Job No 4435

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THERMODYNAMICS

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Analogy

All currencies are not equal

Eg: US$ or A$ or UK£ etc. Have a better purchasing power than Indian Rupee or Thai Baht or Bangladesh Taka similarly,all forms of energy are not the same.

Human civilization has always endeavoured to obtain

- Shaft work
- Electrical energy
- Potential energy to make life easier

Thermodynamics

B. Tech. Ist yrs

Examples (Contd…)

On the other hand we burn,

- Some coal/gas in a power plant to generate electricity.
- Petrol in a car engine.

What is the largest energy we can get out of these efforts?

Thermodynamics allows us to answer some of these questions

- The rest of the universe outside the system close enough to the system to have some perceptible effect on the system is called the surroundings.
- The surfaces which separates the system from the surroundings are called the boundaries as shown in fig below (eg: walls of the kettle, the housing of the engine).

Fundamental Concepts and Definitions

THERMODYNAMICS:

- It is the science of the relations between heat, Work and the properties of the systems.
- How to adopt these interactions to our benefit?

Thermodynamics enables us to answer this question.

Examples

If we like to

- *Rise the temperature of water in kettle*
- *Burn some fuel in the combustion chamber of an aero engine to propel an aircraft.*
- *Cool our room on a hot humid day*
- *Heat up our room on a cold winter night*
- *Have our beer cool.*

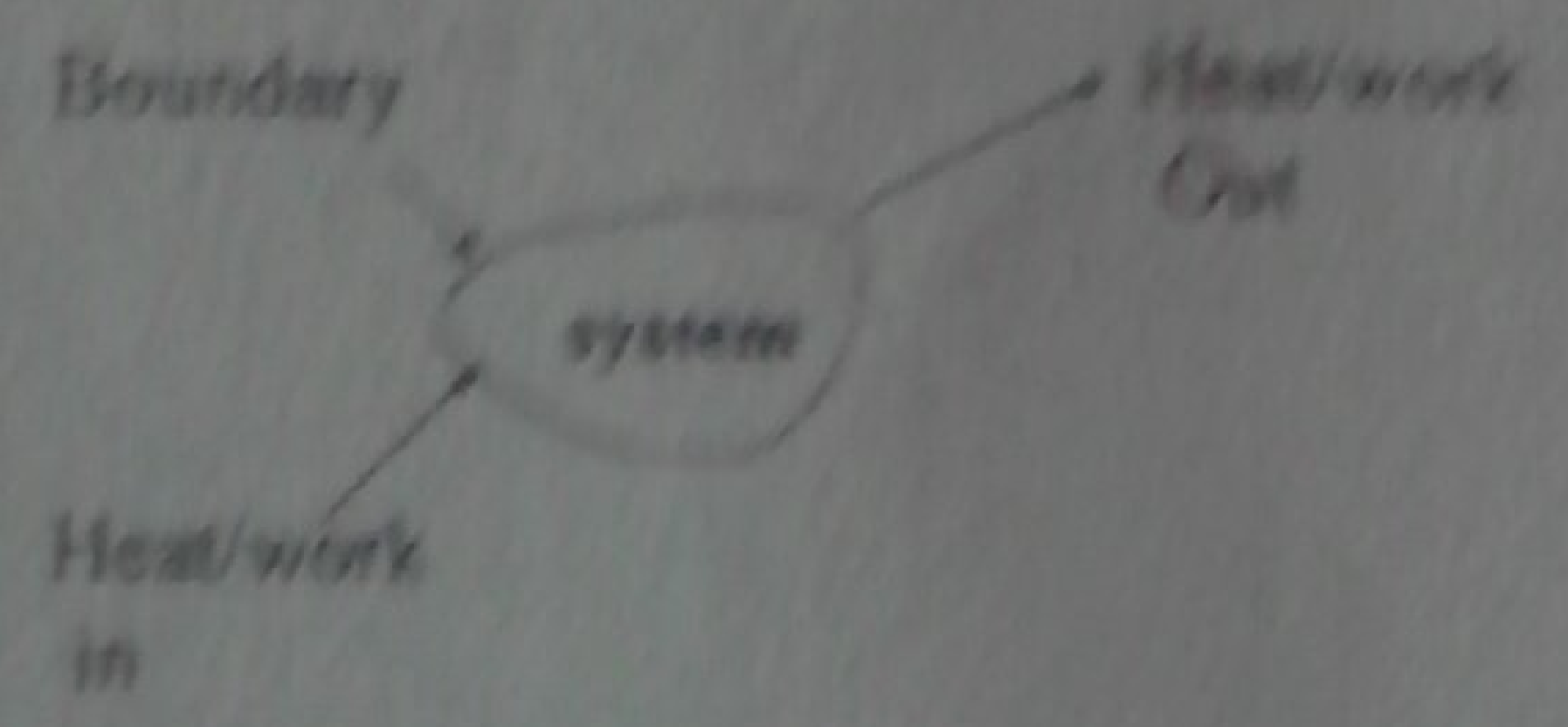
What is the smallest amount of electricity/fuel we can get away with?

Definitions

- In our study of thermodynamics, we will choose *a small part of the universe* to which we will apply the laws of thermodynamics. We call this subset a SYSTEM.
- The thermodynamic system is analogous to the free body diagram to which we apply the laws of mechanics, (i.e. Newton's Laws of Motion).
- The system is a macroscopically identifiable collection of matter on which we focus our attention (eg: the water kettle or the aircraft engine).

Types of System

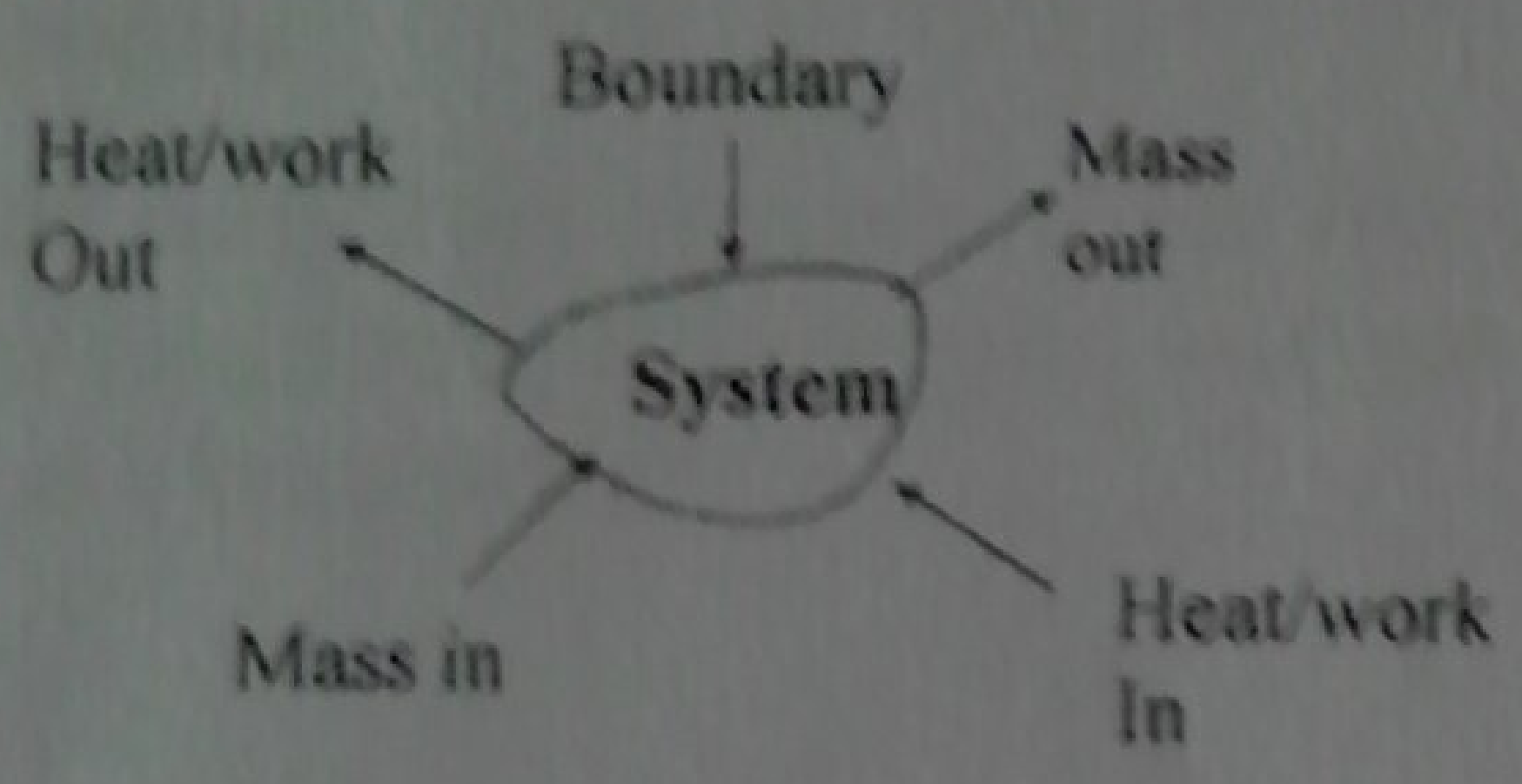
- Closed system - in which no mass is permitted to cross the system boundary i.e. we would always consider a system of constant mass. We do permit heat and work to enter or leave but not mass.



No mass entry or exit

- Open system- in which we permit mass to cross the system boundary in either direction (from the system to surroundings or *vice versa*). In analysing open systems, we typically look at a specified region of space, and observe what happens at the boundaries of that region.

Most of the engineering devices are open system.



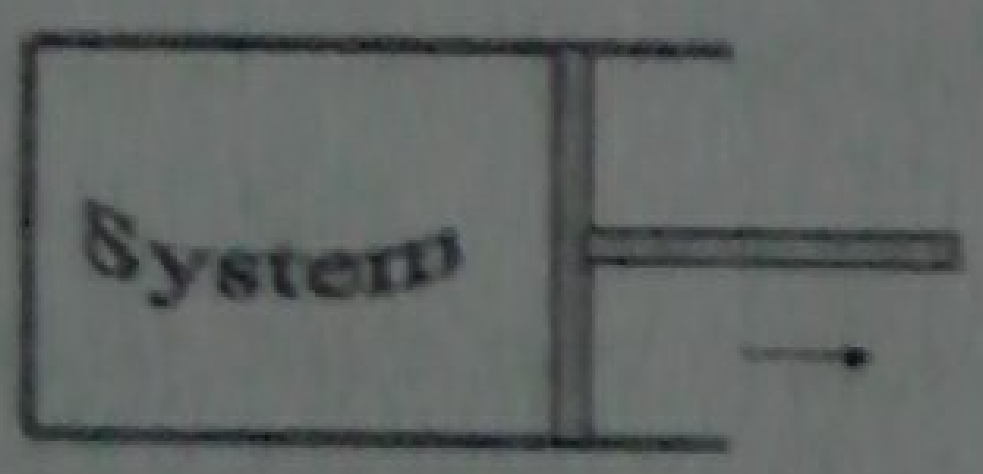
Choice of the System and Boundaries Are at Our Convenience

- We must choose the system for each and every problem we work on, so as to obtain best possible information on how it behaves.
- In some cases the choice of the system will be obvious and in some cases not so obvious.
- Important: you must be clear in defining what constitutes your system and make that choice explicit to anyone else who may be reviewing your work. (eg: *In the exam paper or to your supervisor in the work place later)*

Choice of the System and Boundaries Are at Our Convenience (contd…)

- The boundaries may be at rest or in motion.

eg: If we choose a *system* that has a certain defined quantity of mass (such as gas contained in a piston cylinder device) the *boundaries* must move in such way that they always enclose that particular quantity of mass if it changes shape or moves from one place to another.



Microscopic Approach

- In microscopic approach, the effect of molecular motion is Considered.

eg: At microscopic level the pressure of a gas is not constant, the temperature of a gas is a function of the velocity of molecules.

Most microscopic properties cannot be measured with common instruments nor can be perceived by human senses

Examples (contd...)

We must choose the most appropriate set of properties.

- For example: Anand weighing 72 kg and being 1.75 m tall may be a useful way of identification for police purposes.
- If he has to work in a company you would say Anand graduated from IIT, Chennai in 1985 in mechanical engineering.
- Anand hails from Mangalore. He has a sister and his father is a poet. He is singer. ---If you are looking at him as a bridegroom!!

Categories of Properties

- Extensive property:

  whose value depends on the size or extent of the system (upper case letters as the symbols).

  eg: Volume, Mass (V,M).

  If mass is increased, the value of extensive property also increases.

- Intensive property:

  whose value is independent of the size or extent of the system.

  eg: pressure, temperature (p, T).

- State:

It is the condition of a system as defined by the values of all its properties.

It gives a complete description of the system.

Any operation in which one or more properties of a system change is called a change of state.

- Phase:

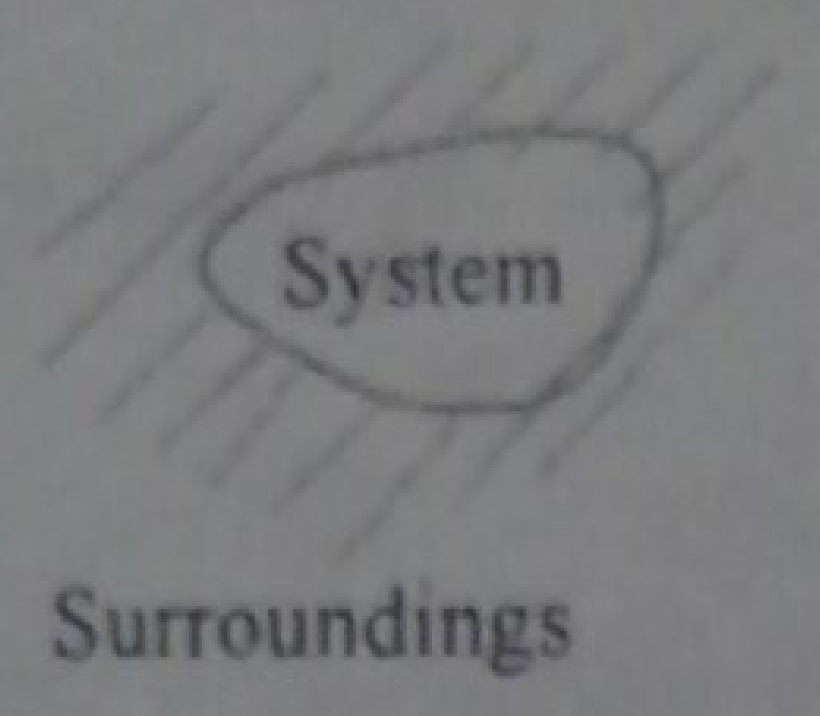
It is a quantity of mass that is homogeneous throughout in chemical composition and physical structure.
e.g. solid, liquid, vapour, gas.
Phase consisting of more than one phase is known as heterogenous system .

Types of Processes

- As a matter of rule we allow one of the properties to remain a constant during a process.
- Construe as many processes as we can (with a different property kept constant during each of them)
- Complete the cycle by regaining the initial state

- •Isothermal (T)
- •Isobaric (p)
- •Isochoric (v)
- •Isentropic (s)
- •Isenthalpic (h)
- •Isosteric (concentration)
- •Adiabatic (no heat addition or removal

- Isolated System - in which there is no interaction between system and the surroundings. It is of fixed mass and energy, and hence there is no mass and energy transfer across the system boundary.



Choice of the System and Boundaries Are at Our Convenience (contd…)

- The boundaries may be real physical surfaces or they may be imaginary for the convenience of analysis.

eg: If the air in this room is the system,the floor,ceiling and walls constitutes real boundaries.the plane at the open doorway constitutes an imaginary boundary.

Macroscopic and Microscopic Approaches

Behavior of matter can be studied by these two approaches.

- In macroscopic approach, certain quantity of matter is considered,without a concern on the events occurring at the molecular level. These effects can be perceived by human senses or measured by instruments.

- eg: pressure, temperature

Property

- It is some characteristic of the system to which some physically meaningful numbers can be assigned without knowing the history behind it.
- These are macroscopic in nature.
- Invariably the properties must enable us to identify the system.
- eg: Anand weighs 72 kg and is 1.75 m tall. We are not concerned how he got to that stage. We are not interested what he ate!!.

Quasi-static Processes (contd…)

- If we remove the weights slowly one by one the pressure of the gas will displace the piston gradually. It is quasistatic.
- On the other hand if we remove all the weights at once the piston will be kicked up by the gas pressure.(This is unrestrained expansion) but we don't consider that the work is done - because it is not in a sustained manner
- In both cases the systems have undergone a change of state.
- Another eg: if a person climbs down a ladder from roof to ground, it is a quasistatic process. On the other hand if he jumps then it is not a quasistatic process.

Equilibrium State (contd)

Nature has a preferred way of directing changes.

eg:

- water flows from a higher to a lower level
- Electricity flows from a higher potential to a lower one
- Heat flows from a body at higher temperature to the one at a lower temperature
- Momentum transfer occurs from a point of higher pressure to a lower one.
- Mass transfer occurs from higher concentration to a lower one

Definition Of Temperature and Zeroth Law Of Thermodynamics

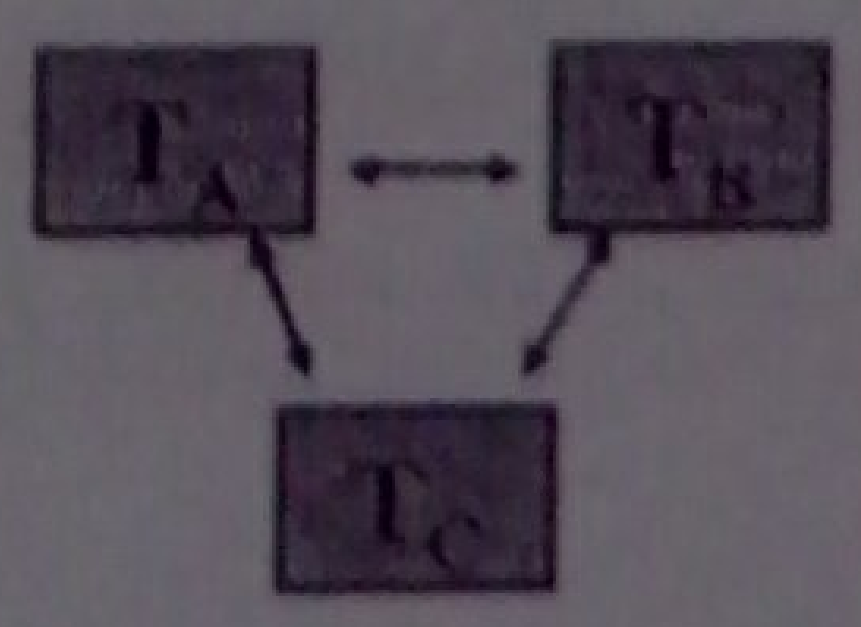
- Temperature is a property of a system which determines the degree of hotness.
- Obviously, it is a relative term.

eg: A hot cup of coffee is at a higher temperature than a block of ice. On the other hand, *ice is hotter than liquid hydrogen.*

Thermodynamic temperature scale is under evolution. What we have now in empirical scale.

Zeroth Law

- If two systems (say A and B) are in thermal equilibrium with a third system (say C) separately (that is A and C are in thermal equilibrium; B and C are in thermal equilibrium) then they are in thermal equilibrium themselves (that is A and B will be in thermal equilibrium



Examples (contd…)

- All of them are properties of Anand. But you pick and choose a set of his traits which describe him best for a given situation.
- Similarly, among various properties by which a definition of a thermodynamic system is possible, a situation might warrant giving the smallest number of properties which describe the system best.

Property (contd..)

Specific property:

- It is the value of an extensive property per unit mass of system. (lower case letters as symbols) eg: specific volume, density (v, ρ).
- It is a special case of an intensive property.
- Most widely referred properties in thermodynamics:
- Pressure; Volume; Temperature; *Entropy; Enthalpy; Internal energy*

(Italicised ones to be defined later)

Path And Process

The succession of states passed through during a change of state is called the *path of the system*. A system is said to go through a process if it goes through a series of changes in state. Consequently:

- **A** system may undergo changes in some or all of its properties.
- A process can be construed to be the locus of changes of state

Processes in thermodynamics are like streets in a city

eg: we have north to south; east to west; roundabouts; crescents

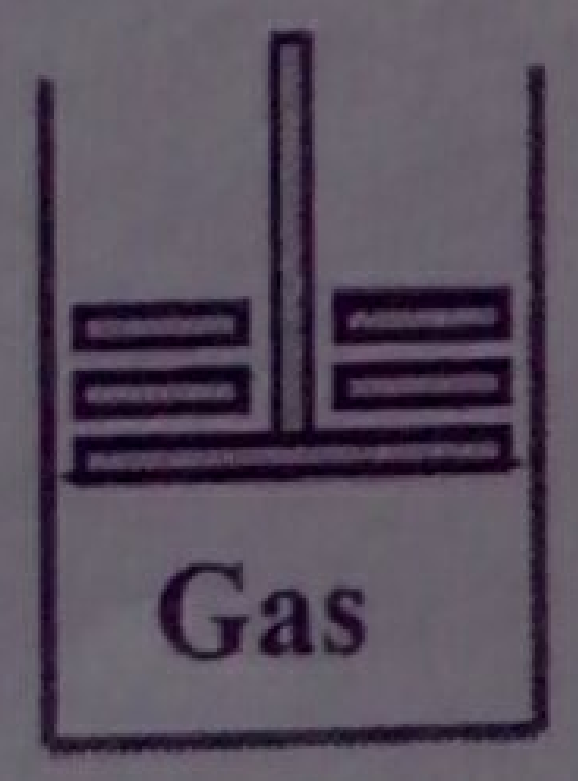
Quasi-static Processes

The processes can be restrained or unrestrained

We need restrained processes in practice.

A quasi-static process is one in which

- The deviation from thermodynamic equilibrium is infinitesimal.
- All states of the system passes through are equilibrium states.



Equilibrium State

- A system is said to be in an equilibrium state if its properties will not change without some perceivable effect in the surroundings.
- Equilibrium generally requires all properties to be uniform throughout the system.
- There are mechanical, thermal, phase, and chemical equilibria

Types of Equilibrium

Between the system and surroundings, if there is no difference in

- Pressure → Mechanical equilibrium
- Potential → Electrical equilibrium
- Concentration of species → Species equilibrium
- Temperature → Thermal equilibrium

No interactions between them occur.
They are said to be in equilibrium.

Thermodynamic equilibrium implies all those together.
A system in thermodynamic equilibrium does not deliver anything.

Zeroth Law Of Thermodynamics (Contd…)

- Two systems are said to be equal in temperature, when there is no change in their respective observable properties when they are brought together. In other words, "when two systems are at the same temperature they are in thermal equilibrium" (They will not exchange heat).

Note:They need not be in thermodynamic equilibrium.

Explanation of Zeroth Law

- Let us say T_A,T_B and T_C are the temperatures of A,B and C respectively.
- A and c are in thermal equilibrium. $T_a = t_c$
- B and C are in thermal equilibrium. $T_b = t_c$

Consequence of of '0'th law

- A and B will also be in thermal equilibrium $T_A = T_B$
- Looks very logical
- All temperature measurements are based on this LAW.

Module 2

Work and Heat

Traits of Engineers

- All our efforts are oriented towards how to convert heat to work or vice versa:

Heat to work ➡ Thermal power plant

Work to heat ➡ Refrigeration

- Next, we have to do it in a sustained manner (we cant use fly by night techniques!!)

- We require a combination of processes.
- Sustainability is ensured from a cycle
- A system is said to have gone through a cycle if the initial state has been regained after a series of processes

Types of Work Interaction

Types of work interaction

- Expansion and compression work (displacement work)
- Work of a reversible chemical cell
- Work in stretching of a liquid surface
- Work done on elastic solids
- Work of polarization and magnetization

Various Types of Work

- Displacement work (pdV work)
- Force exerted, $F = p.A$
- Work done

$dW = F.dL = p.A\,dL = p.dV$

- If the piston moves through a finite distance say 1-2,Then work done has to be evaluated by integrating $\delta W = \int pdV$

We Concentrate On Two Categories Of Heat And Work

- Thermodynamic definition of work:

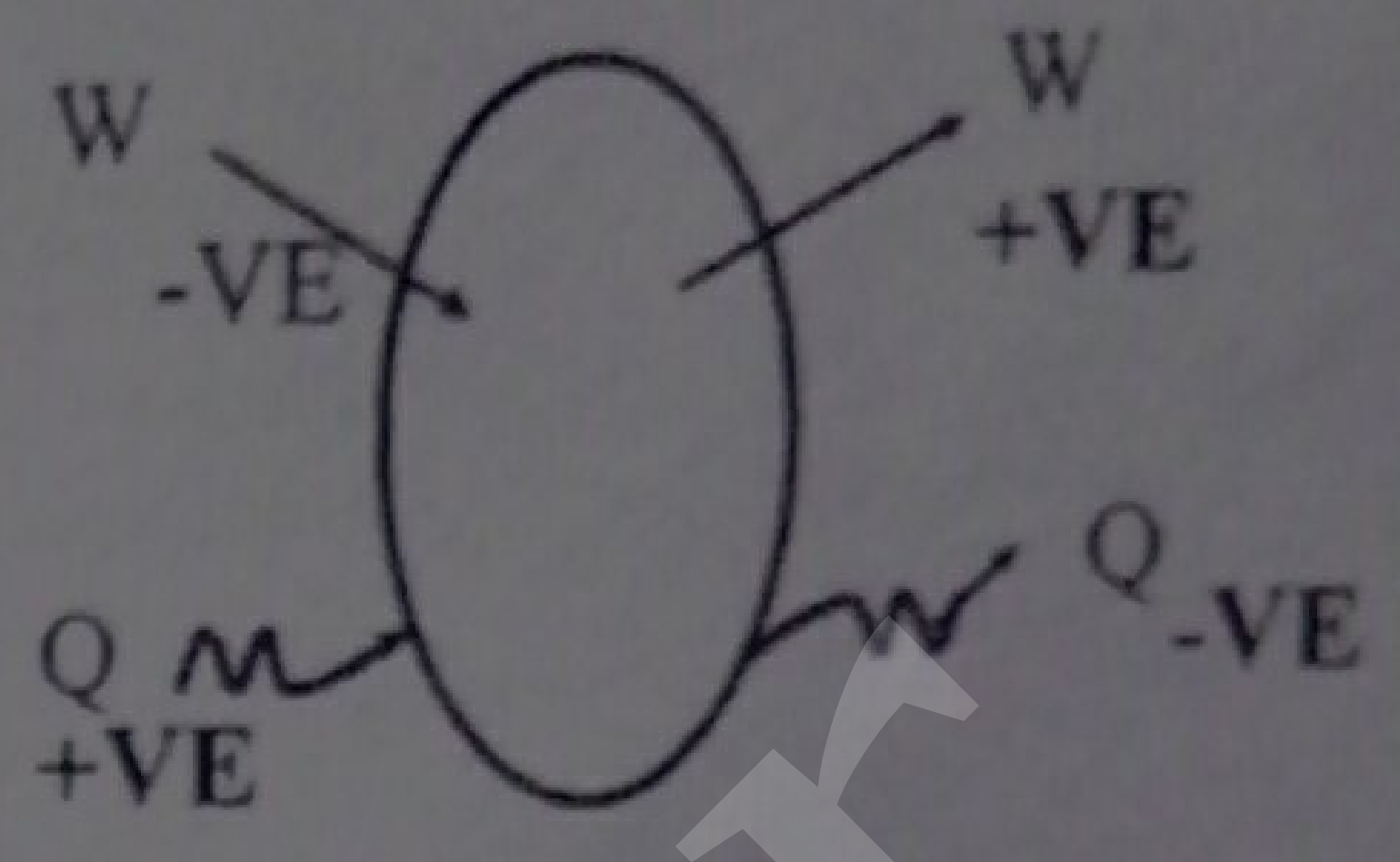
  Positive work is done by a system when the sole effect external to the system could be reduced to the rise of a weight.

- Thermodynamic definition of heat:

  It is the energy in transition between the system and the surroundings by virtue of the difference in temperature.

Sign Conventions

- 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



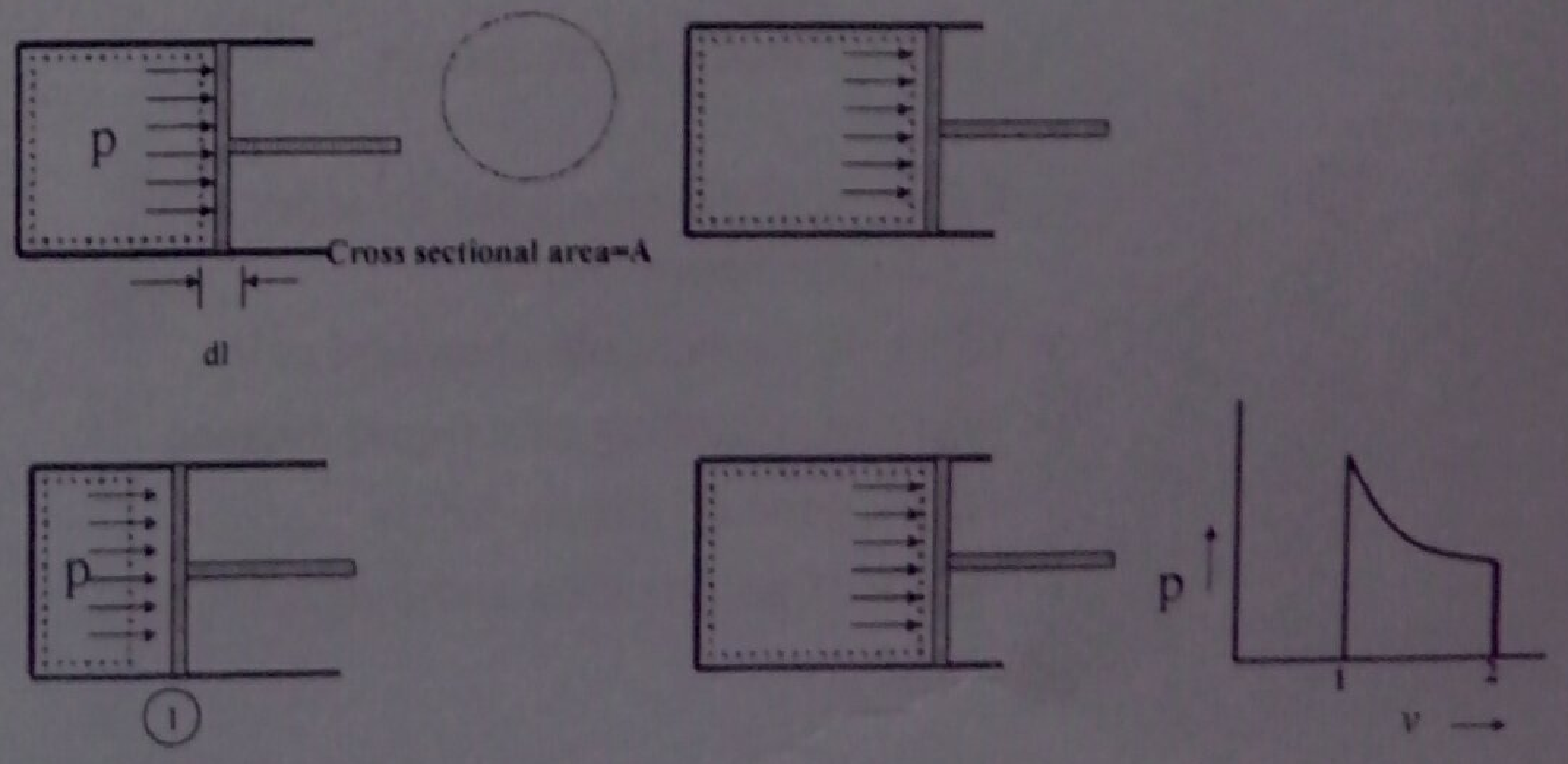
Notes on Heat

- All temperature changes need not be due to heat alone

  eg: Friction
- All heat interaction need not result in changes in temperature

  eg: condensation or evaporation

Work (Contd…)



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Discussion on Work Calculation

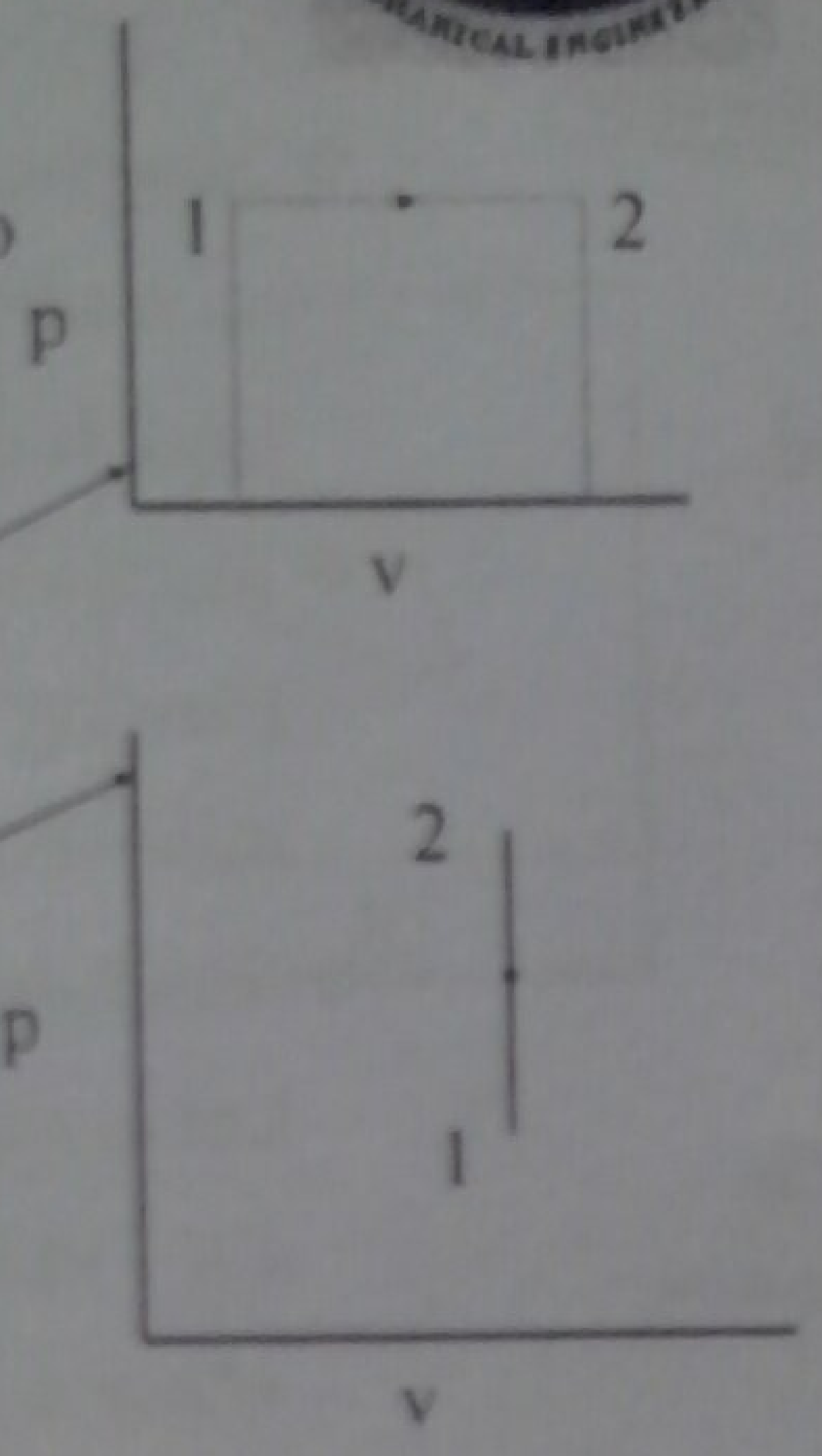
The system (shown by the dotted line) has gone through a change of state from 1 to 2.We need to know how the pressure and volume change.

