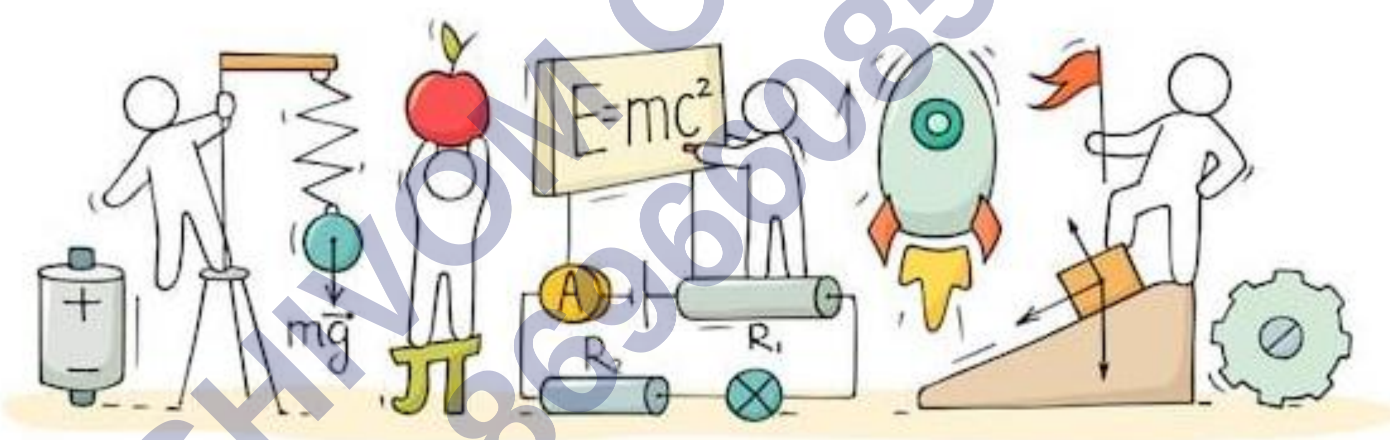
PHYSICS

Chapter 12: Thermodynamics



Thermodynamics

Introduction

Thermodynamics is that branch of physics which deals with concepts of heat and temperature and their relation to energy and work.

We can also consider it as a macroscopic science which deals with bulk systems and tells us about system as a whole.

In this chapter we will learn about the laws of thermodynamics which describes the system in terms of macroscopic variables, reversible and irreversible processes. Finally we will also learn on what principle heat engines, refrigerators and Carnot engine work.

Examples: - Refrigerator, steam engine

Refrigerator

Steam Engine

Thermal Equilibrium

Two systems are said to be in thermal equilibrium if the temperatures of the two systems are equal.

In mechanics if the net force on a system is zero, the system is in equilibrium.

In Thermodynamics equilibrium means all the macroscopic variables (pressure, temperature and volume) don't change with time. They are constant throughout.

For Example:

Consider two bodies at different temperatures one is at 30^0C and another at 60^0C then the heat will flow from body at higher temperature to the body at lower temperature.

Heat will flow till both bodies acquire same temperature.

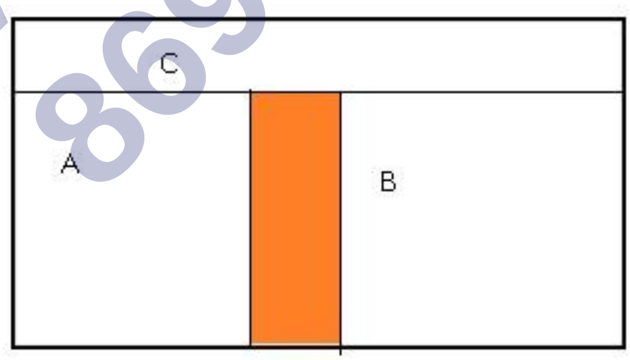
This state when there is no heat flow between two bodies when they acquire the same temperature is known as thermal equilibrium.

In the above case if consider a hot cup of coffee will become cold after sometime if it is kept on the table as there will heat flow between the hot coffee and surroundings. When the cup of coffee attains the same temperature as of room temperature then there will be no flow of heat.

Zeroth Law of Thermodynamics

Zeroth law of thermodynamics states that when two systems are in thermal equilibrium through a third system separately then they are in thermal equilibrium with each other also.

Foreg: - Consider two systems A and B which are separated by an adiabatic wall. Heat flow happens between systems A and C, and between B and C, due to which all 3 systems attain thermal equilibrium.



Systems A and B are in thermal equilibrium with C. Then they will be in equilibrium with each other also.

Zeroth Law of Thermodynamics suggested that there should be some physical quantity which should have same value for the system to be in thermal equilibrium.

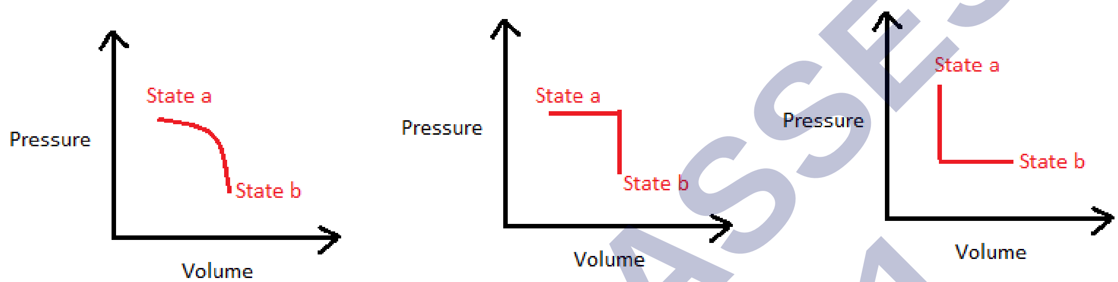
This physical quantity which determines whether system is in equilibrium or not is Temperature.

Temperature is the quantity which determines whether the system is in thermal equilibrium with the neighbouring system.

When the temperature becomes equal then the flow of heat stops.

Heat, Internal Energy and Work

We already know what heat is. It is a form of energy but it always comes into the picture when energy is being transferred from one system to another. Suppose we are at an initial state ‘a’ and want to go to a final state ‘b’. We can do that by various processes (as shown in the figure) and the heat energy released or absorbed in all the processes is different. So we can see that heat does not depend on the state of the system.



So there was a need to define another term that was dependent on the state of the system. This is termed as Internal Energy.

Internal Energy

Internal energy definition is given as:

The energy contained within the system associated with random motions of the particles along with the potential energies of the molecules due to their orientation.

The energy due to random motion includes translational, rotational, and vibrational energy. It is represented as U. So now we can say, since internal energy is a state function and in all the processes shown above the change in internal energy from state, ‘a’ to state ‘b’ will be the same.

Internal Energy Formula

The following is the formula for internal energy:

$\Delta U = Q + W$

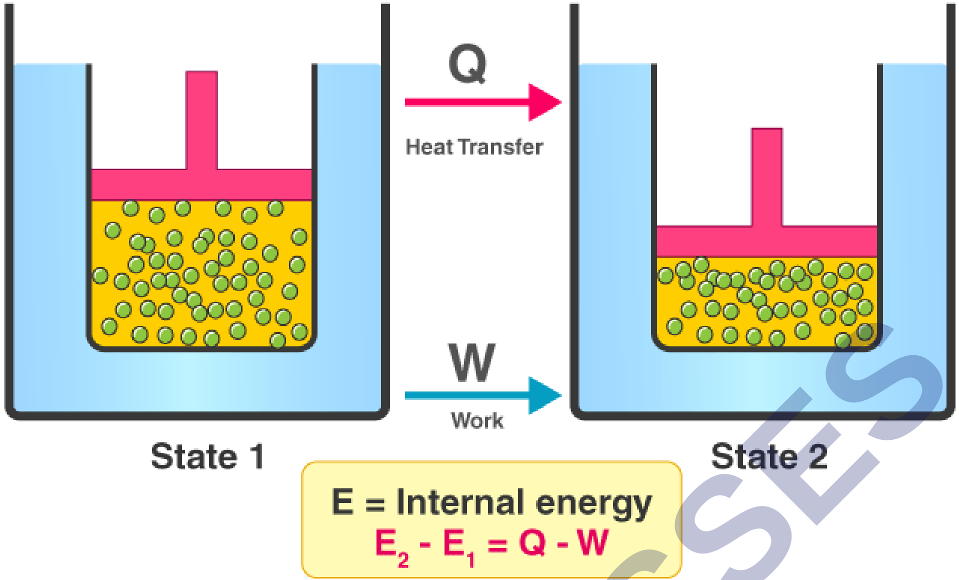
Where,

ΔU is the internal energy

Q is the heat added to the system

W is the work done by the system

First Law of Thermodynamics



A thermodynamic system in an equilibrium state possesses a state variable known as the internal energy(E). Between two systems the change in the internal energy is equal to the difference of the heat transfer into the system and the work done by the system.

