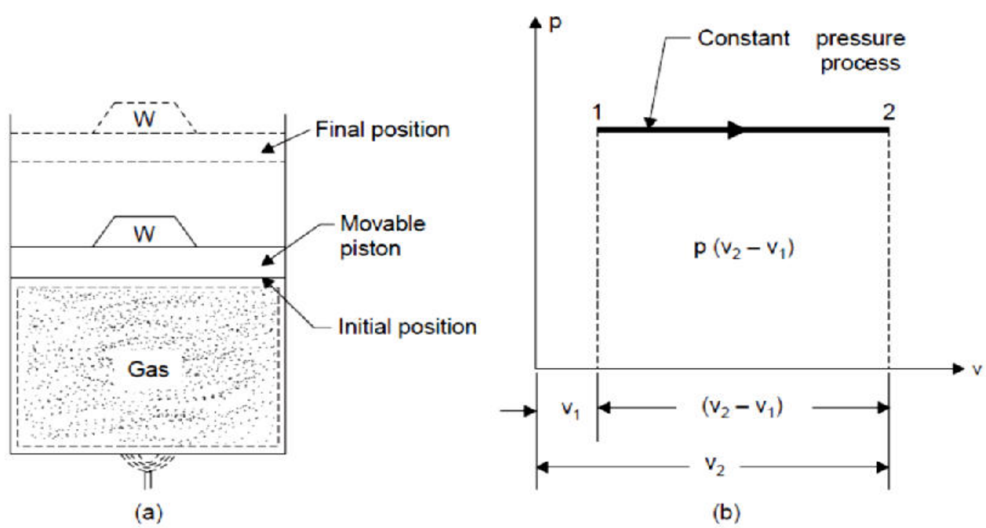
Following are the important non-flow processes, which are commonly used in engineering applications:

A. Constant Volume Process (Isochoric)
B. Constant Pressure Process (Isobaric)
C. Constant Temperature Process (Isothermal)
D. Adiabatic Process ($Q = 0$) ***or*** Isentropic Process (Reversible Adiabatic; $S = C$)
E. Polytropic Process

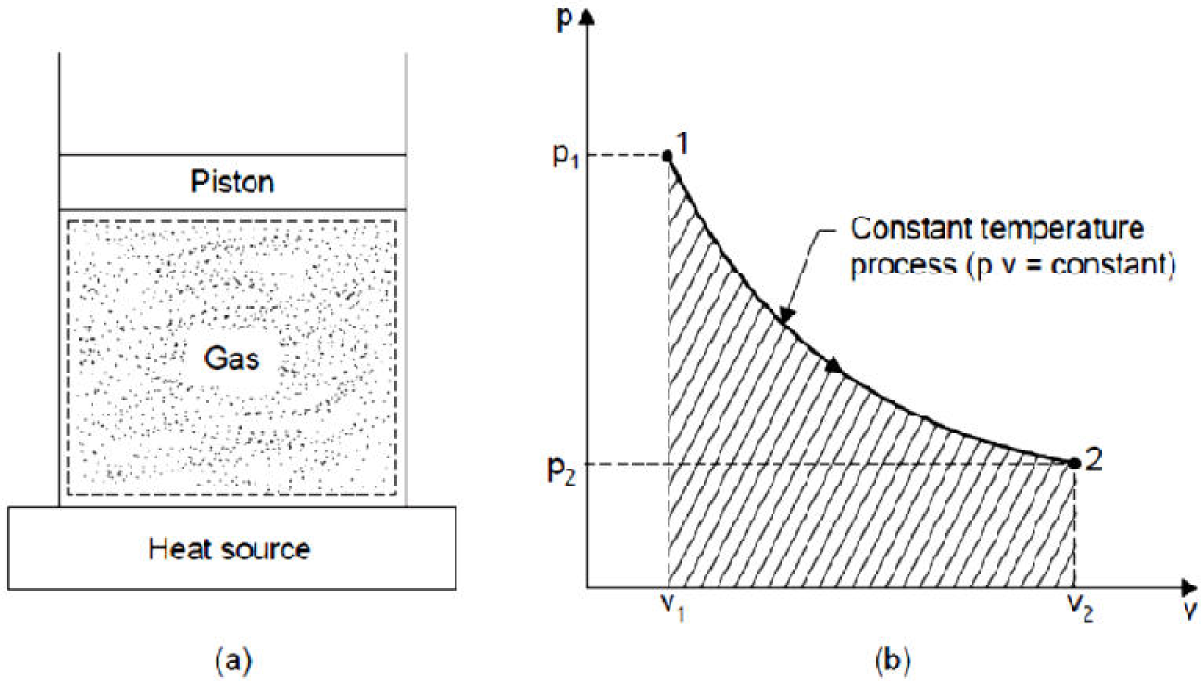
Below Figures shows schematic and P-v diagram for all the processes listed above.



