- **(EF 15002) Foundation of Mechanical Engineering**

- **Examination Scheme**
- Test (I & II) - 40 marks
  End Sem. Exam - 60 marks

- **Contents**
- Unit 1 Introduction to Thermodynamics
- Unit 2 Energy Conversion Devices
- Unit 3 Heat Transfer
- Unit 4 Machine elements
- Unit 5 Machine Tools
- Unit 6 Energy Sources

Unit I
basic concepts of thermodynamics

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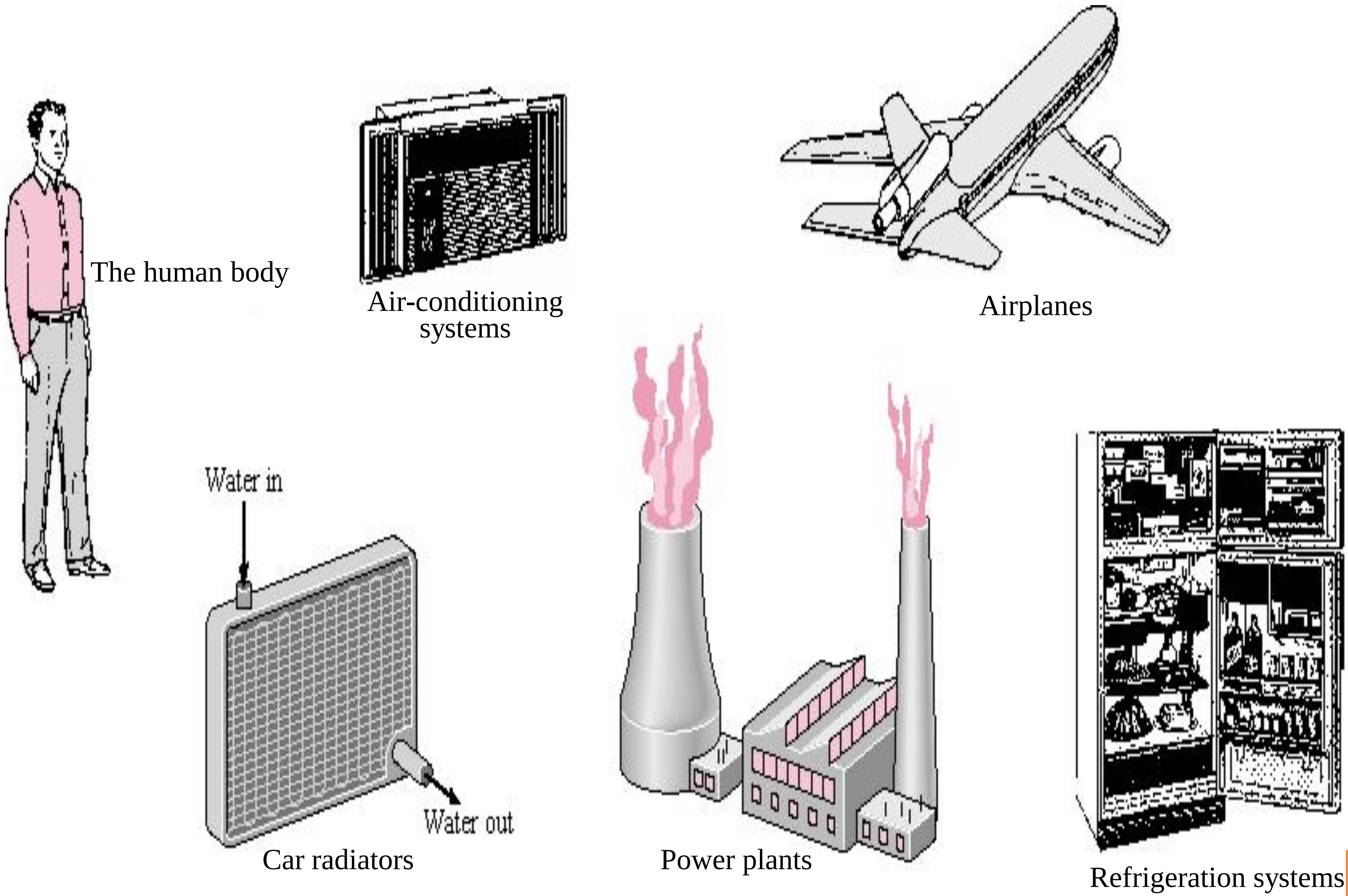
CONTENTS

- Basic Concepts, Properties, Equilibrium
- Thermodynamic work and heat
- Laws of thermodynamics and their applications
- Concept of Heat Engine, Refrigerator and Heat Pump
- Carnot efficiency and Carnot COP

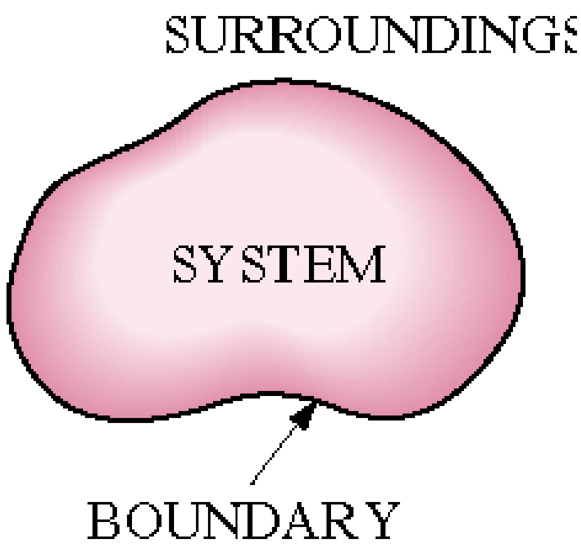
Basic concepts

- Thermodynamics→The study of thermodynamics is concerned with ways energy is stored within a body and how energy transformations, which involve heat and work, may take place.
- Science of 3 E's namely **Energy, Entropy and Equilibrium**
- Approaches to studying thermodynamics
  - Macroscopic (Classical thermodynamics)
    - study large number of particles (molecules) that make up the substance in question
    - does not require knowledge of the behavior of individual molecules
  - Microscopic (Statistical thermodynamics)
    - concerned within behavior of individual particles (molecules)
    - study average behavior of large groups of individual particles

Applications of Thermodynamics



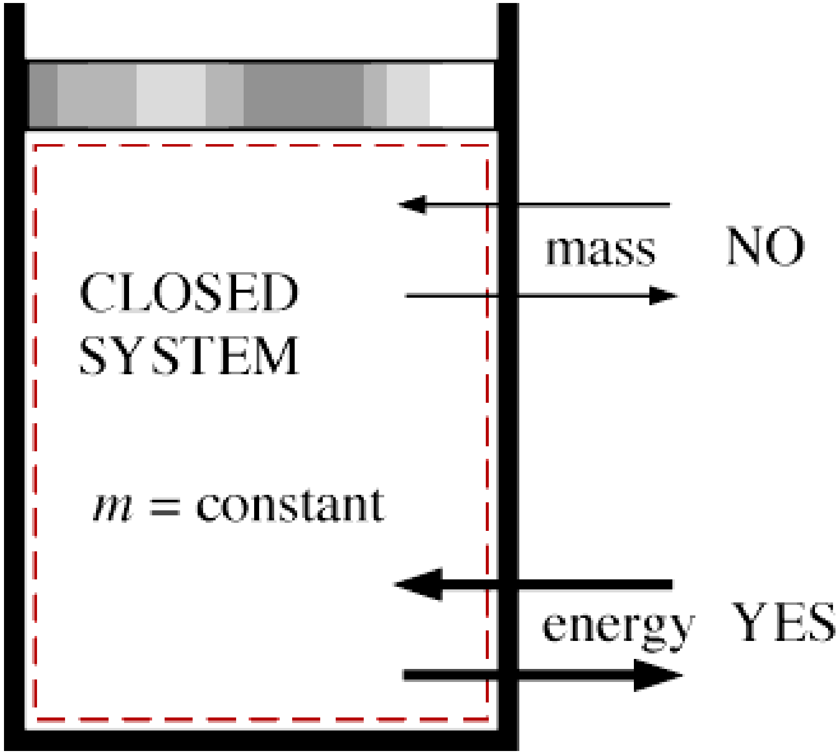
THERMODYNAMIC SYSTEMS



- Thermodynamic System
  - quantity of matter or a region of space chosen for study
- Boundary
  - real or imaginary layer that separates the system from its surroundings
- Surroundings
  - physical space outside the system boundary
- Types of Systems
  - Closed
  - Open
  - Isolated

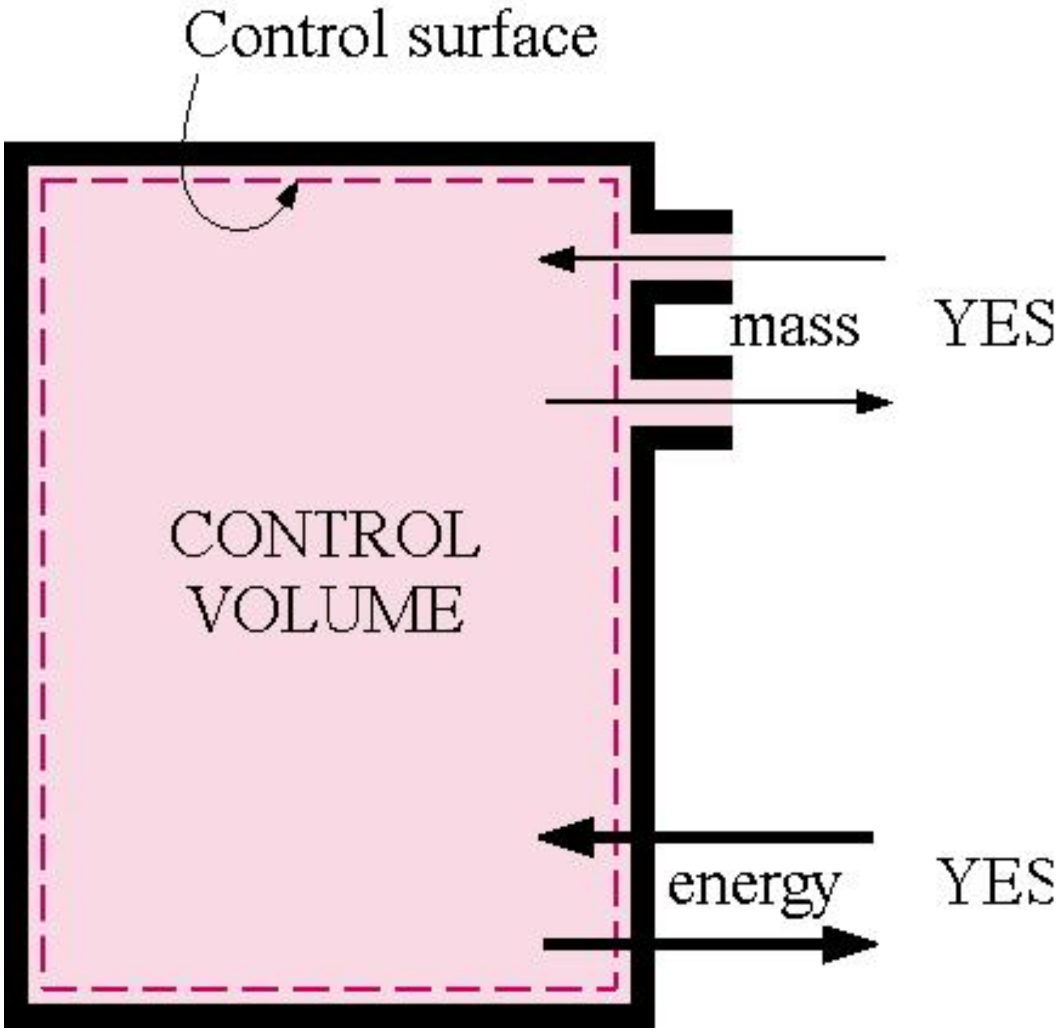
Closed Systems (fixed masses)