The first law of thermodynamics states that the energy of the universe remains the same. Though it may be exchanged between the system and the surroundings, it can't be created or destroyed. The law basically relates to the changes in energy states due to work and heat transfer. It redefines the conservation of energy concept.

The First Law of Thermodynamics states that heat is a form of energy, and thermodynamic processes are therefore subject to the principle of conservation of energy. This means that heat energy cannot be created or destroyed. It can, however, be transferred from one location to another and converted to and from other forms of energy.

To help you understand the meaning of the First Law, we can take the common example of a heat engine. In a Heat engine, the thermal energy is converted into mechanical energy and the process also is vice versa. Heat engines are mostly categorized as an open system. The basic working principle of a heat engine is that it makes use of the different relationships between heat, pressure and volume of a working fluid which is usually a gas. Sometimes phase changes might also occur involving a gas to liquid and back to gas.

First Law of Thermodynamics Equation

The equation for the first law of thermodynamics is given as;

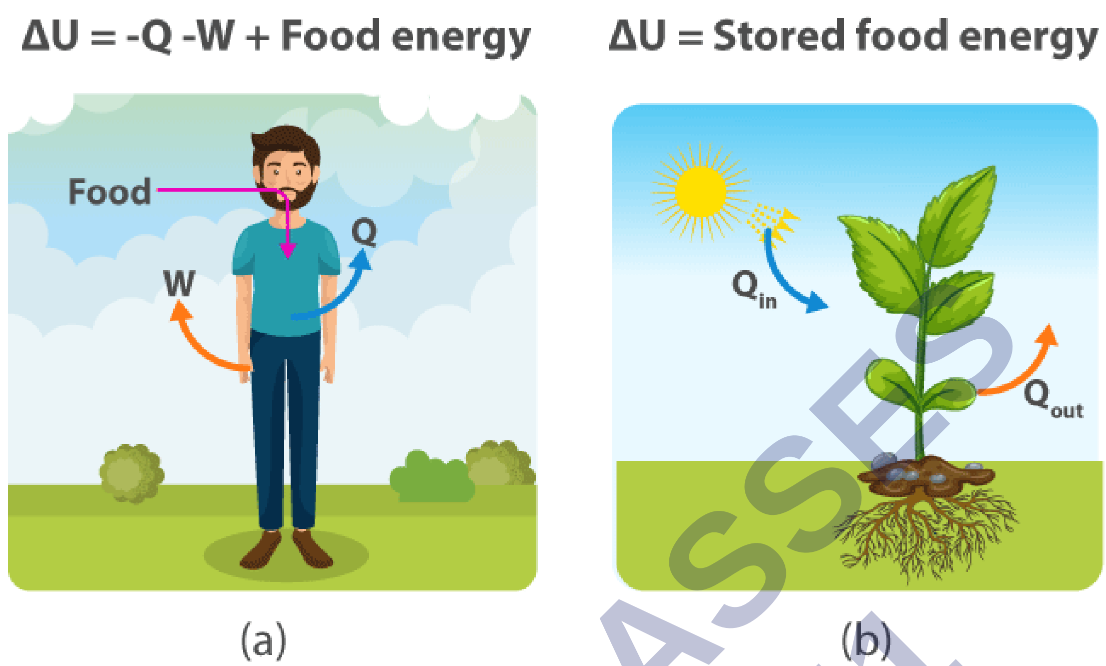
$\Delta U = q + W$

Where,

ΔU = change in internal energy of the system.

q = algebraic sum of heat transfer between system and surroundings.

W = work interaction of the system with its surroundings.



For an isolated system, energy (E) always remains constant.

Internal Energy is a point function and property of the system. Internal energy is an extensive property (mass-dependent) while specific energy is an intensive property (independent of mass).

For an ideal gas, the internal energy is a function of temperature only.

Specific heat capacity

Specific heat is defined as the amount of heat required to raise the temperature of a body per unit mass.

It depends on:

Nature of substance

Temperature

Denoted by 's'

$$s = \left(\frac{\Delta Q}{m\Delta T}\right)$$

where m= mass of the body

ΔQ = amount of heat absorbed or rejected by the substance

ΔT= temperature change

Unit - J kg^{-1} K^{-1}

If we are heating up oil in a pan, more heat is needed when heating up one cup of oil compared to just one tablespoon of oil. If the mass s is more the amount of heat required is more to increase the temperature by one degree.

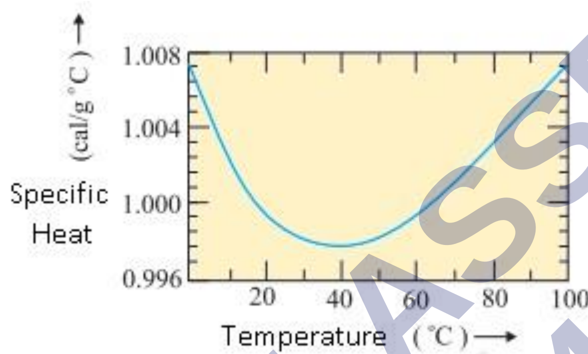
Specific heat capacity of water

Calorie: - One calorie is defined to be the amount of heat required to raise the temperature of 1g of water from 14.5 °C to 15.5 °C.

In SI units, the specific heat capacity of water is 4186 J kg^{-1} K^{-1}e.

4.186 J g^{-1} K^{-1}.

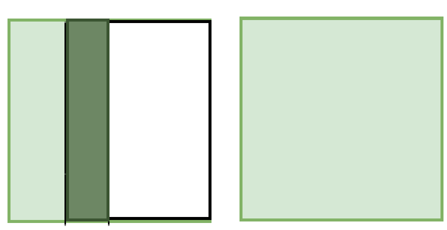
The specific heat capacity depends on the process or the conditions under which heat capacity transfer takes place.



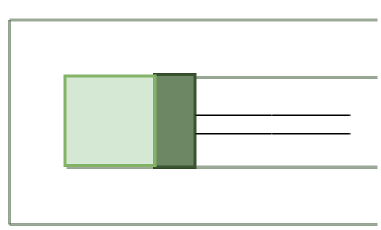
Thermodynamic State Variables and Equation of State

A system is said to be in a thermodynamics state of equilibrium if the macroscopic variables that change the state of the system do not change over time. These macroscopic variables include pressure, temperature, mass, and composition that does not change with time. For example, gas is stored inside a container that is completely insulated from its surroundings, with fixed values of pressure, volume, temperature, mass, and composition that do not change with time, is in a state of equilibrium.

The equilibrium of a gas can be described by its pressure, temperature, volume, and mass. It is not necessary that a thermodynamic system is always in equilibrium. For example, if gas at equilibrium is allowed to expand, it does not remain in thermodynamic equilibrium. The figure below shows the expansion of gases when they are left to expand:



(a)



(b)

Thermodynamics variables describe the state of the system at equilibrium. These various state variables are not necessarily independent.

These variables can be divided into two types:

Extensive Variables

Intensive Variables

Extensive Variables: These variables are the state variables that indicate the size of the system. For example, Volume can be considered an extensive variable because it gives us an idea about the size of the system.

Intensive Variables: These variables are the state variables that do not give us any information about the size of the system but indicate different information about the system. Examples of such variables are pressure, temperature, etc.