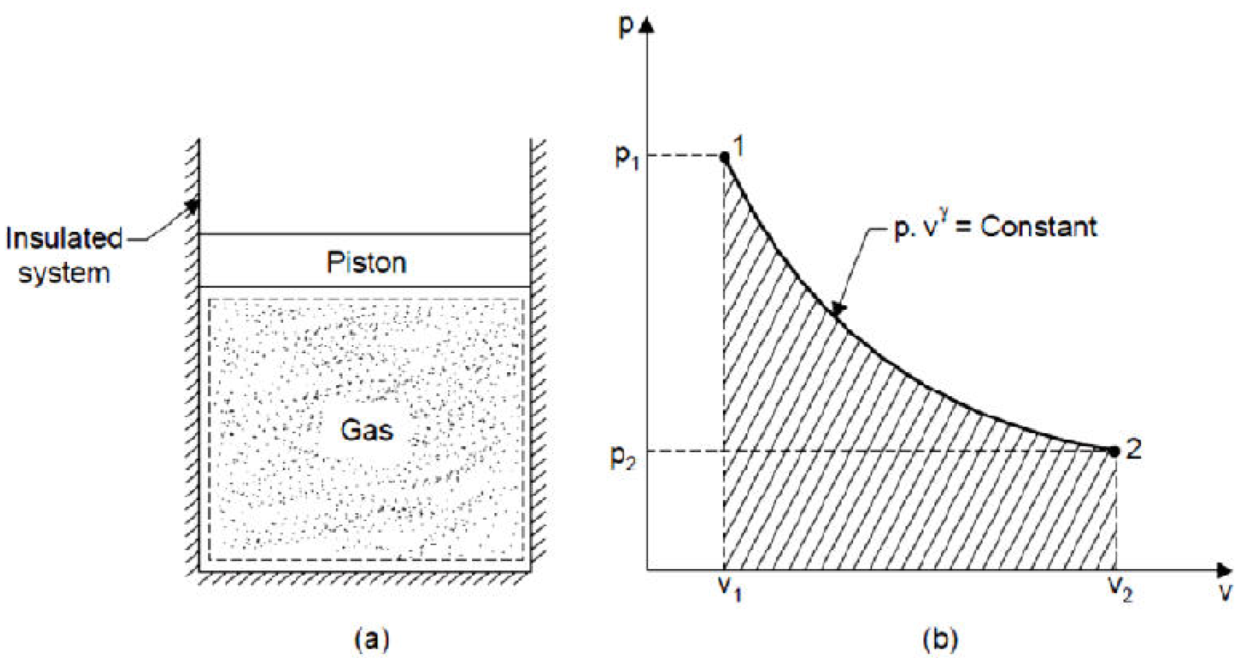
Constant volume process (Isochoric)



Constant pressure process (Isobaric)