Energy, not mass, crosses closed-system boundaries



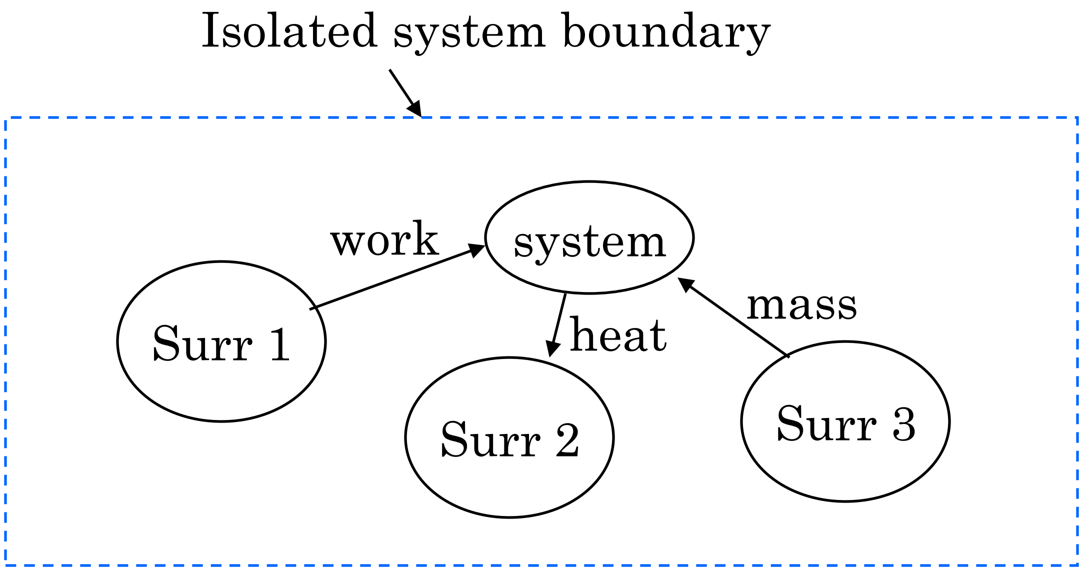
Open Systems (Control Volumes)

Mass and Energy Cross Control Volume Boundaries



Isolated System

- No interaction between system and surroundings.
- No mass or energy cross the system boundary.
- typically a collection of the a main system (or several systems) and its surroundings is considered an isolated system



PROPERTIES

- Thermodynamic system at any time can be identified by certain observable and measurable characterisitics like Pressure, temperature, volume etc.
- Any characteristic of a system in equilibrium is called a property.
- Types of properties
  - Extensive properties - vary directly with the size of the system

    Examples: volume, mass, total energy
  - Intensive properties - are independent of the size of the system

    Examples: temperature, pressure, color
- Extensive properties per unit mass are intensive properties.

  specific volume   v = Volume/Mass = V/m

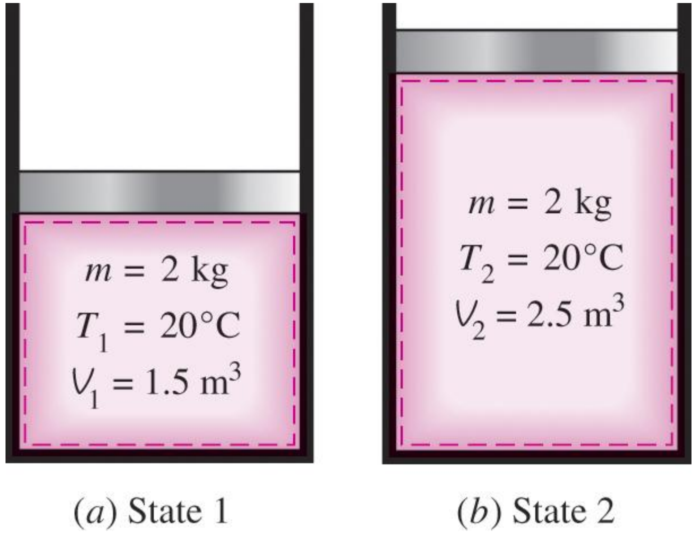
  density   r = Mass/Volume = m/V

State & Equilibrium

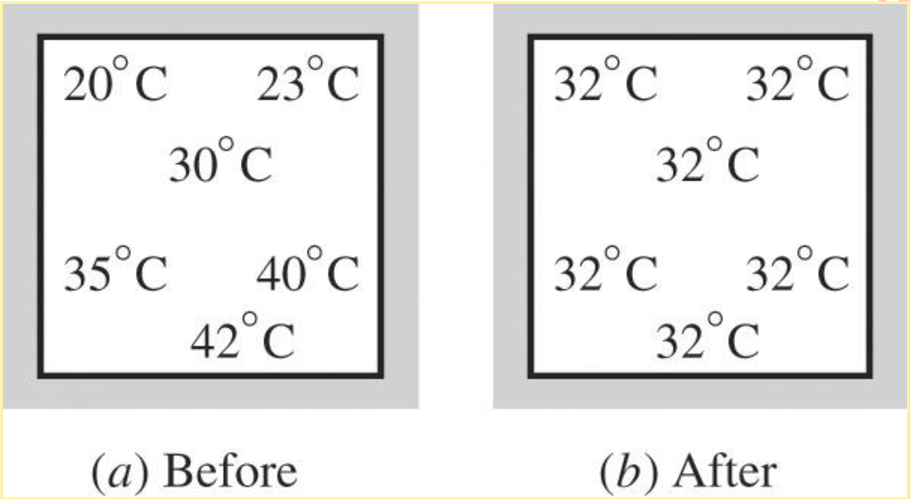
- State of a system
  - system that is not undergoing any change
  - all properties of system are known & are not changing
  - if one property changes then the state of the system changes
- Thermodynamic equilibrium
  - "equilibrium" - state of balance
  - A system is in equilibrium if it maintains thermal (uniform temperature), mechanical (uniform pressure), phase (mass of two phases), and chemical equilibrium

STATE AND EQUILIBRIUM

- Thermodynamics deals with *equilibrium* states.
- **Equilibrium**: A state of balance.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium**: If the temperature is the same throughout the entire system.
- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.



A system at two different states.



A closed system reaching thermal equilibrium.

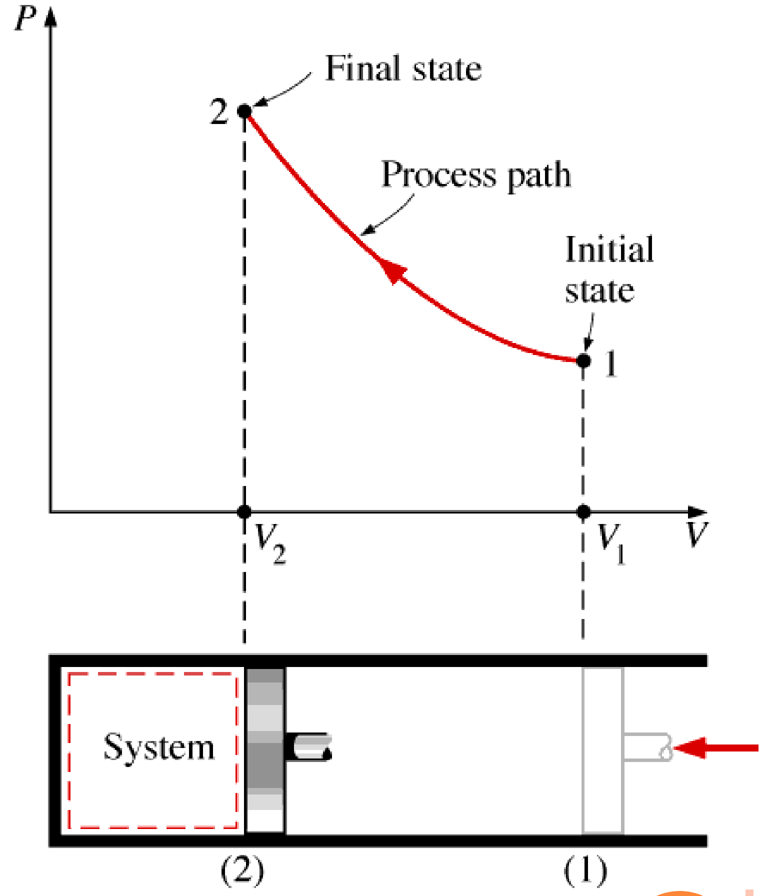
THERMODYNAMIC PROCESSES & PATHS

- Path
  - series of states which a system passes through during a process
- Process
- A complete specification of the path iis referred to as a process.
  - when a system changes from one equilibrium state to another one
  - some special processes:
    - isobaric process - constant pressure process
    - isothermal process - constant temperature process
    - isochoric process - constant volume process
    - isentropic process - constant entropy (Chap. 6) process

Compression Process

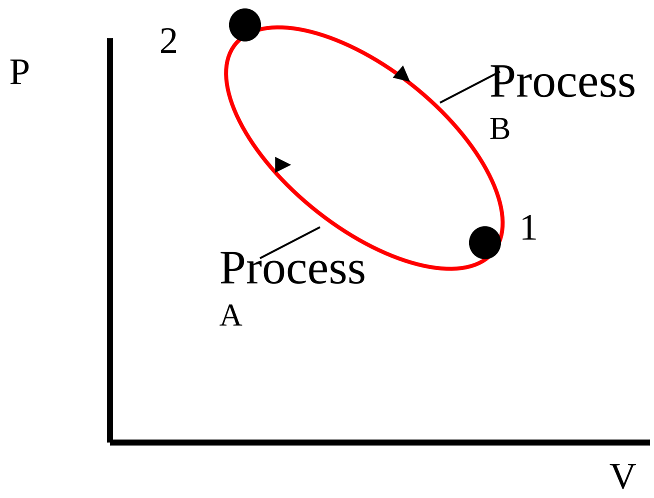
Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.