State Equation

State Equation describes the relationship between state variables of a thermodynamic system. The equation of state is completely defined in terms of pressure, temperature and volume. For example, in the case of ideal gases. The state equation becomes,

$$PV = RT$$

Or

$$PV = \text{Constant}$$

In the case of an isothermal process,

$P_1V_1 = P_2V_2$

These equations of state are for ideal gases.

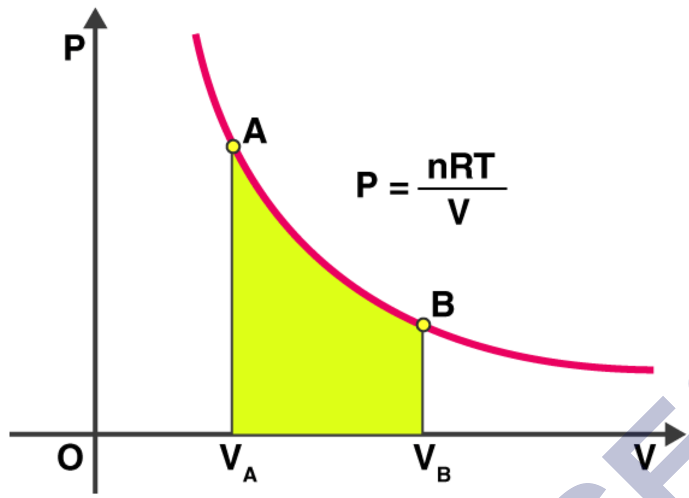
Thermodynamic Processes & Types

We know that if we have to take a thermodynamic system from the initial to the final state, we have several paths that can be taken. In this article, we will be discussing those thermodynamic processes. Before that, we will see what a quasi-static process is. It has been discussed that state variables are defined only when the thermodynamic system is in equilibrium with the surrounding. So a process in which the system is in thermodynamic equilibrium with the surrounding is known as a quasi-static process at each moment.

The Thermodynamic Processes

Isothermal Process:

It is a thermodynamic process in which temperature remains constant. We know,



$W = \int PdV$

According to Gas law,

$PV = nRT$

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

Using this value of P in work done, we get,

$W = nRT \int_{V_A}^{V_B} \frac{dV}{V}$

$W = nRTln\frac{V_B}{V_A}$

Adiabatic Process:

It is a thermodynamic process in which no heat is exchanged between the system and the surrounding. So, Q = 0. Mathematically this process is represented as

$PV^{\gamma} = K(constant)$

$W = \int PdV$

Substituting P, we get,

$W = K \int_{V_i}^{V_f} \frac{dV}{V^{\gamma}}$

$W = K\frac{(V_f^{1-\gamma} - V_i^{1-\gamma})}{1-\gamma}$

For adiabatic process,

$\Delta U = -W$

Isochoric Process:

In isochoric process the change in volume of thermodynamic system is zero. A volume change is zero, so the work done is zero.

Volume of the system = Constant

Change in volume = 0

If, change in volume = 0, then work done is zero.

According to the 1st law of thermodynamic law

Q = W + dU

If W = 0

Q = dU

Isobaric Process:

The pressure remains constant during this process. So,

$$W = P(V_f - V_i)$$

So if volume increases, work done is positive, else negative.

Cyclic Process:

It is a process in which the final state of the system is equal to the initial state. As we know, change in internal energy is a state function, so, in this case, ΔU = 0.

Quasi-static process:

In thermodynamics, a quasi-static process is referred to as a slow process.

It is a process that happens at an infinitesimally slow rate.

A quasi-static process has all of its states in equilibrium.

A quasi-static process is one in which the system is in thermodynamic equilibrium with its surroundings at all times.

Second Law of Thermodynamics

The second law of thermodynamics states that any spontaneously occurring process will always lead to an escalation in the entropy (S) of the universe. In simple words, the law explains that an isolated system's entropy will never decrease over time.

Nonetheless, in some cases where the system is in thermodynamic equilibrium or going through a reversible process, the total entropy of a system and its surroundings remains constant. The second law is also known as the Law of Increased Entropy.

The second law clearly explains that it is impossible to convert heat energy to mechanical energy with 100 per cent efficiency. For example, if we look at the piston in an engine, the gas is heated to increase its pressure and drive a piston. However, even as the piston moves, there is always some leftover heat in the gas that cannot be used for carrying out any other work. Heat is wasted and it has to de discarded. In this case, it is done by transferring it to a heat sink or in the case of a car engine, waste heat is discarded by exhausting the used fuel and air mixture to the atmosphere. Additionally, heat generated from friction that is generally unusable should also be removed from the system.

Second Law of Thermodynamics Equation

Mathematically, the second law of thermodynamics is represented as:

$\Delta S_{univ} > 0$

where ΔS_{univ} is the change in the entropy of the universe.

Entropy is a measure of the randomness of the system or it is the measure of energy or chaos within an isolated system. It can be considered as a quantitative index that describes the quality of energy.

Meanwhile, there are few factors that cause an increase in entropy of the closed system. Firstly, in a closed system, while the mass remains constant there is an exchange of heat with the surroundings. This change in the heat content creates a disturbance in the system thereby increasing the entropy of the system.

Secondly, internal changes may occur in the movements of the molecules of the system. This leads to disturbances which further causes irreversibilities inside the system resulting in the increment of its entropy.

Different Statements of The Law

There are two statements on the second law of thermodynamics which are;

Kelvin- Plank Statement

Clausius Statement

Kelvin-Planck Statement

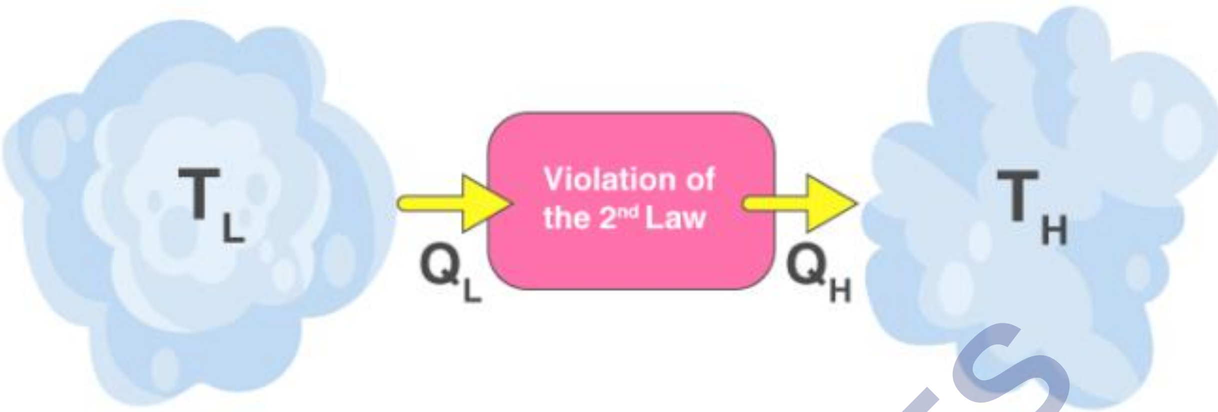
It is impossible for a heat engine to produce a network in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

Exceptions:

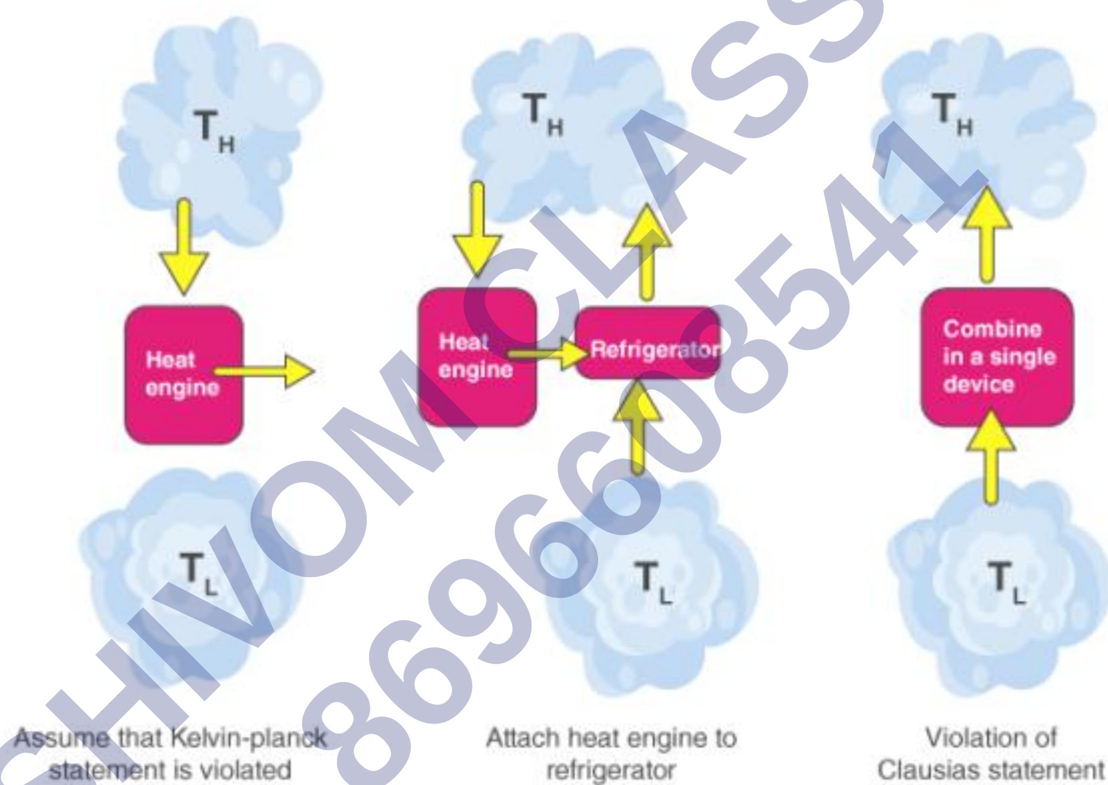
If Q_2 =0 (i.e., $W_{net} = Q_1$, or efficiency=1.00), the heat engine produces work in a complete cycle by exchanging heat with only one reservoir, thus violating the Kelvin-Planck statement.

Clausius's Statement

It is impossible to construct a device operating in a cycle that can transfer heat from a colder body to a warmer one without consuming any work. Also, energy will not flow spontaneously from a low-temperature object to a higher temperature object. It is important to note that we are referring to the net transfer of energy. Energy transfer can take place from a cold object to a hot object by transfer of energetic particles or electromagnetic radiation. However, the net transfer will occur from the hot object to the cold object in any spontaneous process. And some form of work is needed to transfer the net energy to the hot object. In other words, unless the compressor is driven by an external source, the refrigerator won't be able to operate. The heat pump and refrigerator work on Clausius's statement.



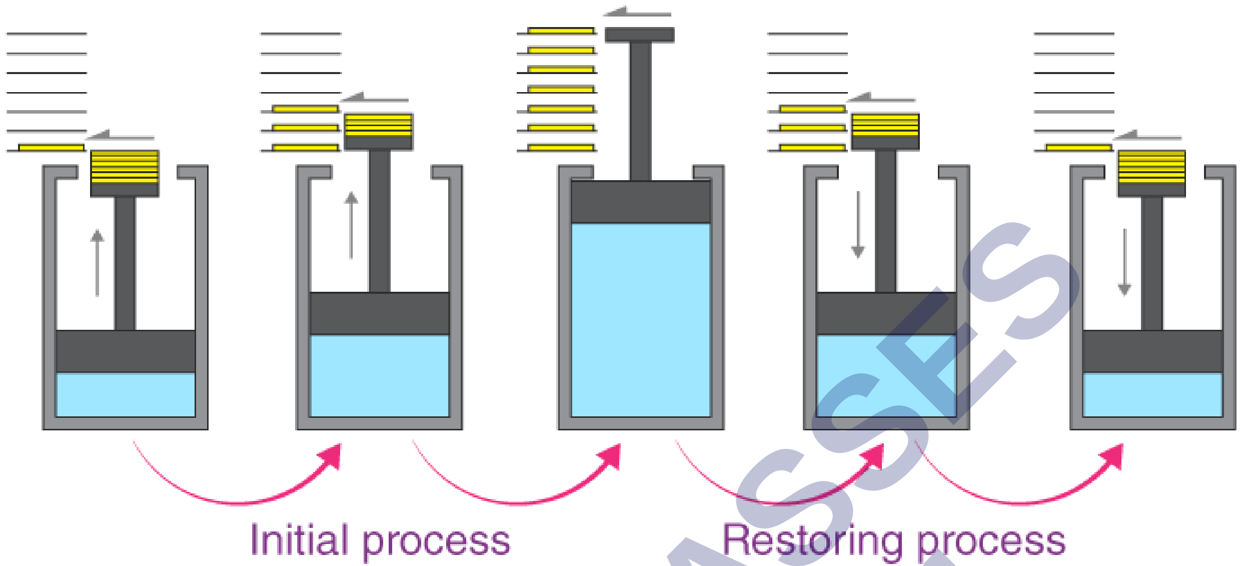
Both Clausius's and Kelvin's statements are equivalent i.e a device violating Clausius's statement will also violate Kelvin's statement and vice versa.



In addition to these statements, a French physicist named Nicolas Léonard Sadi Carnot also known as the "father of thermodynamics," basically introduced the Second Law of Thermodynamics. However, as per his statement, he emphasized the use of caloric theory for the description of the law. Caloric (self-repellent fluid) relates to heat and Carnot observed that some caloric was lost in the motion cycle.

Reversible And Irreversible Processes

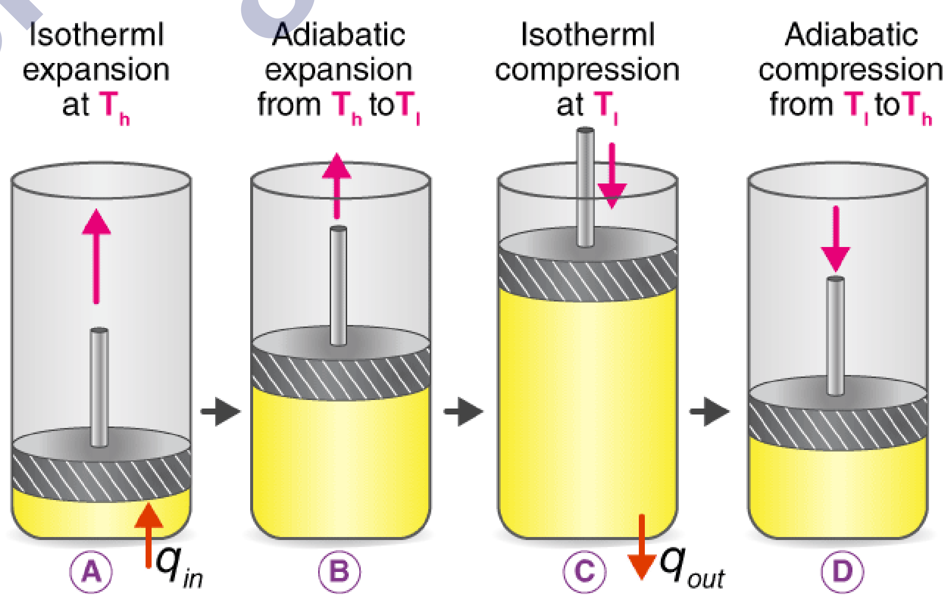
We see so many changes happening around us every day, such as boiling water, rusting of iron, melting ice, burning of paper, etc. In all these processes, we observe that the system in consideration goes from an initial state to a final state where some amount of heat is absorbed from the surroundings and some amount of work W is done by the system on the surrounding. Now, for how many such systems can the system and the surrounding be brought back to their initial state? With common examples such as rusting and fermentation, we can say that it is not possible in most cases. In this section, we shall learn about reversible and irreversible processes.