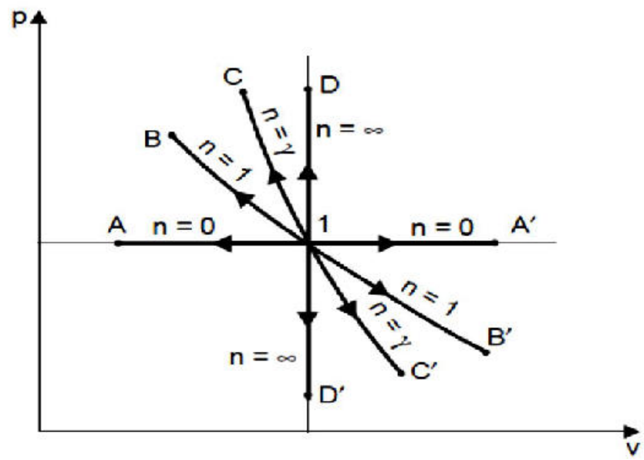


Constant temperature process (Isothermal)



Reversible Adiabatic Process (Isentropic process)

- In a Polytropic process, the index n depends only on the heat and work quantities during the process. The various processes considered earlier are special cases of Polytropic process for a perfect gas. This is illustrated on P-v diagram in below Figure.



Polytropic process for different values on index 'n'

☺ ***For Air (Perfect Gas)***

$R = 0.287 KJ/kg - k$

$C_p = 1.005 KJ/kg - k$

$C_v = 0.718 KJ/kg - k$

$\gamma = 1.4$

Relationship between R, C_p, C_v and γ

$R = C_p - C_v$

$\gamma = \frac{C_p}{C_v}$

Problems:1

In steam power plant 1 kg of water per second is supplied to the boiler. The enthalpy and velocity of water entering the boiler are 800 kJ/kg and 5 m/s. The water receives 2200 kJ/kg of heat in the boiler at constant pressure. The steam after passing through the turbine comes out with a velocity of 50 m/s, and its enthalpy is 2520 kJ/kg. The inlet is 4 m above the turbine exit. Assuming the heat losses from the boiler and the turbine to the surroundings are 20 kJ/sec. Calculate the power developed by the turbine. Consider the boiler and turbine as single system.

Solution:

Given Data:

$\dot{m}_w = 1\ kg/sec$

□$_1 = 800\ kJ/kg$

$C_1 = 5\ m/s$

$q_s = 2200\ kJ/kg$

$C_2 = 50\ m/s$

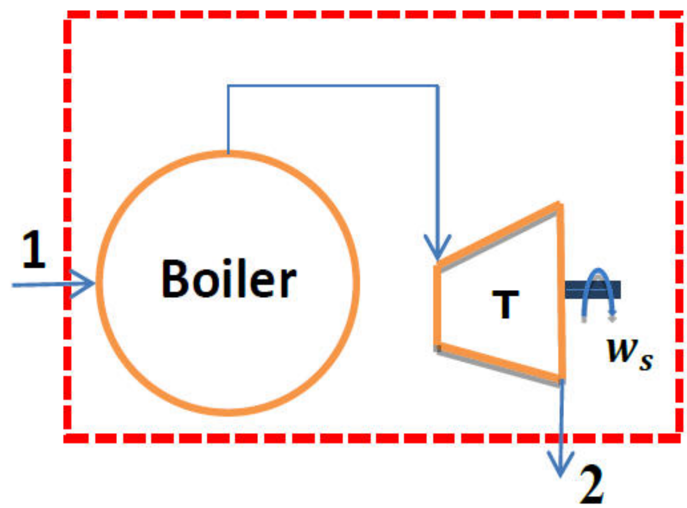
□$_2 = 2520\ kJ/kg$

$Z_1 - Z_2 = 4\ m$

$\dot{Q}_r = -20\ kJ/sec$

$q_r = \frac{\dot{Q}_r}{\dot{m}_w} = \frac{-20}{1}$

q_r=-20kj/kg



Net Heat Transfer to the System,

$q_{net} = q_s - q_r$

$\therefore q_{net} = 2200 - 20$

$\therefore q_{net} = 2180\ kJ/kg$

Apply Steady Flow Energy Equation,

$$h_1 + \frac{V_1^2}{2} + gZ_1 + q_{net} = h_2 + \frac{V_2^2}{2} + gZ_2 + W_{net}$$

