CHAPTER 6

HEAT AND THERMODYNAMICS

STUDENT LEARNING OBJECTIVES

After studying this chapter, the students will be able to.

- Describe the basic assumptions of the kinetic theory of gasses [Including understanding the temperature, pressure and density conditions under which an ideal gas is a good approximation of a real gas]
- State that regions of equal temperature are in thermal equilibrium
- Relate a rise in temperature of an object to an increase in its internal energy
- Apply the equation of state for an ideal gas[expressed as $PV = nRT$, where n = amount of substance (number of moles) and as $PV = Nk_BT$, where N =number of molecules]
- State that the Boltzmann constant k is given by $k_B = R/N_A$
- Use $W = P\Delta V$ for the work done when the volume of a gas changes at constant pressure
- Describe the difference between the work done by a gas and the work done on a gas
- Define and use the first law of thermodynamics [$\Delta U = Q - W$ expressed in terms of the increase in internal energy, the heating of the system (energy transferred to the system by heating) and the work done on the system]
- Explain qualitatively, in terms of particles, the relationship between the pressure, temperature and volume of a gas [Specifically the below case
  - (a) pressure and temperature at constant volume
  - (b) volume and temperature at constant pressure
  - (c) pressure and volume at a constant temperature
- Use the equation, including a graphical representation of the relationship between pressure and volume for a gas at constant temperature
- Justify how the first law of thermodynamics expresses the conservation of energy
- Relate a rise in temperature of a body to an increase in its internal energy
- State the working principle of a heat engine
- Describe the concept of reversible and irreversible processes
- State and explain the second law of thermodynamics
- State the working principle of Carnot's engine
- Describe that refrigerator is a heat engine operating in reverse as that of an ideal heat engine
- Explain that an increase in temperature, increases the disorder of the system
- Explain that increase in entropy means degradation of energy
- Explain that energy is degraded during all natural processes
- Identifying that system tends to become less orderly overtime
- Explain that Entropy, S is a thermodynamic quantity that relates to the degree of disorder of the particles in a system.
- State that the Carnot cycle sets a limit for the efficiency of a heat engine at the temperatures of its heat

HEAT:

It is the energy which flows from a body at high temperature to a body at low temperature if both are brought in thermal contact

OR

"*The amount of **thermal energy** that flows from **one material substance to another** is called heat.* "Heat is not the energy that an object contains in it. Heat is regarded as a form of energy associated with molecular motion."In SI units, heat is expressed in joule (J). $Q = mC\Delta T$

THERMODYNAMICS

It is an important branch of physics. It is all about understanding how heat energy is related to other forms of energy and how it can be converted from one form to another

Example: How a car engine works – it burns fuel (chemical energy), which produces heat, and that heat is then used to make the car move (mechanical energy). Thermodynamics helps us understand these processes. It deals with big-picture properties of systems like **temperature**, **pressure**, and **volume**.

6.1 ASSUMPTIONS OF THE KINETIC THEORY OF GASES

Q. What is the Kinetic Theory of Gases? Explain its assumptions.

Ans

The **Kinetic Theory of Gases** is a basic idea that helps us understand why gases behave the way they do. It explains how the tiny particles (molecules) inside a gas move around and how this movement affects things like pressure and temperature.

The main assumptions of this theory are:

1. **Gas Particles are Always Constantly Moving Randomly:** Let tiny balls constantly zipping around inside a box. Gas molecules do the same – they move in straight lines until they collide into another molecule or the walls of their container.
2. **Volume of Gas Particles is Negligible:** The actual size of individual gas molecules is so small that we can almost ignore it compared to the total space the gas occupies. We treat them like tiny points with no real volume.
3. **No Forces Between Particles (Except During Collisions):** Gas molecules don't attract or push each other away. They only interact when they collide.
4. **Collisions are Perfectly Elastic:** When gas molecules collide with each other or with the container walls they bounce off perfectly. This means no energy is lost as heat or sound during these collisions; the total kinetic energy (energy of motion) remains the same.
5. **Large Number of Particles:** A gas contains a huge number of molecules. This allows us to use statistics (averages) to describe the gas's overall behavior, rather than trying to track every single molecule.
6. **Average Kinetic Energy is Proportional to Temperature:** The faster the gas particles move, the hotter the gas is. Simply put, the average energy of motion of the gas particles is directly related to the absolute temperature of the gas. $T \propto \langle K.E \rangle$
7. **Pressure Comes from Collisions of Gas molecules:** When gas particles hit the walls of their container, they push on the walls. This continuous pushing creates the pressure we measure.
   $P = F/A$
8. **Collisions are Very Quick:** The time it takes for two particles to collide is extremely short compared to the time they spend moving freely between collisions. This simplifies calculations.

Q: What are the limitations of The Kinetic Molecular Theory? When do real gases not behave ideally?