A thermodynamic process (state i → state f) is said to be reversible if the process can be turned back to such that both the system and the surroundings return to their original states, with no other change anywhere else in the universe. As we know, in reality, no such processes as reversible processes can exist. Thus, the reversible processes can easily be defined as idealizations or models of real processes on which the limits of the system or device are to be defined. They help us in incurring the maximum efficiency a system can provide in ideal working conditions and thus the target design that can be set.

Carnot Cycle

A Carnot cycle is defined as an ideal reversible closed thermodynamic cycle. Four successive operations are involved: isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression. During these operations, the expansion and compression of the substance can be done up to the desired point and back to the initial state.



Following are the four processes of the Carnot cycle:

In (a), the process is reversible isothermal gas expansion. In this process, the amount of heat absorbed by the ideal gas is qin from the heat source at a temperature of T_h. The gas expands and does work on the surroundings.

In (b), the process is reversible adiabatic gas expansion. Here, the system is thermally insulated, and the gas continues to expand and work is done on the surroundings. Now the temperature is lower, T_l.

In (c), the process is a reversible isothermal gas compression process. Here, the heat loss q_{out} occurs when the surroundings do the work at temperature T_l.

In (d), the process is reversible adiabatic gas compression. Again, the system is thermally insulated. The temperature again rises back to Th as the surrounding continue to do their work on the gas.

Carnot Engine

The Carnot engine is a theoretical thermodynamic cycle proposed by Leonard Carnot. It estimates the maximum possible efficiency that a heat engine during the conversion process of heat into work and, conversely, working between two reservoirs can possess.

Carnot Theorem

According to Carnot Theorem:

Any system working between T_1 (hot reservoir) and T_2 (cold reservoir) can never have more efficiency than the Carnot engine operating between the same reservoirs.

Also, the efficiency of this type of engine is independent of the nature of the working substance and is only dependent on the temperature of the hot and cold reservoirs.

Top Formulae

- Equation of isothermal changes PV = constant or $P_2 V_2 = P_1 V_1$
- Equation of adiabatic changes

  i. $P_2V_2^{\gamma} = P\ V_1$

  ii. $P^{1-\gamma}T_2^{\gamma} = P_1{}^{-\gamma}T^{\gamma}$

  iii. $T_2V_2^{\gamma-1} = T_1V_1^{\gamma-1}$, where $\gamma = C_p / C_v$

- Work done by the gas in isothermal expansion

$$W = 2.3026\ RT\ \log_{10} \frac{V_2}{V_1}$$

$$W = 2.3026\ RT\ \log_{10} \frac{P_1}{P_2}$$

- Work done in adiabatic expansion

$$W = \frac{R}{(1-\gamma)}(T_2 - T\ )$$

- dQ = dU + dW

  Here, dW = P (dV), small amount of work done

  dQ = m L for change of state

  dQ = mc ΔT for rise in temperature

  dU = change in internal energy

- $$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T}$$

  Where T_1 = temperature of source, T_2 = temperature of sink; Q_1 is the amount of heat absorbed/cycle from the source, Q_2 is the amount of heat rejected/cycle to the sink.

- Useful work done/cycle $W = Q_1 - Q_2$

- Efficiency of Carnot engine is also given by $\eta = \frac{W}{Q_1} = 1 - \frac{T_2}{T_1}$

- Coefficient of performance of a refrigerator

$$\beta = \frac{Q_2}{W} = \frac{T_2}{T_1 - T}; W = Q_1 - Q_2$$

  where Q_2 is the amount of heat drawn/cycle from the sink (at T_2) and W is work done/cycle on the refrigerator. Q_1 is the amount of heat rejected/cycle to the source (air at room temperature T_1).

- $$\beta = \frac{1-\eta}{\eta}$$

Class : 11th Physics

Chapter- 12 : Thermodynamics

Thermodynamics State variable

(i) Extensive – indicate the size of the system. e.g. U, volume, total mass.

(ii) Intensive – do not indicate size of the system. e.g. , pressure & temperature

Thermodynamics Equilibrium

Two systems are in thermal equilibrium with each other if they have the same temperature.

Zeroth Low of Thermodynamics

If two systems A&B are in thermal equilibrium with a third system C, then A&B are in thermal equilibrium with each other.

First Low of Thermodynamics

It is the statement of law of conservation of Energy;

$\Delta Q = \Delta U + \Delta W$

$= \Delta U + P\Delta U$ (Here, $\Delta U = P\Delta U$)

Second Low of Thermodynamics

It is impossible for an engine working between a cyclic process to extract heat from a reservoir and convert completely into work.

Laws

Thermodynamics

Reversible & Irreversible Process

Any process made to proceed in the reverse direction by changing its conditions is called Reversible Process.

Any process which cannot be retraced in the reverse direction exactly is called Irreversible Process.

Heat Engine

Converts continuously heat into mechanical energy in cyclic process.

Efficiency $\eta = \frac{W}{Q} = 1 - \frac{Q_2}{QT_1} = 1 - \frac{T_2}{T_1}$

Carnot Engine

An Ideal engine works on a reversible cycle of four operations in succession.

(i) isothermal expansion,

(ii) adiabatic expansion,

(iii) isothermal compression,

(iv)adiabatic compression.

Efficiency of Carnot's engine

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

Refrigerator and heat pump

Refrigerator is a heat engine working in the reverse direction.

Coefficient of performance,

$$\beta = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

Specific heat capacity Relation

- $\frac{C_P}{C_V} = \gamma$
- Mayer's Equation $C_P - C_V = R$

Branch of Science which deals with concepts of heat & temperature and their interconnection by thermodynamic process

Cyclic Process

In this process, system returns to initial state for a cyclic process $\Delta U = 0$ (zero)

Quasi - static Process

Infinity slow process such that systems remain in thermal & mechanical equilibrium with the surroundings throughout.

Property

The pressure (P) & temperature (T) of the environment can differ from those of the system only infinitesimally.

Isobaric Process

Pressure = Constant

$\frac{V}{T} = $ Constant

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

Adiabatic Process

A thermally insulated system neither gains nor loses heat

$PV^{\gamma} =$ Constant

$TV^{\gamma-1} =$ Constant

$\frac{P^{n-\gamma}}{T^{\gamma}} =$ Constant; $\frac{C_P}{C_v} = \gamma$

Isochoric Process

Volume = Constant

$\frac{P}{T} = $ Constant

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

Isothermal Process

Temperature = Constant

PV= Constant = n RT

$W = \int_{V_1}^{V_2} \frac{nRT}{V} dv$

Important Questions

Multiple Choice questions-

1. A vessel contains a mixture of one mole of oxygen and two moles of nitrogen at 300 K. The ratio of the average rotational kinetic energy per O^2 to per N^2 molecule is

(a) 1 : 1

(b) 1 : 2

(c) 2 : 1

(d) depends on the moment of inertia of the two molecules

2.For a diatomic gas change in internal energy for a unit change in temperature for constant pressure and constant volume is U1 and U2 respectively. What is the ratio of U1 and U2?

(a) 5 : 3

(b) 3 : 5

(c) 1 : 1

(d) 5 : 7

3. An ideal gas heat engine operates in Carnot cycle between 227°C and 127°C. It absorbs 6 × 104 cal of heat at higher temperature. Amount of heat converted to work is:

(a) 2.4 × 104 cal

(b) 6 × 104 cal

(c) 1.2 × 104 cal

(d) 4.8 × 104 cal

4. Which of the following parameters dose not characterize the thermodynamic state of matter?

(a) work

(b) volume

(c) pressure

(d) temperature

5. A Carnot engine whose sink is at 300 K has an efficiency of 40%. By how much should the temperature of source be increased, so as to increase its efficiency by 50% of original efficiency?

(a) 275 K

(b) 325 K

(c) 250 K

(d) 380 K

6. The translational kinetic energy of gas molecules at temperature T for one mole of a gas is

(a) (3/2) RT

(b) (9/2) RT

(c) (1/3) RT

(d) (5/2) RT

7. The temperature of reservoir of Carnots engine operating with an efficiency of 70% is 1000 kelvin. The temperature of its sink is

(a) 300 K

(b) 400 K

(c) 500 K

(d) 700 K

8. A gas is taken through a number of thermodynamic states. What happens to its specific heat?

(a) It is always constant.