Some common properties that are used as coordinates are temperature *T*, pressure *P*, and volume *V* (or specific volume *v*).

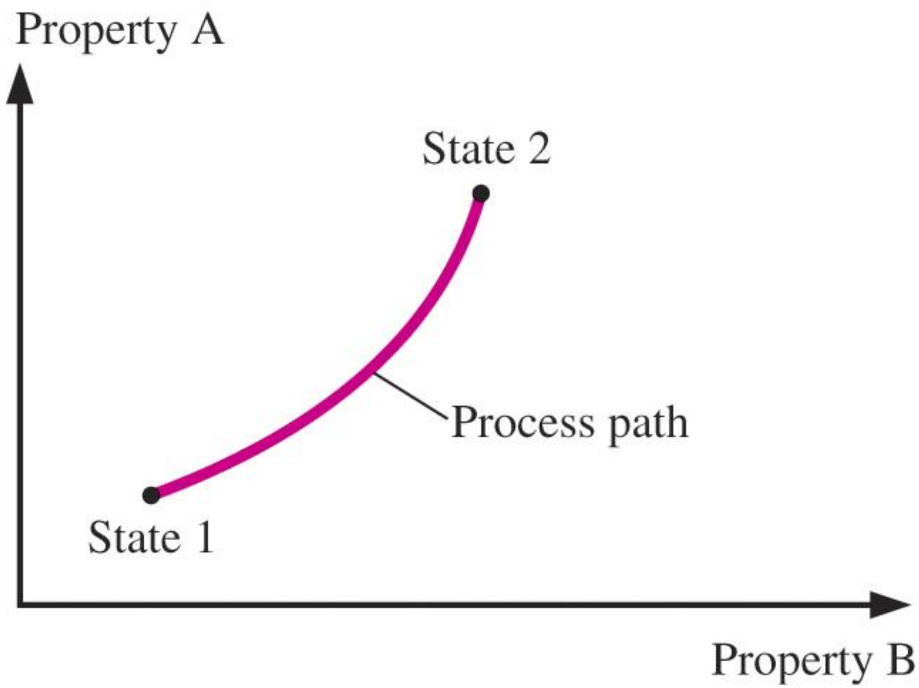


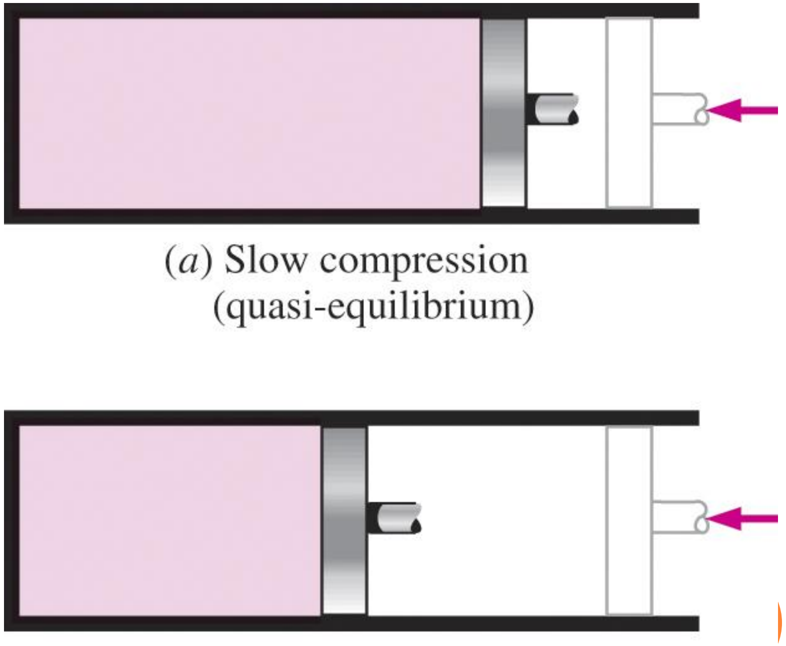
Cycle

- Cycles
  - When system undergoes through a series of processes such that the final state is identical with initial state, it is called a cyclic process.
  - Change in value of any property of a system for a cyclic process is zero.



Quasistatic or quasi-equilibrium process: When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.

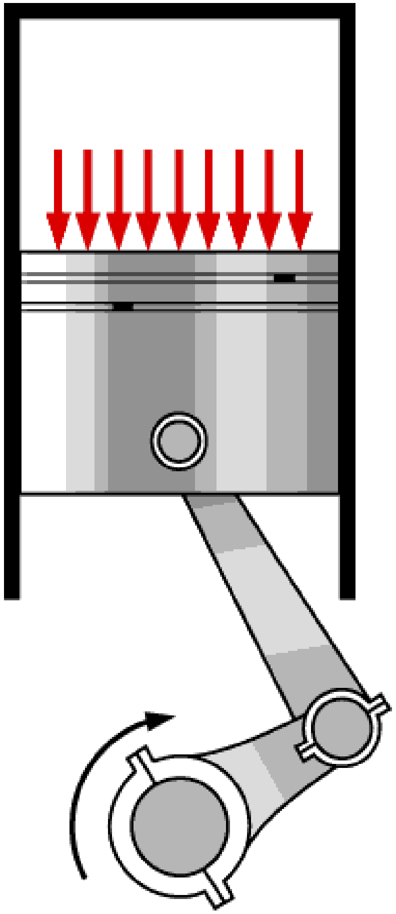




(*a*) Slow compression (quasi-equilibrium)

(*b*) Very fast compression (nonquasi-equilibrium)

Quasi-Equilibrium Processes



- System remains practically in equilibrium at all times
- Easier to analyze (equations of state can apply)
- Work-producing devices deliver the most work
- Work-consuming devices consume the least amount of work

Reversible and irreversible processes

- Reversible process- both system and surroundings can always be restored to original state leaving no trace of process in universe.
- It's a quasi-static process ie every intermediate state in the process mmust be in equilibrium.
- No Friction
- Heat exchange to/from system, if any should be through small temperature difference.
- Irreversible Process-System passes through a sequence of non-equilibrium states.
- Can be carried out only in one direction.
- Occurs at a a finite rate.

TOTAL ENERGY

- Is an extensive property
- Stored energy + energy in transit
- Sum of all forms of energy (i.e., thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, and nuclear) that can exist in a system
- For systems we typically deal with in this course, sum of internal, kinetic, and potential energies

- $E = U + KE + PE$
- E = Total energy of system
- U = internal energy
- KE = kinetic energy = $mV^2/2$
- PE = potential energy = mgz

Internal energy (U)

- The sum of all the microscopic forms of energy is called internal energy.
- It is the energy stored within the body resulting from the kinetic and potential energy of its molecules.

$$U = K + P$$

K- Internal kinetic energy of molecules and

P- Internal potential energy of molecules

Enthalpy (H)

- It is the sum of internal energy and the product of pressure and volume.
- It is also the property of the system.

$$H = U + pV \quad kJ$$

- *Enthalpy per unit mass is referred as specific enthalpy (h)*

$$h = u + pv \; kJ/kg$$

Work and heat

Thermodynamic definition of work:

- Both work and heat are boundary phenomenon.
- Work high grade enrgy, heat low grade energy
- Both heat and work are path functions and inexact differentials

$$\int_1^2 \delta W = W_{12}$$

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

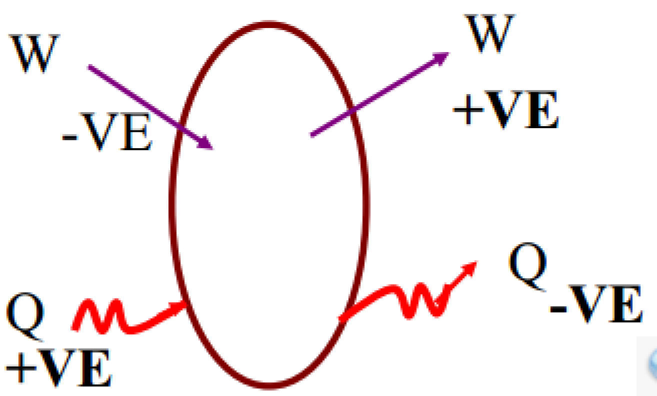
- Both associated with a process and not a state. Unlike “property”, work and heat have no meaning at a state.

WORK AND HEAT

- For Heat flow to take place, temperature difference is required
- In a stable state, there can't be work transfer but heat transfer can be there.
- Sole effect of work transfer external to the system could be reduced to the rising of a weight.

Sign convention

- Work done BY the system is +ve
- Obviously work done ON the system is –ve
- Heat given TO the system is +ve
- Obviously Heat rejected by the system is -ve



FORMS OF WORK TRANSFER

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

Types of work

- Mechanical work
- Two requirement:
  - Force acting on the boundary
  - Boundary must move
- Presence of forces on the boundary without any displacement of boundary doesn’t constitute work and viceversa.