$$W_{net} = (h_1 - h_2) + \left(\frac{V_1^2}{2} - \frac{V_2^2}{2}\right) + g(Z_1 - Z_2) + q_{net}$$

$$W_{net} = (800 - 2520)\times 10^3 + \left(\frac{5^2}{2} - \frac{50^2}{2}\right) + 9.81(4) + (2180\times 10^3)$$

$$\therefore w_{net} = 458801.74\ J/kg$$
$$\therefore w_{net} = 458.801\ kJ/kg$$

Power Developed by the Turbine:

$$P = \dot{m}_w \times w_{net}$$
$$\therefore P = 1 \times 458.801$$
$$\therefore \boldsymbol{P = 458.801\ kW}$$

Problems: 2

Air at a temperature of 15°C passes through a heat exchanger at velocity of 30 m/s, where temperature is raised to 800°C. It then enters a turbine with same velocity of 30m/s and expands until temperature falls to 650°C. On leaving the turbine the air is taken at velocity of 60m/s to a nozzle where it expands until the temperature has fallen to 500°C, If the air flow rate is 2kg/s, calculate (a) rate of heat transfer to air in the heat exchanger, (b) power output from turbine assuming no heat loss and (c) velocity at exit from the nozzle. Assuming no heat loss.

Given Data:

$\dot{m}_a = 2\ kg/sec$

$V_1 = V_2 = 30\ m/s$

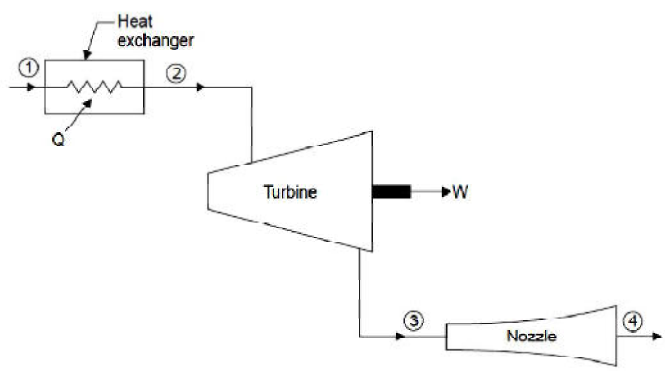
$T_1 = 15\ °C$

$T_2 = 800\ °C$

$T_3 = 650\ °C$

$V_3 = 60\ m/s$

$T_4 = 500\ °C$



[1] Heat Exchanger

- For H.E.
  $w_{net} = 0$
  $Z_1 = Z_2\ (Assume)$
  Also,
  $V_1 = V_2\ (Given)$
- Apply Steady Flow Energy Equation to Heat Exchanger (1 – 2),

$$h_1 + \frac{V_1^2}{2} + gZ_1 + q_{net} = h_2 + \frac{V_2^2}{2} + gZ_2 + W_{net}$$

$q_{net} = (□_2 - □_1)$

$\therefore q_{net} = (T_2 - T_1)$

$\therefore q_{net} = 1.005(800 - 15)$

$\therefore q_{net} = 788.925\ kJ/kg$

- **Rate of Heat transfer:**

$\dot{q}_{net} = \dot{m}_a \times q_{net}$

$\dot{q}_{net} = 2 \times 788.925$

$\boldsymbol{\dot{q}_{net} = 1577.85\ kW}$

[2] Turbine

⇨ For Turbine,

$$q_{net} = 0\ (No\ heat\ loss)$$

$$Z_2 = Z_3\ (Assume)$$

⇨ Apply Steady Flow Energy Equation to Turbine (2 – 3),

$$h_2 + \frac{C_2^2}{2} + gZ_2 + q_{net} = h_3 + \frac{C_3^2}{2} + gZ_3 + w_{net}$$