(b) It increases.

(c) It decreases.

(d) It can have any value depending upon the process of heat absorbed or evolved.

9. Directions: The following has four choices out of which ONLY ONE is correct. A refrigerator with its power on, is kept in a closed room with its door open, then the temperature of the room will _________.

(a) rise

(b) fall

(c) remain the same

(d) depend on the area of the room

10. Directions: The following has four choices out of which ONLY ONE is correct. Which of the following is incorrect regarding the first law of thermodynamics? A. It is not applicable to any cyclic process B. It is a restatement of the principle of conservation of energy C. It introduces the concept of the internal energy D. It

introduces the concept of the entropy

(a) A and D

(b) B and C

(c) C and A

(d) A and B

Very Short:

1. What type of process is Carnot's cycle?
2. Can the Carnot engine be realized in actual practice?
3. A refrigerator transfers heat from a cold body to a hot body. Does this not violate the second law of thermodynamics?
4. What is a heat pump?
5. What forbids the complete conversion of work into heat?
6. Does the internal energy of an ideal gas change in:

   (a) an isothermal process?

   (b) an adiabatic process?
7. What is the specific heat of a gas in an isothermal process and in an adiabatic process? Why?
8. Can the temperature of an isolated system change?
9. Can we increase the coefficient of performance of a refrigerator by increasing the amount of working substance?
10. The door of an operating refrigerator is kept open in a closed room. Will it make the room warm or cool?

Short Questions:

1. Kelvin and Clausius's statements of the Second law of thermodynamics are equivalent. Explain?
2. Two identical samples of gas are expanded so that the volume is increased to twice the initial volume. However, sample number 1 is expanded isothermally while sample number 2 is expanded adiabatically. In which sample is the pressure greater? Why?
3. No real engine can have an efficiency greater than that of a Carnot engine working between the same two temperatures. Why?
4. Explain why two isothermal curves cannot intersect each other?
5. What is the source of energy when gas does work when expands adiabatically?

6. State and explain the zeroth law of thermodynamics?
7. State and explain the first law of thermodynamics. What are the sign conventions?
8. Why cannot a ship use the internal energy of seawater to operate the engine?
9. A certain amount of work is done by the system in a process in which no heat is transferred to or from the system. What happens to the internal energy and the temperature of the system?
10. If an electric fan is switched on in a closed room, will the air of the room be cooled? Why?

Long Questions:

1. Discuss the Carnot cycle and give essential features of a Carnot engine.
2. Derive the expression for the work done during:

   (a) Isothermal process

   (b) Adiabatic process
3. A gas is suddenly compressed to 1/3 of its original volume. Calculate the rise in temperature, the original temperature being 300K and $\gamma = 1.5$.
4. A perfect Qarjiotreiigifae utilizes an ideal gas. The source temperature is 500K and since the temperature is 375 K. If the engine takes 600 Kcal per cycle from the source, compute:

   (a) the efficiency of The engine.

   (b) work done per cycle,

   (c) heat rejected to the sink per cycle.
5. A refrigerator has, to transfer an average of 263 J of heat per second from temperature – 10°C to 25°C. Calculate the average power consumed assuming ideal reversible cycle and no other losses.

Assertion Reason Questions:

1. **Directions:** Each of these questions contain two statements, Assertion and Reason. Each of these questions also has four alternative choices, only one of which is the correct answer. You have to select one of the codes (a), (b), (c) and (d) given below.

   (a) If both assertion and reason are true and the reason is the correct explanation of the assertion.
   (b) If both assertion and reason are true but reason is not the correct explanation of the assertion.
   (c) If assertion is true but reason is false.
   (d) If the assertion and reason both are false.

Assertion: When a bottle of cold carbonated drink is opened, a slight fog forms around the opening.
Reason: Adiabatic expansion of the gas causes lowering of temperature and condensation of water vapours.

2. **Directions:** Each of these questions contain two statements, Assertion and Reason. Each of these questions also has four alternative choices, only one of which is the correct answer. You have to select one of the codes (a), (b), (c) and (d) given below.

   (a) If both assertion and reason are true and the reason is the correct explanation of the assertion.
   (b) If both assertion and reason are true but reason is not the correct explanation of the assertion.
   (c) If assertion is true but reason is false.
   (d) If the assertion and reason both are false.

   Assertion: In adiabatic compression, the internal energy and temperature of the system get decreased.
   Reason: The adiabatic compression is a slow process

✓ Answer Key:

Multiple Choice Answers-

1. Answer: (a) 1 : 1
2. Answer: (c) 1 : 1
3. Answer: (c) 1.2 × 104 cal
4. Answer: (a) work
5. Answer: (c) 250 K
6. Answer: (a) (3/2) RT
7. Answer: (a) 300 K
8. Answer: (d) It can have any value depending upon the process of heat absorbed or evolved.
9. Answer: (a) rise
10. Answer: (a) A and D

Very Short Answers:

1. Answer: Cyclic process.
2. Answer: No. It is an ideal heat engine.
3. Answer: No. This is because external work is being performed.
4. Answer: A heat pump is a device that uses mechanical work to remove heat.

5. Answer: The second law of thermodynamics.
6. Answer: (a) No.

   (b) Yes.
7. Answer: It is infinite in isothermal process because $\Delta T = 0 \left(C = \frac{\Delta Q}{m\Delta T}\right)$ and zero in an adiabatic process as ΔQ = 0.
8. Yes, in an adiabatic process the temperature of an isolated system changes. It increases when the gas is compressed adiabatically.
9. Answer: No.
10. Answer: The room will be slightly warmed.

Short Questions Answers:

1. Answer: Suppose we have an engine that gives a continuous supply of work when it is cooled below the temperature of its surroundings.

   This is a violation of Kelvin's statement. Now if the work done by the engine is used to drive a dynamo which produces current and this current produces heat in a coil immersed in hot water, then we have produced a machine which causes the flow of heat from a cold body to the hot body without the help of an external agent. This is a violation of Clausius's statement. Hence both statements are equivalent.
2. Answer: Pressure is greater in sample number 1 as can be explained: For isothermal expansion.

   $P_1V_1 = P_2V_2$ for no. 1 sample

   Now $V_2 = 2V_1$

   $\therefore P_1V_1 = P_2 2V_1$

   or

   $P_2 = \frac{P_1}{2}$ ...(i)

   Now for adiabatic expansion (for sample 2)

   $P_1V_1^{\gamma} = P_2V_2^{\gamma}$

   Or

   $$P_2 = P_1\left(\frac{V_1}{V_2}\right)^{\gamma} = P_1\left(\frac{V_1}{2V_1}\right)^{\gamma}$$

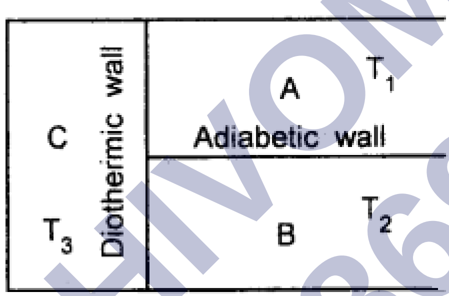
   $$= \frac{P_1}{2^{\gamma}} \text{ ...(ii)}$$

∴ From (i) and (ii) we find that pressure is greater in sample 1 as $\gamma > 1$.

3. Answer: A Carnot engine is an ideal engine from the following points of view:
    1. There is no friction between the walls of the cylinder and the piston.
    2. The working substance is an ideal gas i.e. the gas molecules do not have molecular attraction and they are points in size.

   However these conditions cannot be fulfilled in a real engine and hence no heat engine working between the same two temperatures can have an efficiency greater than that of a Carnot, engine.
4. Answer: If they intersect, then at the point of intersection, the volume and pressure of the gas will be the same at two different temperatures which is not possible.
5. Answer: During adiabatic expansion, the temperature and hence the internal energy of the gas decreases. Thus work is done by the gas at the cost of its internal energy.
6. Answer: It states that if two systems A and B are in thermal equilibrium with a third system C, then A and B must.be in thermal equilibrium with each other.