Mechanical work

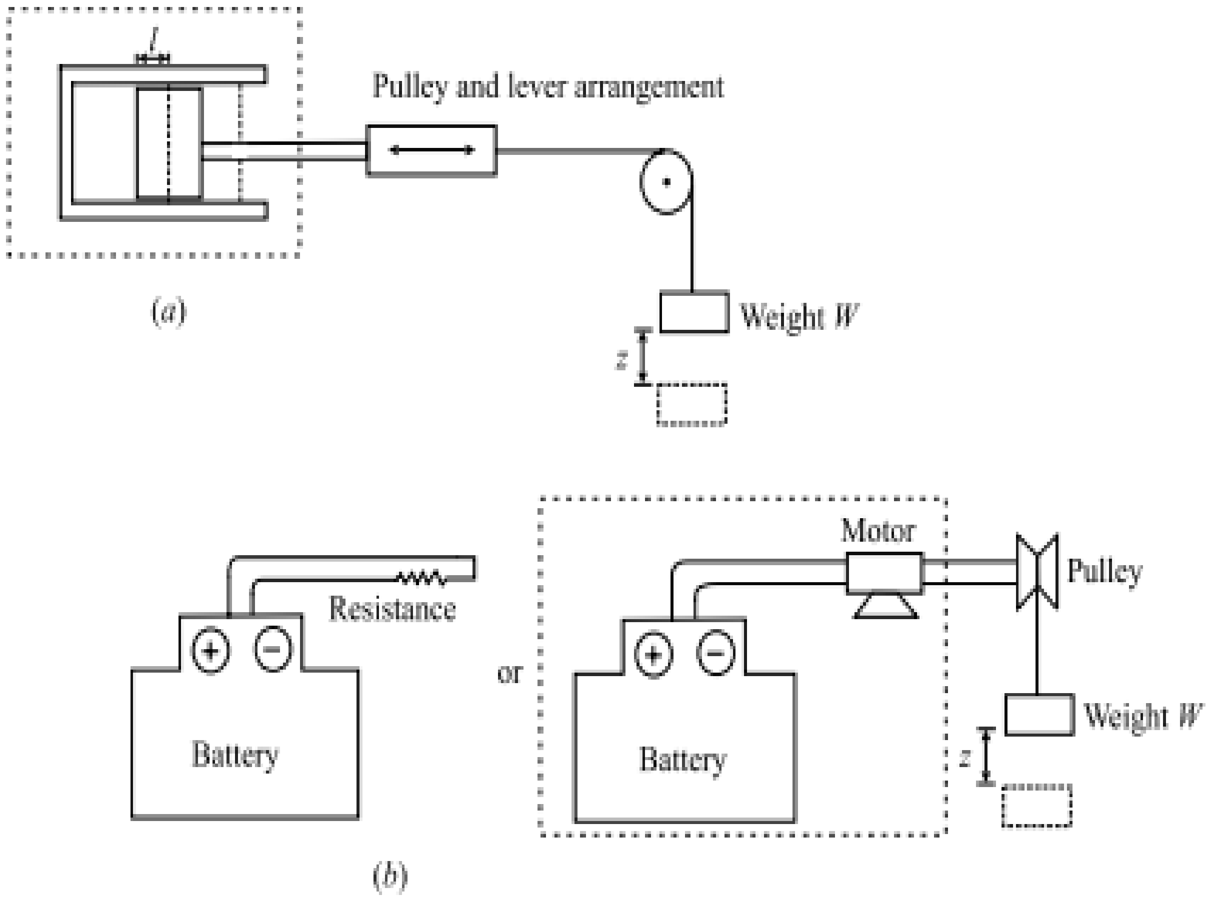
- The work done by a system is expressed as a product of force *(F)* and displacement *(s)*

$$W = Fs$$

- If the force not constant, the work done is obtained by adding the differential amounts of work. $W = \int_1^2 F\,ds$

THERMODYNAMIC WORK

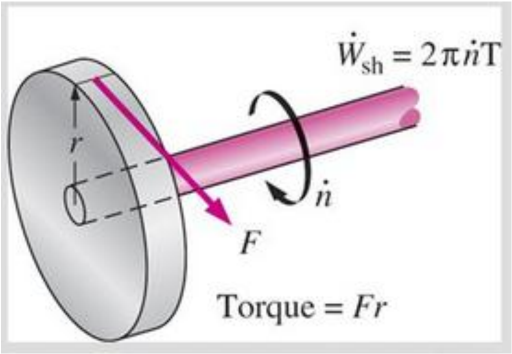
Work is said to be done by a system if the sole effect on everything external to the system is equivalent to raising of a weight



Thermodynamic Work

Shaft work

- The shaft work is associated with energy transmission with a rotating shaft.



- It is the product of torque (product of force and radius of shaft) and angular displacement.

- Consider a shaft or radius r, rotating with n rpm and F is the force acting through an arm radius r.

Shaft work

Torque = Force X radius

$$T = Fr \qquad \therefore F = \frac{T}{r}$$

This force acts through a displacement per unit time (s)

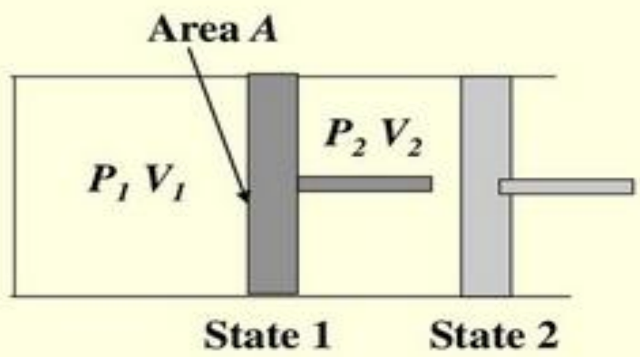
$$s = 2\pi r.(n/60)$$

Then the shaft work per unit time

$$W_{sh} = Fs = \frac{T}{r} \text{ X } 2\pi r(n/60)$$

$$= 2\pi nT / 60 \text{ watt}$$

PdV Work



Let the Piston be moving from Thermodynamic Equilibrium State 1 (P_1, V_1) to State 2 (P_2, V_2).

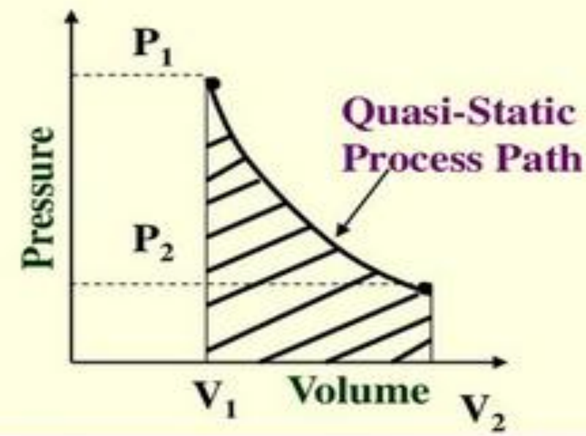
Let the values at any intermediate Equilibrium State is given by P and V.

For an Infinitesimal displacement, dL, the Infinitesimal Work done is;

$$\boxed{dW = F * dL = P*A*dL = PdV}$$

Similarly, for Process 1 – 2; we can say that;

$$\boxed{W_{1-2} = \int_{V_1}^{V_2} PdV}$$



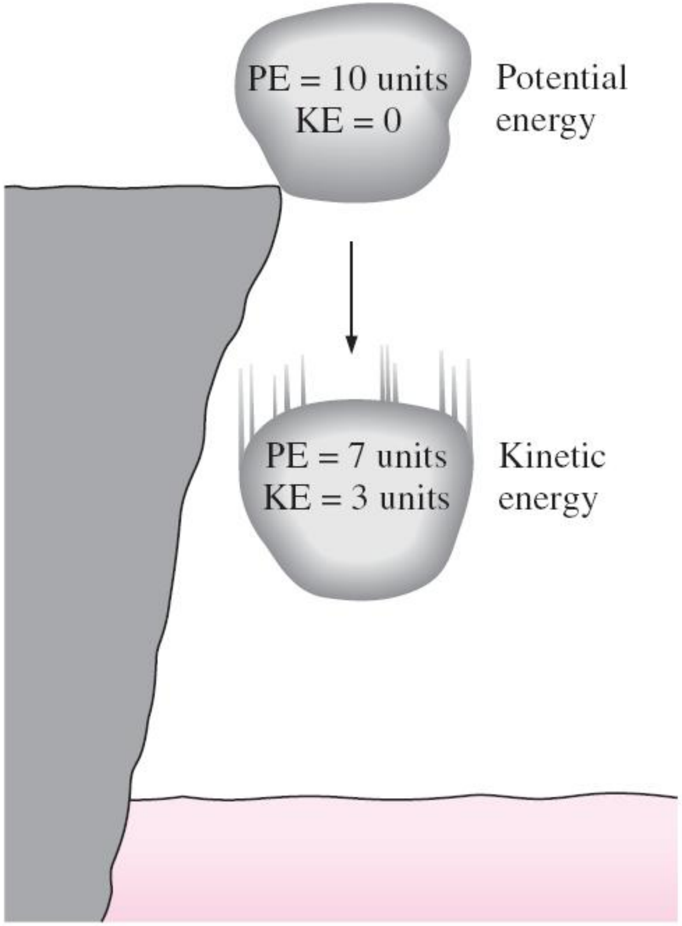
Note: The integration $\int_{V_1}^{V_2} PdV$ can be performed only on a quasi-static path

THE FIRST LAW OF THERMODYNAMICS

•During an interaction, energy can change from one form to another but the total
 amount of energy remains constant.
•Heat and work are equivalent

• Energy is conserved in any transformation

•Energy can change form (for example chemical to thermal)



“Energy can be neither created nor destroyed”

PRINCIPLE OF CONSERVATION OF ENERGY

- For a System undergoing change of state
- When work and heat transfer takes place simultaneously then the conservation of energy principle reveals that

$$Q = W + \Delta E$$

$$Q - W = \Delta E$$

Where Q= net heat transfer across system boundaries

W= Net work transfer in all forms

ΔE= Net change in total energy of the system

ie. The net energy transfer is stored/accumulated in the system in the form of internal energy.

Ex.- The gas is heated inside the cylinder as a result of heat supply.

Principle of conservation of energy

- For the process that only involves heat transfer but no work interaction.

  Ex.- A hot potato taken from oven is exposed to room air, then its energy will decrease. The principle of conservation of energy can be expressed as

$$Q = \Delta E$$

Where $\Delta E = E_2 - E_1$ *as* $W = 0$

In absence of any work interaction between a system and its surroundings, the amount of heat transfer is equal to the change in the energy of the system.