$$\therefore w_{net} = (h_2 - h_3) + \left(\frac{C_2^2}{2} - \frac{C_3^2}{2}\right)$$

$$\therefore w_{net} = C_p(T_2 - T_3) + \left(\frac{C_2^2}{2} - \frac{C_3^2}{2}\right)$$

$$\therefore w_{net} = 1.005 \times 10^3 \times (800 - 650) + \left(\frac{30^2}{2} - \frac{60^2}{2}\right)$$

$$\therefore w_{net} = 149400\ J/kg$$

⇨ **Power Output from Turbine:**

$$P = \dot{m}_a \times w_{net}$$

$$P = 2 \times 149400$$

$$\boldsymbol{P = 298800\ W}$$

[3] Nozzle

⇨ For Nozzle.

$$w_{net} = 0$$

$$Z_1 = Z_2\ (Assume\ that\ nozzle\ is\ horizontal)$$

$$q_{net} = 0\ (No\ heat\ loss)$$

⇨ Apply Steady Flow Energy Equation to Nozzle (3 – 4),

$$h_3 + \frac{C_3^2}{2} + gZ_3 + q_{net} = h_4 + \frac{C_4^2}{2} + gZ_4 + w_{net}$$

$$\therefore \frac{C_4^2}{2} = (h_3 - h_4) + \frac{C_3^2}{2}$$

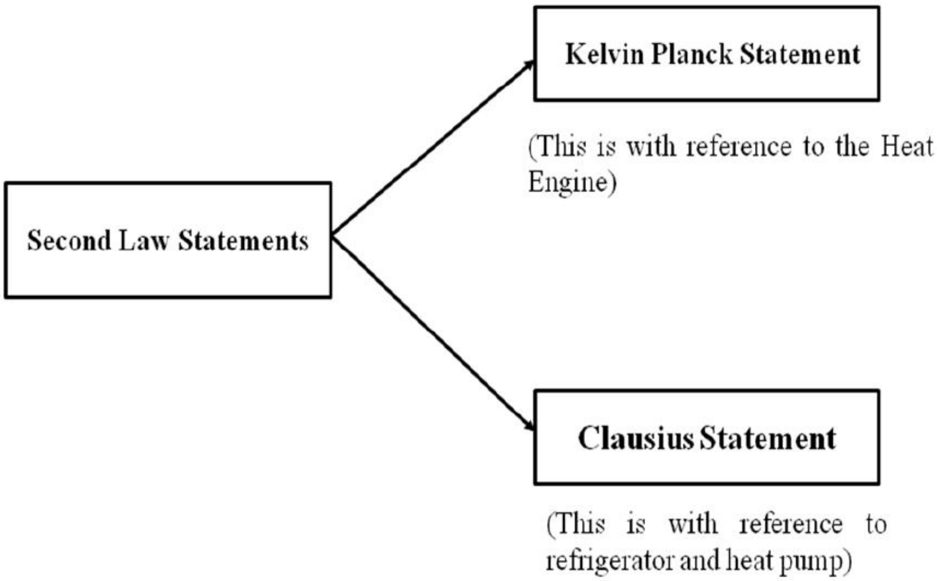
$$\therefore \frac{C_4^2}{2} = C_p(T_3 - T_4) + \frac{C_3^2}{2}$$

$$\therefore \frac{C_4^2}{2} = 1.005 \times 10^3 \times (650 - 500) + \frac{60^2}{2}$$

$$\therefore \frac{C_4^2}{2} = 152550$$

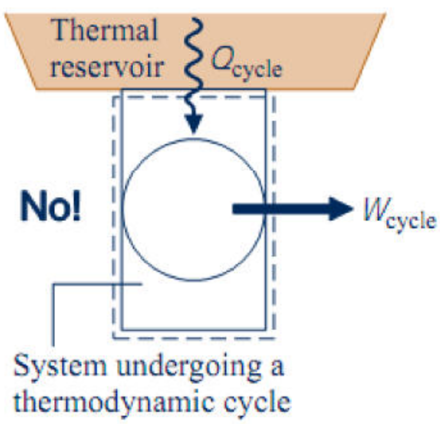
$$\therefore \boldsymbol{C_4 = 552.358\ m/sec}$$