   Explanation: The three systems are shown in the figure. Let T1, T2, T3 be the temperatures of A, B, and C respectively.



   Systems A and C, B and C will exchange heat and after a certain time, they will attain thermal equilibrium separately.

   i.e. $T_1 = T_3$ ....(1)

   and $T_2 = T_3$ .... (2)

   Thus from (1) and (2),

   $T_1 = T_2$

   i.e. A and B are now in thermal equilibrium with each other.
7. Answer: It states that if an amount of heat dQ is added to a system then a part of it may increase its internal energy by an amount dU and the remaining part may be used up as the external work dW done by the system i.e. mathematically,

   $dQ = dU + dW$

= dU + PdV

Sign conventions:

1. Work done by a system is taken as positive while the work done on the system is taken as -ve.
2. The increase in the internal energy of the system is taken as positive while the decrease in the internal energy is taken as negative.
3. Heat added (gained) by a system is taken as positive and the heat lost by the system is taken as negative.

8. Answer: The heat engine can convert the internal energy of seawater if there is a sink at a temperature lower than the temperature of seawater. Since there is no such sink and hence a ship can't use the internal energy of seawater to operate the engine.
9. Answer: The temperature of the system decreases as the system is doing work and no heat transfer is allowed to or from the system. As the temperature of the system decreases, the internal energy of the system also decreases.
10. Answer: No. It will not be cooled, rather it will get heated because the speed of the air molecules will increase due to the motion of the fan. We feel cooler because of the evaporation of the sweat when the fan is switched on.

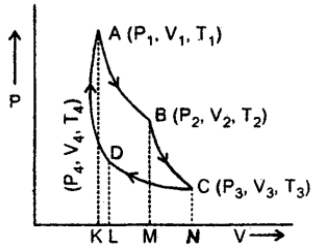
Long Questions Answers:

1. Answer: Carnot cycle: Heat engines essentially have
   1. a source of heat,
   2. a W0fkthg substance
   3. a sink (at a temperature lower than that source) and
   4. mechanical parts.

   Carnot designed an idea engine that operated in the reversible cycle. The cycle consisted of two isotherms and two adiabatic. The heat was taken in or rejected during isothermal expansion or contraction. The Carnot cycle thus consists of four steps (see fig.) Carnot took a perfect gas as the working substance enclosed in a cylinder with perfectly insulting walls fitted with an insulating piston but the bases of the cylinder were conducting

   (1) In the first step of the cycle let P_1, V_1, by the pressure of the gas. It is placed, in contact with the. source of heat at temperature T_1 i.e the cylinder is out on the source. As the gas expands isothermally it absorbs some amount of heat to keep the temperature constant (curve AB)

   The heat absorbed from the source Q_1 is equal to the work done W, in expanding the gas volume from V_1 to V_2 at temperature T_1 so that



$$Q_1 = W_1 = \int_{V_1}^{V_2} RT_1$$

In = Area ABMKA ….(1)

(2) The cylinder is put on insulating and gas is allowed to expand from V_2 to V_3 adiabatically. Its temperature falls from T_1 to T_2 and pressure becomes P_3 and P_2. The work done W is then.

$$W_1 = \int_{V_2}^{V_3} PdV = C_V(T_1 - T_2) = \text{Area BCNMB} \quad .... (2)$$

(3) In this part of the cycle the cylinder is put with its conducting base in contact with a sink as temperature T_2 and gas is compressed isothermally. It rejects Q_2 heat at constant temperature T_2, the work done on the gas is [pressure volume change to (P_4, V_4) from (P_3, V_3)].

$$Q_2 = W_3 = \int_{V_3}^{V_4} PdV = -RT\ln\frac{V_3}{V_2} = \text{Area CNLDC} \quad .... (3)$$

(4) In the last step of the cycle, the cylinder's base is again put on the insulating stand, and the gas is compressed adiabatically so that the system returns back to its original state at A i.e. from (P4, V4) to (P1, V1) at temperature T1 via curve DA. Now the work done on the gas is.

$$W_4 = \int_{V_4}^{V_1} PdV = C_V(T_2 - T_1) = -C_V(T_1 - T_2)$$

= Area DLKAD …. (4)

From equation (2) and (4), it is clear that $W_4 = W_2$

If W = net work done by the engine in one cycle, then

$W = W_1 + W_2 + (-W_3) + (-W_4)$

$= W_1 - W_3$ = Area ABCDA $= Q_1 - Q_2$ …..(5)

The efficiency of the Carnot engine (η): It is defined as the ratio of work done by the engine to the energy supplied to the engine in a cycle.

i.e $\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$

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

Using equations (1) and (3)

$$\frac{Q_1}{Q_2} = \frac{RT_1 ln\frac{V_2}{V_1}}{RT_2 ln\frac{V_3}{V_4}} \quad ...(7)$$

Since B and C lie on the same adiabatic so

$T_1V_2^{\gamma-1}; = T_2V_3^{\gamma-1}$

or

$$\frac{T_1}{T_2} = \left(\frac{V_3}{V_2}\right)^{\gamma-1} \quad ....(8)$$

Also D and A lie on the same adiabatic so

$T_1V_1^{\gamma-1} = T_2V_4^{\gamma-1}$

or

$$\frac{T_1}{T_2} = \left(\frac{V_4}{V_1}\right)^{\gamma-1} \quad ....(9)$$

∴ from (8) and (9), we get

$$\left(\frac{V_3}{V_2}\right)^{\gamma} = \left(\frac{V_4}{V_1}\right)^{\gamma}$$

$$\ln\frac{V_3}{V_4} = \ln\frac{V_2}{V_1} \quad ...(10)$$

∴ from (7) and (10), we get

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}\frac{ln\left(\frac{V_2}{V_1}\right)}{ln\left(\frac{V_2}{V_1}\right)} = \frac{T_1}{T_2} \quad .... (11)$$

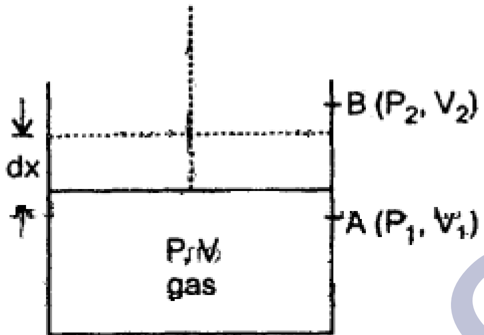
∴ from (6) and (11), we get

$$\eta = 1 - \frac{T_2}{T_1}$$

or $$\eta = \left(1 - \frac{T_2}{T_1}\right) \times 100$$

1. The interesting aspect of η of Carnot engine is that it is independent of the nature of the working substance. But Carnot used an ideal gas operation which is not strictly followed by real gases or fuel
2. Theoretically, η can be 100%.
3. The efficiency of Carnot's ideal engine depends only on the temperature of the scarce and the sink.
4. The efficiency of any reversible engine working between the same two temperatures is the same.

2. Answer: Consider one mole of a perfect gas contained in a cylinder having conducting walls and fitted with a movable piston.



Let P, V be the pressure and volume of the gas corresponding to this state.

Let dx = distance by which piston moves outward at constant pressure P so that its volume increases by dV.

Let a = area of cross-section of the piston.