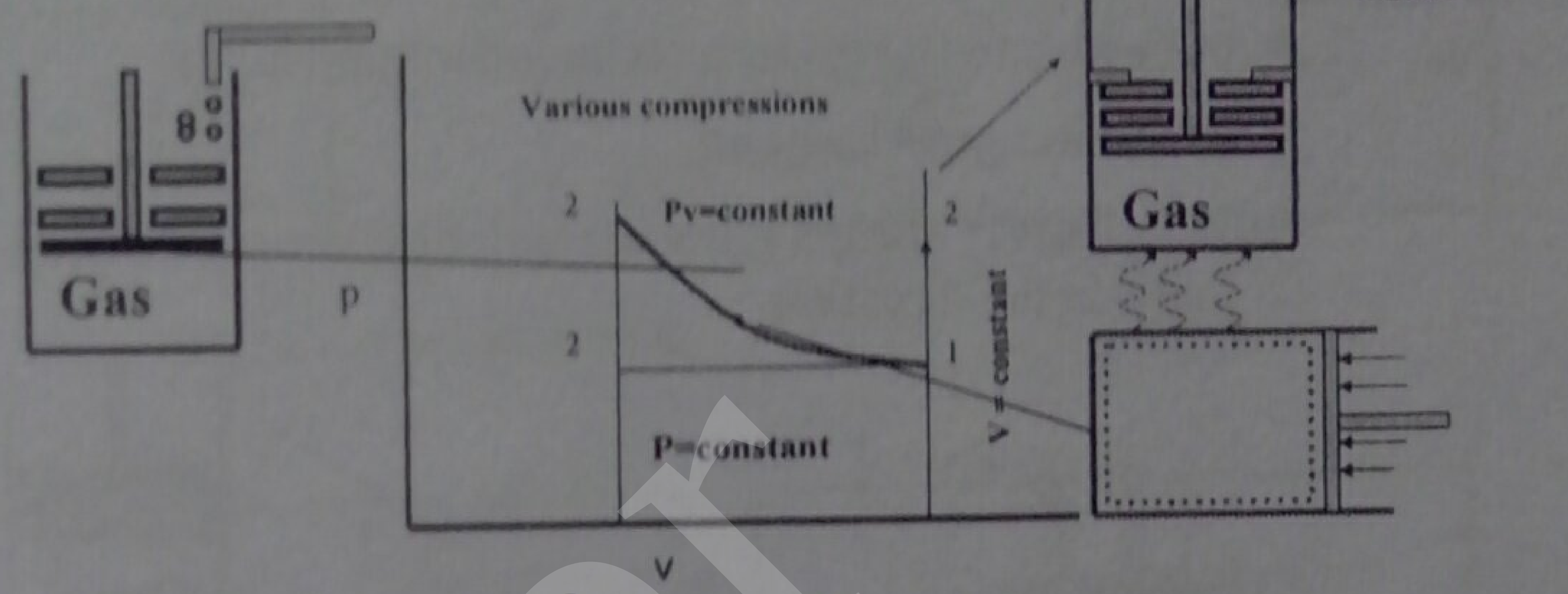
Possibilities:

- Pressure might have remained constant

  or
- It might have undergone a change as per a relation p (V)

  or
- The volume might have remained constant In general the area under the process on p-V plane gives the work





- n= 0 Constant pressure (${V_2}>{V_1}$ - expansion)
- n=1 pv=constant (${p_2}<{p_1}$; ${V_2}>{V_1}$ - expansion)
- n= ∞ Constant volume (${p_2}<{p_1}$ - cooling)

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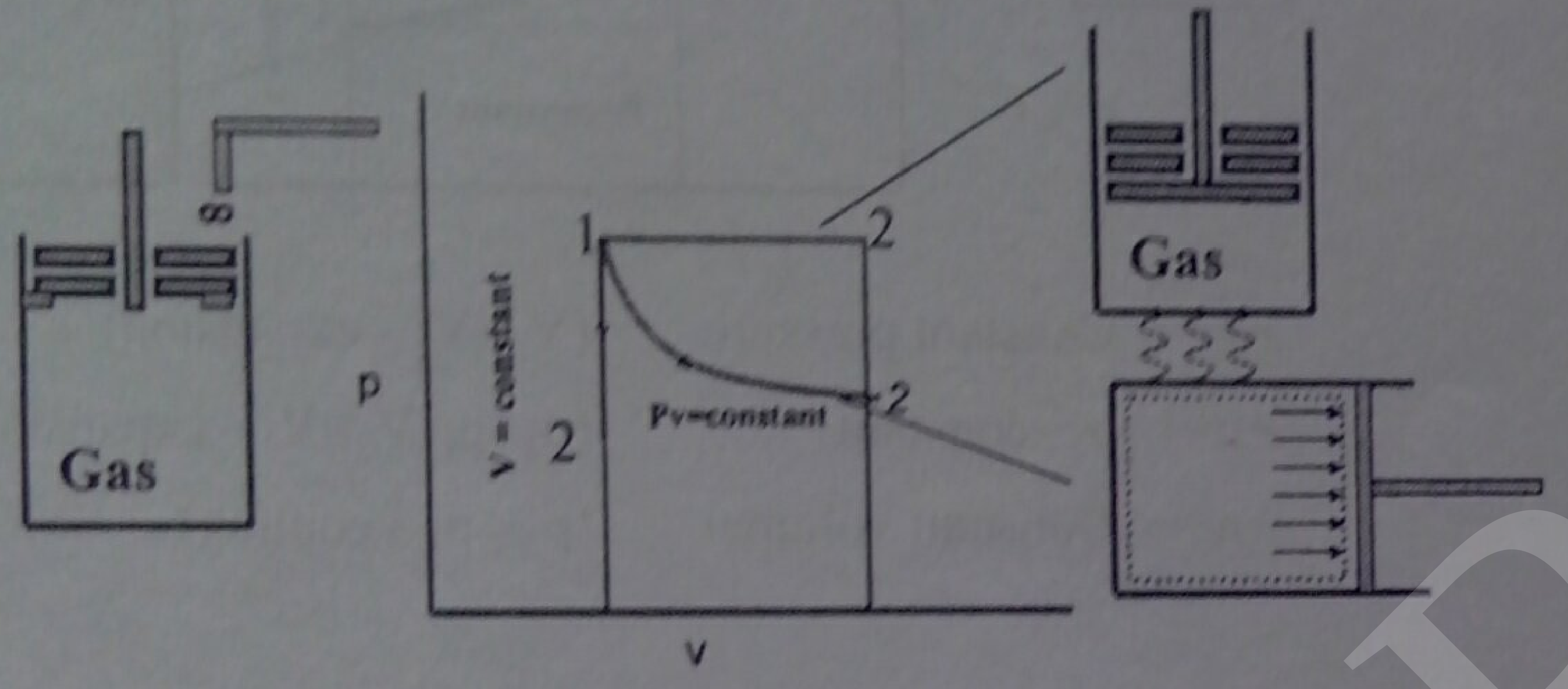
Other Possible Process

- pv=constant (it will be a rectangular hyperbola)
- In general pv^n= constant

IMPORTANT: always show the states by numbers/alphabet and indicate the direction.



Others Forms Of Work

- Stretching of a wire:

Let a wire be stretched by dL due to an application of a force F

Work is done on the system. Therefore dW=-FdL

- Electrical Energy:

Flowing in or out is always deemed to be work

dW= -EdC= -EIdt

- Work due to stretching of a liquid film due to surface tension:

Let us say a soap film is stretched through an area dA

dW= -σdA

where σ is the surface tension.

First Law of Thermodynamics

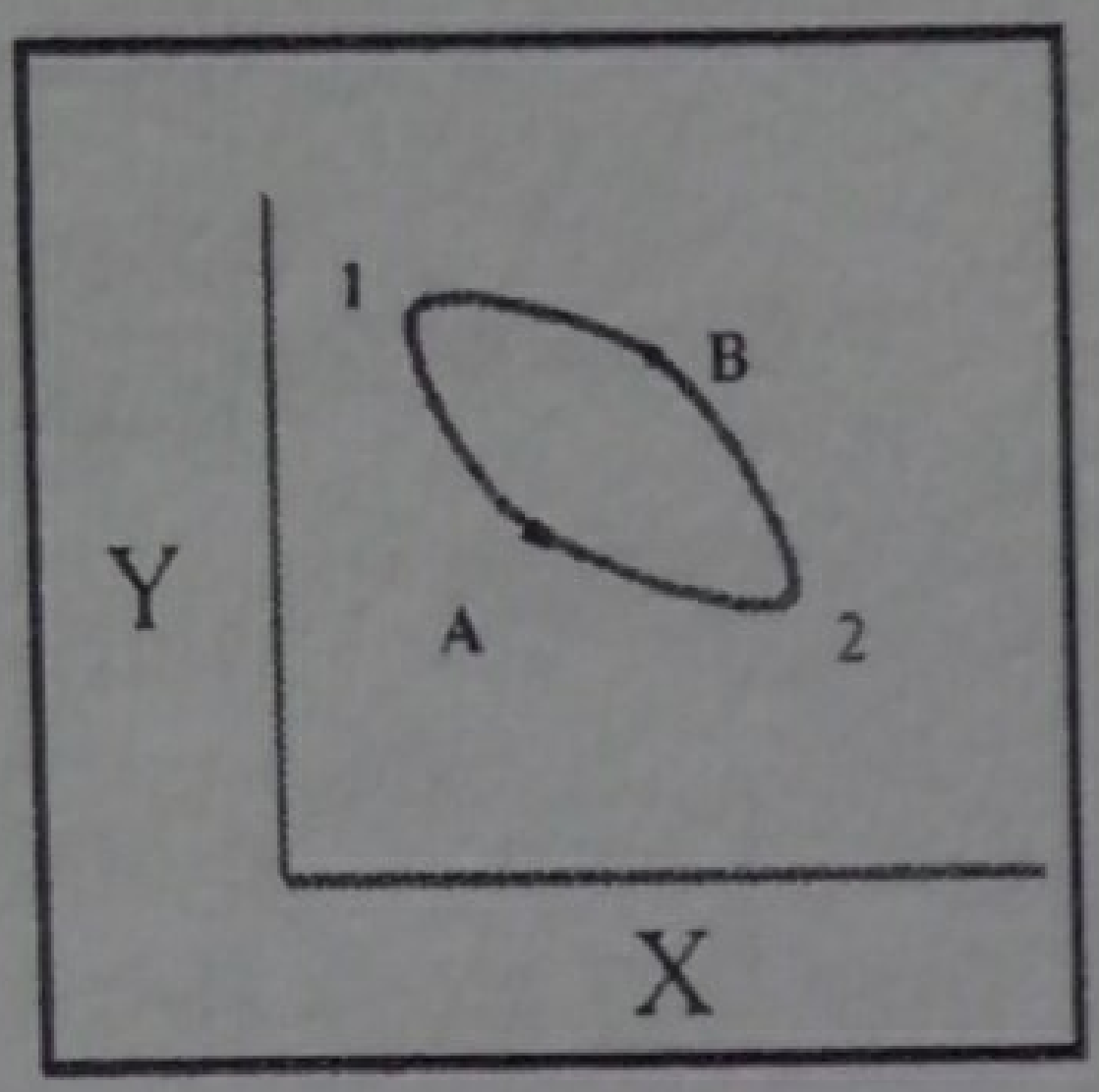
Statement:

- When a closed system executes a complete cycle the sum of heat interactions is equal to the sum of work interactions.

Mathematically

- $\Sigma Q = \Sigma W$

The summations being over the entire cycle



First Law (Contd…)

$$Q_{A1-2} = \int_1^2 \delta Q$$

Along path A

$$\int_1^2 (\delta Q - \delta W) + \int_2^1 (\delta Q - \delta W) = 0$$

Along path A, Along path B

Which can be written as

$$\int_1^2 (\delta Q - \delta W) - \int_1^2 (\delta Q - \delta W) = 0$$

Along path A, Along path B

$$\int_1^2 (\delta Q - \delta W) = \int_1^2 (\delta Q - \delta W)$$

Along path A, Along path B

First Law (contd…)

- This implies that the difference between the heat and work interactions during a process is a property of the system.
- This property is called the energy of the system. It is designated as E and is equal to some of all the energies at a given state.

First Law(contd…)

- An isolated system which does not interact with the surroundings Q=0 and W=0. Therefore, E remains constant for such a system.
- Let us reconsider the cycle 1-2 along path A and 2-1 along path B as shown in fig.
- Work done during the path A = Area under 1-A-2-3-4
- Work done during the path B = Area under 1-B-2-3-4
- Since these two areas are not equal, the net work interaction is that shown by the shaded area.

Module 3

First law of thermodynamics

First Law (Contd…)

Alternate statement:

When a closed system undergoes a cycle the cyclic integral of heat is equal to the cyclic integral of work.

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

In other words for a two process cycle

$$Q_{A1-2}+Q_{B2-1}=W_{A1-2}+W_{B\,2-1}$$

First Law (contd…)

- Since A and B are arbitrarily chosen, the conclusion is, as far as a process is concerned (A or B) the difference $\delta Q - \delta W$ remains a constant as long as the initial and the final states are the same. The difference depends only on the end points of the process. Note that Q and W themselves depend on the path followed. But their difference does not.

First Law(contd…)

We enunciate the FIRST LAW for a process as

$\delta Q - \delta W = dE$

E consists of ➡ $E=U+KE+PE$

U -internal energy

KE - the kinetic energy

PE - the potential energy

For the whole process A ⟹ $Q-W=E_2-E_1$

Similarly for the process B ⟹ $Q-W=E_1-E_2$

First Law (contd…)

- Thus, the first law can be construed to be a statement of conservation of energy - in a broad sense.
- In the example shown the area under curve A < that under B
- The cycle shown has negative work output or it will receive work from the surroundings. Obviously, the net heat interaction is also negative. This implies that this cycle will heat the environment. (as per the sign convention).

Engineering Implications

- When we need to derive some work, we must expend thermal/internal energy.
- Whenever we expend heat energy, we expect to derive work interaction (or else the heat supplied is wasted or goes to to change the energy of the system).
- If you spend money, either you must have earned it or you must take it out of your bank balance!!
- !!There is nothing called a free lunch!!

Engineering Applications (contd…)

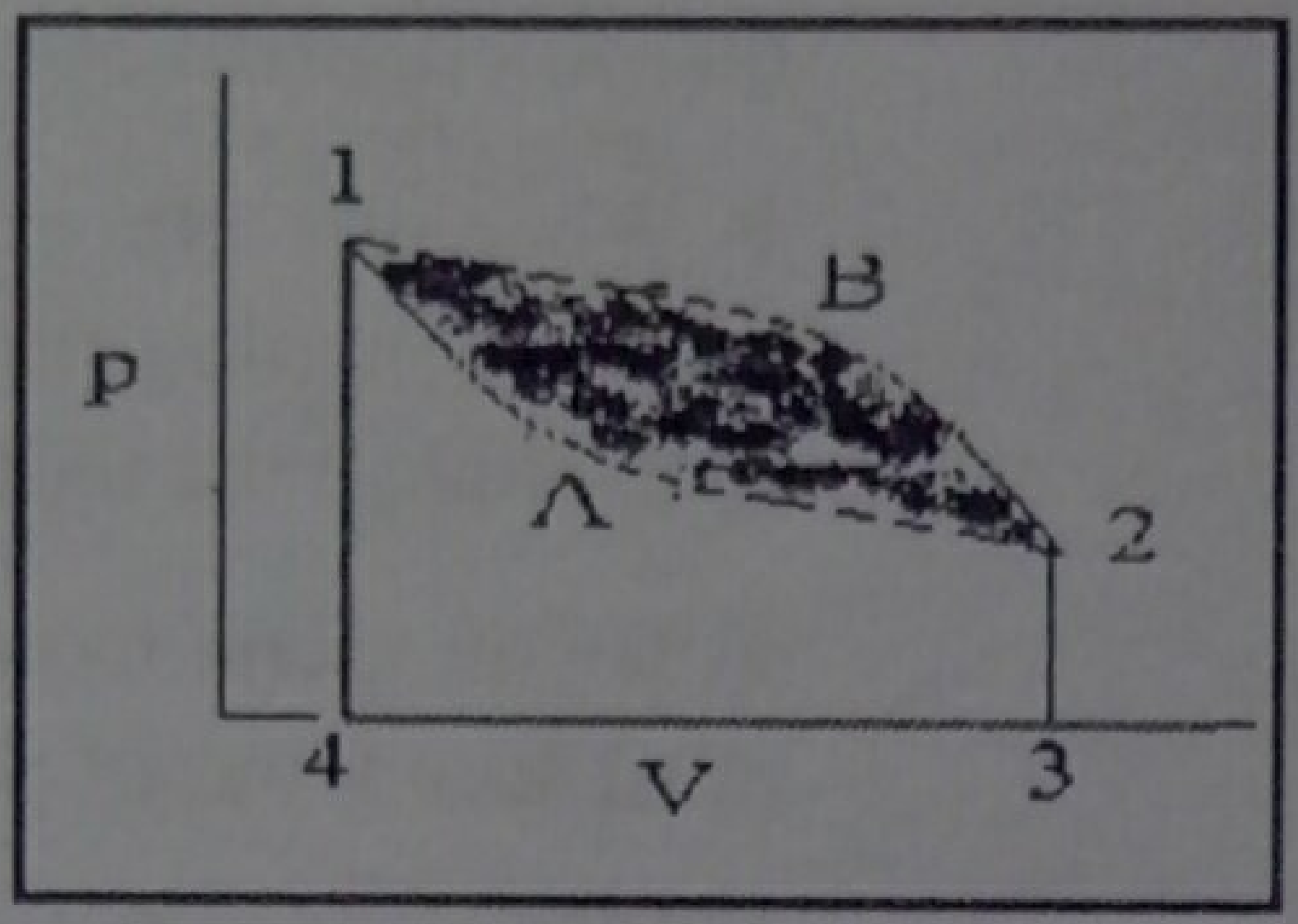
- It appears that heat (Q) is not a property of the system but the energy (E) is.
  - ❖ How do we distinguish what is a property of the system and what is not?
- The change in the value of a "property" during a process depends only on the end states and not on the path taken by a process.
- In a cycle the net in change in "every property" is zero.

Analogy

- Balance in your bank account is a property. The deposits and withdrawals are not.
- A given balance can be obtained by a series of deposits and withdrawals or a single large credit or debit!

First Law (Contd…)

- The net area is 1A2B1.
- Therefore some work is derived by the cycle.
- First law compels that this is possible only when there is also heat interaction between the system and the surroundings.
- In other words, if you have to get work out, you must give heat in.



First Law(contd…)

- For a process we can have Q=0 or W=0
- We can extract work without supplying heat(during a process) but sacrificing the energy of the system.
- We can add heat to the system without doing work(in process) which will go to increasing the energy of the system.
- Energy of a system is an extensive property

Engineering implications (contd…)

- The first law introduces a new property of the system called the energy of the system.
- It is different from the heat energy as viewed from physics point of view.
- We have "energy in transition between the system and the surroundings" which is not a property and "energy of the system" which is a property.

Engineering implications (contd…)

- If the magnitude of an entity related to the system changes during a process and if this depends only on the end states then the entity is a property of the system. (Statement 3 is corollary of statement 1)

HEAT and WORK are not properties because they depend on the path and end states.

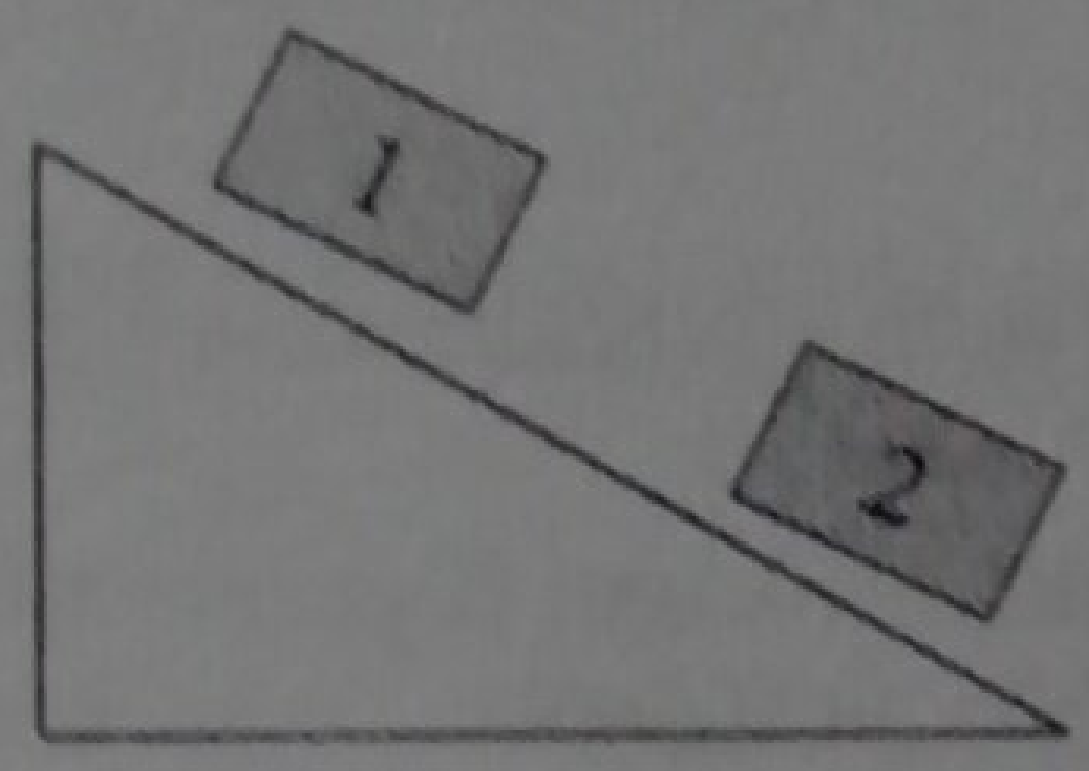
HEAT and WORK are not properties because their net change in a cycle is not zero.

Analogy(Contd)

- Between 2 successive 1 Januarys you had made several deposits and several withdrawals but had the same balance, then you have performed a cycle. - *it means that they have been equalled by prudent budgeting!!*

- Energy - balance; Deposits - heat interactions; Withdrawals - work interactions.
- Mathematically properties are called point functions or state functions
- Heat and work are called path functions.

Analogy (contd…)



Conducting plane; Insulating rough block in vacuum

System	Q	W	ΔE
Block	0	+	-
Plane	0	-	+
Block+plane	0	0	0

First law (Contd…)

- Extensive properties are converted to specific extensive properties (which will be intensive properties) ., i.E.., U and E with the units kJ/kg.
- A system containing a pure substance in the standard gravitational field and not in motion by itself, if electrical, magnetic fields are absent (most of these are satisfied in a majority of situations) ‘u’ will be ‘e’.

Flow Process

Steady flow energy equation:

- Virtually all the practical systems involve flow of mass across the boundary separating the system and the surroundings. Whether it be a steam turbine or a gas turbine or a compressor or an automobile engine there exists flow of gases/gas mixtures into and out of the system.
- So we must know how the first Law of thermodynamics can be applied to an open system.

Analogy (contd…)

Balance is deposits *minus* withdrawals	Energy is heat *minus* work
❖ If there are no deposits and if you have enough balance, you can withdraw. But the balance will Will diminish	If the system has enough energy you can extract work without adding heat.but the energy diminish
❖ If you don't withdraw but keep depositing your balance will go up.	If you keep adding heat but don't extract any work, the system energy will go up.

Analogy (contd…)

To sum up:

I law for a cycle:	$\oint \delta Q = \oint \delta W$
I law for a process is	$Q - W = \Delta E$
For an isolated system	$Q=0$ and $W=0$.

Therefore $\Delta E=0$

Analogy (Contd…)

- ➢ The first law introduces the concept of energy in the thermodynamic sense.
- ➢Does this property give a better description of the system than pressure, temperature, volume, density?

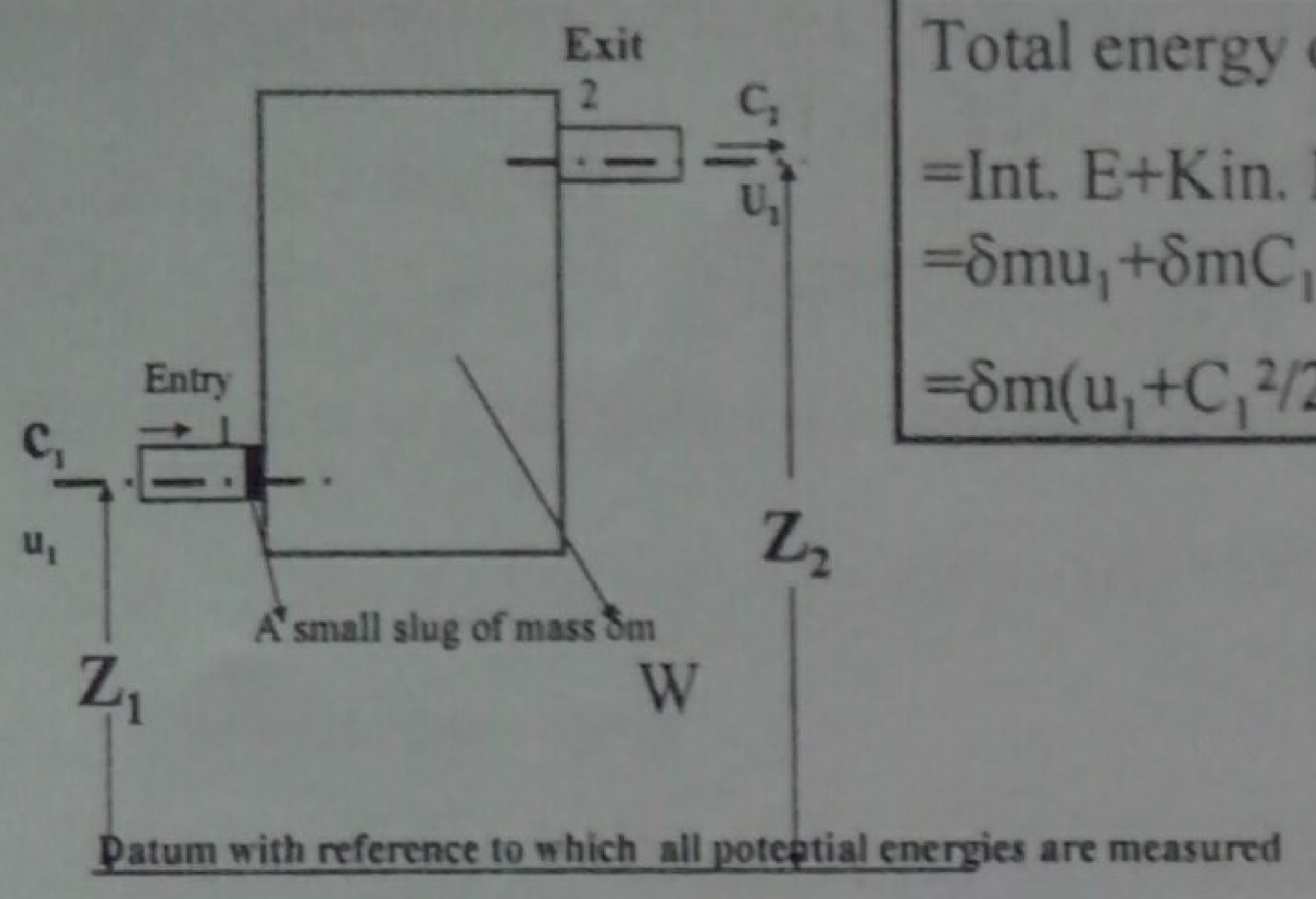
The answer is yes, in the broad sense.

- ➢ It is U that is often used rather than E. (Why? - KE and PE can change from system to system).
- ➢They have the units of kJ

First law (Contd…)

➢The I law now becomes $Q - W = \Delta U$	$\delta Q - \delta W = \delta U$
➢Per unit mass of the contents of the system	$(Q - W)/m = \Delta u$
➢If only displacement work is present	$\delta Q - pdV = dU$
➢Per unit mass basis	$\delta q - pdv = du$
➢Which can be rewritten as	$\delta q = du + pdv$

SFEE(Contd…)



Total energy of the slug at entry

=Int. E+Kin. E+ Pot. E

$=\delta m u_1+\delta m C_1^2/2+\delta m g Z_1$

$=\delta m(u_1+C_1^2/2+gZ_1)$

Focus attention on slug at entry-1

SFEE(Contd…)

- To push this slug in the surroundings must do some work.

If p_1 is the pressure at 1,

v_1 is the specific volume at 1,

This work must be $-p_1 dm\ v_1$

(-ve sign coming in because it is work done on the system)

SFEE (contd…)

- The energy of the system should have been

$= E' + \delta m\ (u_2+C_2^2/2+gZ_2)$

- So that even after the slug has left, the original E' will exist.

- We assume that δm is the same. This is because what goes in must come out.

SFEE (contd…)

- The net work interaction for the system is
- $W+p_2\delta m\ v_2-p_1\delta m\ v_1=W+\delta m(p_2 v_2-p_1 v_1)$
- Heat interaction Q remains unaffected.
- Now let us write the First law of thermodynamics for the steady flow process.