Statements of Second Law (Lect-7)



Kelvin-Planck Statement of the Second law

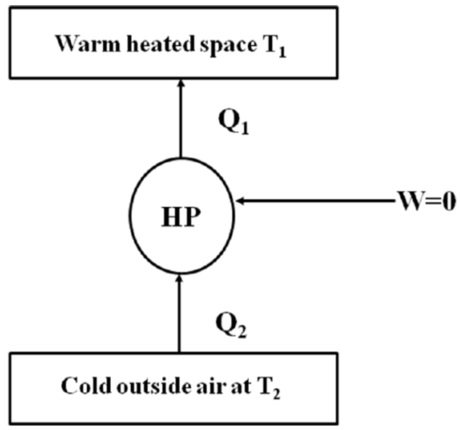
It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.



(A heat engine that violates the Kelvin-Planck statement)

Clausius Statement:

It is impossible to construct a device that operates in a cycle and produce no effect other than the transfer of heat from a low temperature body to a high temperature body.

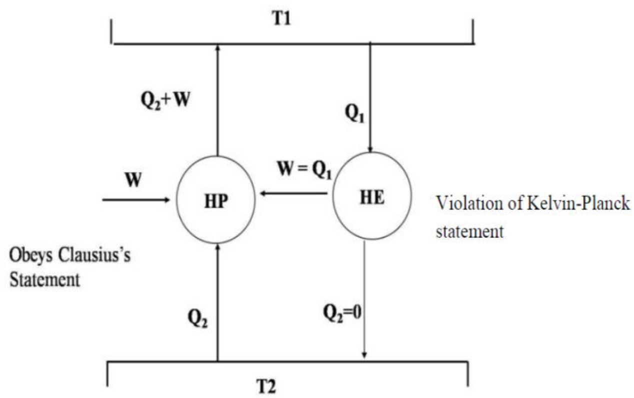


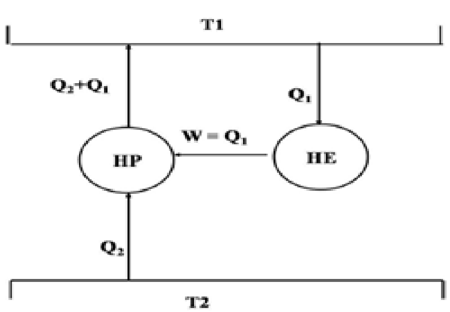
A refrigerator that violates the Clausius statement of the second law.

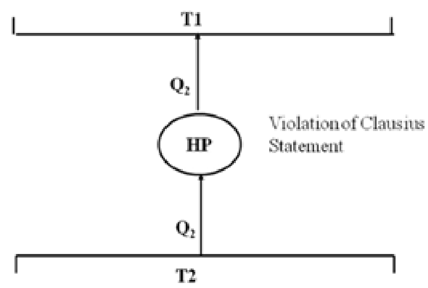
Equivalence of Kelvin Planck and Clausius Statements:

The equivalence of the statement is demonstrated by showing that the violation of each statement implies the violation of other.