THE FIRSTLAW OF THERMODYNAMICS FOR A CONTROL MASS UNDERGOING A CYCLE

“When a system undergoes a thermodynamic cycle, the net heat transfer is equal to the net work transfer. The heat and work are mutually convertible.”

i.e net work output during a cyclic process is equal to net heat input.

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

PERPETUAL MOTION MACHINE OF FIRST KIND (PMM1)

- Its impossible to construct an engine which operating in a cycle produces continuous work (or kinetic energy) from nothing.
- According to I law of thermodynamics, PMM1 is impossible
- PMM1 is a fictitious machine

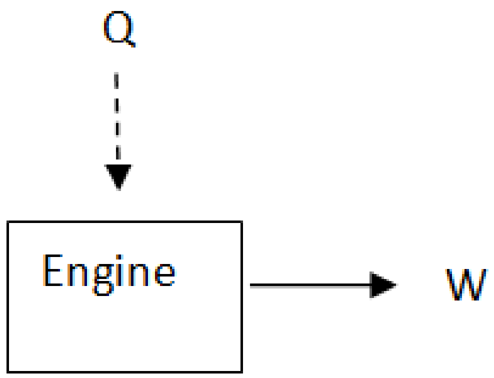


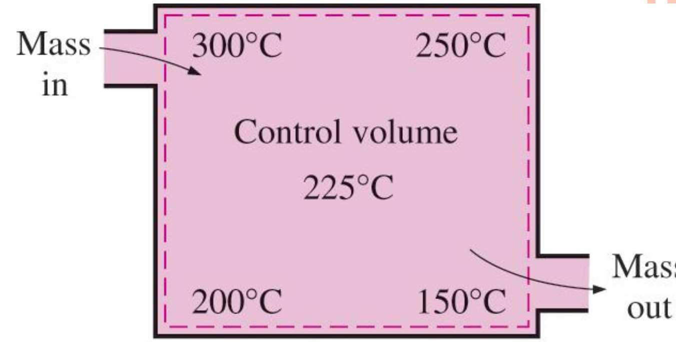
Fig :PMM1

Application of first law of thermodynamics to flow processes

- Virtually all the practical systems involve flow of mass across the boundary separating the system and the surroundings like turbine, compressor or an automobile engine.
- To analyze open systems, concept of control volume(CV) is used, wherein a fixed region in space is considered through which the mass flow takes place. A fluid stream enter the CV at inlet and exits at outlet.

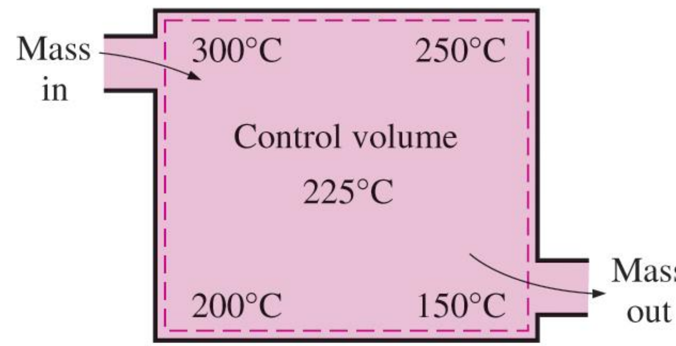
THE STEADY-FLOW PROCESS

- The term *steady* implies *no change with time*. The opposite of steady is *unsteady*, or *transient*.
- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as *steady-flow devices*.
- **Steady-flow process**: A process during which a fluid flows through a control volume steadily.
- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.

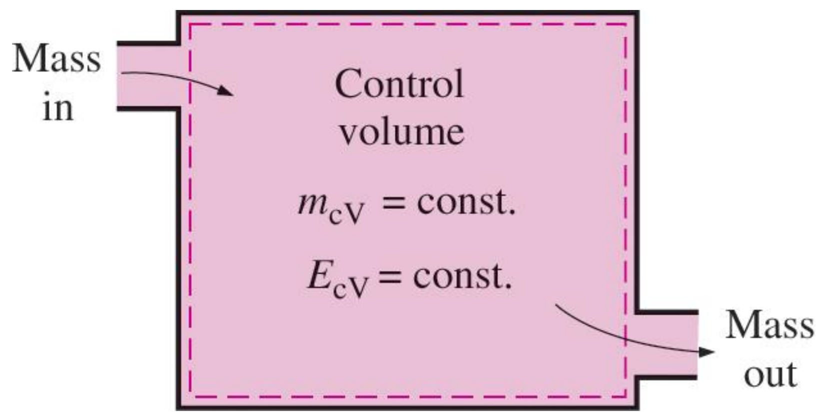


Time: 1 PM

During a steady-flow process, fluid properties within the control volume may change with position but not with time.



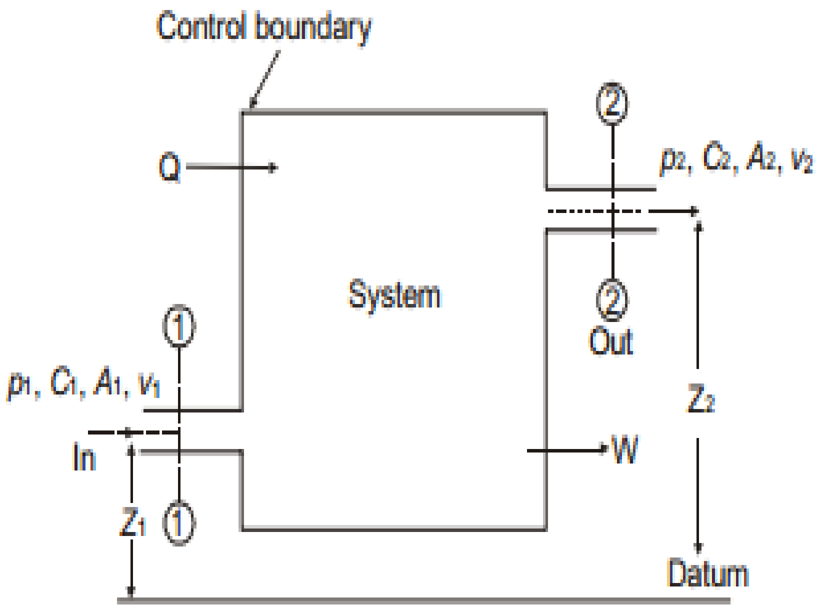
Time: 3 PM



Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

Steady flow energy equation (SFEE)

- Assumptions:
  - Constant mass flow rate through the system ie. No accumulation of mass in CV
  - Only work and heat interactions between the system and surroundings considered
  - Steady flow ie. state of fluid at any point remains constant with time
  - Only KE, PE and flow energies are considered.



Inlet at section 1-1, outlet at 2-2, Heat addition per unit time Q (in J/sec) and work done per unit time by system W (in J/sec)

Steady flow energy equation (SFEE)

	At section 1–1	At section 2–2
Pressure, (N/m^2)	p_1	p_2
Sp volume, (m^3/kg)	v_1	v_2
Velocity, (m/s)	C_1	C_2
Elevation, (m)	z_1	z_2
Cross-section area, (m^2)	A_1	A_2
Mass flow rate, (kg/s)	m_1	m_2
Internal energy, (J/kg)	u_1	u_2

- Let sp. enthalpy be h_1 and h_2 (J/kg), Q be net rate of heat transfer, W be net rate of work transfer
- ***Total energy flow rate into the control volume = Total energy flow rate out of the control volume***
- Energy balance applied to open system results as: $Q + m_1(e_1 + p_1 v_1) = W + m_2(e_2 + p_2 v_2)$

Steady flow energy equation (SFEE)

Substituting for e_1 and e_2

$$Q + m_1\left(u_1 + \frac{C_1^2}{2} + gz_1 + p_1 v_1\right) = W + m_2\left(u_2 + \frac{C_2^2}{2} + gz_2 + p_2 v_2\right)$$

From definition of enthalpy,

$$h_1 = u_1 + p_1 v_1$$
$$h_2 = u_2 + p_2 v_2$$

Therefore,

$$\boxed{Q + m_1\left(h_1 + \frac{C_1^2}{2} + gz_1\right) = W + m_2\left(h_2 + \frac{C_2^2}{2} + gz_2\right)}$$

Steady flow energy equation (SFEE)

- Above equation is known as steady flow energy equation (SFEE)
- If the mass flow rates at inlet and exit are same ie. $m_1 = m_2 = m$, then

$$Q + m\left(h_1 + \frac{C_1^2}{2} + gz_1\right) = W + m\left(h_2 + \frac{C_2^2}{2} + gz_2\right)$$

All terms above represents energy flow per unit time (J/s)
Divide throughout by m (kg/sec), we get SFEE on unit mass basis as follows:

$$\boxed{q + h_1 + \frac{C_1^2}{2} + gz_1 = w + h_2 + \frac{C_2^2}{2} + gz_2}$$

All terms above eq. represents energy flow per unit mass of fluid. (in J/kg)
Where q=Q/m and w=W/m
The SFEE can be used as a tool for carrying out thermodynamic analysis of various engineering systems.

APLLICATION OF STEADY FLOW ENERGY EQUATION

- Nozzle:
- Device of uniformly varying cross sectional duct used for converting pressure energy of the fluid into KE. For a nozzle,

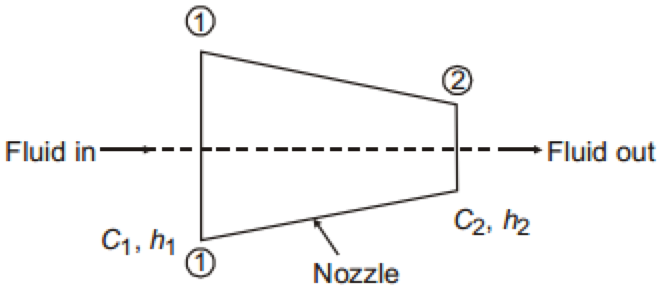
  $\Delta PE = 0$

  Process is adiabetic, so rate of heat transfer q=0

  No shaft work involved, w =0

SFEE eq

$$\boxed{q + h_1 + \frac{C_1^2}{2} + gz_1 = w + h_2 + \frac{C_2^2}{2} + gz_2}$$



Changes to

$h_1 + C_1^2/2 = h_2 + C_2^2/2$

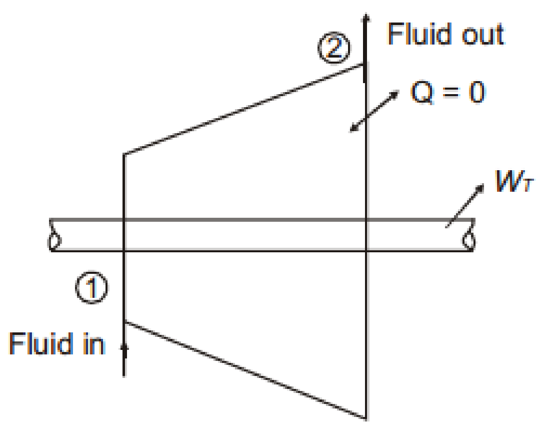
Apllication of steady flow energy equation

- Turbine:
- Device in which high pressure fluid is expanded in generation of positive work output at shaft.