SFEE (contd…)

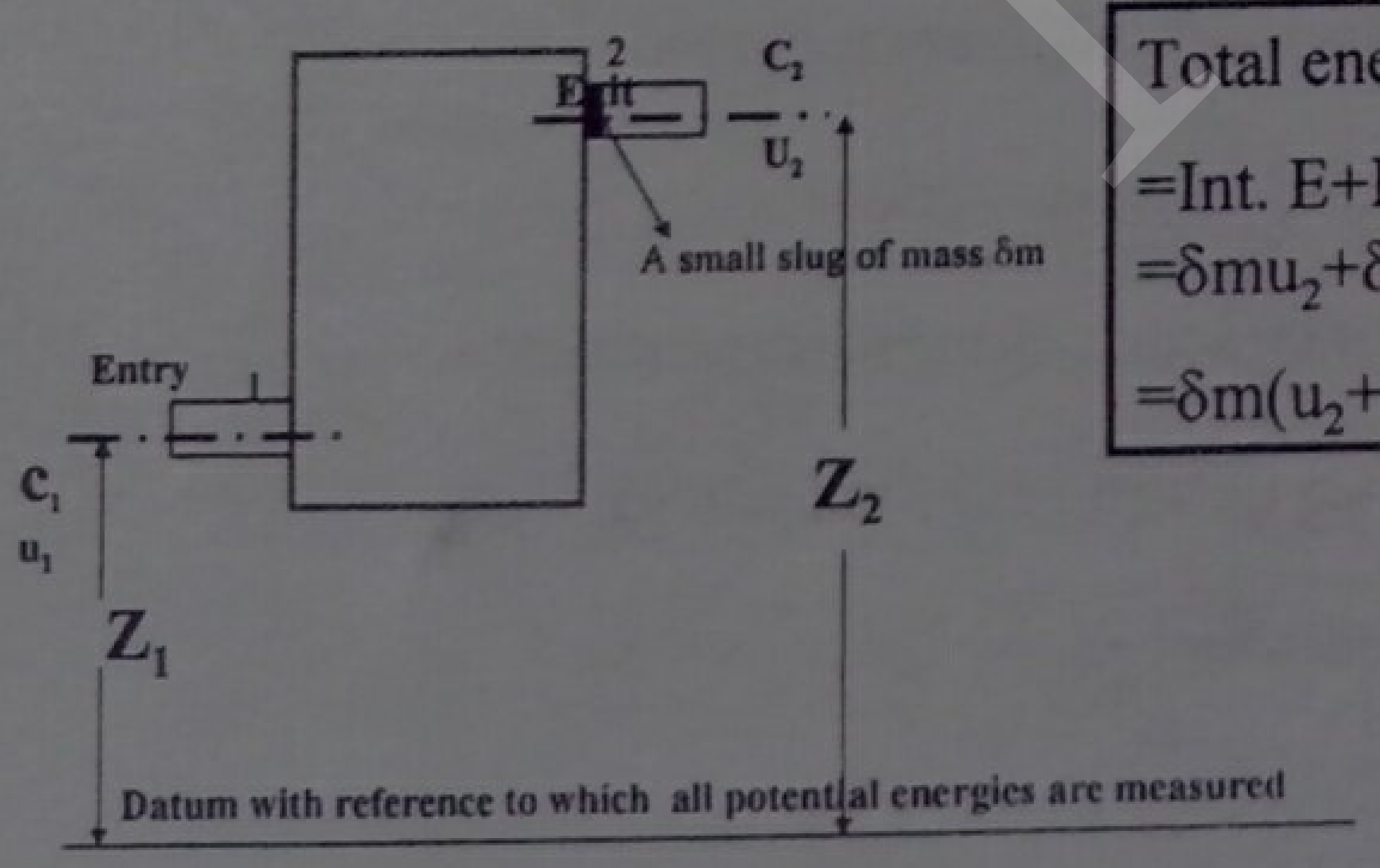
- The fluid entering the system will have its own internal, kinetic and potential energies.
- Let u_1 be the specific internal energy of the fluid entering
- C_1 be the velocity of the fluid while entering
- Z_1 be the potential energy of the fluid while entering
- Similarly let u_2, C_2 and Z_2 be respective entities while leaving.

SFEE(Contd…)

- Initially the system consists of just the large rectangle. Let its energy (including IE+KE+PE) be E'
- The slug is bringing in total energy of $\delta m\,(u_1 + C_1^2/2 + gz_1)$
- The energy of the system when the slug has just entered will be

  $E' + \delta m\,(u_1 + c_1^2/2 + gz_1)$.

SFEE (contd…)



Total energy of the slug at exit

$=$Int. E+Kin. E+ Pot. E

$= \delta m u_2 + \delta m C_2^2/2 + \delta m g Z_2$

$= \delta m(u_2 + C_2^2/2 + gZ_2)$

Focus Attention on Slug at Exit-2

SFEE (contd…)

- To push the slug out, now the system must do some work.

  If p_2 is the pressure at 2,
  v_2 is the specific volume at 2,
  This work must be $+ p_2 \delta m\, v_2$
  (positive sign coming in because it is work done by the system)

SFEE (contd…)

- $Q-[W+dm(p_2 v_2-p_1 v_1)]= dm\,[(u_2+C_2^2/2+gZ_2)-(u_1+C_1^2/2+gZ_1)]$
- $Q-W= dm[(u_2+C_2^2/2+gZ_2+p_2 v_2)-(u_1+C_1^2/2+gZ_1+p_1 v_1)]$
- Recognise that $h=u+pv$ from which $u_2+p_2 v_2=h_2$ and similarly $u_1+p_1 v_1=h_1$
- $Q-W= dm[(h_2+C_2^2/2+gZ_2)-(h_1+C_1^2/2+gZ_1)]$

Per unit mass basis

- $q-w= [(h_2+C_2^2/2+gZ_2)-(h_1+C_1^2/2+gZ_1)]$ or

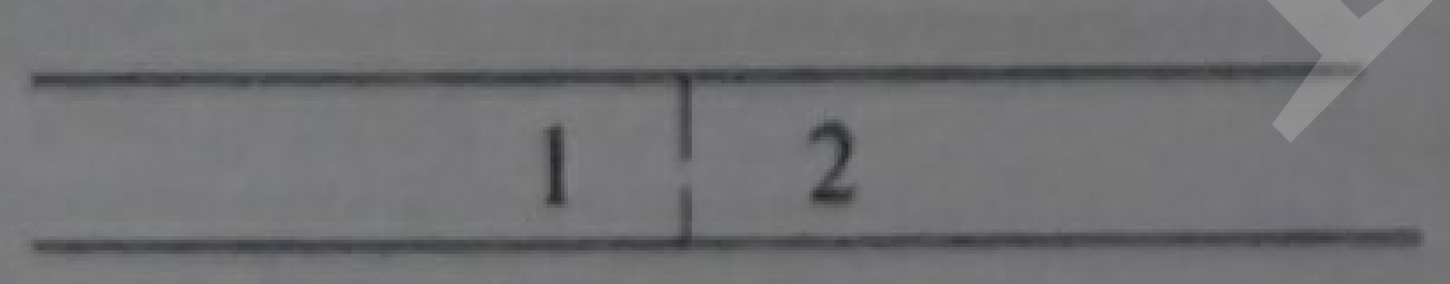
  $= [(h_2-h_1)+(C_2^2/2-C_1^2/2)+g(Z_2-Z_1)]$
- SFEE

Some Notes On SFEE

- If the kinetic energies at entry and exit are small compared to the enthalpies and there is no difference in the levels of entry and exit
- $q-w=(h_2-h_1)=\Delta h$: per unit mass basis or $Q-W= m\Delta h$ (1)
- For a flow process - open system- it is the difference in the enthalpies whereas for a non-flow processes - closed system - it is the difference in the internal energies.

SFEE (Contd…)

Consider a throttling process (also referred to as wire drawing process)



There is no work done (rising a weight) $W=0$

If there is no heat transfer $Q=0$

Conservation of mass requires that $C_1=C_2$

Since 1 and 2 are at the same level $Z_1=Z_2$

From SFEE it follows that $h_1=h_2$

Conclusion: Throttling is a constant enthalpy process (isenthalpic process)

Heat Exchanger (contd…)

- If velocities at inlet and outlet are the same
- All the heat lost by hot fluid is received by the cold fluid. But, for the hot fluid is -ve (leaving the system)
- Therefore $-Q_g= Q_f$

  or $m_g(h_{g1}-h_{g2}) = m_f(h_{f2}-h_{f1})$
- You can derive this applying SFEE to the combined system as well (note that for the combined hot and cold system $Q=0; W=0$
- $0-0 = m_f h_{f2} - m_f h_{f1} + m_g h_{g2} - m_g h_{g1}$

SFEE (contd…)

Now let us write the First law of thermodynamics for the steady flow process.

Heat interaction $= Q$

Work interaction $= W+\delta m(p_2 v_2 - p_1 v_1)$

Internal energy at 2 (E_2) $= [E' + \delta m\,(u_2 + C_2^2/2 + gZ_2)]$

Internal energy at 1 (E_1) $= [E' + \delta m\,(u_1 + C_1^2/2 + gZ_1)]$

Change in internal energy (E_2-E_1)

$$= [E' + \delta m\,(u_2 + C_2^2/2 + gZ_2)] - [E' + \delta m\,(u_1 + C_1^2/2 + gZ_1)]$$

$$= \delta m[(u_2+C_2^2/2+gZ_2) - (u_1+C_1^2/2+gZ_1)]$$

SFEE (contd…)

- The system can have any number of entries and exits through which flows occur and we can sum them all as follows.
- If 1,3,5 … are entry points and 2,4,6… are exit points.

$$Q\text{-}W = [\,m_2(h_2+C_2^2/2+gZ_2) + m_4(h_4+C_4^2/2+gZ_4) + m_6(h_6+C_6^2/2+gZ_6) + \ldots\ldots.]$$

$$-\,[\,m_1(h_1+C_1^2/2+gZ_1) + m_3(h_3+C_3^2/2+gZ_3) + m_5(h_5+C_5^2/2+gZ_5) + \ldots\ldots.]$$

It is required that $m_1+m_3+m_5\ldots.=m_2+m_4+m_6+\ldots..$

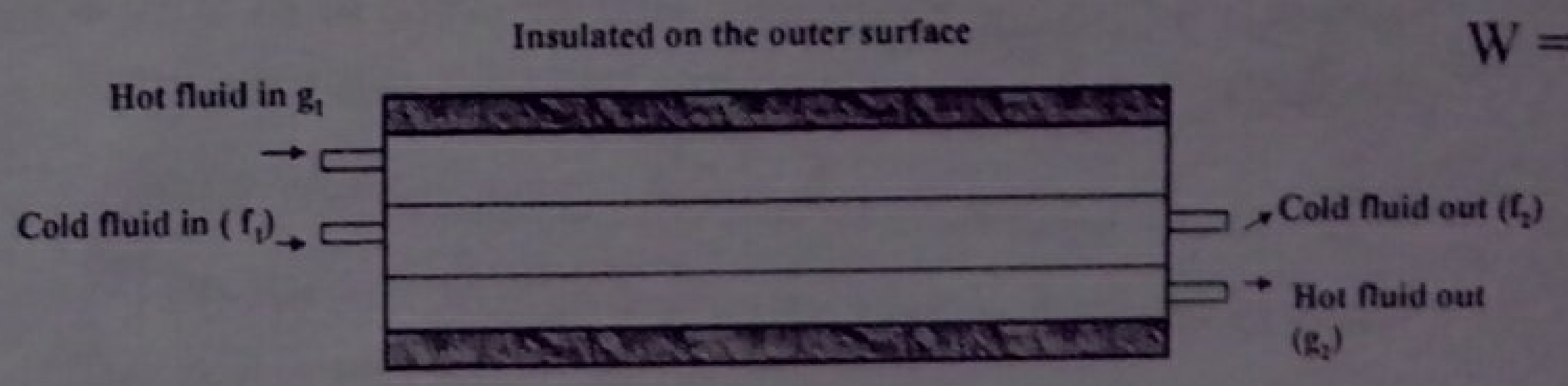
which is the conservation of mass (what goes in must come out)

SFEE (contd…)

- pv is called the "flow work". This is not thermodynamic work and can't rise any weight, but necessary to establish the flow.
- For an adiabatic process q = 0
  - $-w = \Delta h$ (2)
- ie., any work interaction is only due to changes in enthalpy.
- Note that for a closed system it would have been $-w = \Delta u$

Heat Exchanger

W =0

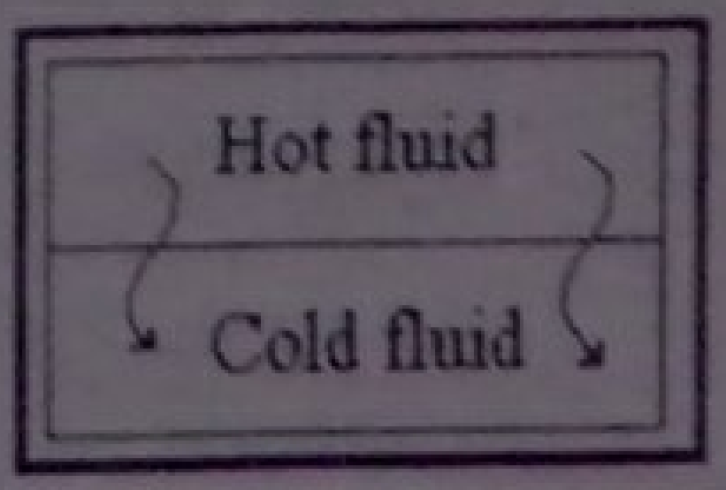


Hot fluid

$Q_g=m_g(h_{g2}-h_{g1})$

Cold fluid

$Q_f=m_f(h_{f2}-h_{f1})$



Adiabatic Nozzle
(Contd…)

- If h_1 is sufficiently high we can convert it into kinetic energy by passing it through a nozzle. This is what is done to steam at high pressure and temperature emerging out of a boiler or the products of combustion in a combustion chamber (which will be at a high temperature and pressure) of a gas turbine plant. Usually, C_1 will be small - but no assumptions can be made.

Air Conditioning Process
(Contd…)

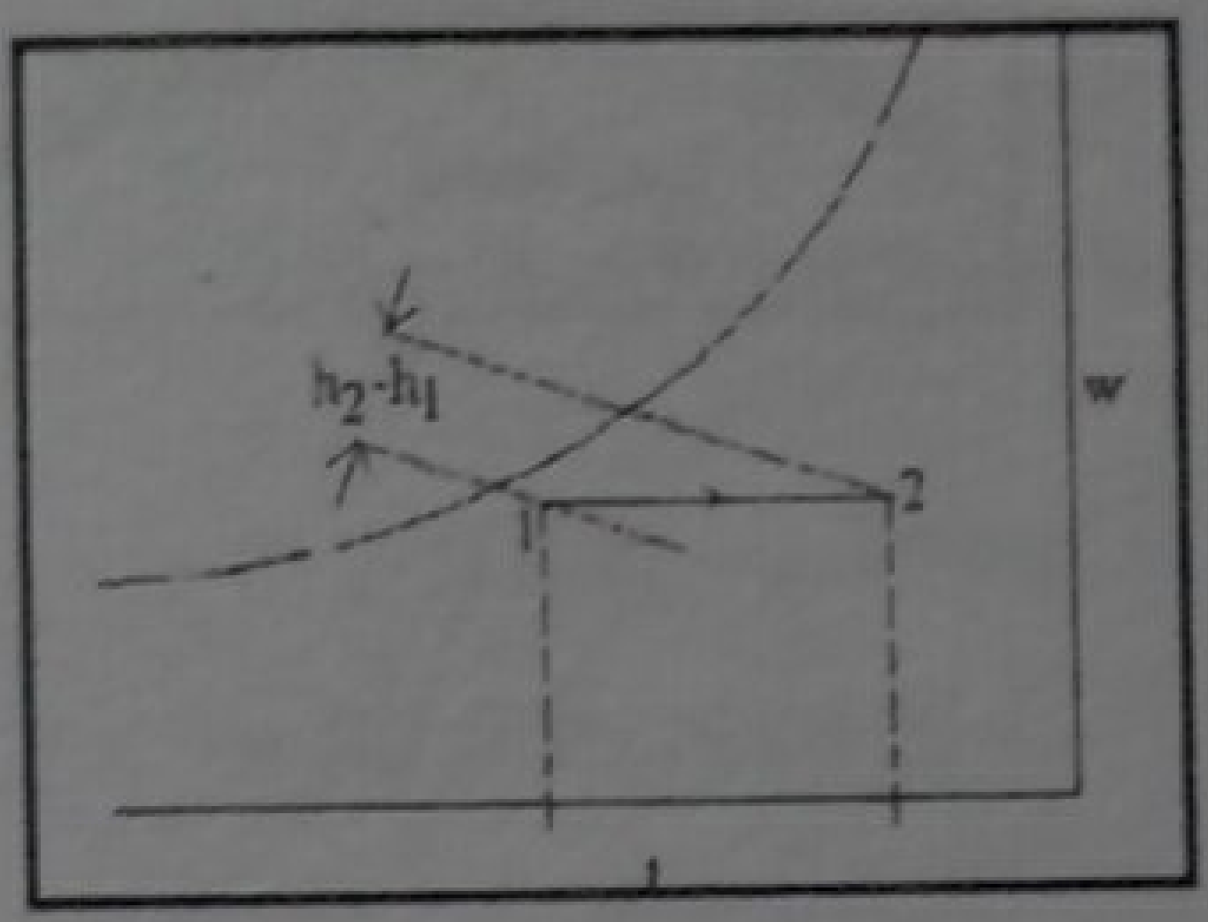
2. Cooling of moist air:

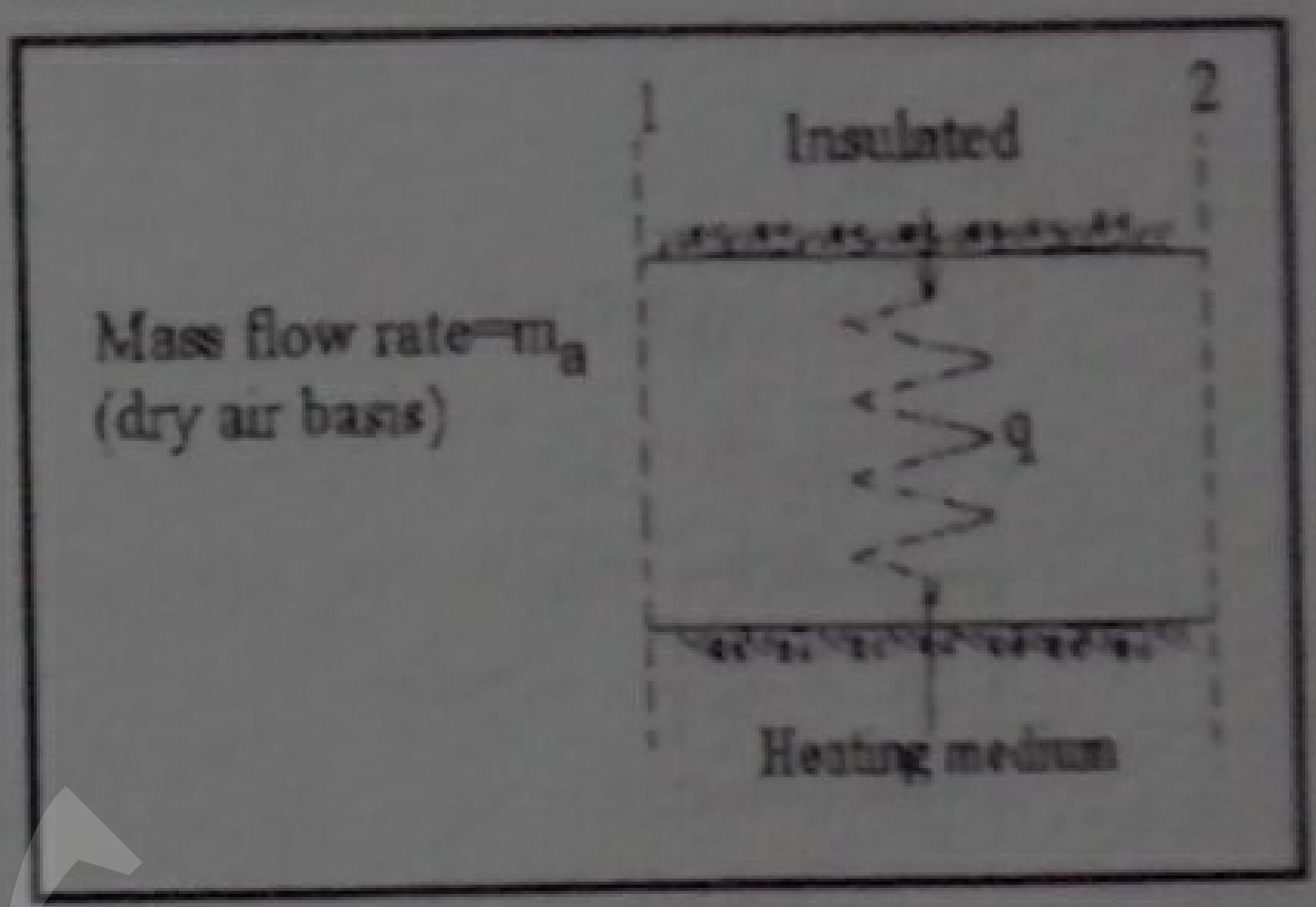
Two possibilities:

a) Sensible cooling (the final state is not below the dew point)

$-q-0= m_a(h_2-h_1)$ or $q= m_a(h_1-h_2)$

Air will leave at a lower enthalpy than at inlet.





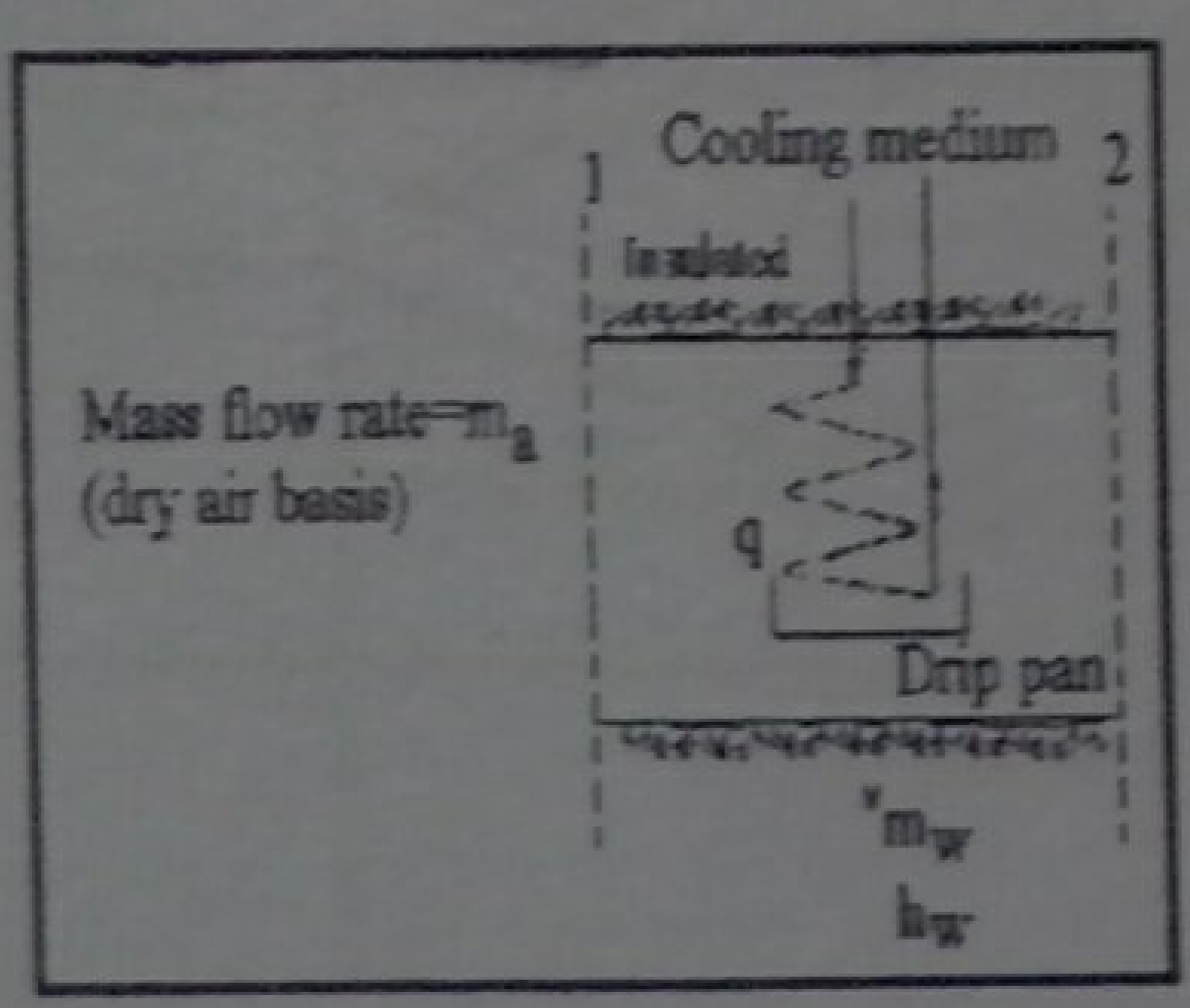
Moisture Air
(Contd…)

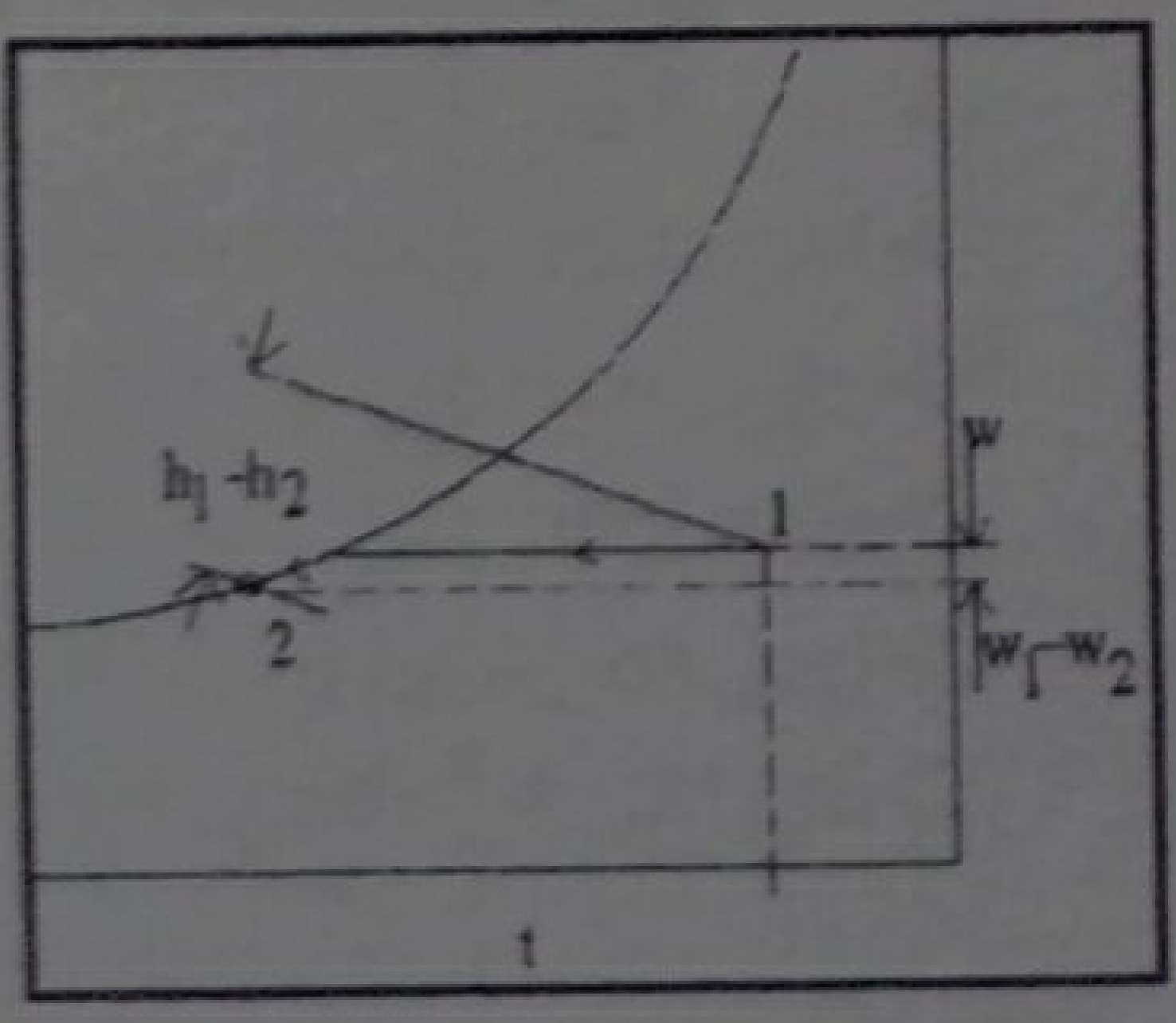
$m_a W_1 = m_a W_2 + m_w$

$m_w = m_a (W_1 - W_2)$

Substituting into SFEE

$q = m_a[(h_1-h_2) - (W_1 - W_2) h_w]$

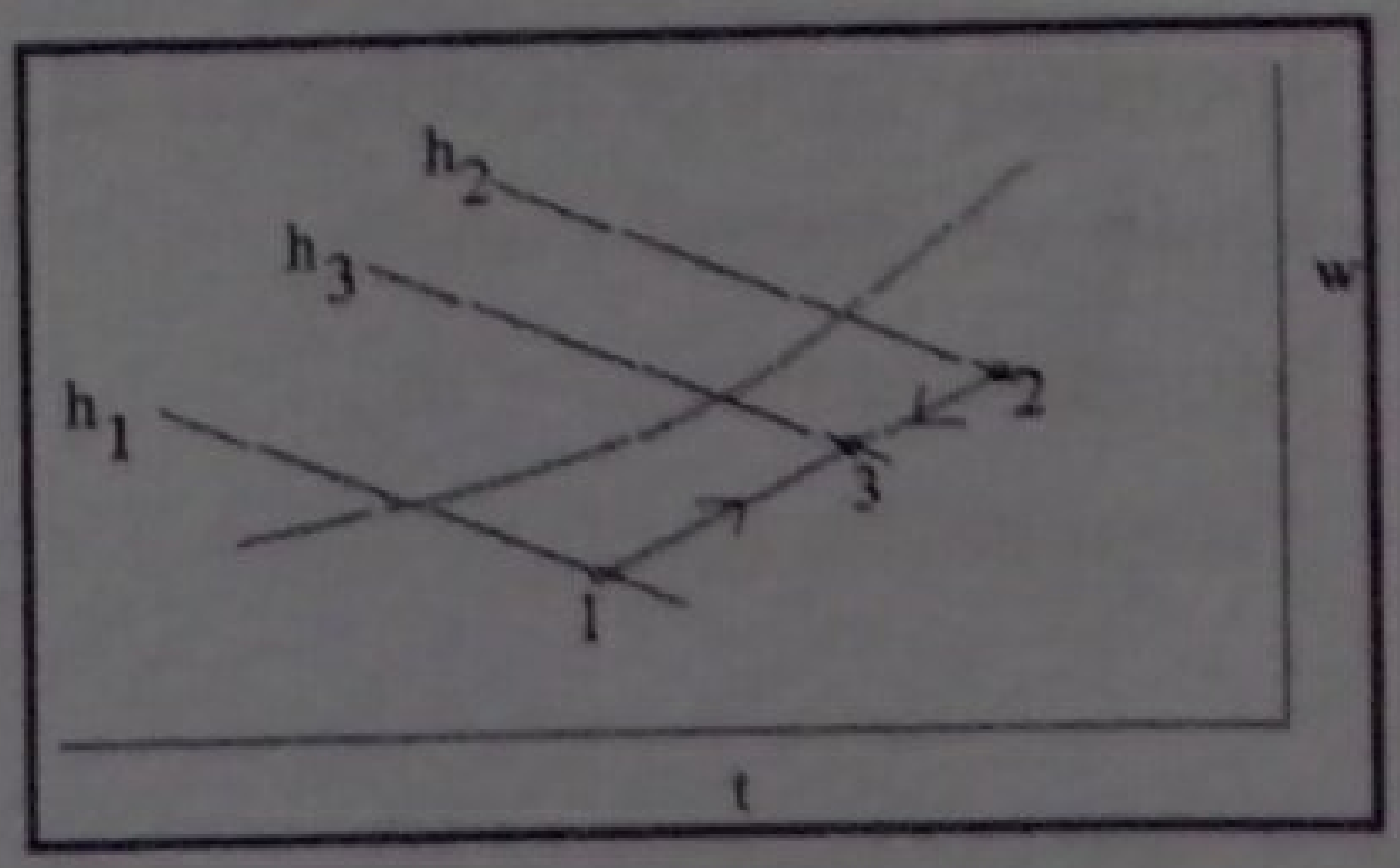




Adiabatic mixture
(contd…)

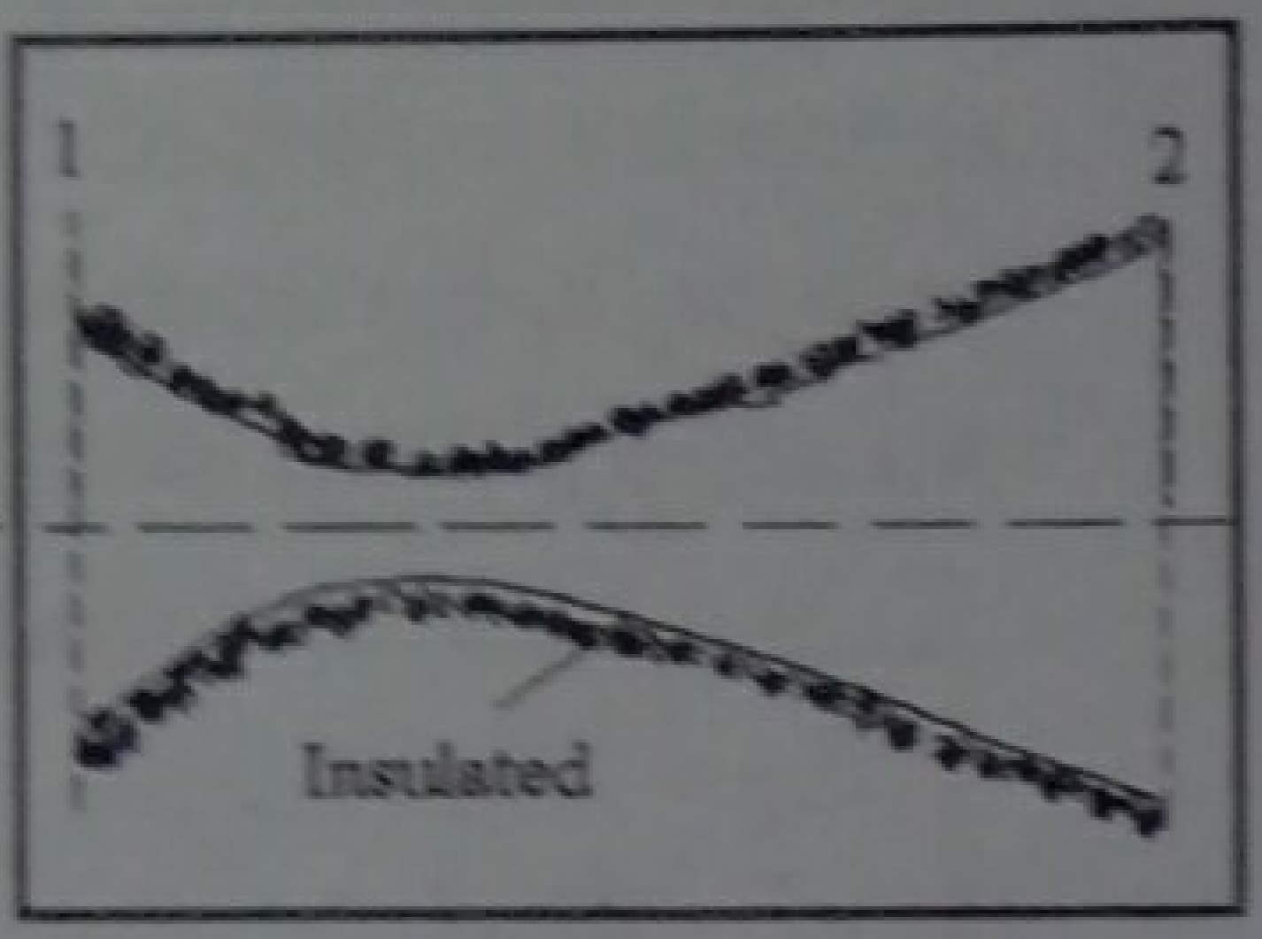
$$\boxed{\frac{(w_3-w_1)}{(w_2-w_3)} = \frac{m_{a2}}{m_{a1}}}$$

$$\boxed{\frac{(t_3-t_1)}{(t_2-t_3)} = \frac{m_{a2}}{m_{a1}}}$$



Adiabatic Nozzle

Normally used in turbine based power production.
It is a system where the kinetic energy is not negligible compared to enthalpy.