CASE-1: Violation of Kelvin-planck statement leads to violation of Clausius statement

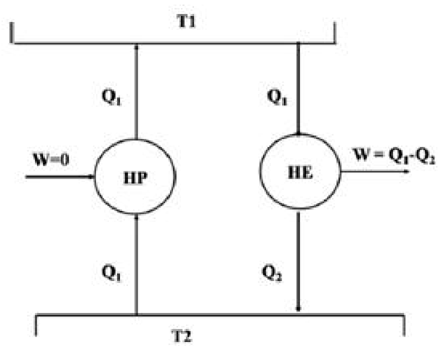


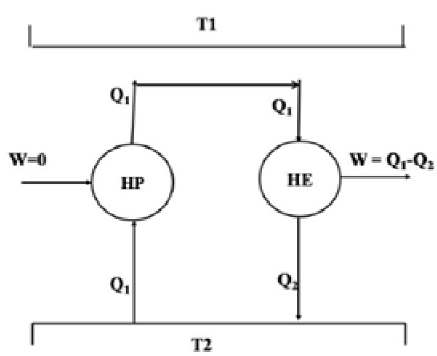


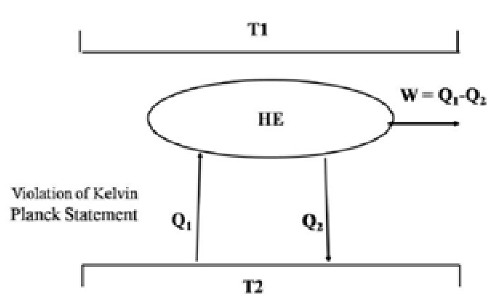


Thus violation Kelvin Planck Statement has lead to the violation of Clausius Statement.

CASE-2: Violation of Clausius statement leads to violation of Kelvin-planck statement:







Thus Violation of Clausius Statement has lead to violation of Kelvin Planck Statements.

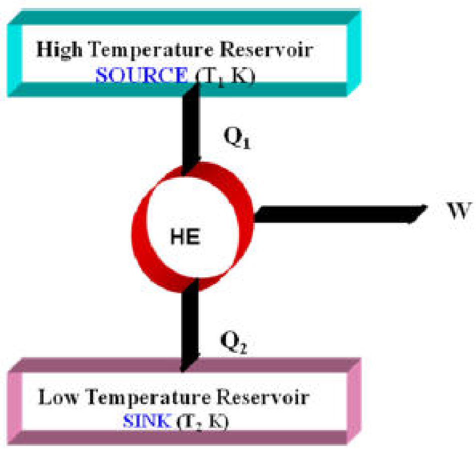
Aspects of the second law
1. To identify the direction of process.
2. Establishing conditions for equilibrium.
3. It also asserts that energy has quality as well as quantity.
3. It is also used in determining the theoretical limits for the performance of heat engines and refrigerators.
4. Defining a temperature scale independent of the properties of any thermometric substance.

Thermal Energy Reservoir (TER): It is a hypothetical body with a relatively large thermal energy capacity that can supply or absorb finite amount of heat without undergoing any change in temperature. Examples: Oceans, rivers, atmospheric air etc.

- TER that supplies energy in the form of heat is called a source
- TER that absorbs energy in the form of heat is called a sink

Application of second law: (Lect-8)

Heat Engines: Heat engine is a cyclic device, used to convert heat to work. Heat engine can be characterized by the following points.
1. They receive heat from a high temperature source (solar energy, oil-furnace etc.)
2. They convert part of this heat to work (usually in the form of a rotating shaft)
3. They reject the remaining waste heat to a low temperature sink (the atmosphere, rivers, etc)
4. They operate on a cycle.



Q_1 = amount of heat supplied to steam in boiler from a high-temperature source.
Q_2 = amount of heat rejected from steam in condenser to a low temperature sink.
W = net work output of this heat engine.