  Expansion in turbine assumed to be adiabatic type to obtain maximum output., therefore q=0

  SFEE changes to

  $h_1 + C_1^2/2 = h_2 + C_2^2/2 + w$



APLLICATION OF STEADY FLOW ENERGY EQUATION

- Compressor:
- Work absorbing device used for increasing the pressure of the fluid.

  Adiabatic compression assumed so $q = 0$

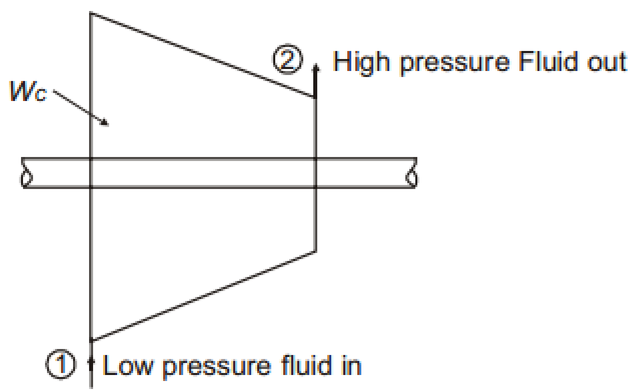
  Let us assume change in KE and PE to be negligible between 1 and 2

SFEE changes to

$h_1 = h_2 - w$

ie enthalpy of the fluid increases

by the amount of work input.



CONTINUITY OF MASS EQUATION

- States that in a steady flow, the mass flow rate of fluid at any section is the same as at any other section.

  ie. $m_1 = m_2$

$$\frac{A_1 C_1}{v_1} = \frac{A_2 C_2}{v_2}$$

Where, A_1, A_2 = Cross sections at section 1 and 2 (m^2)
C_1, C_2 = flow velocity at sections 1 and 2 (m/s)
v_1, v_2 = specific volumes at section 1 and 2 (m^3/kg)

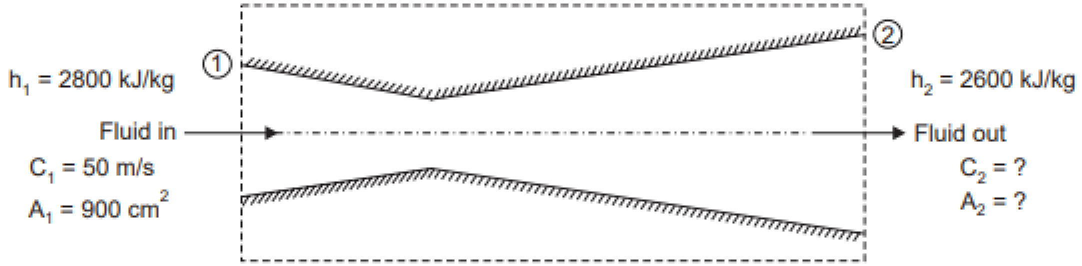
Numerical problems

Q1) At the inlet to a certain nozzle the enthalpy of fluid passing is 2800 kJ/kg, and the velocity is 50 m/s. At the discharge end the enthalpy is 2600 kJ/kg. The nozzle is horizontal and there is negligible heat loss from it.

(i) Find the velocity at exit of the nozzle.

(ii) If the inlet area is 900 cm^2 and the specific volume at inlet is 0.187 m^3/kg, find the mass flow rate.

(iii) If the specific volume at the nozzle exit is 0.498 m^3/kg, find the exit area of nozzle.



Conditions of fluid at inlet (1) :

Enthalpy, $h_1 = 2800$ kJ/kg

Velocity, $C_1 = 50$ m/s

Area, $A_1 = 900\ \text{cm}^2 = 900 \times 10^{-4}\ \text{m}^2$

Specific volume, $v_1 = 0.187\ \text{m}^3/\text{kg}$

Conditions of fluid at exit (2) :

Enthalpy, $h_2 = 2600$ kJ/kg

Specific volume, $v_2 = 0.498\ \text{m}^3/\text{kJ}$

Area, $A_2 = ?$

Mass flow rate, $\dot{m} = ?$

(*i*) **Velocity at exit of the nozzle, C_2 :**

Applying energy equation at '1' and '2', we get

$$h_1 + \frac{C_1^2}{2} + Z_1 g + Q = h_2 + \frac{C_2^2}{2} + Z_2 g + W$$

Here $Q = 0,\ W = 0,\ Z_1 = Z_2$

$$\therefore \quad h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$$

$$\frac{C_2^2}{2} = (h_1 - h_2) + \frac{C_1^2}{2}$$

$$= (2800 - 2600) \times 1000 + \frac{50^2}{2} = 201250\ \text{N-m}$$

$$\therefore \quad C_2^2 = 402500$$

$$\therefore \quad \mathbf{C_2 = 634.4\ m/s.} \quad \textbf{(Ans.)}$$

(*ii*) **Mass flow rate $\dot{m}$:**

By continuity equation,

$$\dot{m} = \frac{AC}{v} = \frac{A_1C_1}{v_1} = \frac{900 \times 10^{-4} \times 50}{0.187} \text{ kg/s} = 24.06 \text{ kg/s}$$

∴ **Mass flow rate = 24.06 kg/s. (Ans.)**

(*iii*) **Area at the exit, A_2 :**

Now,

$$\dot{m} = \frac{A_2 C_2}{v_2}$$

$$24.06 = \frac{A_2 \times 634.4}{0.498}$$

∴

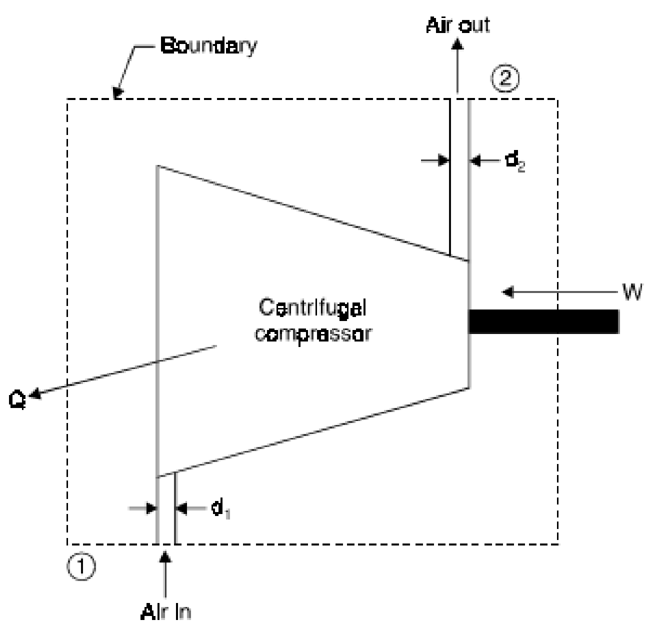
$$A_2 = \frac{24.06 \times 0.498}{634.4} = 0.018887 \text{ m}^2 = 188.87 \text{ cm}^2$$

Hence, **area at the exit = 188.87 cm^2. (Ans.)**

- Q2) 12 kg of air/minute is delivered by a centrifugal air compressor. The inlet and outlet conditions of air are $C_1 = 12$ m/s, $p_1 = 1$ bar, $v_1 = 0.5$ m^3/kg and $C_2 = 90$ m/s, $p_2 = 8$ bar, $v_2 = 0.14$ m^3/kg. The increase in enthalpy of air passing through the compressor is 150 kJ/kg and heat loss to the surroundings is 700 kJ/min.

  Find : (i) Motor power required to drive the compressor ; (ii) Ratio of inlet to outlet pipe diameter.

Assume that inlet and discharge lines are at the same level



Solution. Quantity of air delivered by the compressor, $m = \frac{12}{60} = 0.2$ kg/s.

Conditions of air at the inlet 1 :

Velocity, $C_1 = 12$ m/s

Pressure, $p_1 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$

Specific volume, $v_1 = 0.5 \text{ m}^3/\text{kg}$

Conditions of air at the outlet 2 :

Velocity, $C_2 = 90$ m/s

Pressure, $p_2 = 8 \text{ bar} = 8 \times 10^5 \text{ N/m}^2$

Specific volume, $v_2 = 0.14 \text{ m}^3/\text{kg}$

Increase in enthalpy of air passing through the compressor,

$$(h_2 - h_1) = 150 \text{ kJ/kg}$$

Heat lost to the surroundings,

$$Q = -700 \text{ kJ/min} = -11.67 \text{ kJ/s.}$$

(*i*) **Motor power required to drive the compressor :**

Applying energy equation to the system,

$$m\left(h_1 + \frac{C_1^2}{2} + Z_1 g\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + Z_2 g\right) + W$$

Now $\qquad Z_1 = Z_2$

$$\therefore \quad m\left(h_1 + \frac{C_1^2}{2}\right) + Q = m\left(h_2 + \frac{C_2^2}{2}\right) + W$$

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

$$= 0.2\left[-150 + \frac{12^2 - 90^2}{2 \times 1000}\right] + (-11.67)$$

$$= -42.46 \text{ kJ/s} = -42.46 \text{ kW}$$

$\therefore$ **Motor power required (or work done on the air) = 42.46 kW. (Ans.)**

(*ii*) **Ratio of inlet to outlet pipe diameter, $\frac{\mathbf{d_1}}{\mathbf{d_2}}$:**

The mass of air passing through the compressor is given by

$$m = \frac{A_1 C_1}{v_1} = \frac{A_2 C_2}{v_2}$$

$$\therefore \quad \frac{A_1}{A_2} = \frac{C_2}{C_1} \times \frac{v_1}{v_2} = \frac{90}{12} \times \frac{0.5}{0.14} = 26.78$$

$$\therefore \quad \left(\frac{d_1}{d_2}\right)^2 = 26.78 \quad \text{or} \quad \frac{d_1}{d_2} = 5.175$$

Hence ratio of inlet to outlet pipe diameter = 5.175. (Ans.)