Q=0

W=0

SFEE becomes

$0-0=h_2-h_1+(c_2^2/2-c_1^2/2)$

$\boxed{\frac{c_2^2}{2} - \frac{c_1^2}{2}} = h_1-h_2$

Analysis of Air Conditioning Process

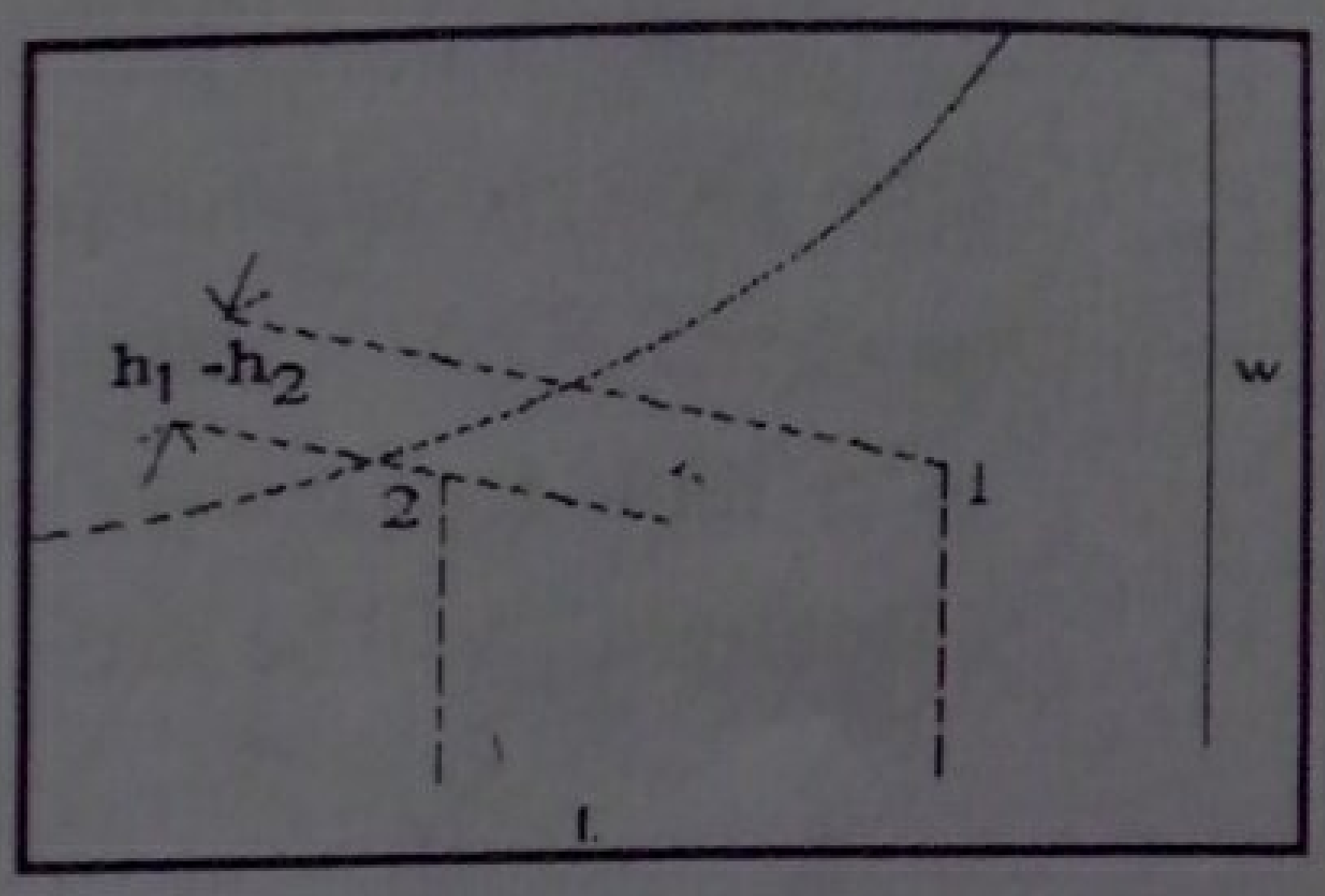
1.Heating of Moist Air

Application of SFEE

(system excluding the heating element)

$q-0= m_a(h_2-h_1)$

Air will leave at a higher enthalpy than at inlet.



Moist Air (contd…)

b.Moisture separates out

- SFEE yields

$-q-0= m_a(h_2-h_1) + m_w h_w$

- Moisture conservation

Humidity ratio of entering air at 1=W_1

Moisture content = $m_a W_1$

Humidity ratio of leaving air at 2 =W_2

Moisture content = $m_a W_2$

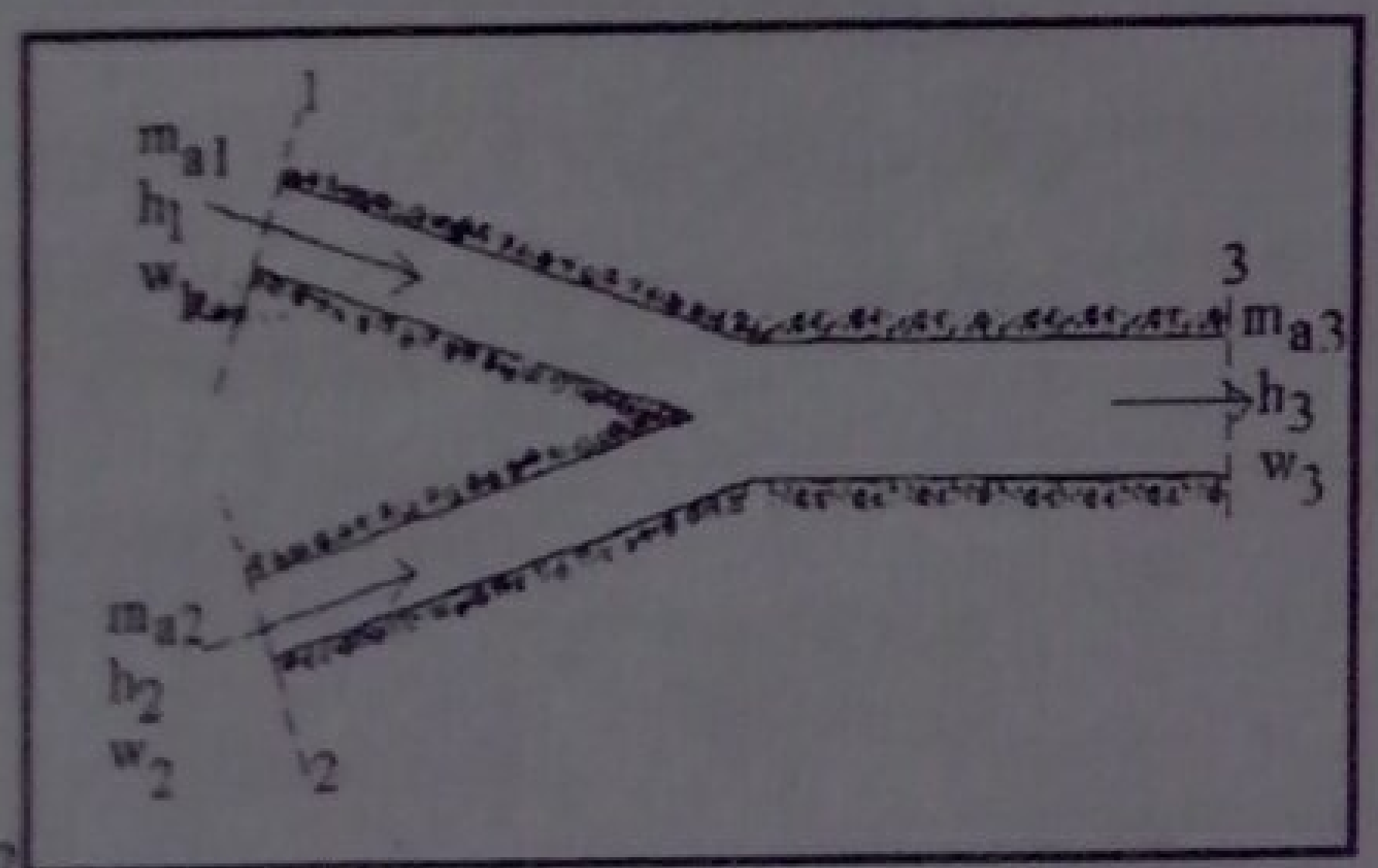
Moisture removed = m_w

- What enters must go out !

3.Adiabatic Mixture of Two Streams of Air at Separate States

SFEE

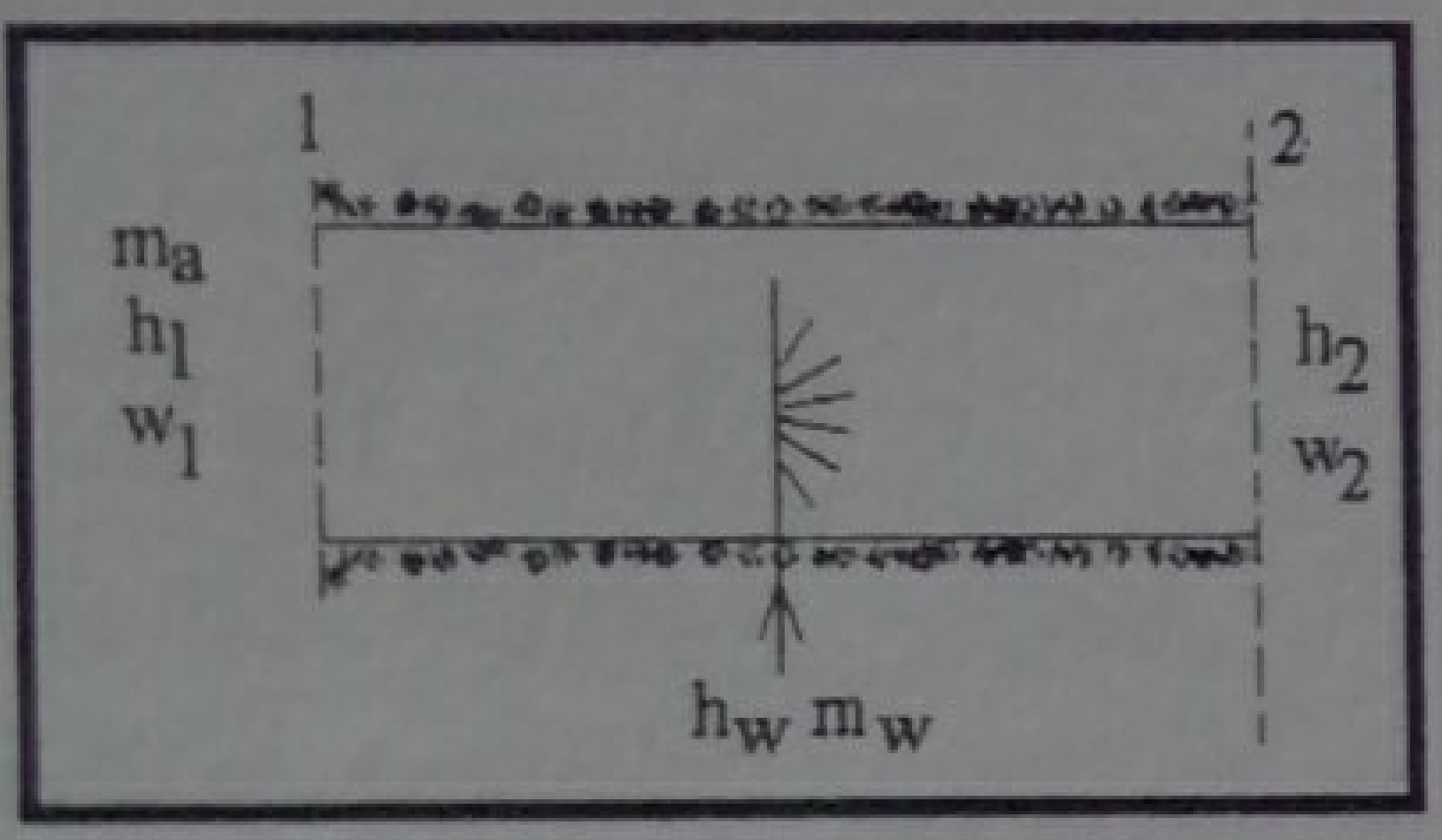
- $0-0=m_{a3}h_3-m_{a1}h_1-m_{a2}h_2$
- Dry air conservation
- $m_{a3} = m_{a1} + m_{a2}$
- Moisture conservation
- $m_{a3} w_3= m_{a1} w_1+ m_{a2} w_2$
- Eliminate m_{a3}
- $(m_{a1}+m_{a2})h_3=m_{a1}h_1+ m_{a2}h_2$
- $m_{a1} (h_3- h_1) =m_{a2} (h_2- h_3)$

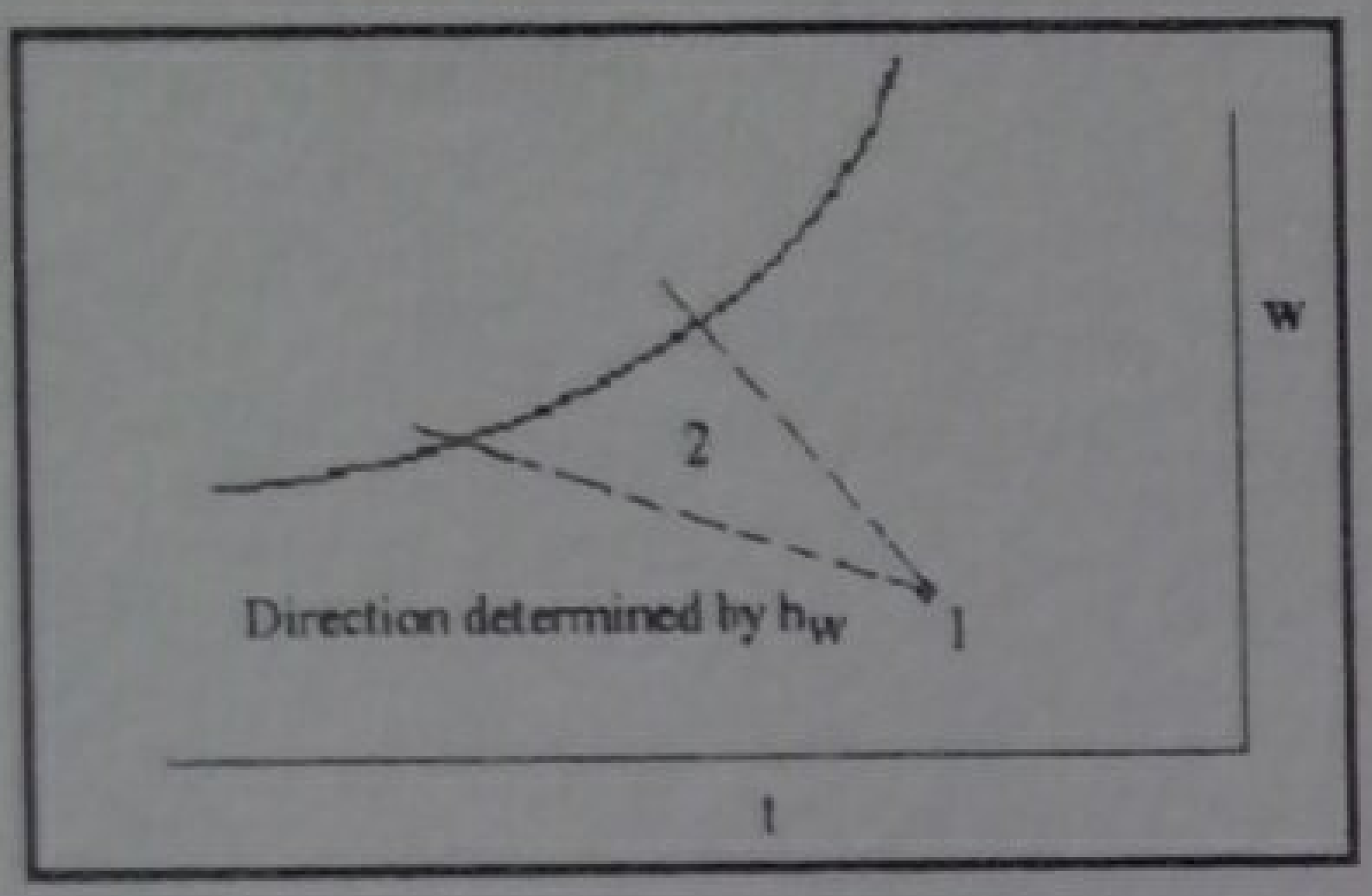


4.Spraying of Water Into a Stream of Air

SFEE

- ➢ $0\text{-}0= m_a h_2 - m_a h_1 - m_w h_w$
- ❖ Moisture conservation
- ➢ $m_a w_2 = m_a w_1 + m_w$
- ➢ or $m_w = m_a (w_2 - w_1)$
- ➢ Substitute in SFEE
- ➢ $m_a(h_2 - h_1) = m_a (w_2 - w_1) h_w$
- ➢ or $h_w = (h_2 - h_1) / (w_2 - w_1)$



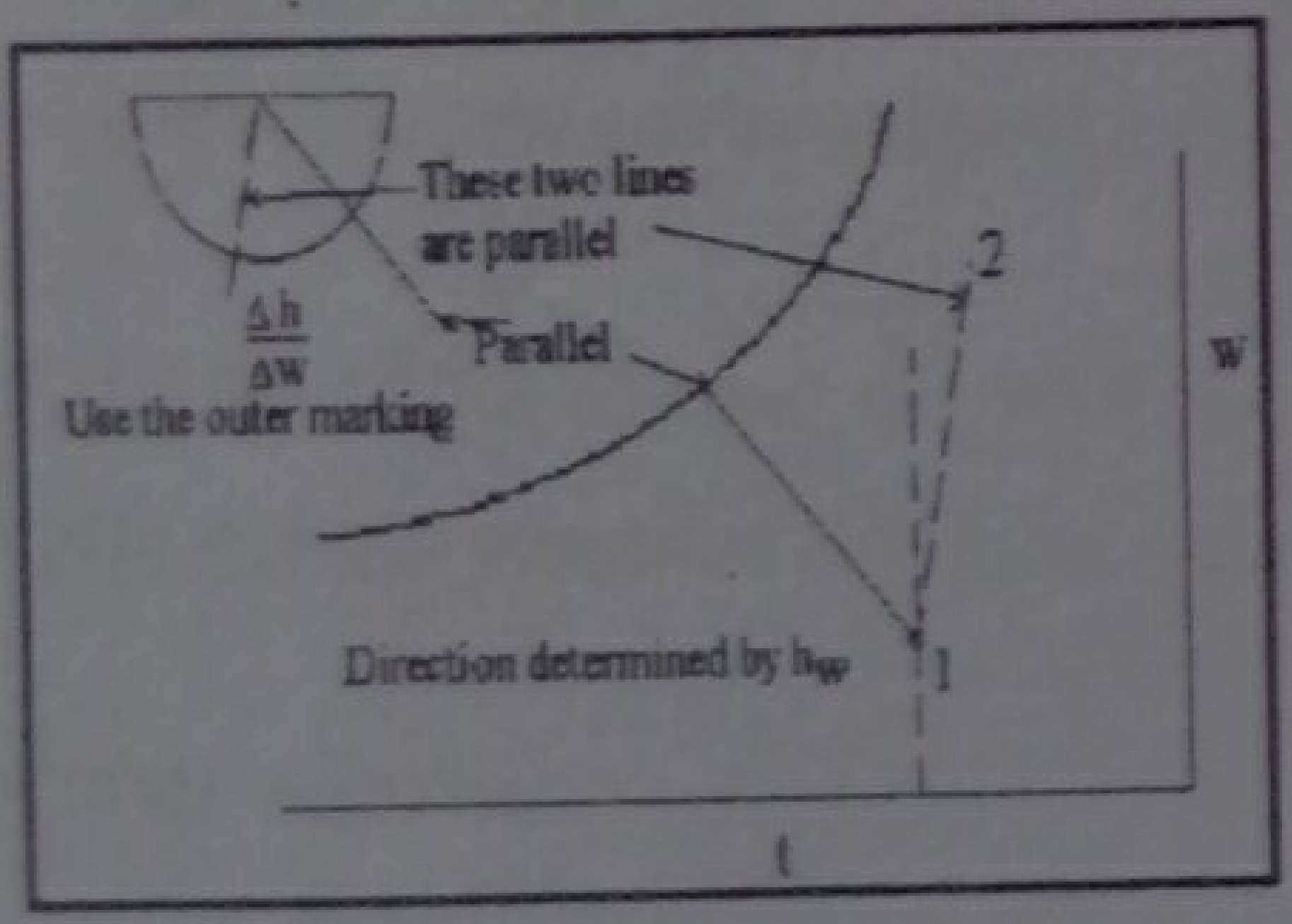


5. Injecting steam into a stream of air

- ➢ The mathematical treatment exactly the same as though water is injected
- ➢ The value of h_w will be the enthalpy of steam
- ➢ There is problem in cases 4 and 5!
- ➢ We don't know where exactly the point 2 lies
- ➢ All that we know is the direction in which 2 lies with reference to 1.

Injecting Stream(contd…)

From the centre of the circle draw a line connecting the value of which is equal to Δh/Δw. (Note that h_w units are kJ/g of water or steam). Draw a line parallel to it through 1.



Adiabatic mixture (contd…)

Moral: 1. The outlet state lies along the straight line joining the states of entry streams

Moral: 2. The mixture state point divides the line into two segments in the ratio of dry air flow rates of the incoming streams

Spraying of Water (contd…)

Moral: The final state of air leaving lies along a straight line through the initial state Whose ~~direction is fixed by the enthalpy of water~~ injected

Injecting Steam (contd…)

- On a Cartesian co-ordinate system that information would have been adequate.
- !!But, in the psychrometric chart h and w lines are not right angles!!
- HOW TO CONSTRUCT THE LINE 1-2 FOR CASES 4 AND 5 ??

Module 5

Basics of energy conversation cycles

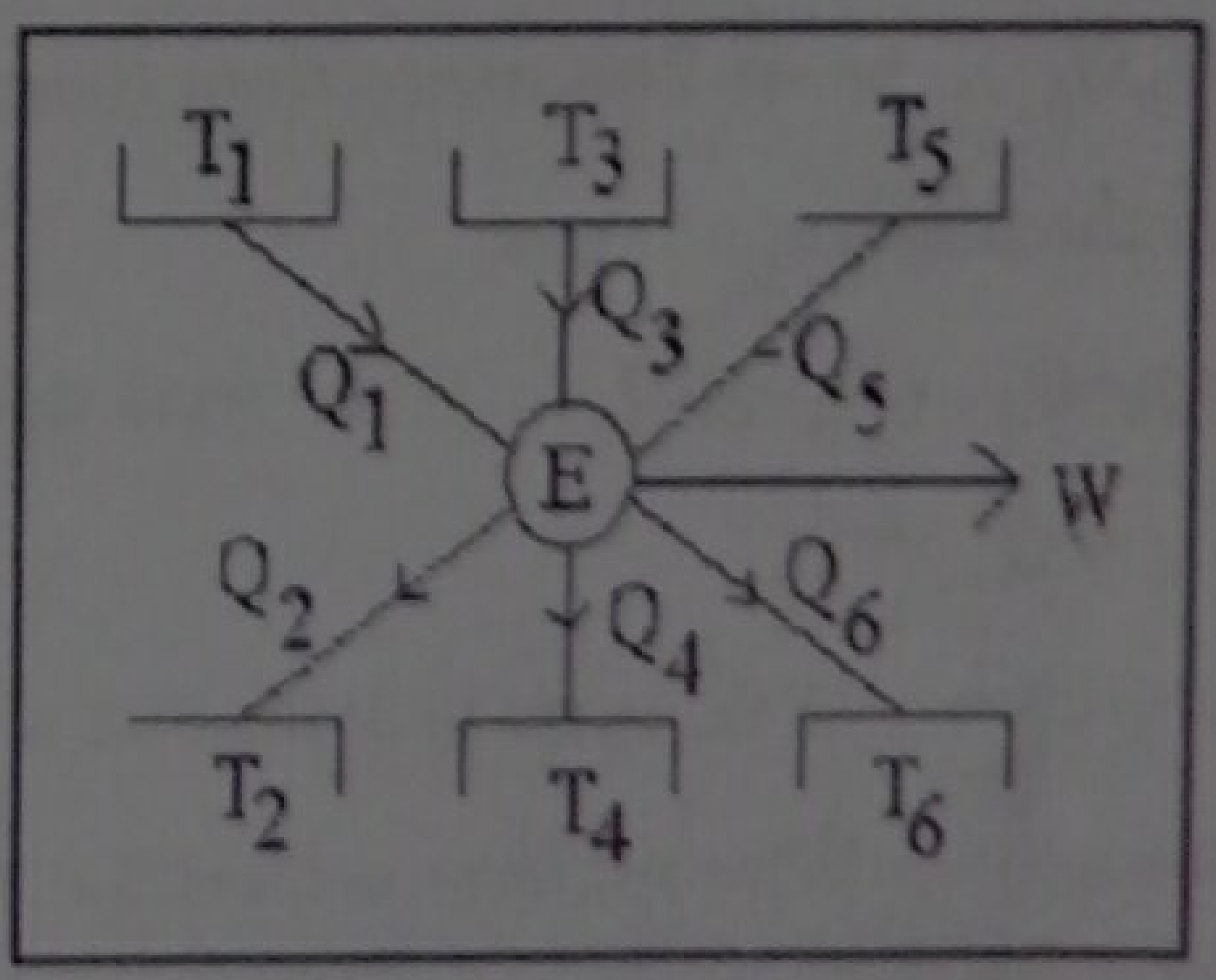
Heat Engines (contd…)

- A minimum of 3 such processes are required to construct a cycle.
- All processes need not have work interactions (eg: isochoric)
- All processes need not involve heat interactions either (eg: adiabatic process).

Heat Engines (Contd…)

- Commonsense tells us that to return to the same point after going round we need at one path of opposite direction.
- I law <u>does not forbid</u> all heat interactions being +ve nor all work interactions being -ve.
- But, we know that you can't construct a cycle with all +ve or
- All -ve Q's nor with all +ve or all -ve W's
- Any cycle you can construct will have some processes with
- Q +ve some with -ve.

Heat Engines (Contd…)



Heat Engines and Efficiencies

- The objective is to build devices which receive heat and produce work (like an aircraft engine or a car engine) or receive work and produce heat (like an air conditioner) in a sustained manner.
- All operations need to be cyclic. The cycle comprises of a set of processes during which one of the properties is kept constant (V,p,T etc.)

Heat Engines (Contd…)

- A cycle will consist of processes: involving some positive work interactions and some negative.
- If sum of +ve interactions is > -ve interactions the cycle will produce work
- If it is the other way, it will need work to operate.
- On the same lines some processes may have +ve and some -ve heat interactions.