Thermal efficiency: The fraction of the heat input that is converted to net work output is a measure of the performance of the heat engine.

$$\textit{Thermal efficiency}(\eta) = \frac{\text{Net work output}}{\text{Total heat input}}$$

$$\eta_{th} = \frac{W}{Q_1}$$

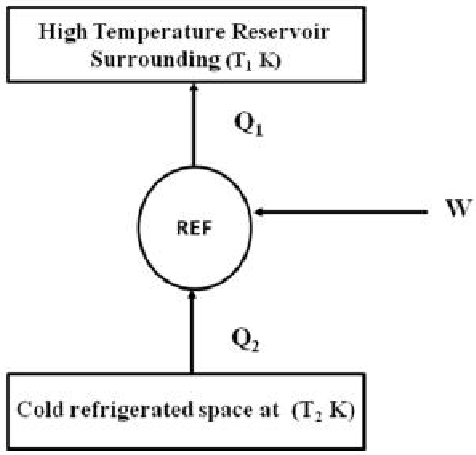
$$\eta_{th} = 1 - \frac{Q_2}{Q_1}$$

Refrigerator: Refrigerators are cyclic devices, used to transfer heat from a low temperature medium to a high temperature medium. The working fluid used in the refrigeration cycle is called a refrigerant. The most frequently used refrigeration cycle is the vapor-compression refrigeration cycle.

Coefficient of Performance (COP):

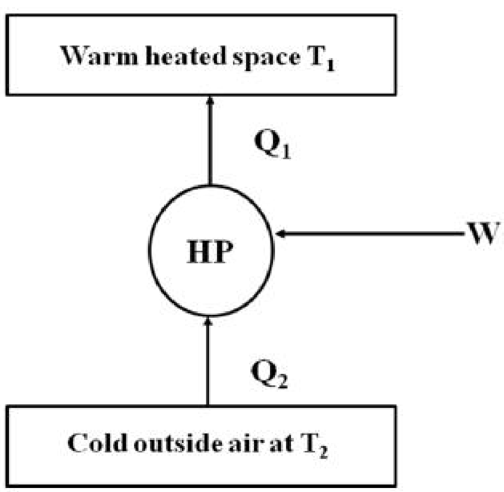
$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_2}{W}$$

$$COP_R = \frac{Q_2}{Q_1 - Q_2}$$



(Refrigerator)

Heat Pumps: Heat pumps are another cyclic devices, used to transfer heat from a low temperature medium to a high temperature medium. The objective of a heat pump is to maintain a heated space at a high temperature. This is accomplished by absorbing heat from a low temperature source, such as cold outside air in winter and supplying this heat to the high temperature medium such as a house**.**



$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_1}{W}$$

$$COP_{HP} = \frac{Q_1}{Q_1 - Q_2}$$

Relation between COP_{HP} and COP_R

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

:Problems:

An engine works between the temperature limits of 1775 K and 375 K. What can be the maximum thermal efficiency of this engine ?

A reversible engine is supplied with heat from two constant temperature sources at 900 K and 600 K and rejects heat to a constant temperature sink at 300 K. The engine develops work equivalent to 90 kJ/s and rejects heat at the rate of 56 kJ/s. Estimate : 1. Heat supplied by each source, and 2. Thermal efficiency of the engine.

A cold storage is to be maintained at – 5°C while the surroundings are at 35°C. The heat leakage from the surroundings into the cold storage is estimated to be 29 kW. The actual C.O.P of the refrigeration plant is one -third of an ideal plant working between the same temperatures. Find the power required to drive the plant.

Find the co-efficient of performance and heat transfer rate in the condenser of a refrigerator in kJ/h which has a refrigeration capacity of 12000 kJ/h when power input is 0.75 kW.

A domestic food refrigerator maintains a temperature of – 12°C. The ambient air temperature is 35°C. If heat leaks into the freezer at the continuous rate of 2 kJ/s determine the least power necessary to pump this heat out continuously.

A house requires 2×10^5 kJ/h for heating in winter. Heat pump is used to absorb heat from cold air outside in winter and send heat to the house. Work required to operate the heat pump is 3×10^4 kJ/h. Determine :

(*i*) *Heat abstracted from outside ;*

(*ii*) *Co-efficient of performance.*

What is the highest possible theoretical efficiency of a heat engine operating with a hot reservoir of furnace gases at 2100°C when the cooling water available is at 15°C ?