Limitations of first law of thermodynamics

- Doesn't differentiate between heat and work and assures full convertibility of one into other. Full conversion of work into heat is possible but not vice versa.
- Doesn't explain the direction of a process. Its impossible to predict from I law whether process can occur or not.

II LAW OF THERMODYNAMICS

- Some important terms:
- Heat reservoir: Source of infinite heat energy and finite amount of heat absorbed/rejected from it will not affect its temperature. ie. Temperature of reservoir remains constant.
- Heat source: Heat reservoir which supplies heat to a system. (Higher temp body)
- Heat Sink: Heat reservoir which absorbs heat from the system. (lower temp body)

Heat engine

- Device used for converting heat supplied into useful work.

  Let Q_1 is heat supplied from source to engine

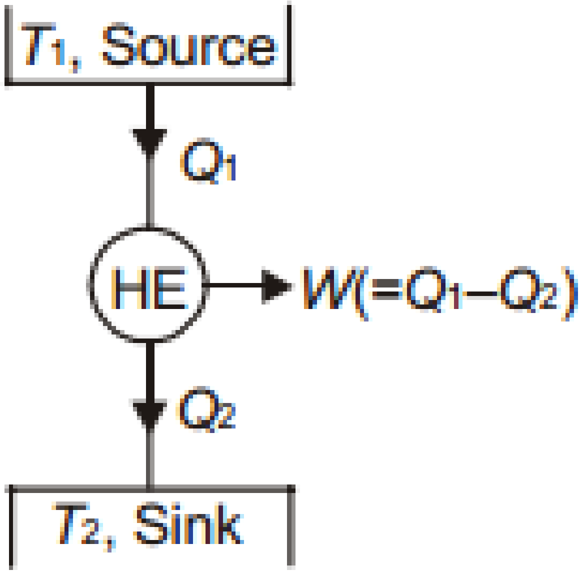
  Q_2 be heat rejected from engine to sink

Then,

Net work output $W = Q_1 - Q_2$

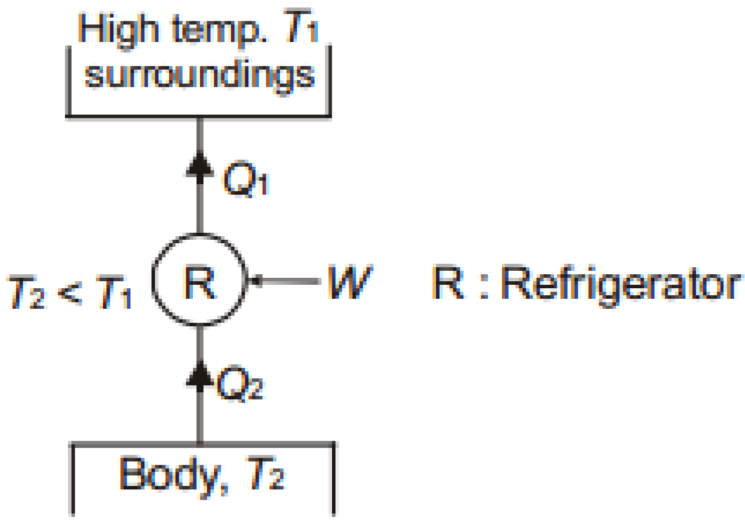
Thermal efficiency of heat engine

$$\eta_{\text{heat engine}} = \frac{\text{Net work}}{\text{Heat supplied}} = \frac{W}{Q_1}$$



Refrigerator

- Device operating in a cycle maintains a body at a lower temp than that of surroundings.
- Hot body temp and cold body temp T1 and T2 respectively, Q_1 and Q_2 are associated heat flow rates. Then,

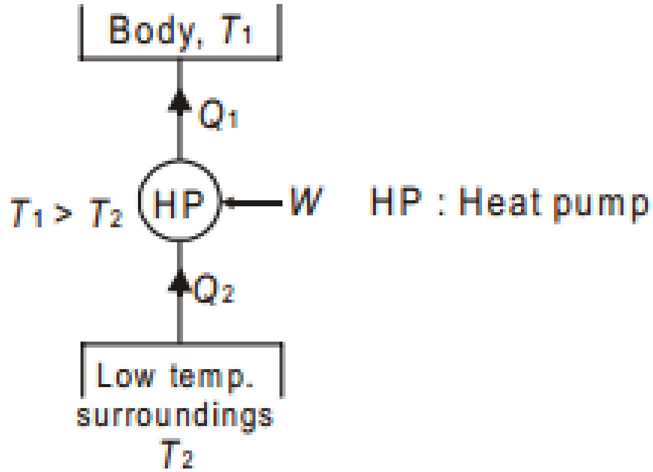


$$(\text{COP})_{\text{refrigerator}} = \frac{\text{Desired effect}}{\text{Net work}} = \frac{Q_2}{W}$$

$$W = Q_1 - Q_2$$

$$(\text{COP})_{\text{refrigerator}} = \frac{Q_2}{Q_1 - Q_2}$$

HEAT PUMP



- Device used for extracting heat from a low temperature surroundings and sending it to high temperature body, while operating in a cycle.
- In other words heat pump maintains a body or system at temperature higher than temperature of surroundings, while operating in cycle
- With usual notation,

$$(COP)_{HP} = \frac{Q_1}{W}$$

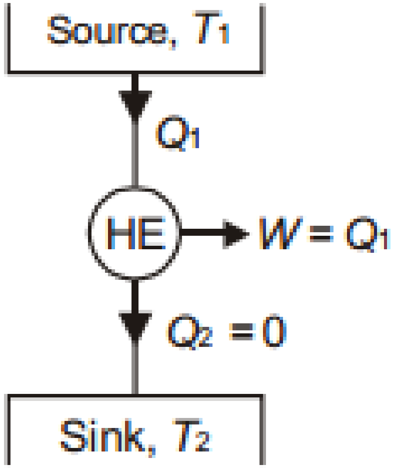
$$W = Q_1 - Q_2$$

$$\boxed{(COP)_{HP} = \frac{Q_1}{Q_1 - Q_2}}$$

COP value of heat pump and refrigerator can be related as:

$$(COP)_{HP} = (COP)_{refrigerator} + 1$$

Statements for II law of thermodynamics



- Kelvin plank statement:

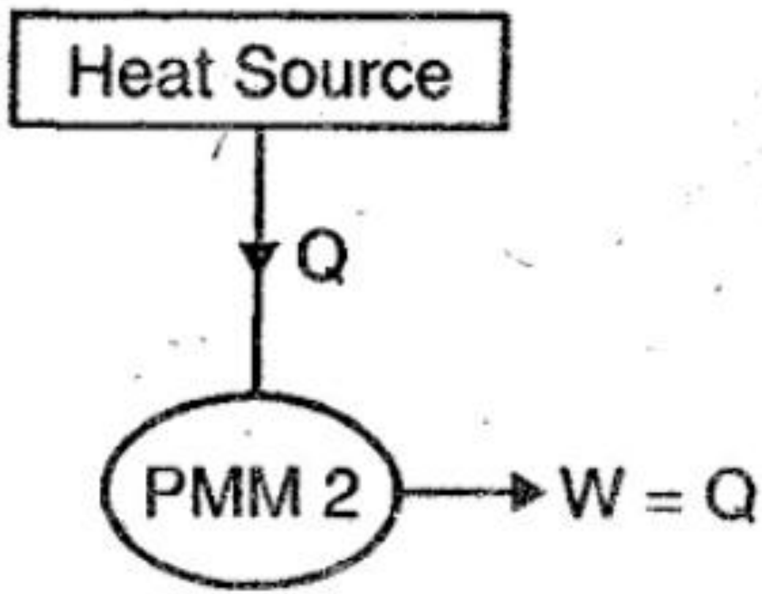
"It is impossible for a device operating in a cycle to produce net work while exchanging heat with bodies at single fixed temperature".

It says that, a heat engine cannot have 100% efficiency. i.e. no heat engine can convert all heat supplied to useful work. The heat engine receives heat from a high temperature body and reject some amount of heat to the lower temperature body. The difference in between heat supplied and heat rejected is work done by heat engine.

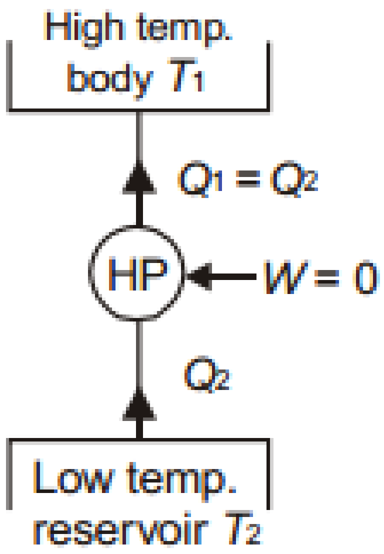
Perpetual Motion Machine of the second kind

- Second law restricts that process proceeds in a certain direction and not in opposite direction.

- A perpetual motion machine of the second kind, or **PMM2** is one which converts all the heat input into work while working in a cycle.



- Clausius Statement:



"It is impossible to have a device that while operating in a cycle produces no effect other than transfer of heat from a body at low temperature to a body at higher temperature."

ie. Heat can't flow from lower temp to higher temp body without the aid of an external work.

- Carnot's Principle:

  "Heat transfer from a heat reservoir is proportional to its temperature."

  $Q / T = \text{constant}, K$

Therefore,

$\eta_{HE} = 1 - (Q_2/Q_1) = 1 - (T_2/T_1)$

$(COP)_{refrigerator} = Q_2 / (Q_1 - Q_2) = T_2 / (T_1 - T_2)$

$(COP)_{heat\ pump} = Q_1 / (Q_1 - Q_2) = T_1 / (T_1 - T_2)$

Carnot theorem states that "any engine cannot have efficiency more than that of reversible engine operating between same temperature limits."