Heat Engines (Contd…)

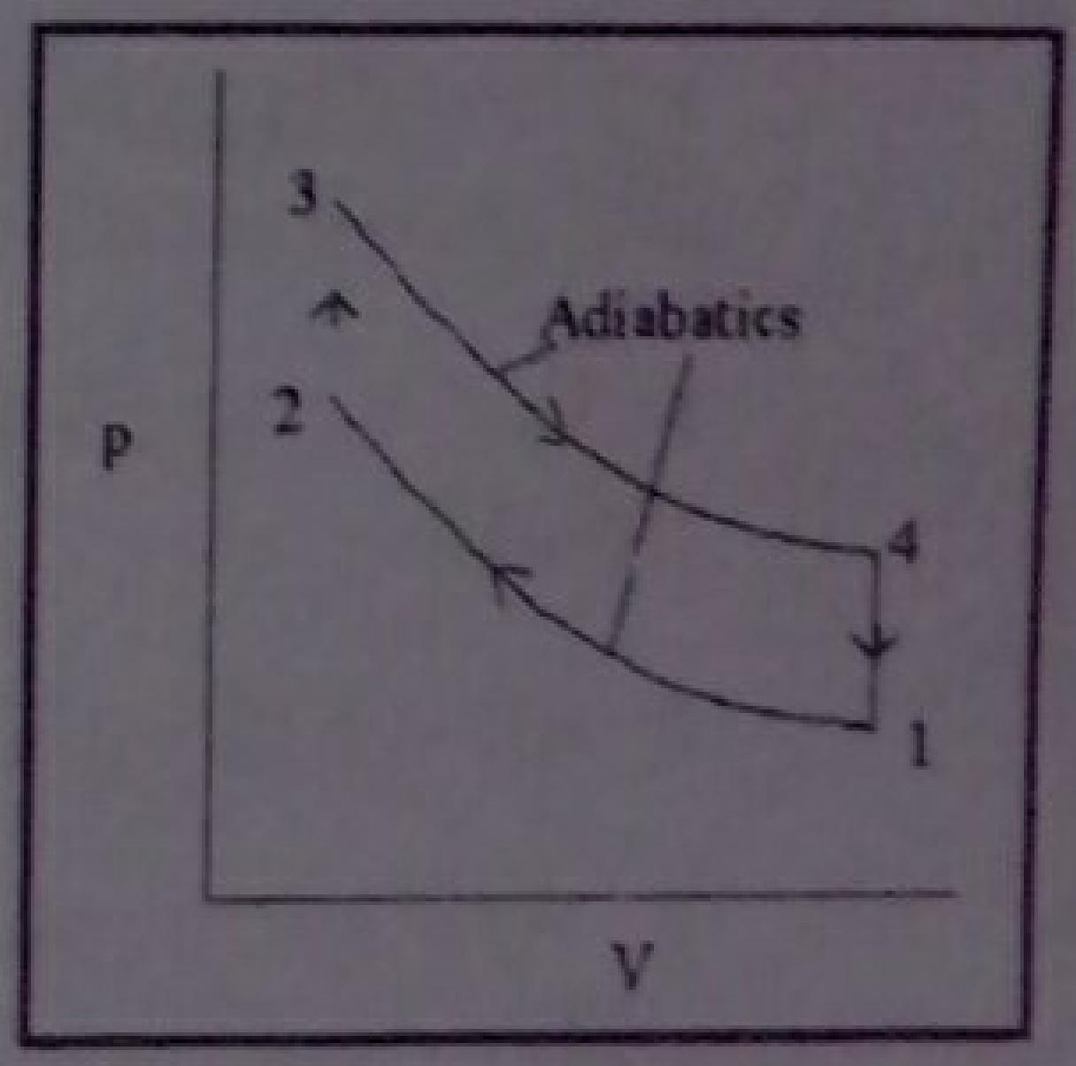
- Let Q_1, Q_3, Q_5 …. be +ve heat interactions (Heat supplied)
- Q_2, Q_4, Q_6 …. be -ve heat interactions (heat rejected)
- From the first law we have
- $Q_1+Q_3+Q_5 .. - Q_2-Q_4-Q_6 - ... =$ Net work delivered (W_{net})
- $\Sigma Q_{+ve} - \Sigma Q_{-ve} = W_{net}$
- The efficiency of the cycle is defined as $\eta = W_{net} / \Sigma Q_{+ve}$
- Philosophy → What we have achieved ÷ what we have spent to achieve it

Otto Cycle

Consider the OTTO Cycle (on which your car engine works)

It consists of two isochores and two adiabatics

- There is no heat interaction during 1-2 and 3-4
- Heat is added during constant volume heating (2-3) Q2-3= cv (T3-T2)
- Heat is rejected during constant volume cooling (4-1) Q4-1= cv (T1-T4)
- Which will be negative because T4 >T1

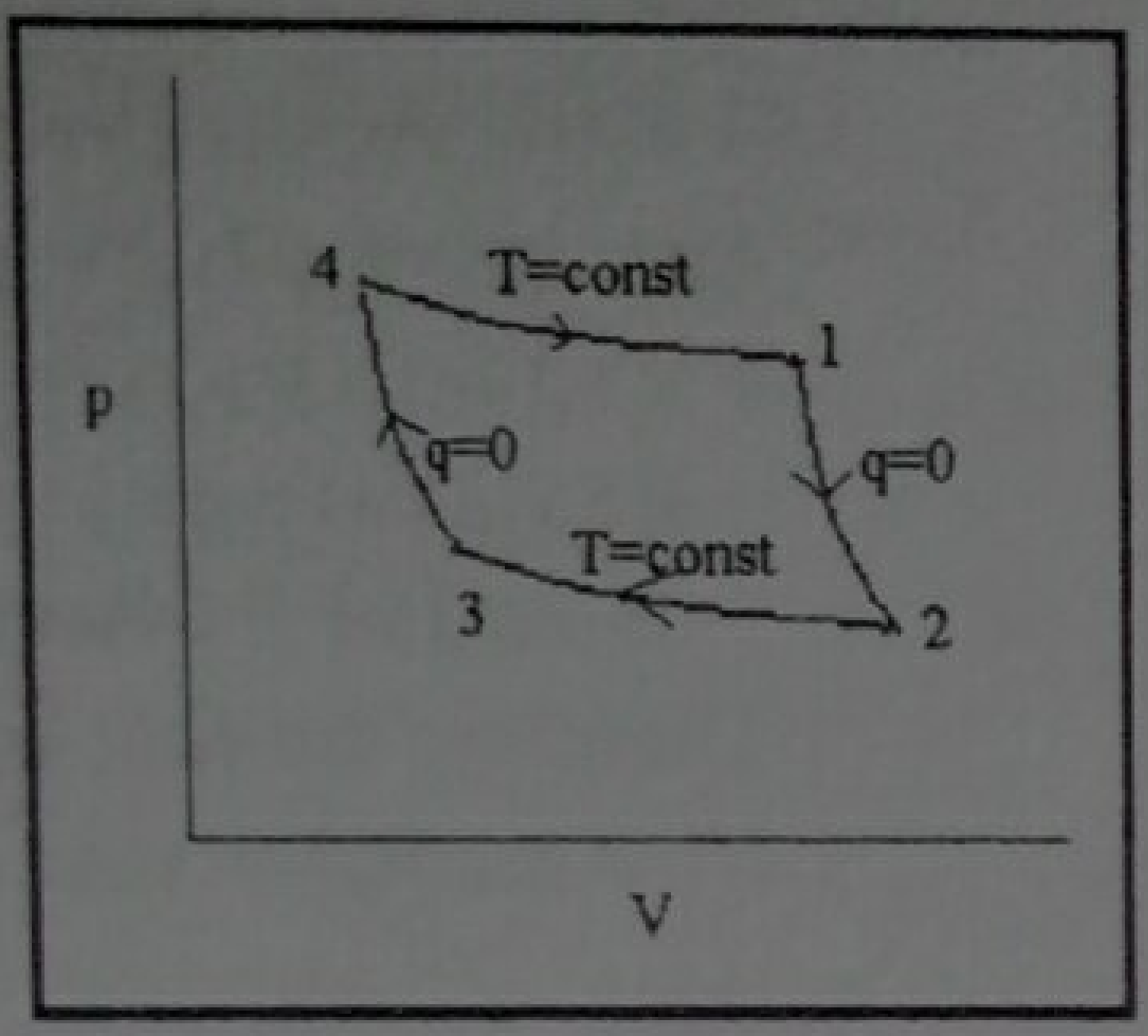


Carnot Cycle

Consider a Carnot cycle - against which all other cycles are compared

It consists of two isotherms and two adiabatics

- Process 4-1 is heat addition because $v4 < v1$
- Process 2-3 is heat rejection because $v3 < v2$



Carnot Cycle (contd..)

We will show that $(v2/v3) = (v1/v4)$

1 and 2 lie on an adiabatic so do 3 and 4

$p1v1g = p2v2g$ $p4v4g = p3v3g$

Divide one by the other $(p1v1g / p4v4g) = (p2v2g / p3v3g)$ (A)

$(p1/p4)(v1g / v4g) = (p2/p3)(v2g / v3g)$

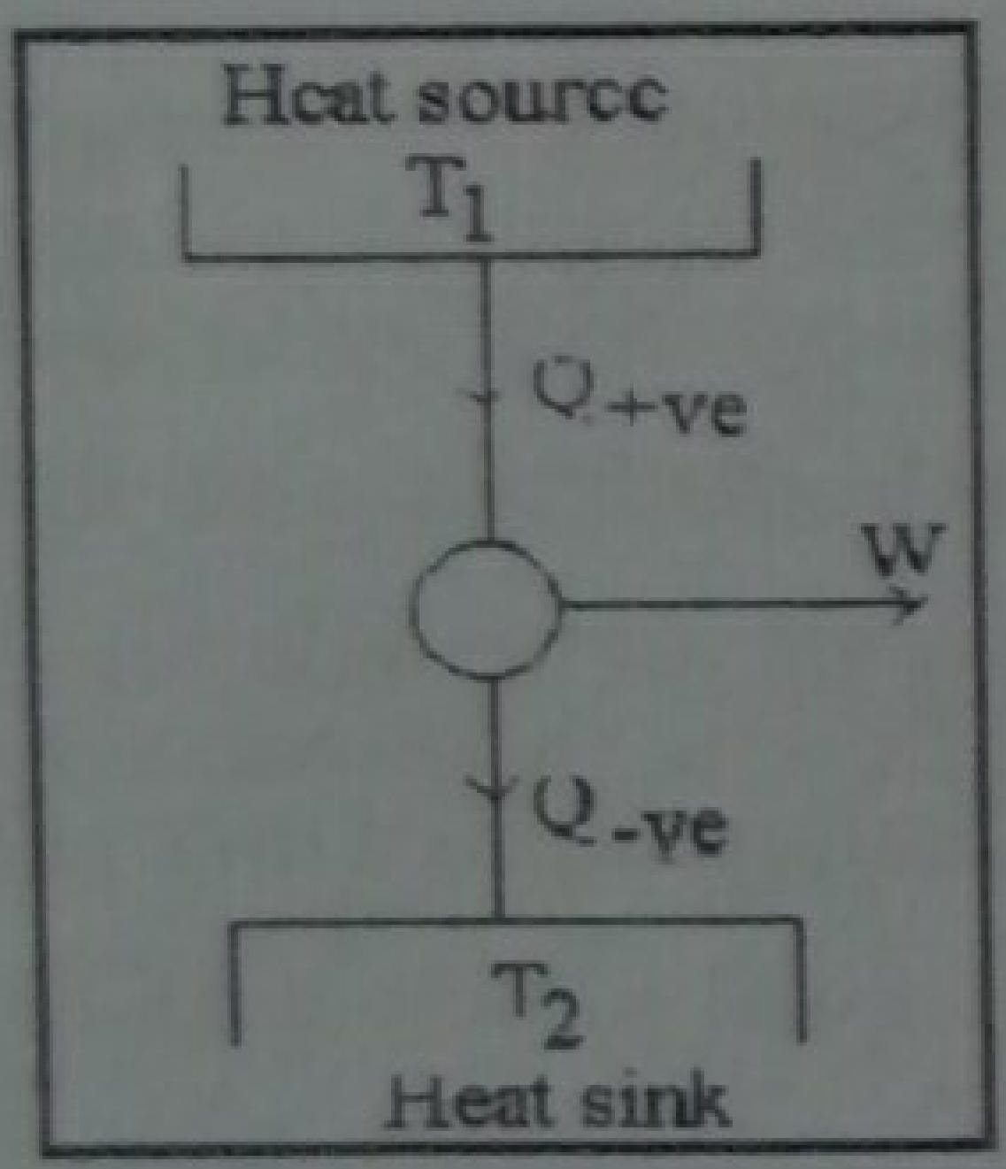
But $(p1/p4) = (v4/v1)$ because 1 and 4 are on the same isotherm

Similarly $(p2/p3) = (v3/v2)$ because 2 and 3 are on the same isotherm

Carnot Cycle (contd..)

Carnot engine has one Q +ve process and one Q -ve process. This engine has a single heat source at T_1 and a single sink at T_2.

If Q +ve > Q -ve; W will be +ve It is a heat engine



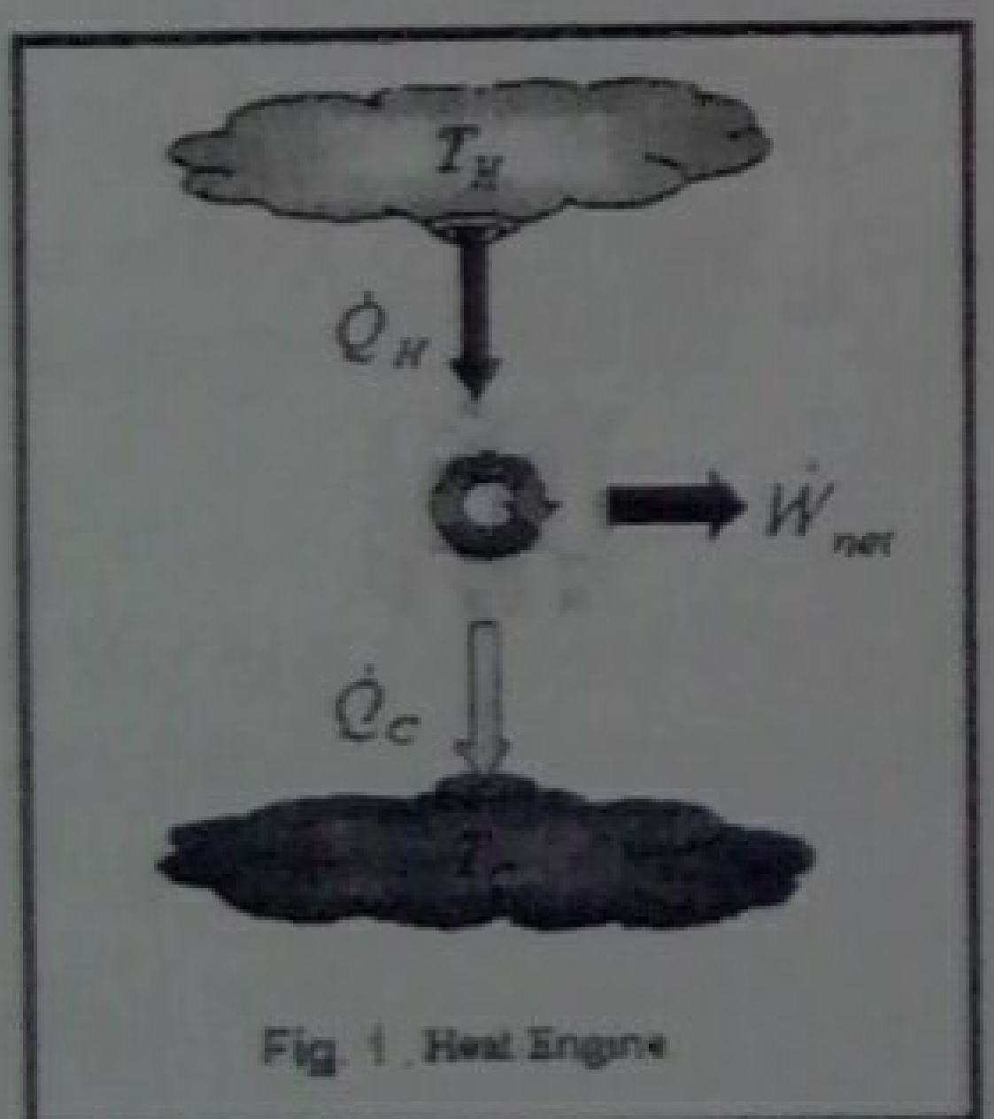
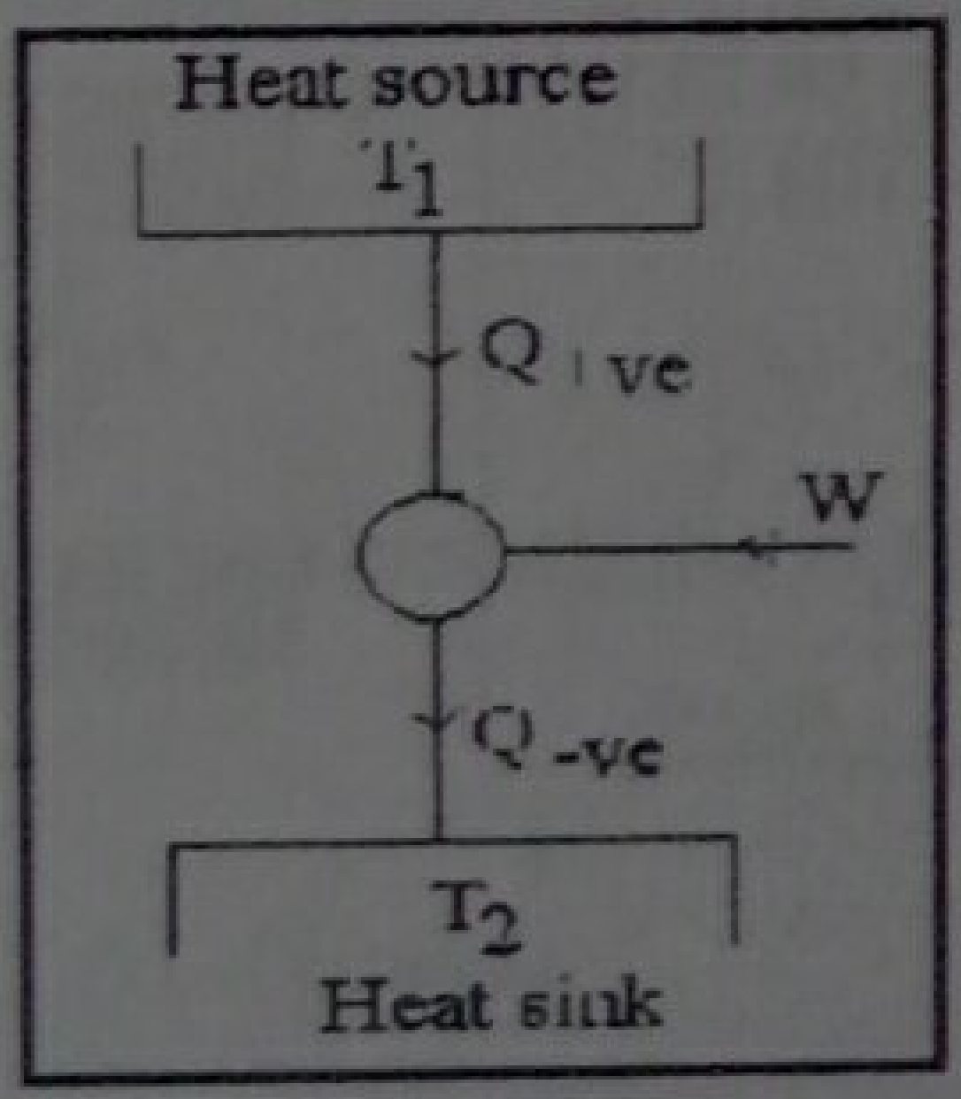


Fig. 1 Heat Engine

Carnot Cycle (contd..)

Q +ve < Q -ve W will be - ve It is not a heat engine

Efficiency is defined only for a work producing heat engine not a work consuming cycle



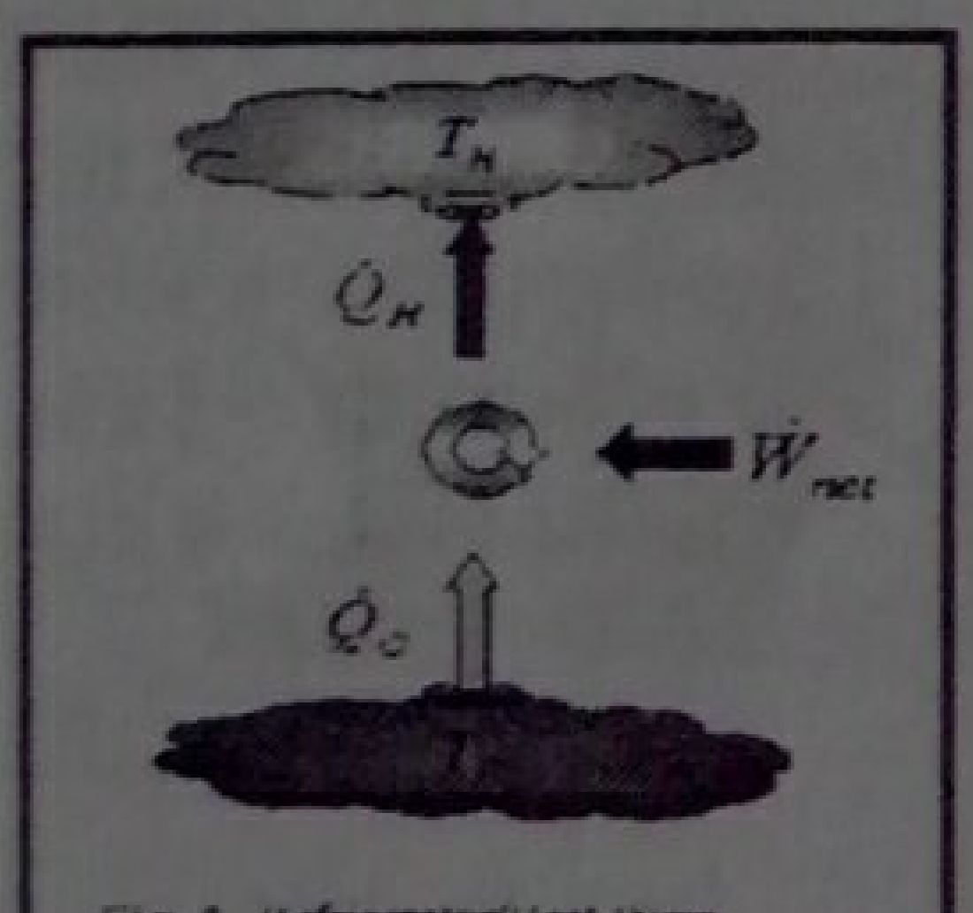


Fig. 1 Refrigerator/Heat Pump

Otto Cycle (Contd…)

- Work done = cv (T3-T2) + cv (T1-T4)
- The efficiency = [cv(T3-T2)+cv(T1-T4)]/[cv(T3-T2)]

  = [(T3-T2) + (T1-T4)]/[(T3-T2)]

  =1 - [(T4-T1) / (T3-T2)]

Carnot Cycle (contd..)

Process	Work	Heat
1-2	(p1v1-p2v2)/(g-1)	0
2-3	p2v2 ln (v3/v2)	p2v2 ln (v3/v2)
3-4	(p3v3-p4v4)/(g-1)	0
4-1	p4v4 ln (v1/v4)	p4v4 ln (v1/v4)
Sum	(p1v1-p2v2 + p3v3-p4v4)/(g-1) + RT2 ln (v3/v2) + RT1ln (v1/v4)	RT2 ln (v3/v2) + RT1ln (v1/v4)

But,p1v1 = p4v4 and p2v2 = p3v3

Therefore the first term will be 0

!!We reconfirm that I law works!!

Carnot Cycle (contd..)

Therefore A becomes (v1 / v4)g-1= (v2/v3)g-1

which means (v2/v3) = (v1/v4)

Work done in Carnot cycle = RT1ln (v1/v4) + RT2 ln (v3/v2)

= RT1ln (v1/v4) - RT2 ln (v2/v3)

=R ln (v1/v4) (T1- T2)

Heat supplied = R ln (v1/v4) T1

The efficiency = (T1- T2)/T1

In all the cycles it also follows that Work done=Heat supplied - heat rejected

Carnot Cycle (contd..)

It will turn out that Carnot efficiency of (T1- T2)/T1 is the best we can get for any cycle operating between two fixed temperatures.

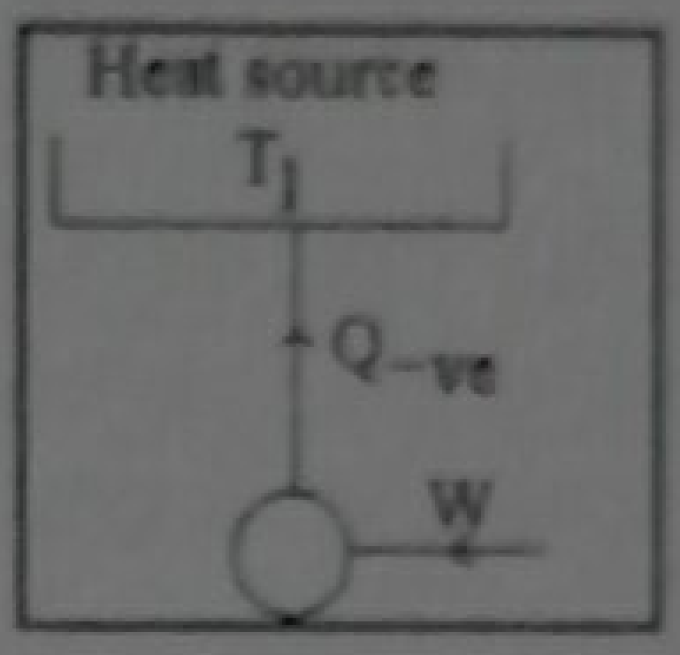
Chapter 6

Second Law of Thermodynamics

Second Law Of Thermodynamics (contd…)

Is it possible to construct a heat engine with only one -ve heat interaction?

Is the following engine possible?



The answer is yes, because
This is what happens in a
stirrer

Enunciation of II Law of Thermodynamics

Statement 1: It is impossible to construct a device which operating in a cycle will produce no effect other than raising of a weight and exchange of heat with a single reservoir.

Note the two underlined words.

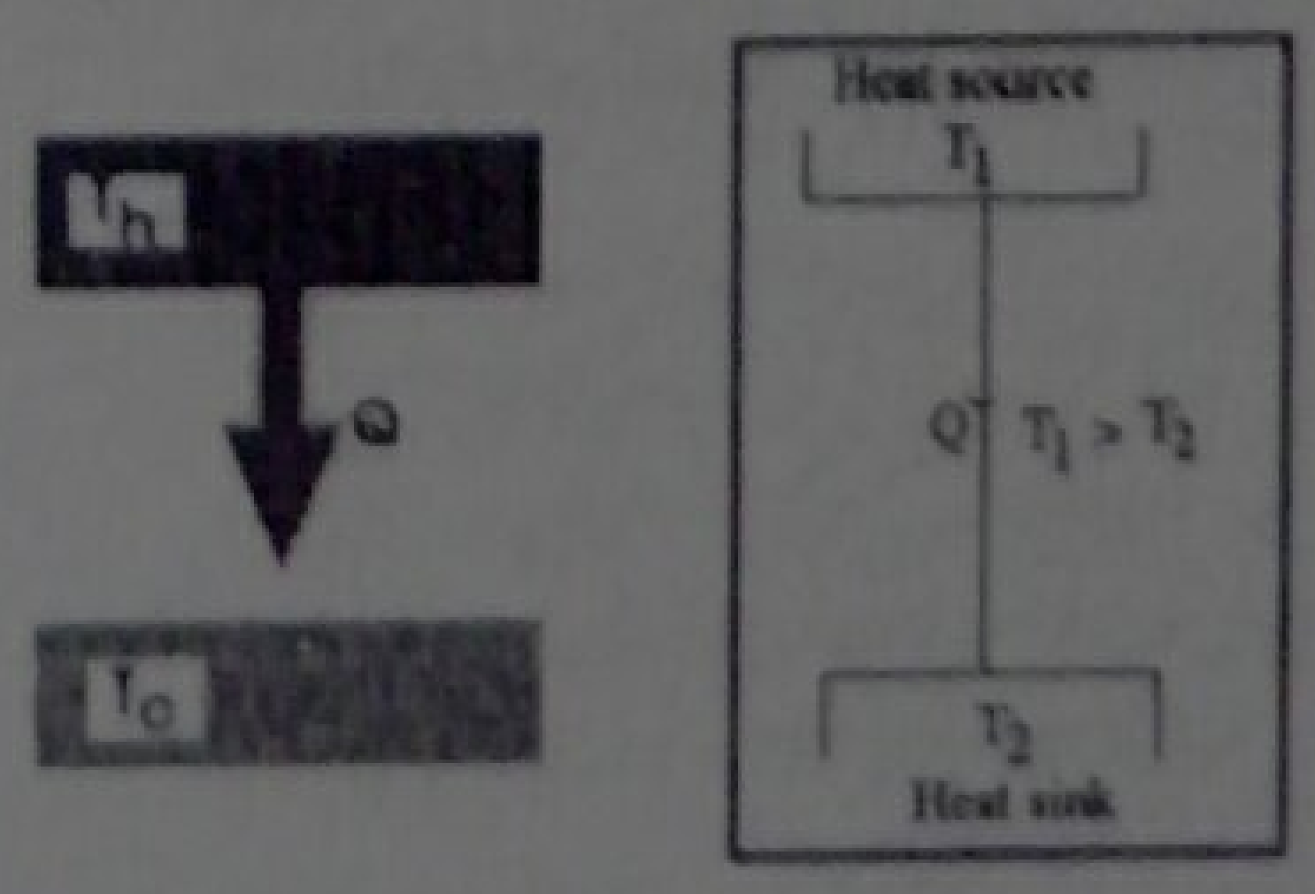
II Law applies only for a cycle - not for a process!! (We already know that during an isothermal process the system can exchange heat with a single reservoir and yet deliver work)

!!There is nothing like a 100% efficient heat engine!!

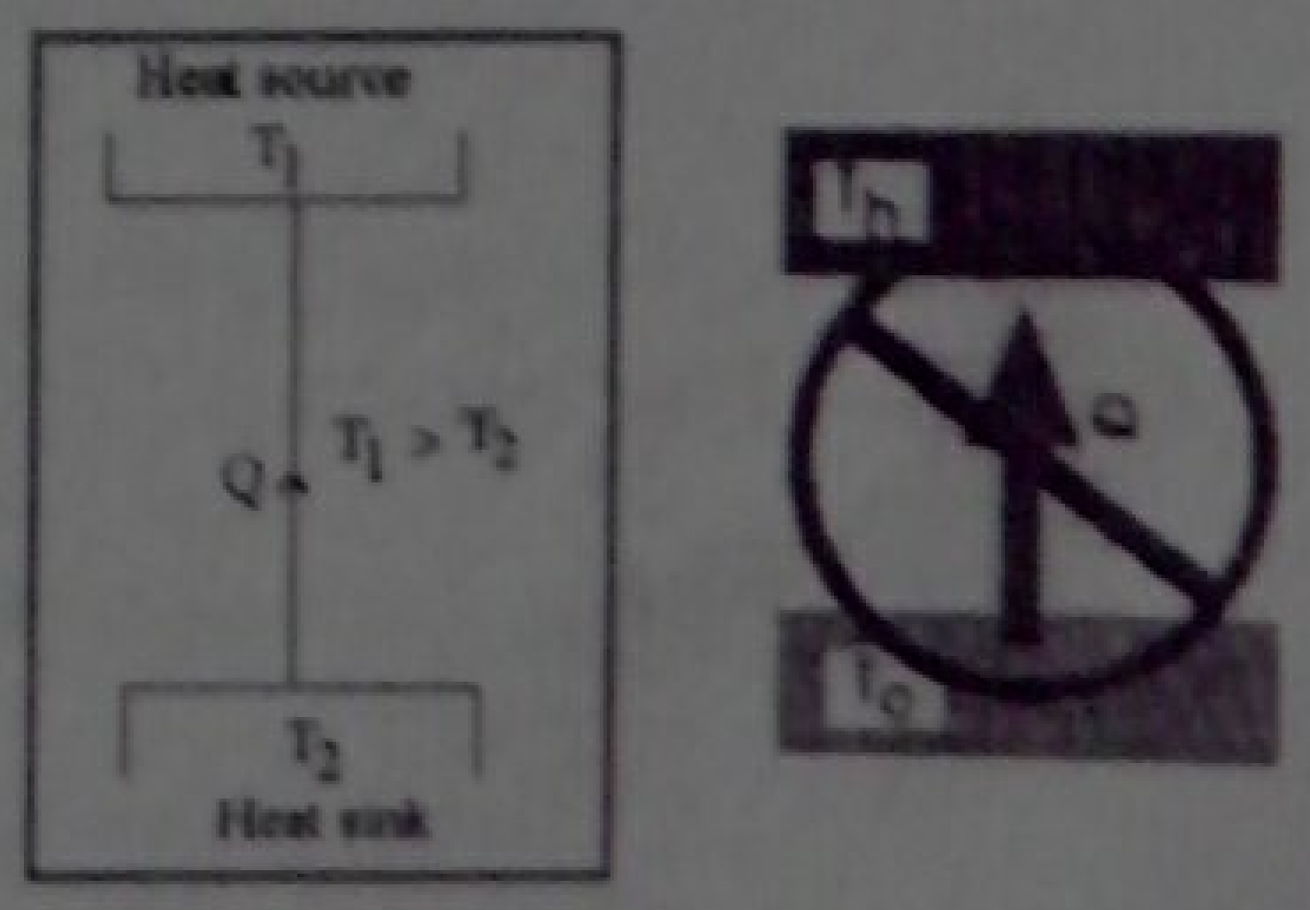
Common sense tells us that

1Heat flows from a body at higher temperature to a body at lower temperature

A hot cup of coffee left in a room becomes cold. We have to expend energy to rise it back to original temperature



Possible



Not possible

(you can't make room heat up your coffee!!)