(a) If dW = work done in moving the piston by dx, then .

dW = force on piston × dx

= P a dx

= PdV ...(i)

Where dV = a dx = volume

Let the system goes from initial state A(P_1, V_1) to final state B(P_2, V_2)

If W = total work done from A to B, then

$$W = \int_A^B dW = \int_{V_1}^{V_2} PdV \quad .... (ii)$$

Also we know that $PV = RT$ (n = 1 here)

$$P = \frac{RT}{V} \quad .... (iii)$$

∴ From (*ii*) and (*iii*), we get

$$W = RT\int_{V_1}^{V_2} \frac{1}{V} dV = RT[\log_e V]_{V_1}^{V_2}$$

= RT ($\log_e V_2 - \log_e V_1$)

= RT $\log_2 \frac{V_2}{V_1}$

= 2.303 RT $\log_{10} \frac{V_2}{V_1}$

(b) From equation (ii) of case (a), we get

$$W = \int_{V_1}^{V_2} PdV \quad .... (ii)$$

We know that an adiabatic process is represented mathematically by the equation:

PV^γ = constant = K

Or

$$P = \frac{K}{V^\gamma} \; ... (iii)$$

∴ from (ii) and (iii), we get

$$W = \int_{V_1}^{V_2} KV^{-\gamma} dV = K\left[\frac{V^{1-\gamma}}{1-\gamma}\right]_{V_1}^{V_2}$$

$$= \frac{K}{1-\gamma}\left[V_2^{1-\gamma} - V_1^{1-\gamma}\right]$$

$$= \frac{1}{1-\gamma}\left[KV_1^{1-\gamma} - KV_2^{1-\gamma}\right]$$

$$= \frac{1}{1-\gamma}\left[P_1V_1^{\gamma}V_1^{1-\gamma} - P_2V_2^{\gamma}V_2^{1-\gamma}\right]$$

$$= \frac{1}{1-\gamma}\left[P_1V_1 - P_2V_2\right]$$

$$= \frac{1}{1-\gamma}\left[RT_1 - RT_2\right] \quad (\because PV = RT)$$

$$W = \frac{R}{\gamma-1}\left[T_1 - T_2\right].$$

3. Answer: Let V_1 = Initial volume

V_2 = Final volume = $\frac{V_1}{3}$

Or

$$\frac{V_1}{V_2} = 3$$

$T_1 = 300K$

$T_2 - T_1 = ?$

$\gamma = 1.5$

We know that for an adiabatic change,

$$T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1}$$

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

$$= 300\,(3)^{1.5-1} = 300\sqrt{3}$$

$$= 300 \times 1.732 = 519.6\ K$$

$\therefore$ Rise in temperature $= T_2 - T_1$

$$= 519.6 - 300 = 219.6\ K$$

4. Answer: Here, $T_1 = 50.0$ K

$T_2 = 375$ k

Q_1 = Heat absorbed per cycle

= 600 K cal

$\therefore$ (a) Using tig relation,

$\eta = 1 - \frac{T_2}{T_1}$, we get

$\eta = \frac{T_1 - T_2}{T_1} = \frac{500 - 375}{500}$

$= \frac{125}{500} = 0.25$

$\eta\% = 0.25 \times 100 = 25\%$

(b) Let W = work done per cycle

∴ Using relation

$\eta = \frac{W}{Q_1}$, we get

$W = \eta Q1$

$= 0.25 \times 600$ K cal

= 150 K cal

$= 150 \times 10^3 \times 4.2$ J

$= 6.3 \times 10^5$ J.

(c) Let Q_2 = heat rejected to the sink

∴ Using the relation

$W = Q_1 - Q_2$, we get

$Q_2 = Q_1 - W = 600 - 150 = 450$ K cal

5. Answer: Here, $T_1 = 25 + 273 = 298$ K

$T_2 = -10 + 273 = 263$ K

$Q_2 = 263\ Js^{-1}$

we know that

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

$$\text{or} \quad Q_1 = \frac{T_1}{T_2} \times Q_2 = \frac{298}{263} \times 263$$

$= 298\ Js^{-1}$

∴ Average power consumed $= Q_1 - Q_2$

$= (298 - 263)\ Js^{-1}$

= 35W

Assertion Reason Answer:

1. If both assertion and reason are true and the reason is the correct explanation of the

assertion.

Explanation:

When a bottle of cold carbonated drink is opened. A slight fog forms around the opening. This is because of adiabatic expansion of gas causes lowering of temperature and condensation of water vapours.

2. If the assertion and reason both are false.

Explanation:

Adiabatic compression is a rapid action and both the internal energy and the temperature increases.

Case Study Questions-

1. Zeroth Law of Thermodynamics states that two systems in thermal equilibrium with a third system separately are in thermal equilibrium with each other. The Zeroth Law clearly suggests that when two systems *A* and *B,* are in thermal equilibrium, there must be a physical quantity that has the same value for both. This thermodynamic variable whose value is equal for two systems in thermal equilibrium is called temperature (*T*). Thus, if *A* and *B* are separately in equilibrium with C, $TA = TC$ and $TB = TC$. This implies that $TA = TB$ i.e. the systems A and B are also in thermal equilibrium. Zeroth Law of Thermodynamics leads to the concept of internal energy of a system. We know that every bulk system consists of a large number of molecules. Internal energy is simply the sum of the kinetic energies and potential energies of these molecules. A certain amount of heat is supplied to the system' or 'a certain amount of work was done by the system its energy changes.

i. **Three thermodynamic systems are at temperature of 50^0 c .what can we say about them?**

   a. Heat flows between them
   b. It obeys Zeroth Law of Thermodynamics
   c. Temperature of one system will increase and temperature of remaining two will decrease
   d. None of these

ii. **Zeroth law of thermodynamics helped in the creation of which scale?**

   a. Temperature
   b. Heat energy
   c. Pressure
   d. Internal energy

iii. **State Zeroth Law of Thermodynamics**

iv. **Define Internal energy of system**

2. **Kelvin-Planck statement:** No process is possible whose sole result is the absorption of heat from a reservoir and the complete conversion of the heat into work. **Clausius statement:** No process is possible whose sole result is the transfer of heat from a colder object to a hotter object. It can be proved that the two statements above are completely equivalent. A thermodynamic process is reversible if the process can be turned back such that both the system and the surroundings return to their original states, with no other change anywhere else in the universe. a reversible process is an idealized motion. A process is reversible only if it is quasi-static (system in equilibrium with the surroundings at every stage) and there are no dissipative effects. For example, a quasi-static isothermal expansion of an ideal gas in a cylinder fitted with a frictionless movable piston is a reversible process. The free expansion of a gas is irreversible. The combustion reaction of a mixture of petrol and air ignited by a spark cannot be reversed. Cooking gas leaking from a gas cylinder in the kitchen diffuses to the entire room. The diffusion process will not spontaneously reverse and bring the gas back to the cylinder. The stirring of a liquid in thermal contact with a reservoir will convert the work done into heat, increasing the internal energy of the reservoir. The process cannot be reversed exactly; otherwise it would amount to conversion of heat entirely into work, violating the Second Law of Thermodynamics. Irreversibility is a rule rather an exception in nature.

i. **The diffusion process is**
   a. Reversible process
   b. Irreversible process

ii. **A quasi-static isothermal expansion of an ideal gas in a cylinder fitted with a frictionless movable piston is**
   a. Reversible process
   b. Irreversible process

iii. **State Kelvin Planck statement.**

iv. **State Clausius statement.**

v. **Define reversible processes and irreversible processes of thermodynamics.**

Case Study Answer-

1. **Answer**

i. (b) It obeys Zeroth Law of Thermodynamics

ii. (a) Temperature

iii. Zeroth Law of Thermodynamics states that two systems in thermal equilibrium with a third system separately are in thermal equilibrium with each other. i.e. when two systems *A* and *B,* are in thermal equilibrium individually with system C then these two systems are also in thermal equilibrium with each other.

iv. Internal energy is the sum of the kinetic energies and potential energies of all the molecules possesses by system.

2. Answer

i. (b) Irreversible process

ii. (a) Reversible process

iii. Kelvin-Planck statement states that We cannot construct any device like the heat engine that operates on a cycle, absorbs the heat energy, and completely transforms this energy into an equal amount of work. Some of the heat gets released into the atmosphere. Practically no device bears 100% thermal efficiency.

iv. According to clausius It is nearly impossible for heat to move by itself from a temperature that is lower in temperature to a reservoir that is at a higher temperature. That is we can say that the transfer of heat can only occur spontaneously from high temperature to temperature. i.e No process is possible whose sole result is the transfer of heat from a colder object to a hotter object without any external work provided to do it in short we cannot construct a refrigerator that can operate without any input work.

v. A thermodynamic process is said to be reversible if both the system and the surroundings return to their original states, with no other change anywhere else in the universe. On the other hand an irreversible process can be defined as a process in which the system and surrounding will not return to their original condition once the process is initiated.