Different corollaries of Carnot theorem are,

(i) Efficiency of all reversible engines operating between same temperature limits is same.

(ii) Efficiency of a reversible engine does not depend on the working fluid in the cycle

- Q1) A heat engine receives heat at the rate of 1500 kJ/min and gives an output of 8.2 kW. Determine : (i) The thermal efficiency ; (ii) The rate of heat rejection.

Solution. Heat received by the heat engine,

$$Q_1 = 1500 \text{ kJ/min}$$

$$= \frac{1500}{60} = 25 \text{ kJ/s}$$

Work output, $W = 8.2 \text{ kW} = 8.2 \text{ kJ/s}$.

(*i*) Thermal efficiency, $\eta_{th} = \dfrac{W}{Q_1}$

$$= \frac{8.2}{25} = 0.328 = 32.8\%$$

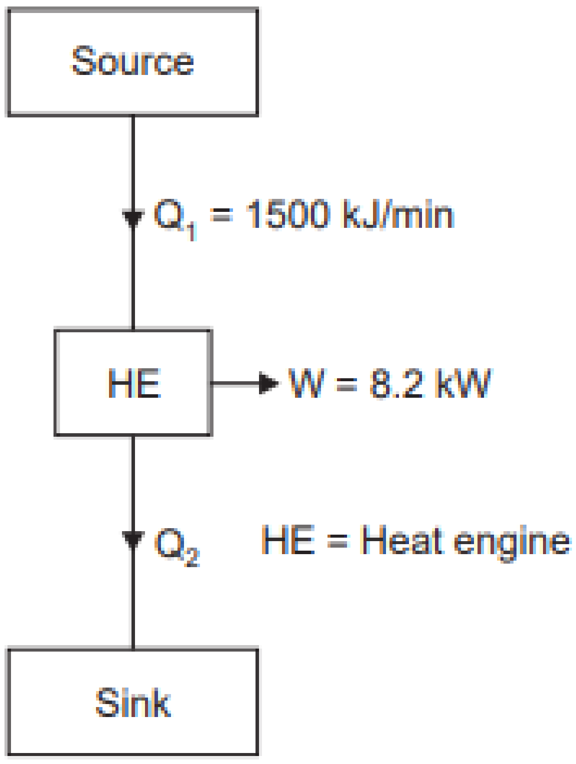
Hence, **thermal efficiency = 32.8%. (Ans.)**

(*ii*) Rate of heat rejection,

$$Q_2 = Q_1 - W = 25 - 8.2$$

$$= 16.8 \text{ kJ/s}$$

Hence, **the rate of heat rejection = 16.8 kJ/s.**



Q2) 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.

Solution. Freezer temperature,

$$T_2 = -12 + 273 = 261 \text{ K}$$

Ambient air temperature,

$$T_1 = 35 + 273 = 308 \text{ K}$$

Rate of heat leakage into the freezer = 2 kJ/s

Least power required to pump the heat :

The refrigerator cycle removes heat from the freezer a same rate at which heat leaks into it (Fig. 5.12).

For minimum power requirement

$$\frac{Q_2}{T_2} = \frac{Q_1}{T_1}$$

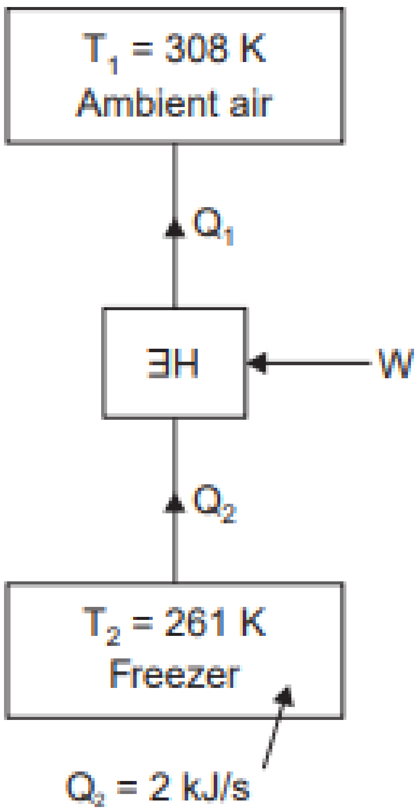
$$\therefore \quad Q_1 = \frac{Q_2}{T_2} \times T_1 = \frac{2}{261} \times 308 = 2.36 \text{ kJ/}$$

$$\therefore \quad W = Q_1 - Q_2$$

$$= 2.36 - 2 = 0.36 \text{ kJ/s} = 0.36 \text{ kW}$$

Hence, *least power required to pump the heat continuou*

= 0.36 kW. (Ans.)



- Q3) A house requires 2 × 105 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 × 104 kJ/h. Determine : (i) Heat abstracted from outside ; (ii) Co-efficient of performance.

Solution. (*i*) Heat requirement of the house, Q_1 (or heat rejected)

$$= 2 \times 10^5 \text{ kJ/h}$$

Work required to operate the heat pump,

$$W = 3 \times 10^4 \text{ kJ/h}$$

Now, $$Q_1 = W + Q_2$$

where Q_2 is the heat abstracted from outside.

$\therefore$ $$2 \times 10^5 = 3 \times 10^4 + Q_2$$

Thus $$Q_2 = 2 \times 10^5 - 3 \times 10^4$$

$$= 200000 - 30000 = 170000 \text{ kJ/h}$$

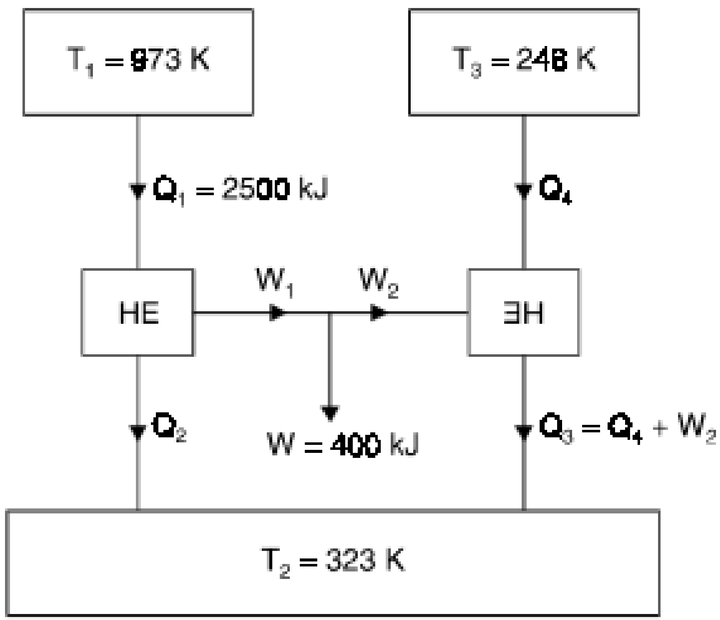
Hence, **heat abstracted from outside = 170000 kJ/h. (Ans.)**

(*ii*) $$(\text{C.O.P.})_{heat\ pump} = \frac{Q_1}{Q_1 - Q_2}$$

$$= \frac{2 \times 10^5}{2 \times 10^5 - 170000} = 6.66$$

Hence, **co-efficient of performance = 6.66. (Ans.)**

- A reversible heat engine operates between two reservoirs at temperatures 700°C and 50°C. The engine drives a reversible refrigerator which operates between reservoirs at temperatures of 50°C and – 25°C. The heat transfer to the engine is 2500 kJ and the net work output of the combined engine refrigerator plant is 400 kJ. (i) Determine the heat transfer to the refrigerant and the net heat transfer to the reservoir at 50°C ; (ii) Reconsider (i) given that the efficiency of the heat engine and the C.O.P. of the refrigerator are each 45 per cent of their maximum possible values.



Temperature, $T_1 = 700 + 273 = 973$ K

Temperature, $T_2 = 50 + 273 = 323$ K

Temperature, $T_3 = -25 + 273 = 248$ K

The heat transfer to the heat engine, $Q_1 = 2500$ kJ

The network output of the combined engine refrigerator plant,

$$W = W_1 - W_2 = 400 \text{ kJ.}$$

(i) Maximum efficiency of the heat engine cycle is given by

$$\eta_{max} = 1 - \frac{T_2}{T_1} = 1 - \frac{323}{973} = 0.668$$

Again, $$\frac{W_1}{Q_1} = 0.668$$

$\therefore$ $$W_1 = 0.668 \times 2500 = 1670 \text{ kJ}$$

$$(\text{C.O.P.})_{max} = \frac{T_3}{T_2 - T_3} = \frac{248}{323 - 248} = 3.306$$

Also, $$\text{C.O.P.} = \frac{Q_4}{W_2} = 3.306$$

Since, $W_1 - W_2 = W = 400$ kJ

$$W_2 = W_1 - W = 1670 - 400 = 1270 \text{ kJ}$$

$\therefore$ $$Q_4 = 3.306 \times 1270 = 4198.6 \text{ kJ}$$

$$Q_3 = Q_4 + W_2 = 4198.6 + 1270 = 5468.6 \text{ kJ}$$

$$Q_2 = Q_1 - W_1 = 2500 - 1670 = 830 \text{ kJ.}$$

Heat rejection to the 50°C reservoir

$$= Q_2 + Q_3 = 830 + 5468.6 = \mathbf{6298.6 \text{ kJ.}} \quad \textbf{(Ans.)}$$

(*ii*) Efficiency of actual heat engine cycle,

$$\eta = 0.45\ \eta_{max} = 0.45 \times 0.668 = 0.3$$

$\therefore$ $$W_1 = \eta \times Q_1 = 0.3 \times 2500 = 750 \text{ kJ}$$

$\therefore$ $$W_2 = 750 - 400 = 350 \text{ kJ}$$

C.O.P. of the actual refrigerator cycle,

$$\text{C.O.P.} = \frac{Q_4}{W_2} = 0.45 \times 3.306 = 1.48$$

$\therefore$ $$Q_4 = 350 \times 1.48 = \mathbf{518 \text{ kJ.}} \quad \textbf{(Ans.)}$$

$$Q_3 = 518 + 350 = 868 \text{ kJ}$$

$$Q_2 = 2500 - 750 = 1750 \text{ kJ}$$

Heat rejected to 50°C reservoir

$$= Q_2 + Q_3 = 1750 + 868 = \mathbf{2618 \text{ kJ.}} \quad \textbf{(Ans.)}$$