Common sense tells us that

3.Current flows from a point of higher potential to lower one

Battery can discharge through a resistance, to get the charge

4. You can mix two gases or liquids. But to separate them you have to spend a lot of energy. (You mix whisky and soda without difficulty - but can't separate the two - Is it worthwhile?)
5. All that one has to say is "I do". To get out of it one has to spend a lot of money
6. When you go to a bank and give 1US$ you may get Rs 49. But if you give Rs 49 to the bank they will give you only 95 US cents (*if you are lucky !!*). You spend more.

Definitions of Reversible Process

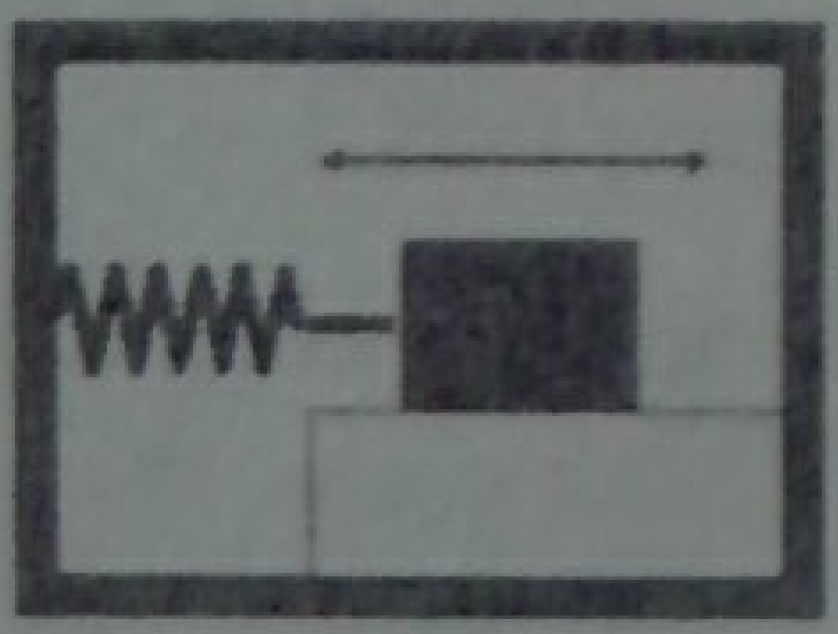
❖A process is reversible if after it, means can be found to restore the system and surroundings to their initial states.

Some reversible processes:

➢Constant volume and constant pressure heating and cooling - the heat given to change the state can be rejected back to regain the state.

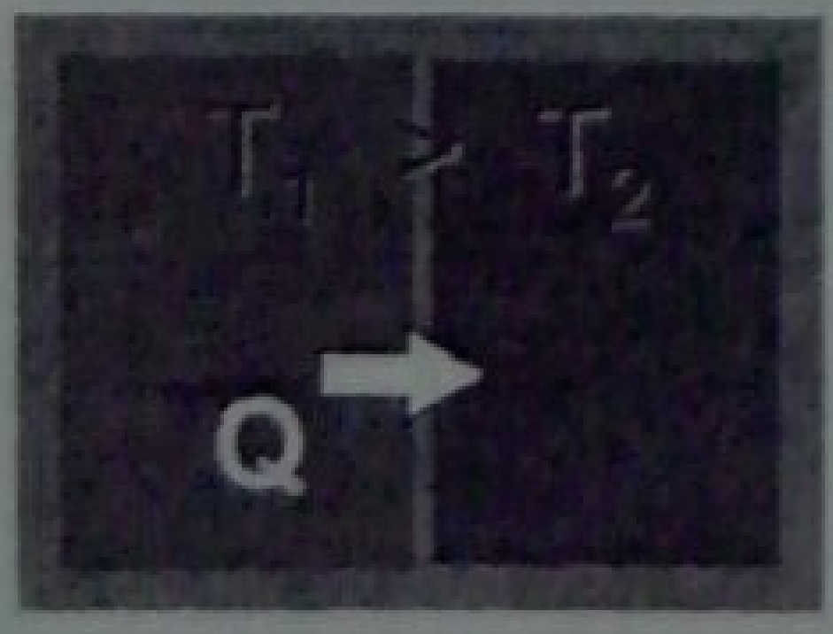
Some Irreversible Process

motion with friction

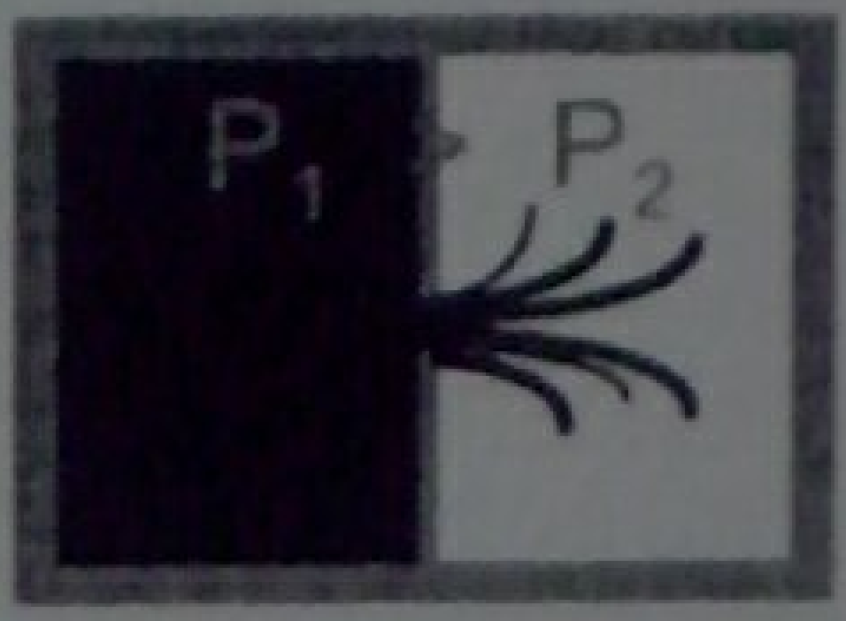


spontaneous chemical reaction

heat transfer



unrestrained expansion



Reversible Cycle

➢A cycle consisting of all reversible processes is a reversible cycle. Even one of the processes is irreversible, the cycle ceases to be reversible.

Otto, Carnot and Brayton cycles are all reversible.
A reversible cycle with clockwise processes produces work with a given heat input. The same while operating with counter clockwise processes will reject the same heat with the same work as input.

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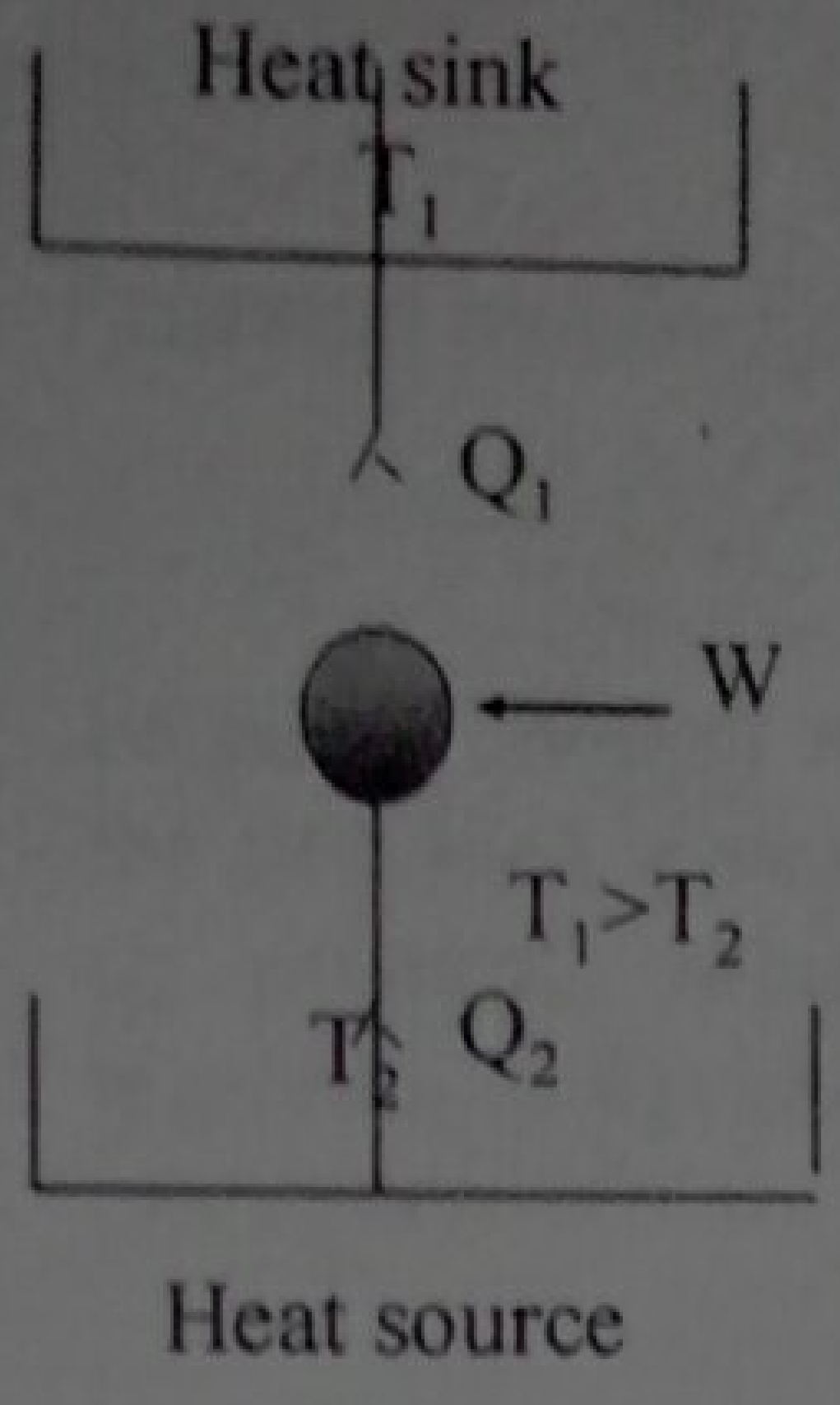
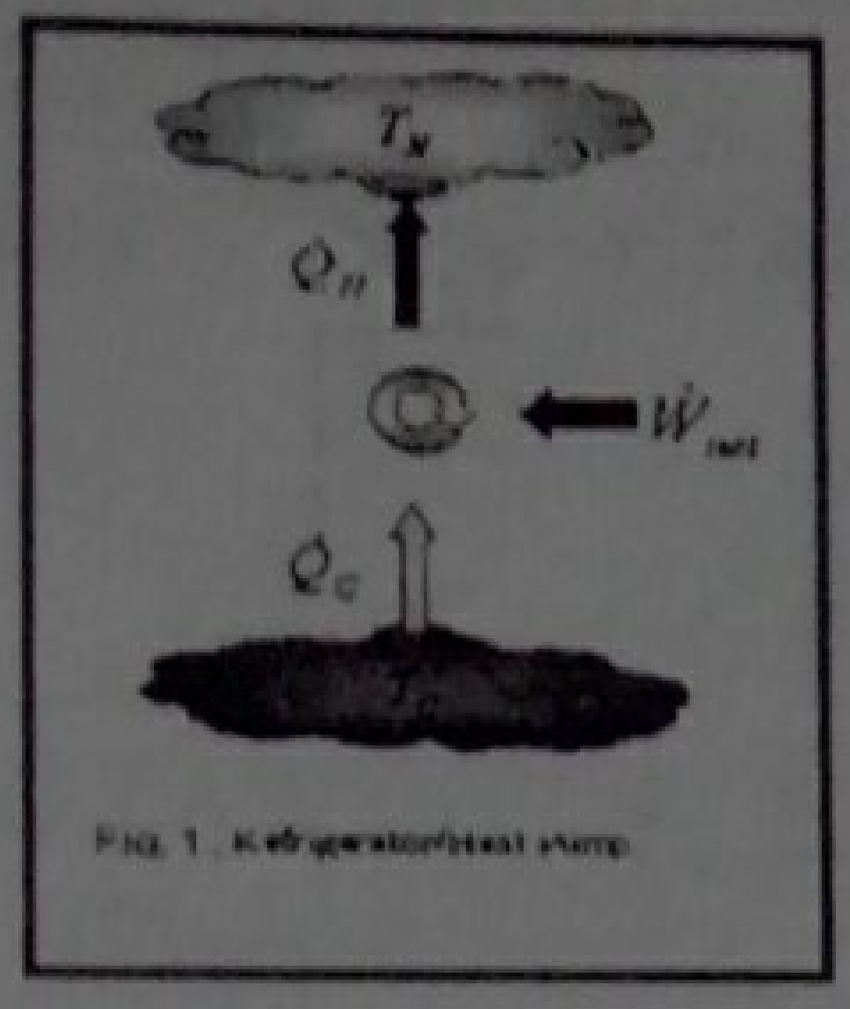
Clausius Statement of II Law of Thermodynamics

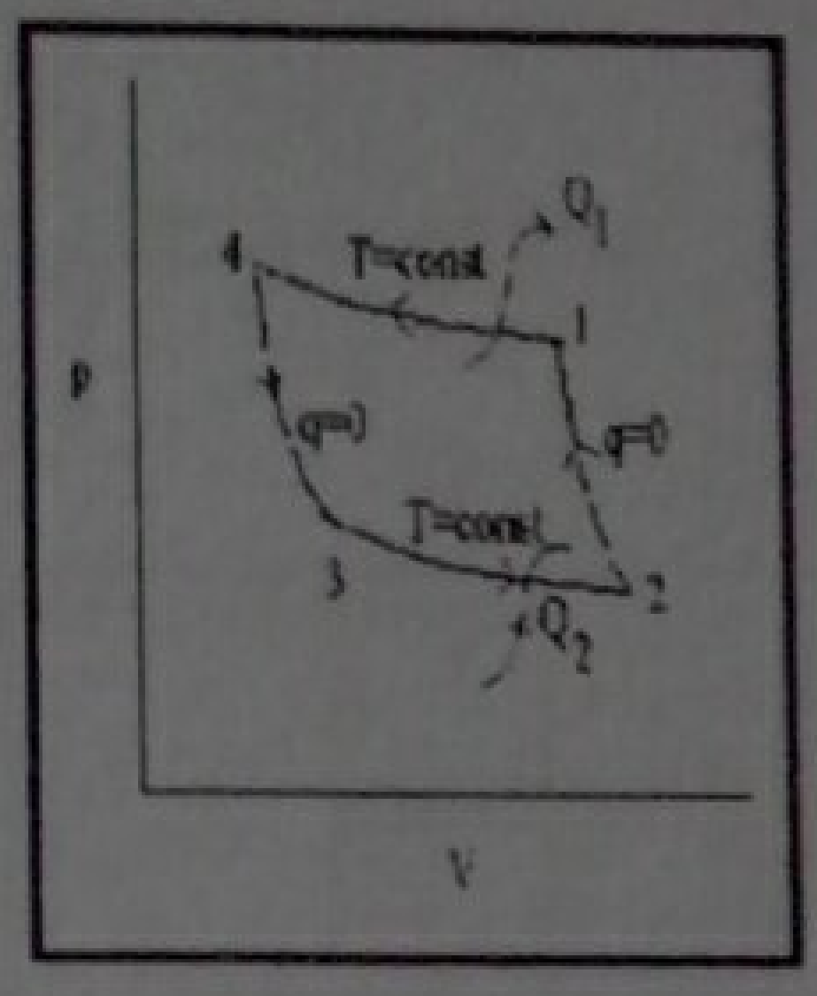
It is impossible to construct a device which operates in a cycle and produces no effect other than the transfer of heat from a cooler body to a hotter body.

❖Yes, you can transfer heat from a cooler body to a hotter body by expending some *energy*.

Carnot Cycle for a Refrigerator/heat Pump







$T_H=T_1$

$T_C=T_2$

Heat Pump (contd…)

❖ A heat pump

- Invoke the definition: what we have achieved , what we spent for it
- COP_{HP} = heat given out , work done = ½Q_1/W½
- Note : The entity of interest is how much heat could be realised. Work is only a penalty.

Heat Pump (contd…)

Relation between η and COP_{HP}

It is not difficult to see that $\eta\, COP_{HP} = 1$

Apply I law to Carnot cycle as a heat pump/refrigerator:

$-Q_1+Q_2 = -W$ or $Q_1=Q_2+W$

Divide both sides with W $Q_1/W = Q_2/W + 1$

or $COP_{HP} = COP_R+1$

The highest COP_{HP} obtainable therefore will be $T_1/(T_1-T_2)$

and highest COP_R obtainable therefore will be $T_2/(T_1-T_2)$

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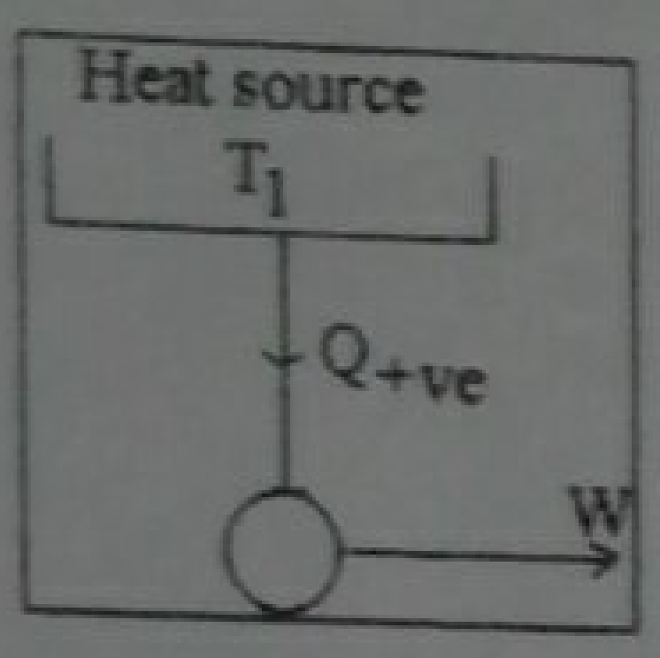
Leads Up To Second Law Of Thermodynamics

It is now clear that we can't construct a heat engine with just one +ve heat interaction.

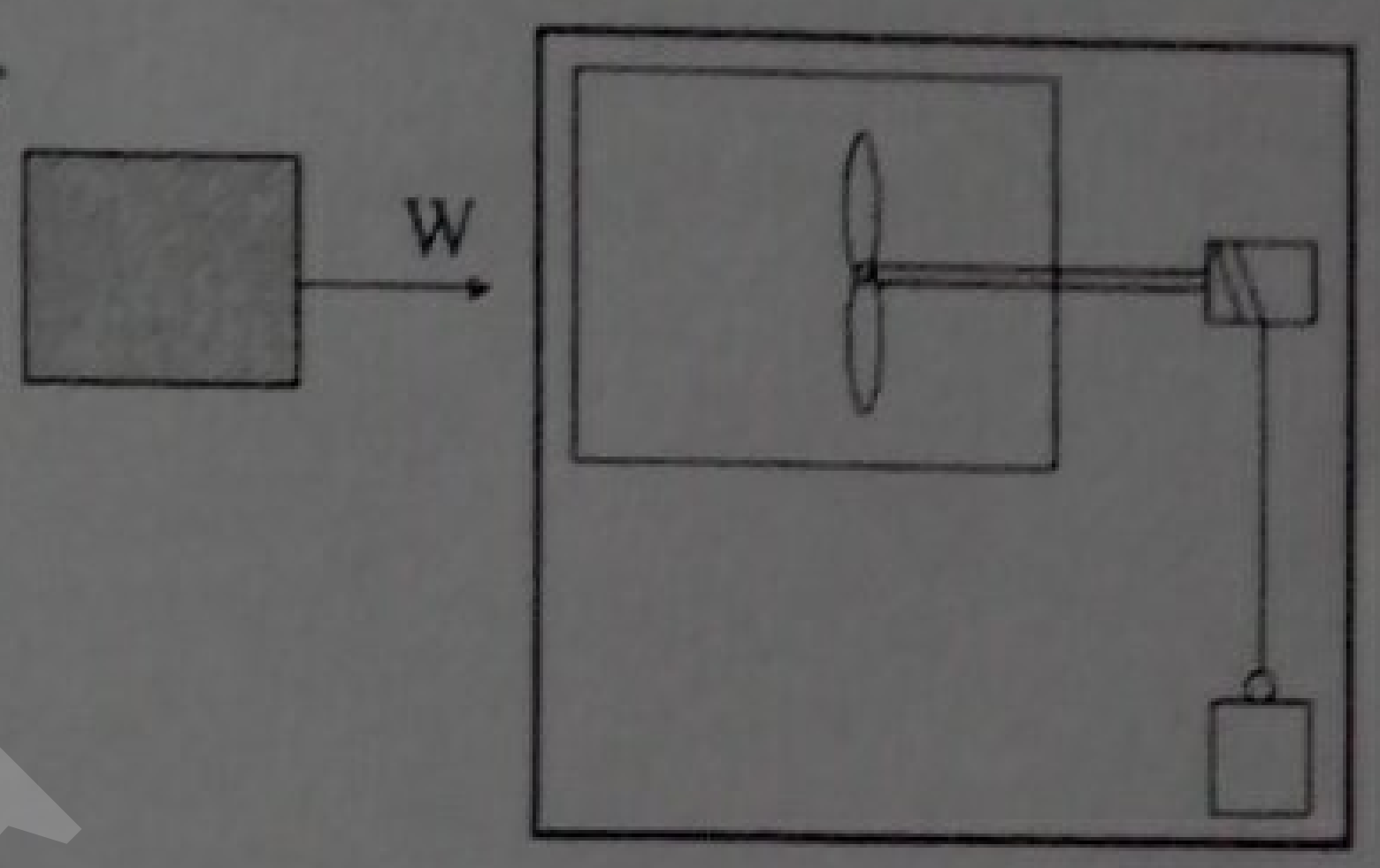


The above engine is not possible.

Second Law Of Thermodynamics (contd…)

Perpetual motion machine of the second kind is not possible.

Perpetual motion machine of the first kind violates I LAW (It produces work without receiving heat)



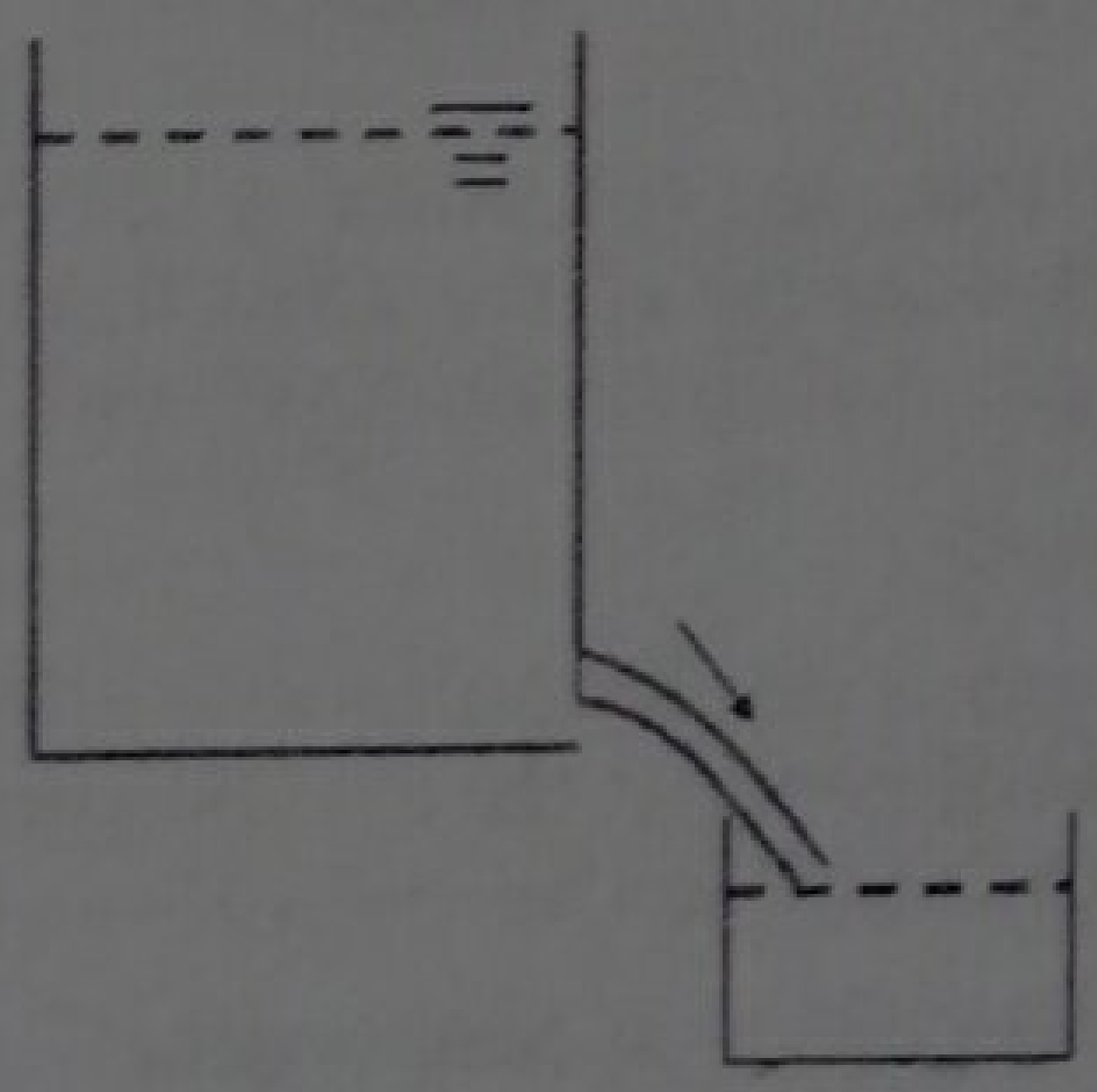
Enunciation of II Law of Thermodynamics

- To enunciate the II law in a different form
- !!! We have to appreciate some ground realities !!!
- All processes in nature occur unaided or spontaneously in one direction. But to make the same process go in the opposite direction one needs to spend energy.

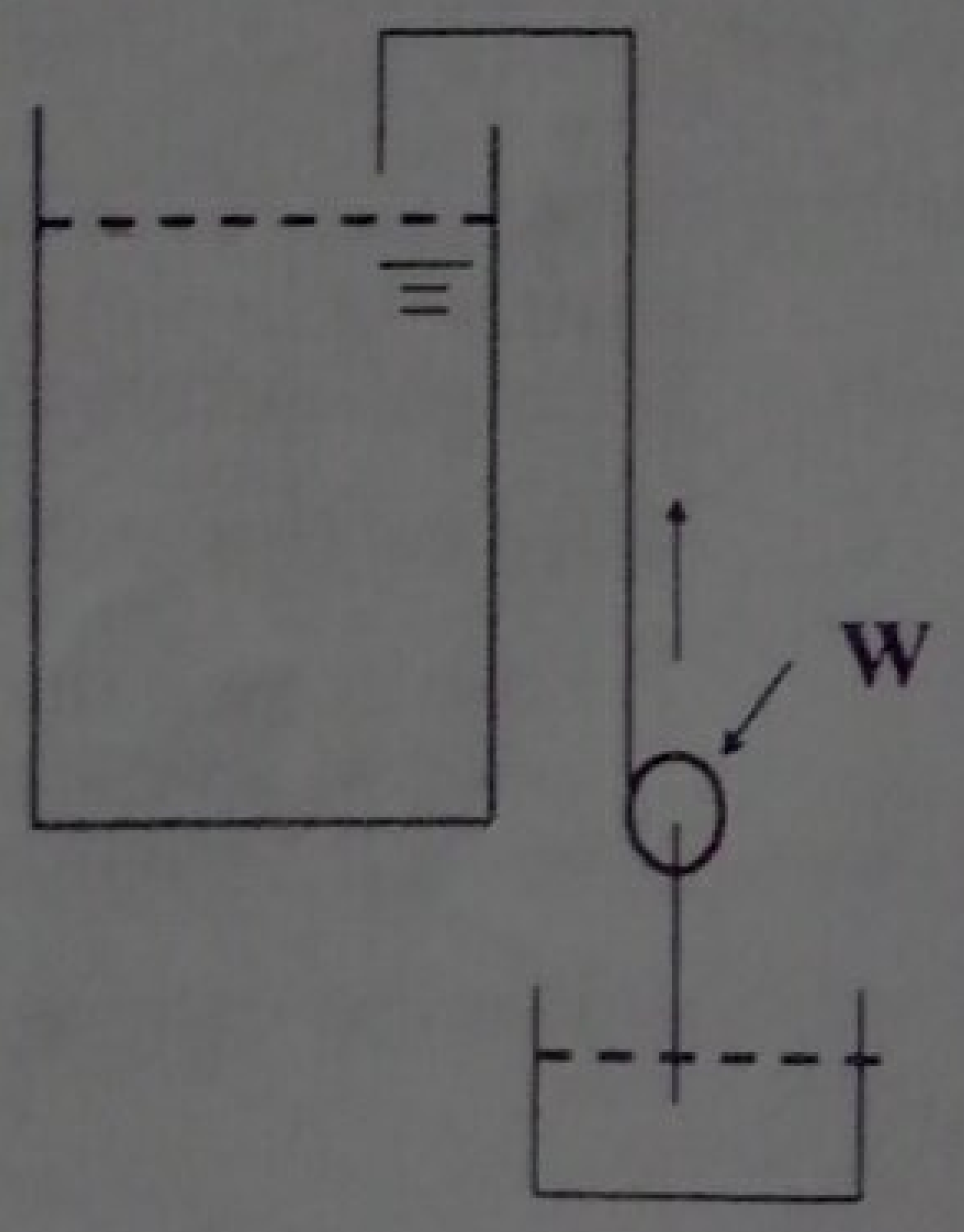
Common sense tells us that

2.Fluid flows from a point of higher pressure or potential. to a lower one

Water from a tank can flow down To get it back to the tank you have to use a pump i.e, you spend energy



Possible



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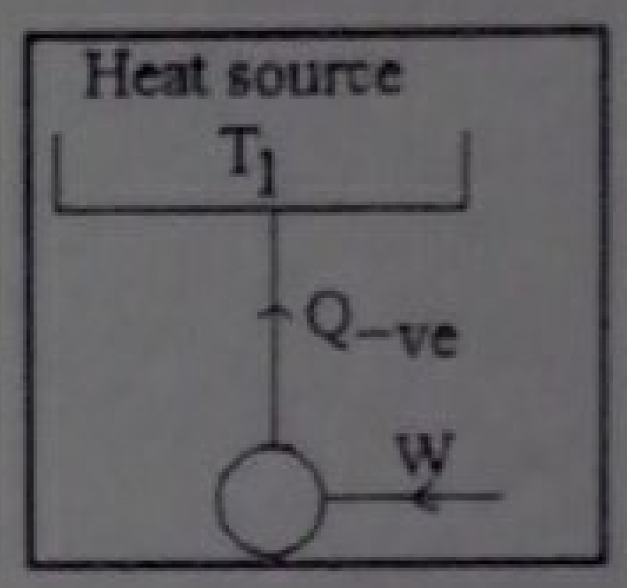
Chapter 6

Second Law of Thermodynamics

Second Law Of Thermodynamics (contd…)

Is it possible to construct a heat engine with only one -ve heat interaction?

Is the following engine possible?



The answer is yes, because
This is what happens in a
stirrer

Enunciation of II Law of Thermodynamics

Statement 1: It is impossible to construct a device which operating in a cycle will produce no effect other than raising of a weight and exchange of heat with a single reservoir.

Note the two underlined words.

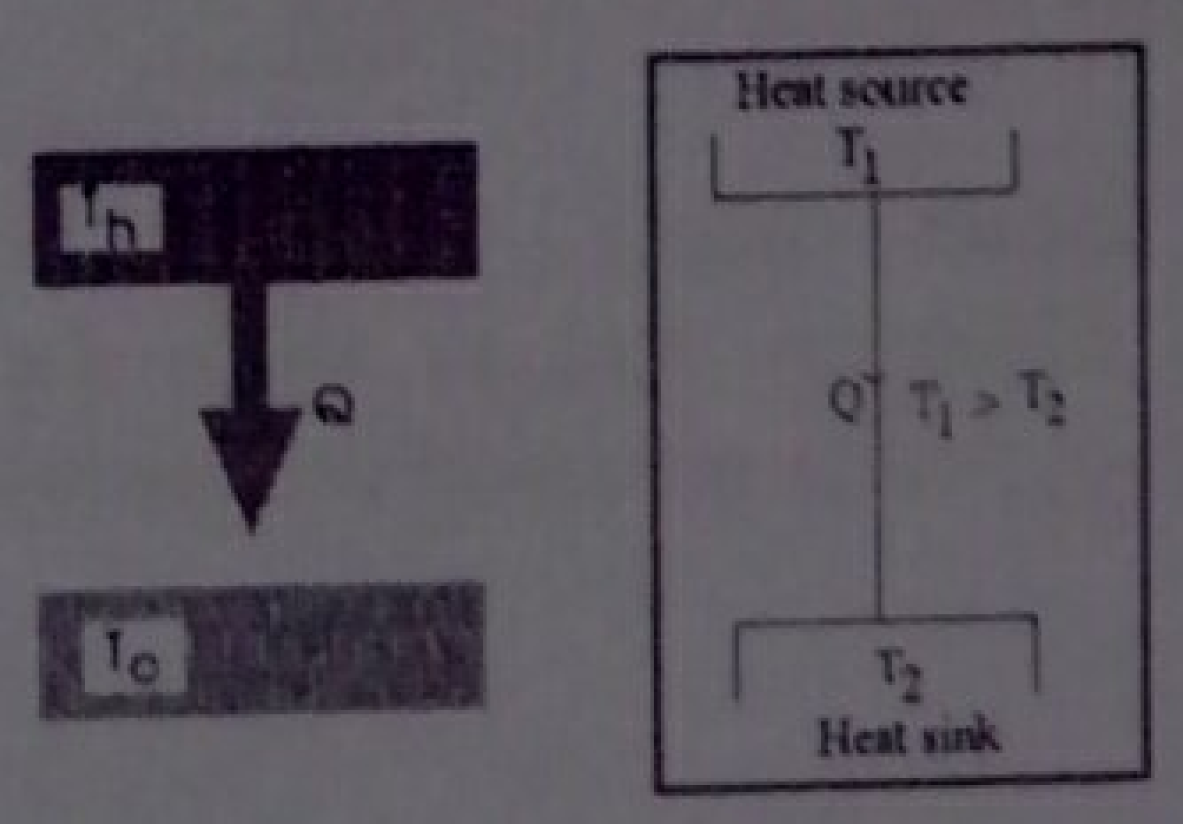
II Law applies only for a cycle - not for a process!! (We already know that during an isothermal process the system can exchange heat with a single reservoir and yet deliver work)

!!There is nothing like a 100% efficient heat engine!!

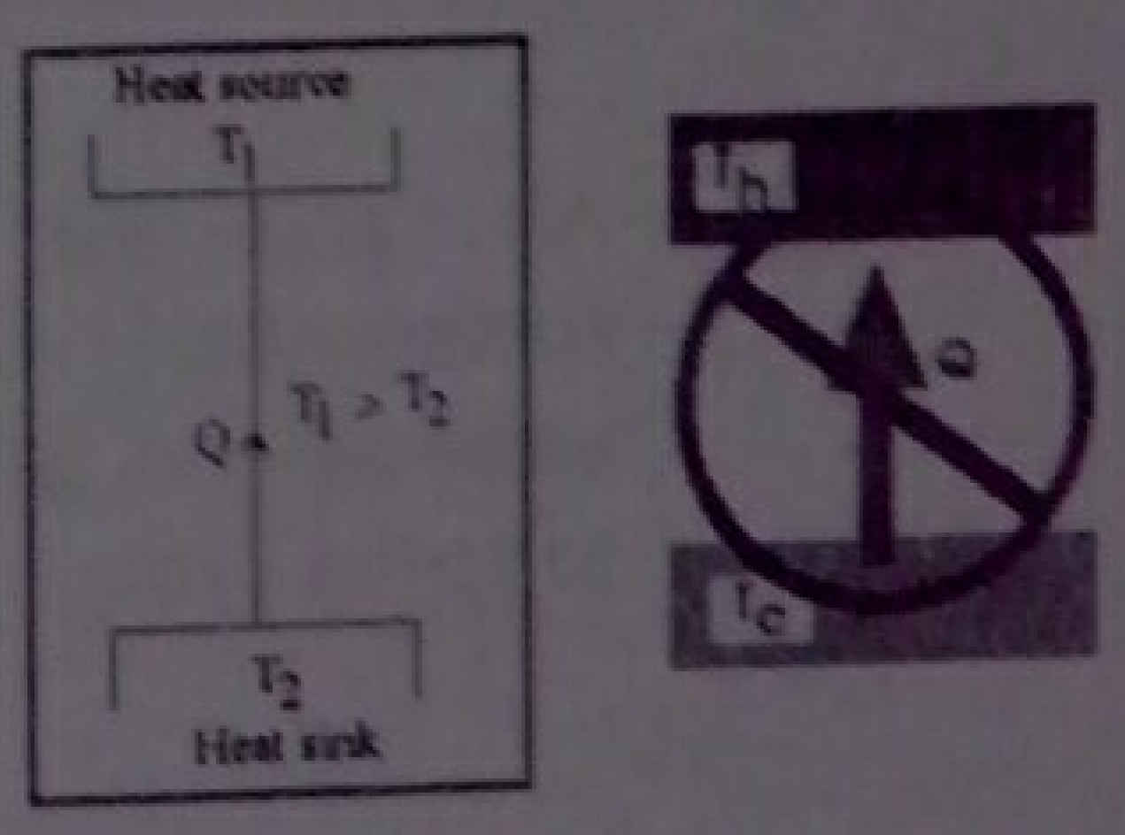
Common sense tells us that

1Heat flows from a body at higher temperature to a body at lower temperature

A hot cup of coffee left in a room becomes cold. We have to expend energy to rise it back to original temperature



Possible



Not possible

(you can't make room heat up your coffee!!)

Common sense tells us that

6. When you go to a bank and give 1US$ you may get Rs 49. But if you give Rs 49 to the bank they will give you only 95 US cents (if you are lucky !!). You spend more.
7. You can take tooth paste out of the tube but can't push it back!!

Moral:

All processes such as 1-7 occur unaided in one direction but to get them go in the other direction there is an expenditure - money, energy, time, peace of mind? ….

They are called irreversible processes

Reversible Process (contd…)

- Isothermal and adiabatic processes -the work derived can be used to compress it back to the original state
- Evaporation and condensation
- Elastic expansion/compression (springs, rubber bands)
- *Lending money to a friend (who returns it promptly)*

Irreversible Process (contd…)

mixing

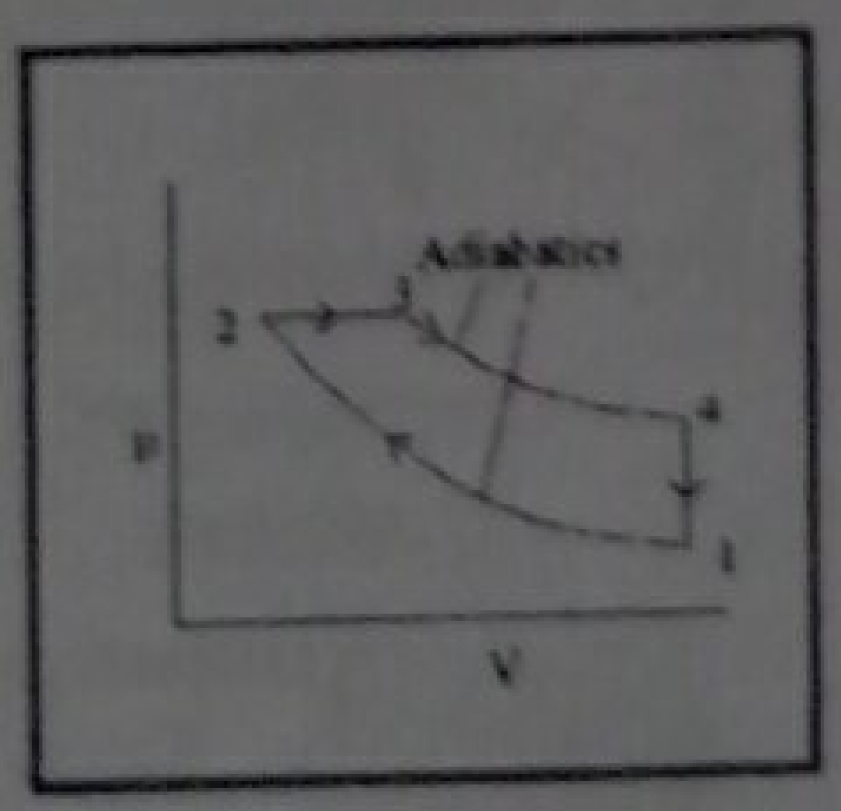
Flow of current through a resistance - when a battery discharges through a resistance heat is dissipated. You can't recharge the battery by supplying heat back to the resistance element!!

Pickpocket

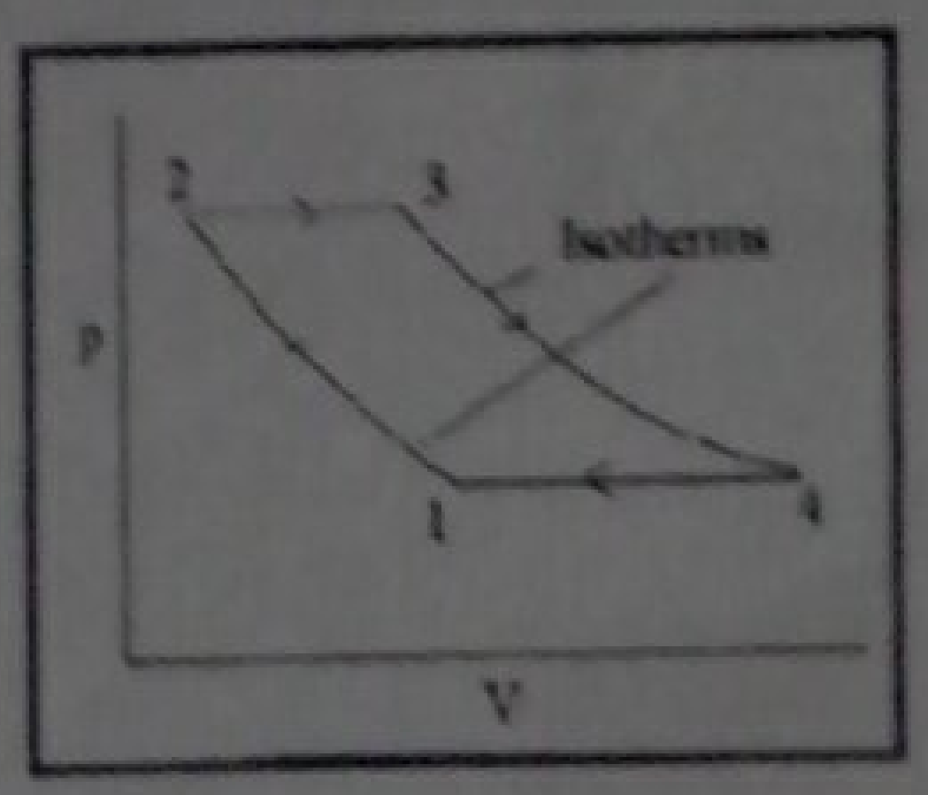
!!!Marriage!!!!

Other reversible cycles:

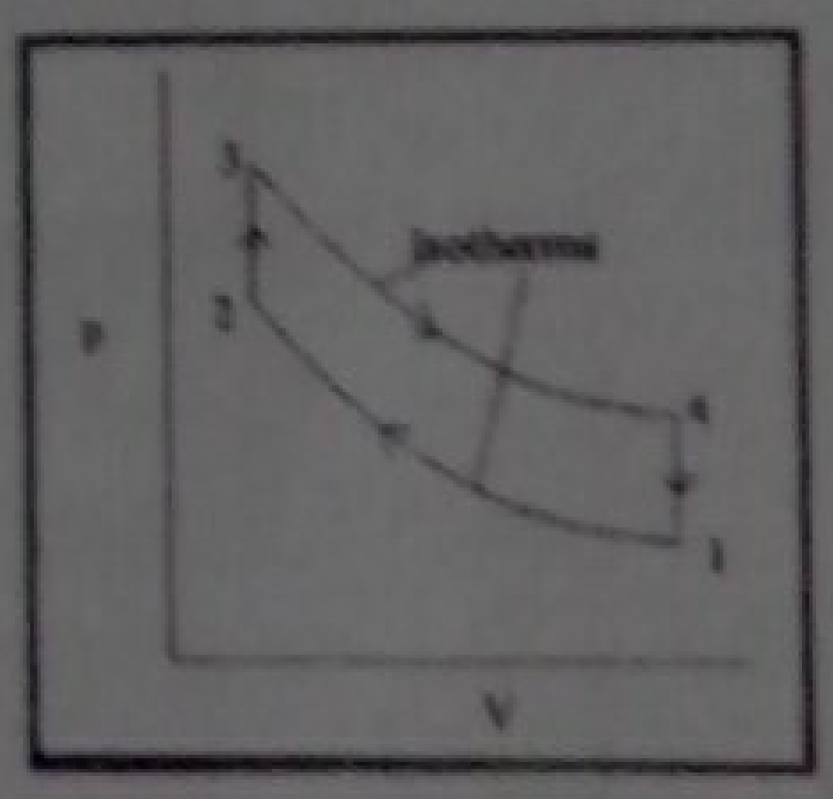
Diesel **cycle**



Ericsson cycle



Stirling cycle



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Common sense tells us that

3.Current flows from a point of higher potential to lower one — Battery can discharge through a resistance, to get the charge

4. You can mix two gases or liquids. But to separate them you have to spend a lot of energy. (You mix whisky and soda without difficulty - but can't separate the two - Is it worthwhile?)

5. All that one has to say is "I do". To get out of it one has to spend a lot of money

6. When you go to a bank and give 1US$ you may get Rs 49. But if you give Rs 49 to the bank they will give you only 95 US cents (*if you are lucky !!*). You spend more.

Definitions of Reversible Process

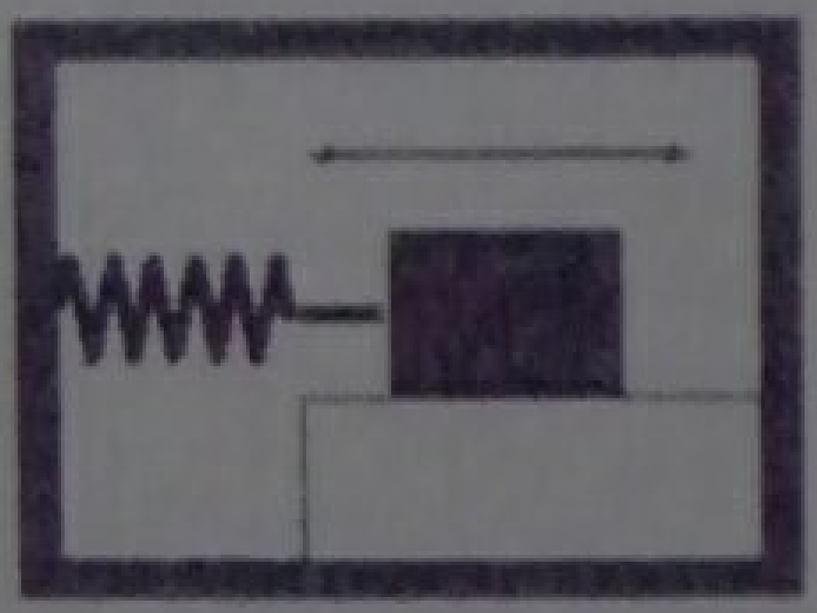
❖A process is reversible if after it, means can be found to restore the system and surroundings to their initial states.

Some reversible processes:

➤Constant volume and constant pressure heating and cooling - the heat given to change the state can be rejected back to regain the state.

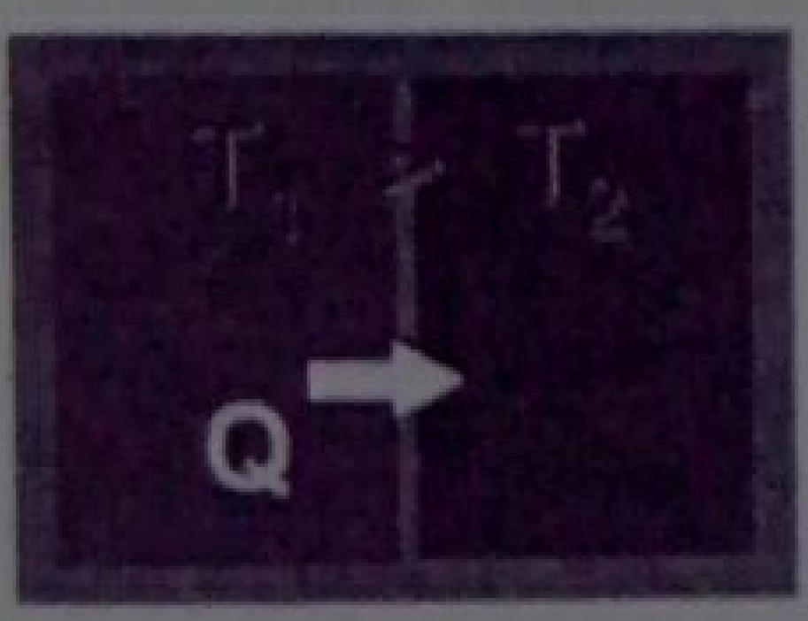
Some Irreversible Process

motion with friction

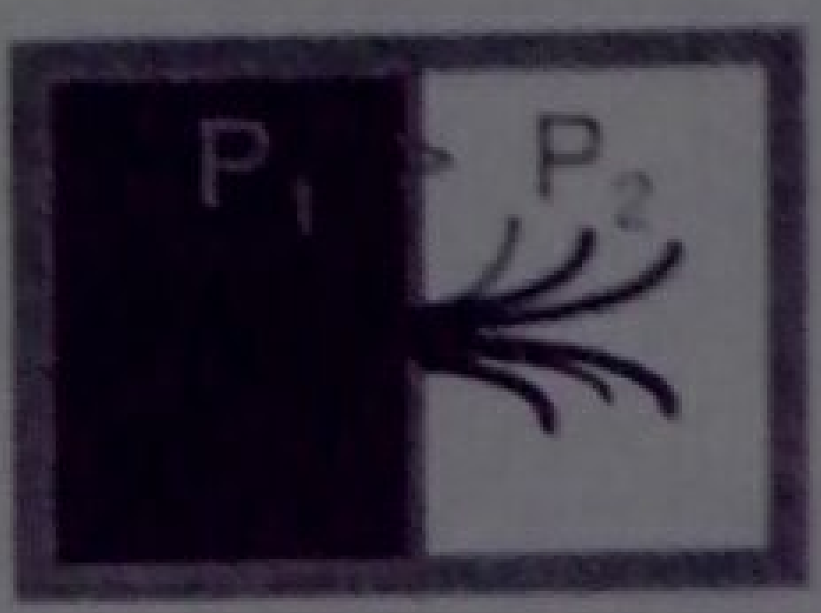


spontaneous chemical reaction

heat transfer



unrestrained expansion



Reversible Cycle

➤A cycle consisting of all reversible processes is a reversible cycle. Even one of the processes is irreversible, the cycle ceases to be reversible.

Otto, Carnot and Brayton cycles are all reversible.
A reversible cycle with clockwise processes produces work with a given heat input. The same while operating with counter clockwise processes will reject the same heat with the same work as input.

Clausius Statement (contd…)

- *Note : It is not obligatory to expend work, even thermal energy can achieve it.*
- Just as there is maximum +ve work output you can derive out of a heat engine, there is a *minimum work* you have to *supply* (-ve) *to a device* achieve transfer of thermal energy from a cooler to a hotter body.

Heat pump

❖*A device which transfers heat from a cooler to a warmer body (by receiving energy) is called a heat pump.* A refrigerator is a special case of heat pump.

Just as efficiency was defined for a heat engine, for a heat pump the coefficient of performance (COP) is a measure of how well it is doing the job.

Heat Pump (contd…)

Reverse cycle air conditioners used for winter heating do the above. Heat from the ambient is taken out on a cold day and put into the room.

The heat rejected at the sink is of interest in a heat pump , ie., Q_1.

In a refrigerator the entity of interest id Q_2.

In this case $COP_R = | Q_2/W |$

NOTE: η ,COP_{HP} COP_R are all positive numbers $\eta<1$ but COPs can be > or < 1

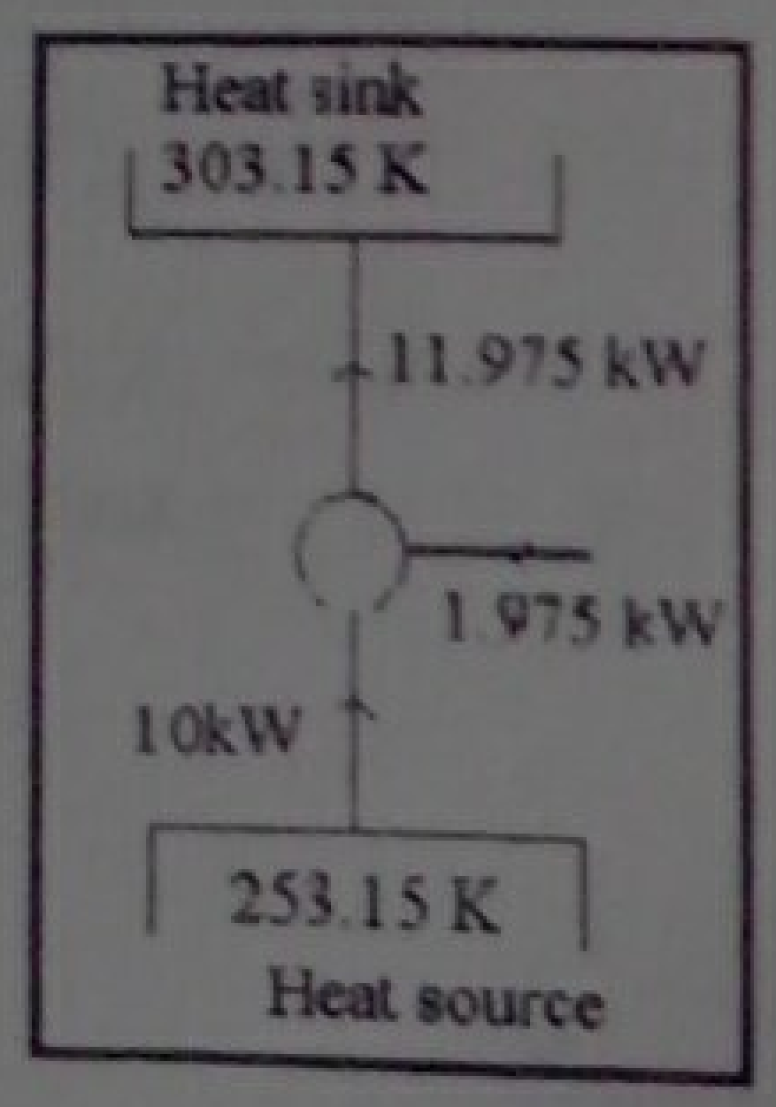
Examples

Eg: If 10 kw of heat is to be removed from a cold store at -20°Cand rejected to ambient at 30°C.

COP_R= 253.15/(303.15-253.15)= 5.063

W= Q_2/ COP_R ; Q_2= 10 kW

Therefore W= 10/5.063 = 1.975 kW



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Clausius Statement of II Law of Thermodynamics

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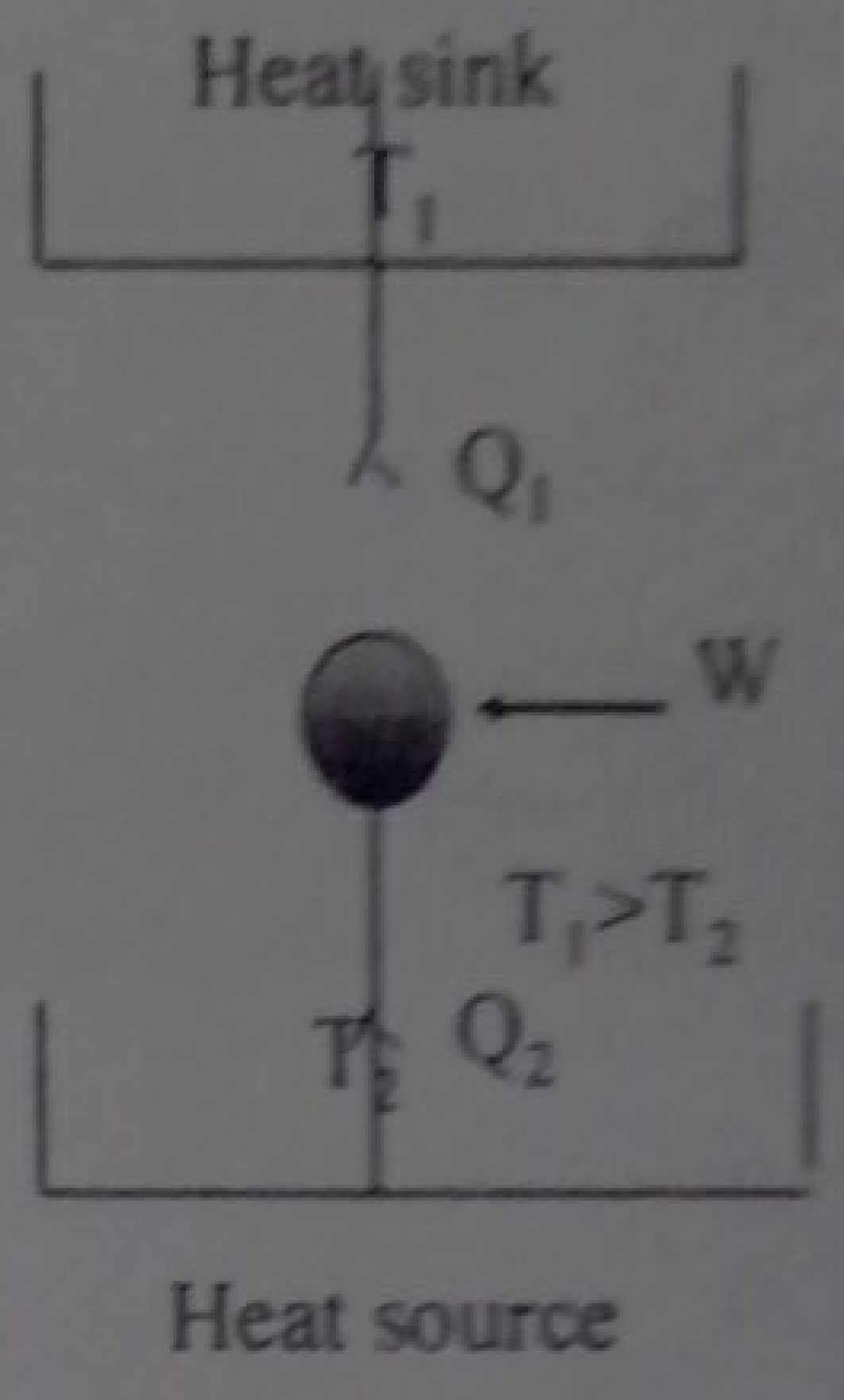
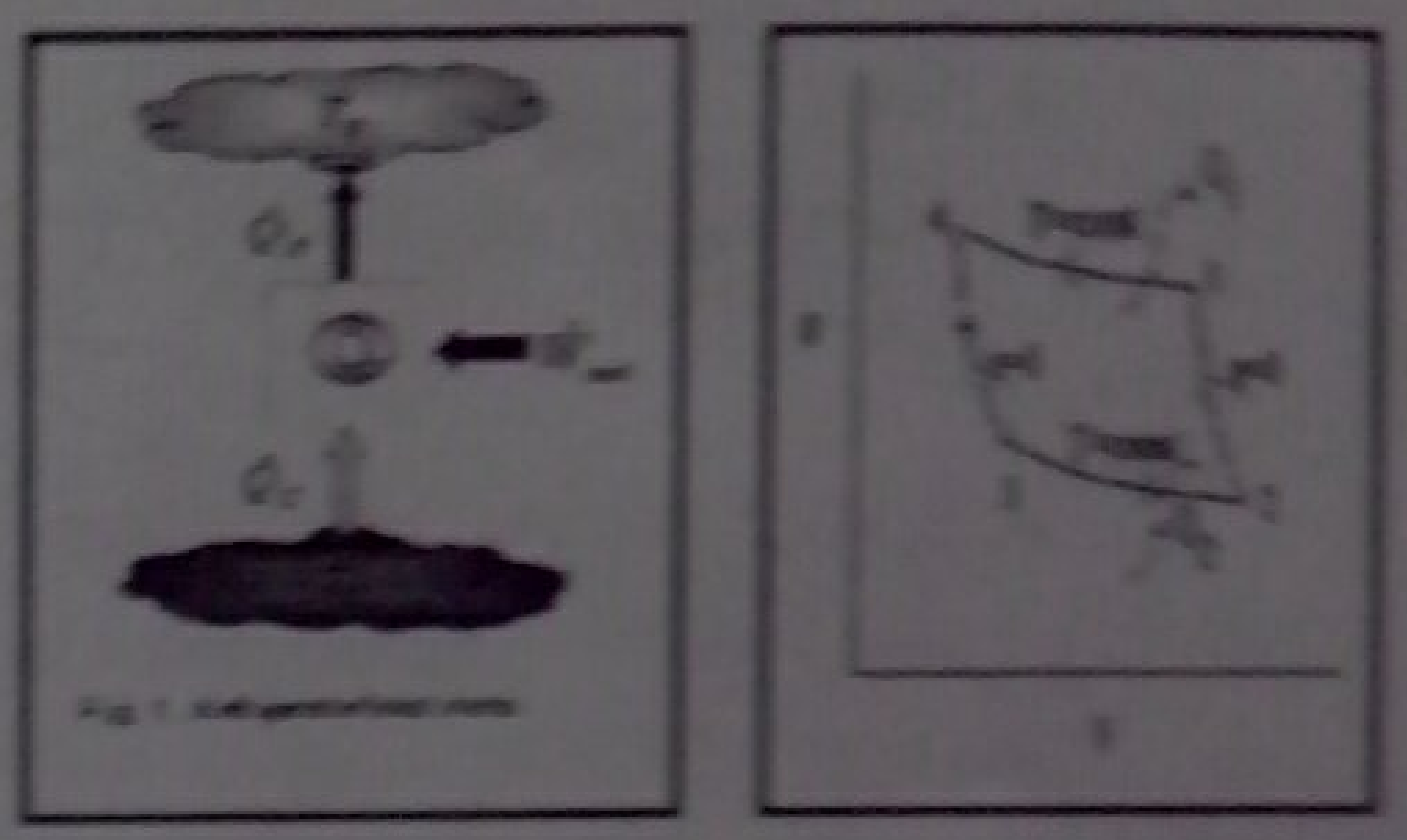




$T_H=T_1$

$T_C=T_2$

Heat Pump (contd…)

❖ A heat pump

- Invoke the definition: what we have achieved , what we spent for it
- COP_{HP} = heat given out , work done = ½Q_1/W½
- Note : The entity of interest is how much heat could be realised. Work is only a penalty.

Heat Pump (contd…)

Relation between η and COP_{HP}

It is not difficult to see that $\eta\, COP_{HP} = 1$

Apply I law to Carnot cycle as a heat pump/refrigerator:

$-Q_1+Q_2=-W$ or $Q_1=Q_2+W$

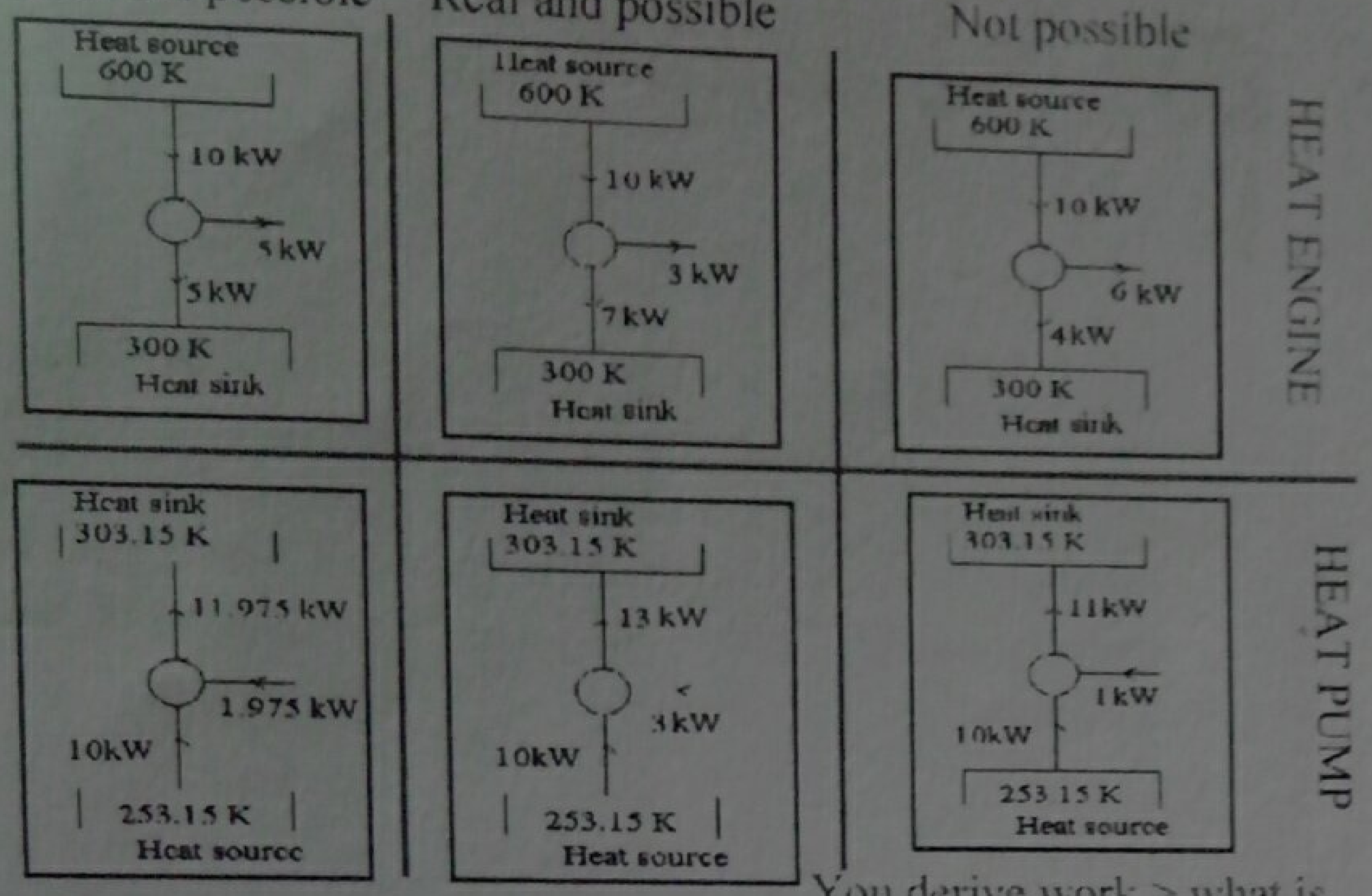
Divide both sides with W $Q_1/W=Q_2/W+1$

or $COP_{HP}=COP_R+1$

The highest COP_{HP} obtainable therefore will be $T_1/(T_1-T_2)$

and highest COP_R obtainable therefore will be $T_2/(T_1-T_2)$

Ideal but possible | Real and possible | Not possible

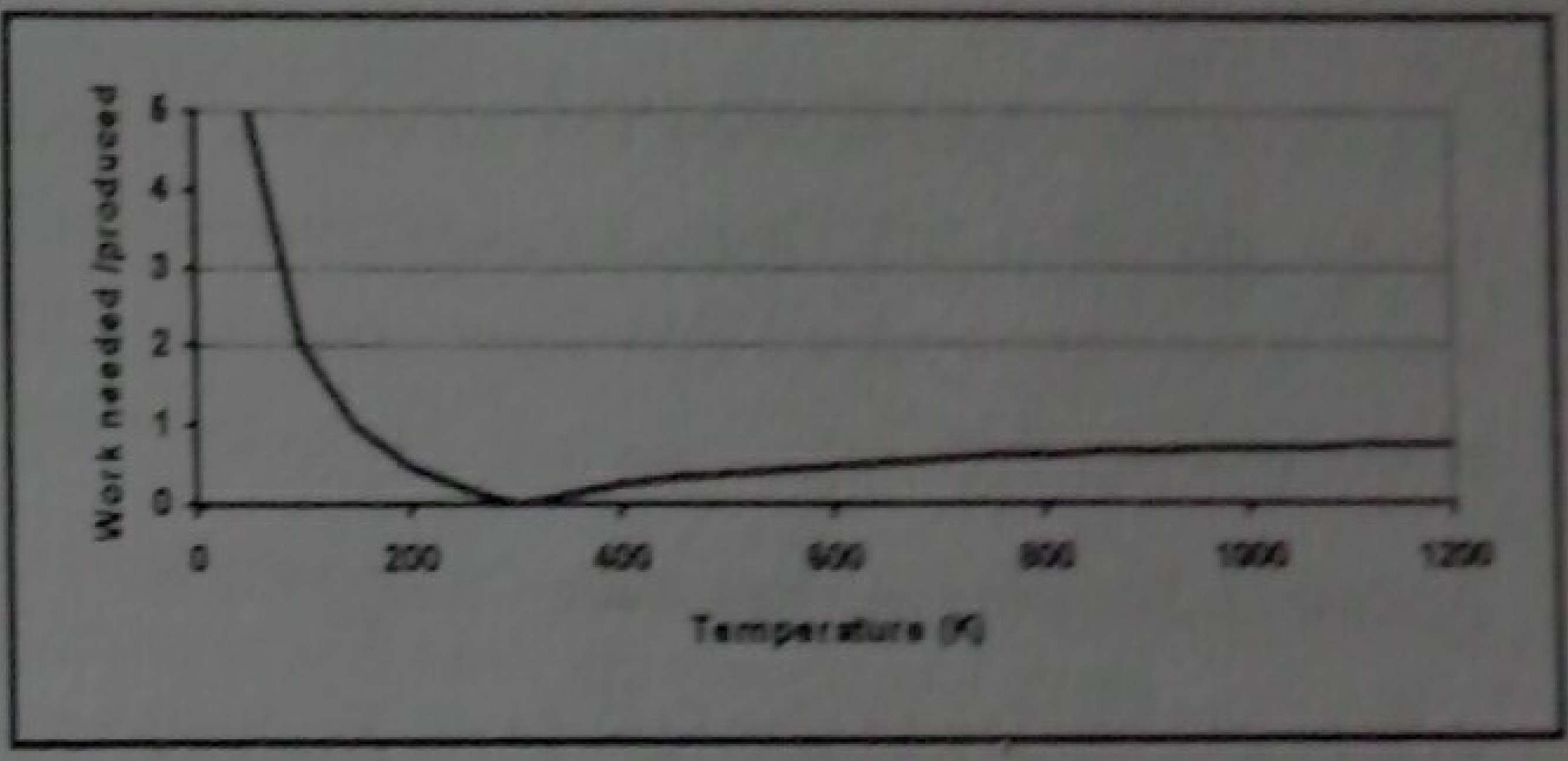


This is the best that can happen

This is what happens in reality

You derive work > what is thermodynamic maximum nor ca
You expend work < what is thermodynamic minimum

Examples (contd…)



Some Interesting Deductions

- Secondly, more interestingly, there isn't enough work available to produce 0 K. In other words, 0 K is unattainable. This is precisely the III LAW.
- Because, we don't know what 0 K looks like, we haven't got a starting point for the temperature scale!! That is why all temperature scales are at best empirical.

Equivalence of Kelvin-Planck and Clausius statements

II Law basically a negative statement (*like most laws in society*). The two statements look distinct. We shall prove that violation of one makes the other statement violation too.

Let us suspect the Clausius statement-it *may be* possible to transfer heat from a body at colder to a body at hotter temperature without supply of work

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Examples (contd…)

❖Another example: Let us say that the outside temperature on a hot summer day is 40°C. We want a comfortable 20°C inside the room. If we were to put a 2 Ton (R) air conditioner, what will be its power consumption?

Answer: 1 Ton (R) = 3.5 kw. Therefore Q_2=7 kW

COP_R= 293.15/(313.15-293.15)= 14.66 ie., W=7/14.66 =0.47 kW

Actually a 2 Ton air-conditioner consumes nearly 2.8 kW (much more than an ideal cycle!!)

Examples (contd…)

Suppose the ambient is at 300 K. We have heat sources available at temperatures greater than this say 400, 500, 600…..K. How much work ca you extract per kW of heat ? Similarly, let us say we have to remove 1 kW of heat from temperatures 250, 200, 150 …. K. How much work should we put in?

Some Interesting Deductions

➢Firstly, there isn't a meaningful temperature of the source from which we can get the full conversion of heat to work. Only at ∞ temp. one can dream of getting the full 1 kW work output.

Summation of 3 Laws

You can't get something for nothing

To get work output you must give some thermal energy

You can't get something for very little

To get some work output there is a minimum amount of thermal energy that needs to be given

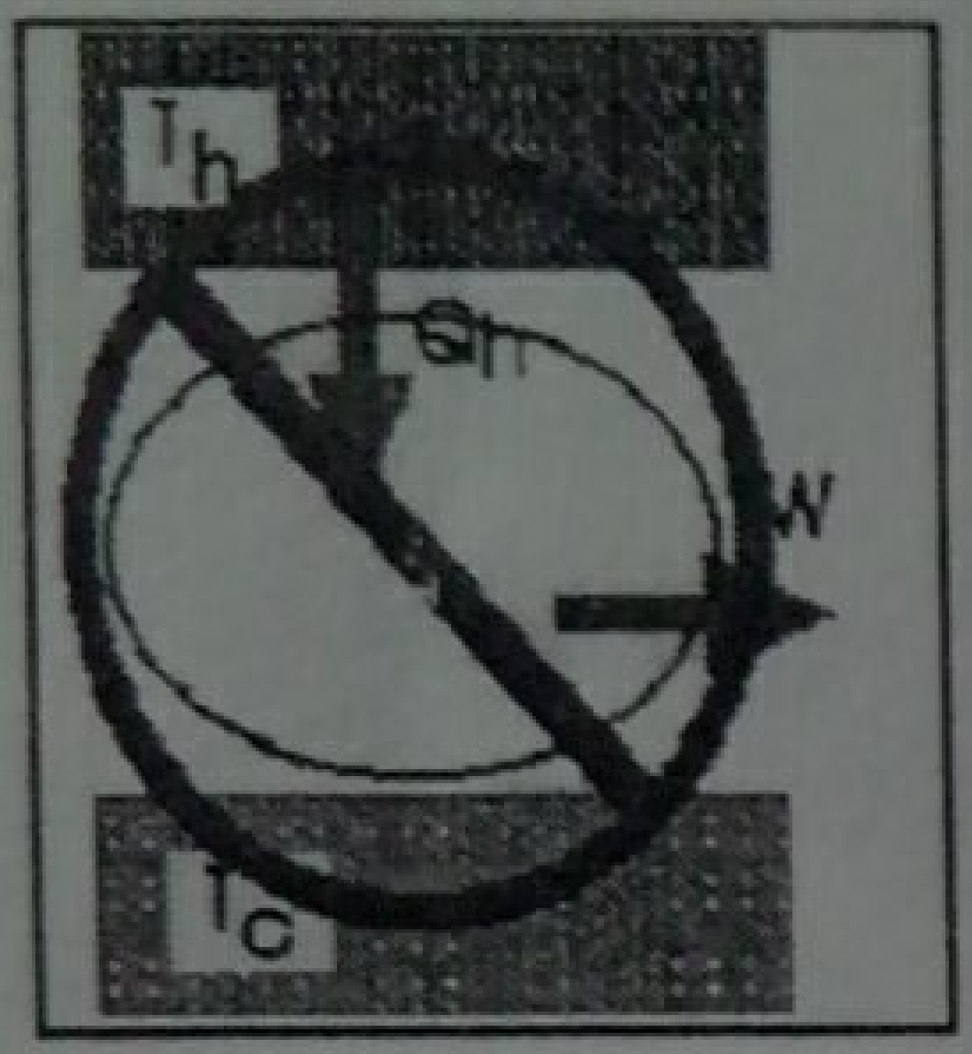
You can't get every thing

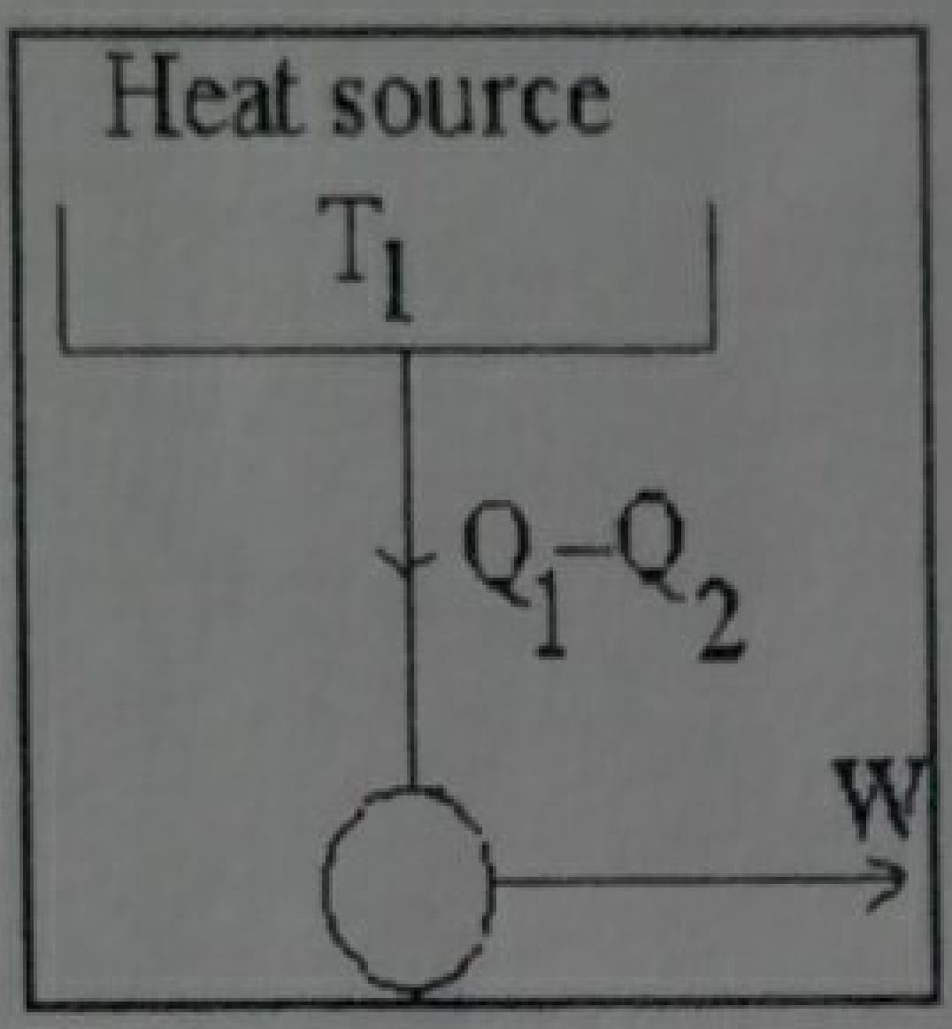
However much work you are willing to give 0 K can't be reached.

Violation of all 3 laws: try to get everything for nothing

Equivalence of Kelvin-Planc and Clausius statements

Combine the two. The reservoir at T_2 has not undergone any change (Q_2 was taken out and by pseudo-Clausius device and put back by the engine). Reservoir 1 has given out a net Q_1-Q_2. We got work output of W. Q_1-Q_2 is converted to W with no net heat rejection. This is violation of Kelvin-Planck statement.





Equivalence of Kelvin-Planck and Clausius statements

Moral: If an engine/refrigerator violates one version of II Law,

it violates the other one too.

All reversible engine operating between the same two fixed temperatures will have the same η and COPs.

If there exists a reversible engine/ or a refrigerator which can do better than that, it will violate the Clausius statement.

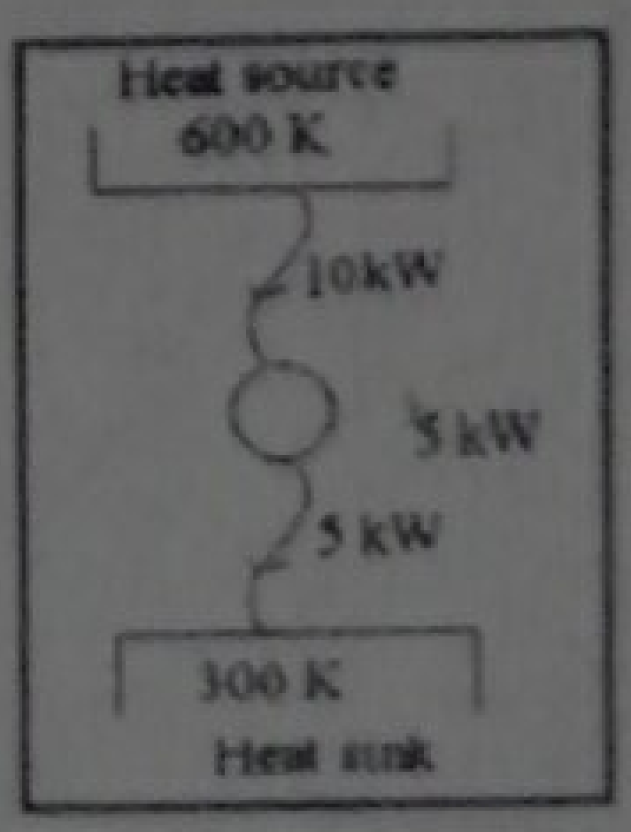
Equivalence of Kelvin-Planck and Clausius statements (contd…)

SUM UP

- Heat supplied = Q_1; Source temperature = T_1 ;Sink temperature= T_2
- Maximum possible efficiency = W/Q_1= (T_1-T_2)/T_1
- Work done = W= Q_1(T_1-T_2)/T_1

Equivalence of Kelvin-Planck and Clausius statements

- Heat rejected = -ve heat interaction = -Q_2= (Q_1-W)= Q_1T_2/T_1
- For a reversible heat engine operating in a cycle $Q_1/T_1+Q_2/T_2= 0$
- or S(Q/T) = 0

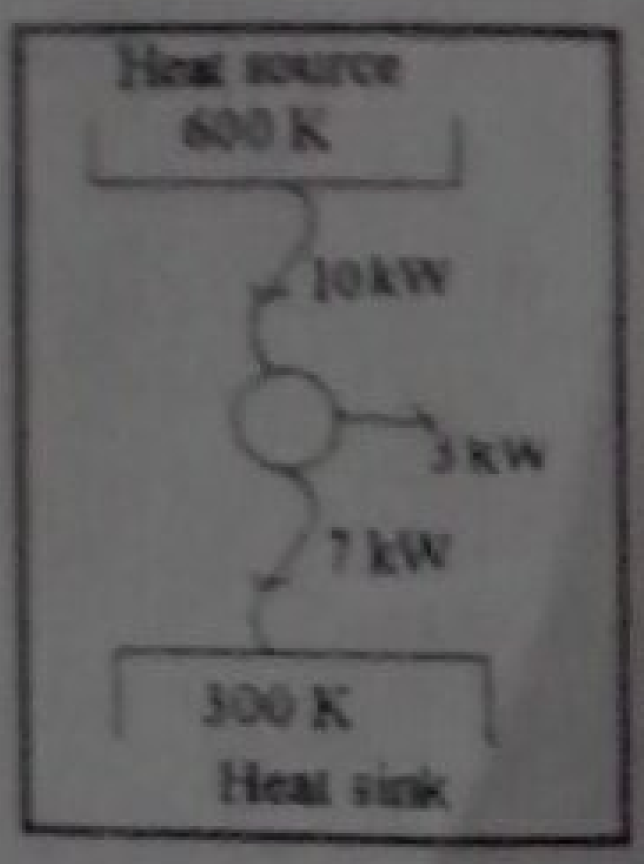


Ideal engine

10,000/600 +(-5000/300)=0

Not so efficient engine

10,000/600+ (-7000/300) < 0



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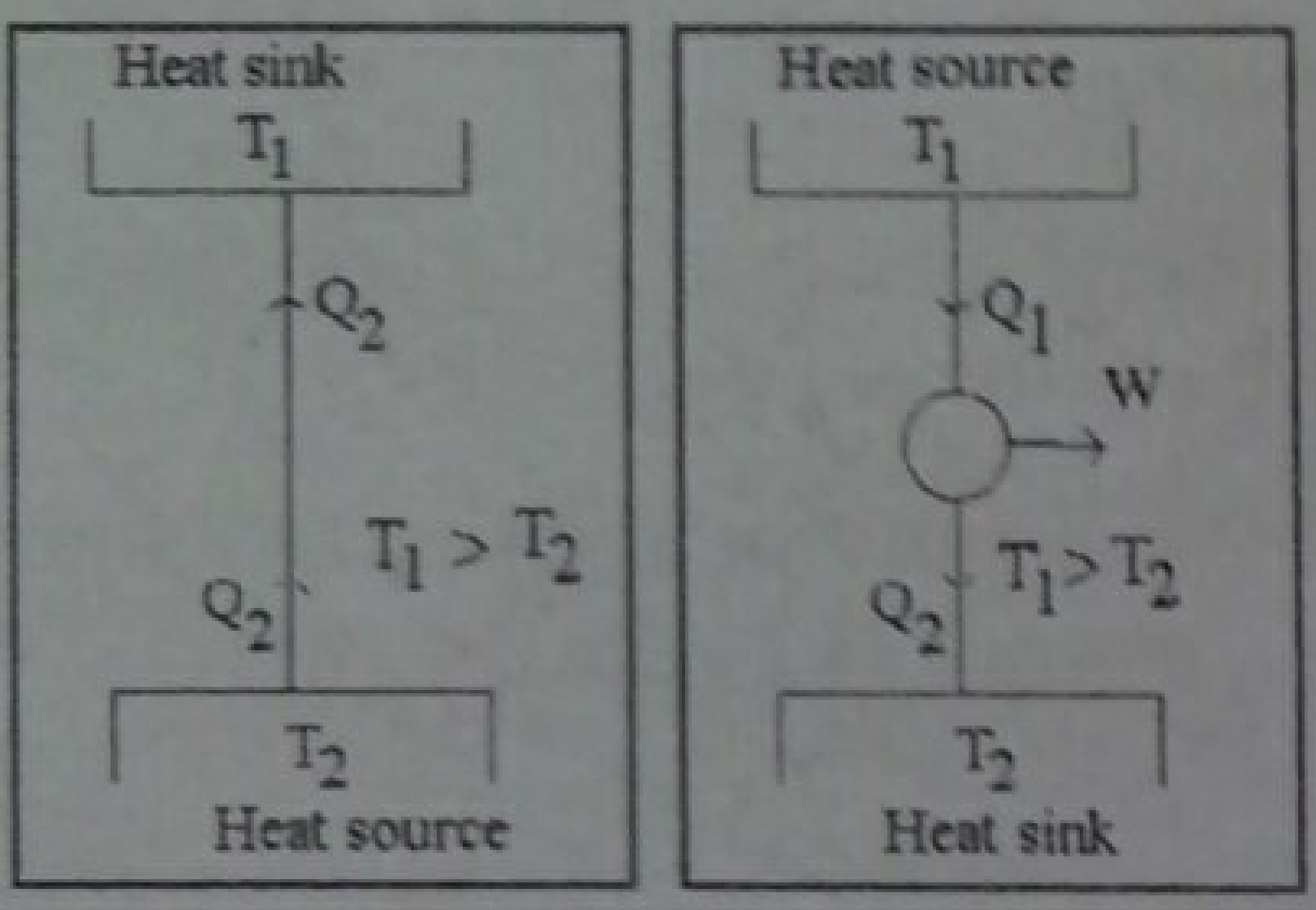
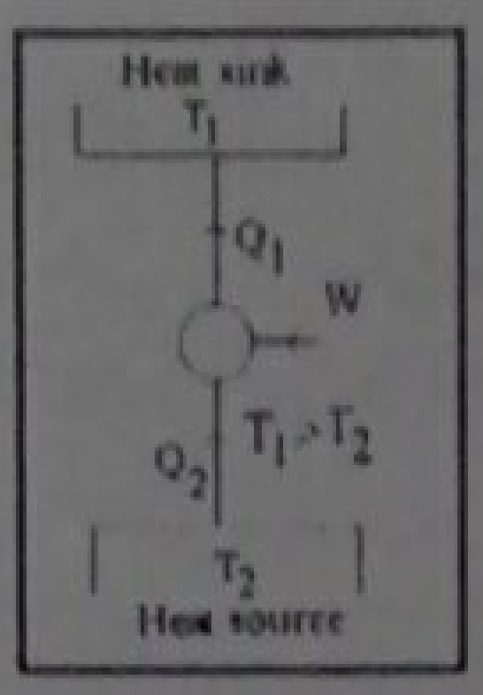
Equivalence of Kelvin-Planck and Clausius statements

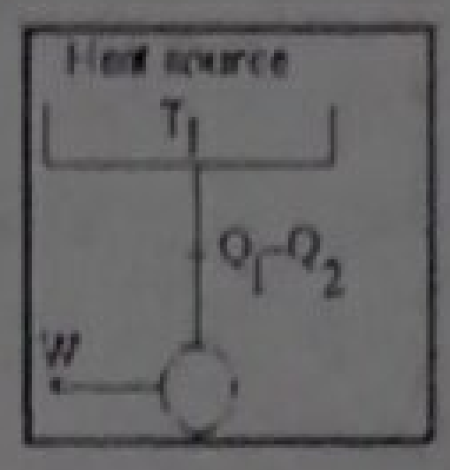


Let us have a heat engine operating between T_1 as source and T_2 as a sink. Let this heat engine reject exactly the same Q_2 (as the pseudo-Clausius device) to the reservoir at T_2. To do this an amount of Q1 needs to be drawn from the reservoir at T_1. There will also be a $W = Q_1 - Q_2$

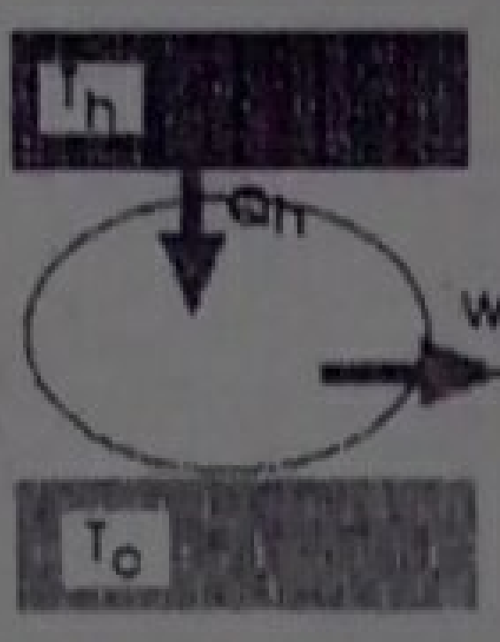
Equivalence of Kelvin-Planck and Clausius statements

- Let us assume that Clausius statement is true and suspect Kelvin-Planck statement





May be possible?



Pseudo Kelvin Planck engine requires only Q_1-Q_2 as the heat interaction to give out W (because it does not reject any heat) which drives the Clausius heat pump

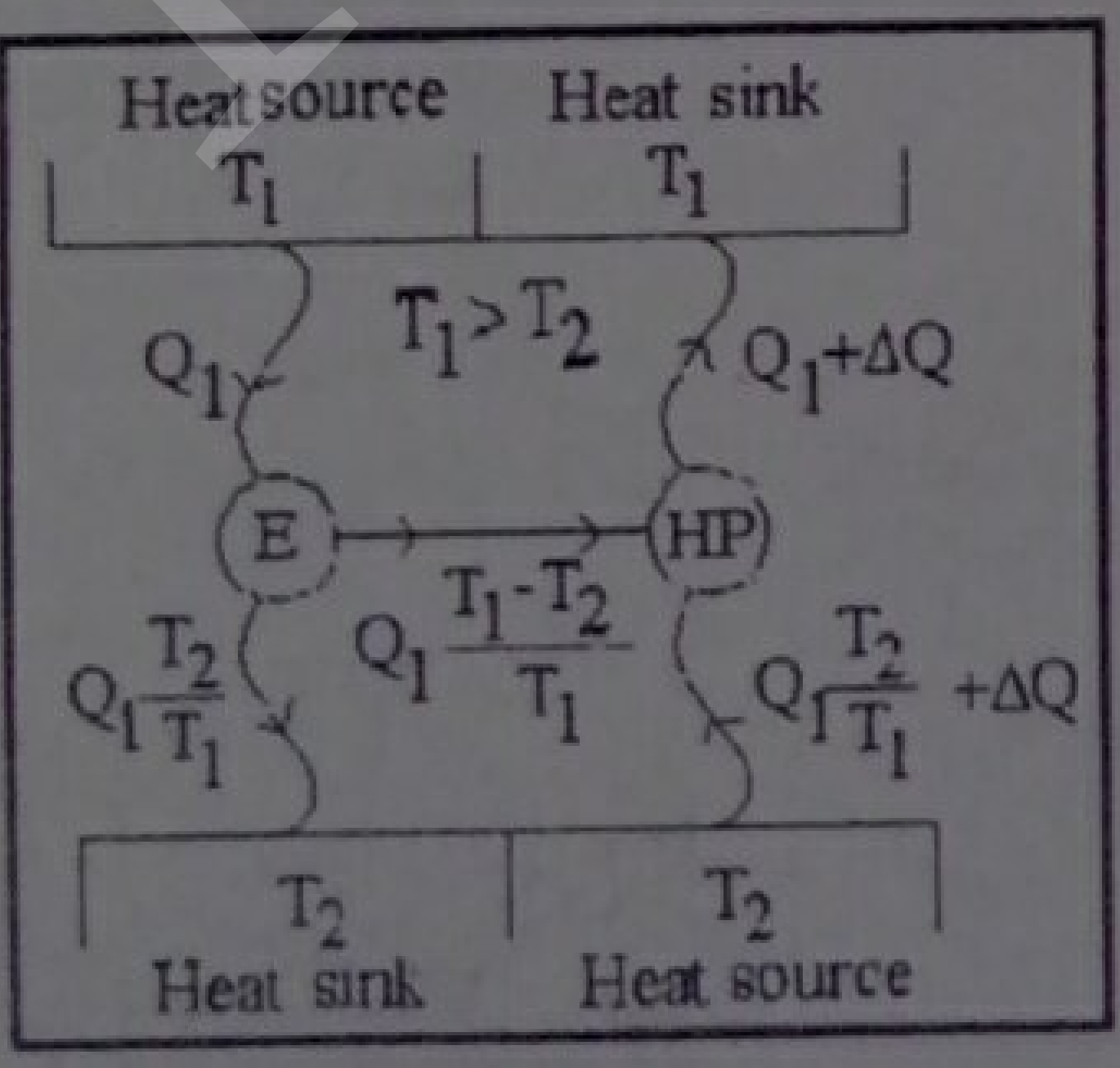
Combining the two yields

- The reservoir at T_1 receives Q_1 but gives out Q_1-Q_2 implying a net delivery of Q_2 to it.
- Q_2 has been transferred from T_2 to T_1 without the supply of any work!!
- *A violation of Clausius statement*

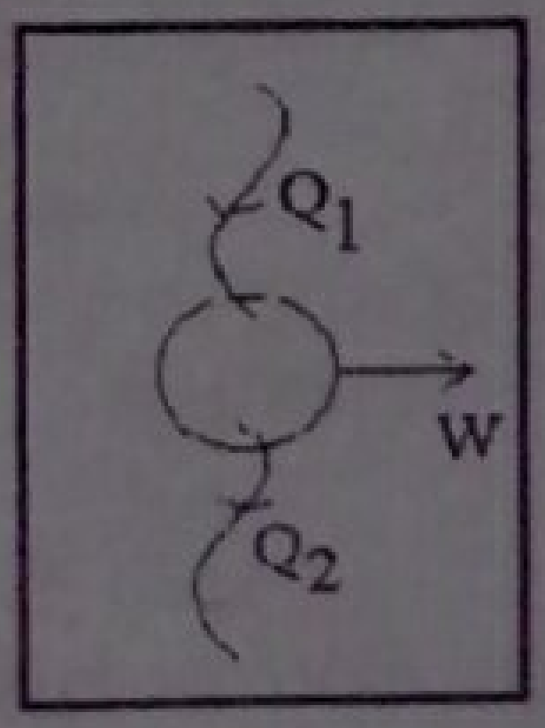
Equivalence of Kelvin-Planck and Clausius statements

Let us presume that the HP is super efficient!!

For the same work given out by the engine E, it can pick up an extra DQ from the low temperature source and deliver over to reservoir at T1. The net effect is this extra DQ has been transferred from T2 to T1 with no external work expenditure. *Clearly, a violation of Clausius statement!!*



Equivalence of Kelvin-Planck and Clausius statements (contd…)



Applying I Law

Sum of heat interactions = sum of work interactions

$Q_1 + Q_2 = W = Q_1 (T_1 - T_2)/T_1$

Q_1 is +ve heat interaction; Q_2 is -ve heat interaction