LIMITATION OF KINETIC MOLECULAR THEORY

What are the limitations of The kinetic Molecular Theory? When do real gases not behave ideally?

The assumptions above are perfect for **ideal gases**. However, real gases (like air, oxygen, etc.) don't always follow these rules perfectly. They behave like ideal gases mostly when:

- **Pressure is low:** At low pressures, the molecules are far apart, so the forces between them become very weak and can be ignored.
- **Temperature is high:** At high temperatures, molecules move very fast, so their kinetic energy is much greater than any small attractive forces between them.

In simple terms, real gases behave like ideal gases when their molecules are far apart and moving very fast, so they don't "feel" each other much.

> **For your information**
>
> Real gases approach ideal behaviour under:
> (i) low pressure
> (ii) high temperature

Q: What is the Equation of State for an Ideal Gas? Explain its components.

Equation of State for an Ideal Gas

A gas that perfectly follows the kinetic theory is called an **ideal gas**. The relationship between its pressure (P), volume (V), and absolute temperature (T) is given by the **Ideal Gas Equation**:

$$PV = nRT \text{ (Equation 6.1)}$$

Where:

- P = Pressure of the gas (in Pascals, Pa)
- V = Volume of the gas (in cubic meters, m3)
- n = Number of moles of the gas
- R = Universal Gas Constant (its value is 8.3145 J mol^{-1} K^{-1})
- T = Absolute temperature of the gas (in Kelvin, K)

This equation tells us that for a fixed amount of gas, the product of its pressure and volume is directly proportional to its absolute temperature.

Q HOW IS THE NUMBER OF MOLES ('N') UNDERSTOOD AND CALCULATED IN THE IDEAL GAS EQUATION? OR WHY REAL GASES OBEY GENERAL GAS LAWS AT LOW PRESSURE AND HIGH TEMPERATURE?

Real Gas to Behave like an Ideal Gas

The number of moles (n) tells us how much gas we have. It can be found using:

$$n = \frac{\text{Mass of Gas}}{\text{Molar Mass of Gas}} = \frac{m}{M} \text{ Where:}$$

- m = Mass of the gas
- M = Molar mass of the gas

We can also express the ideal gas equation using density (ρ):

$$PV = nR$$

$$PV = \frac{m}{M}RT$$

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

$$PM = \rho RT \qquad \because \rho = \frac{m}{V}$$

$$\rho = \frac{PM}{RT} = \frac{M}{R} \times \frac{P}{T} \qquad \because \frac{M}{R} = \text{Constant}$$

$$\rho \propto \frac{P}{T}$$

This shows that the density of a gas is low at low pressure and high temperature. This makes sense because at low pressure and high temperature, the gas molecules are spread out (large distance between them), making intermolecular forces negligible, which is why real gases behave more like ideal gases under these conditions.

Q HOW CAN THE IDEAL GAS EQUATION BE EXPRESSED IN TERMS OF THE BOLTZMANN CONSTANT (k_B)? DERIVE THIS RELATION.

We can also write the ideal gas equation in terms of the number of molecules (N) instead of moles (n).

We know that the number of moles (n) can also be defined using the total number of molecules (N) and Avogadro's number (NA):

$$n = \frac{N}{N_A} \quad \ldots 1$$

Substitute this into the ideal gas equation ($PV = nRT$):

$$PV = \frac{N}{N_A}RT = N\frac{R}{N_A}T \quad \ldots 2$$

The term $k_B = \frac{R}{N_A}$ is called the Boltzmann constant (k_B).

$$k_B = \frac{R}{N_A} \text{ (Equation 6.2)}$$

The value of the Boltzmann constant is 1.38×10^{-23} J K^{-1}.

Now, substitute k_B back into the equation ... 2:

$$PV = Nk_BT \text{ (Equation 6.3)}$$

This is another form of the ideal gas equation in term of Boltzmann constant, very useful when dealing with the number of individual molecules.

Q WHAT ARE THE VARIOUS GAS LAWS? EXPLAIN THEIR RELATIONSHIPS BETWEEN P, V, AND T

These laws describe how the pressure, volume, and temperature of an ideal gas are related when one of them is kept constant.

Statement: For a fixed amount of an ideal gas, if the temperature is kept constant, the pressure (P) is inversely proportional to its volume (V). This means if you increase the pressure, the volume decreases, and vice versa.

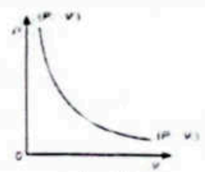


Fig 6.1

Mathematically:

$$P \propto \frac{1}{V} \text{ (at constant T)}$$

Or, $$PV = \text{constant}$$

For two different states of the same gas at constant temperature:

$$P_1V_1 = P_2V_2$$

Graphical Representation: A curve showing pressure decreasing as volume increases.

Q What is Charles' Law? State its mathematical form and graphical representation.

Statement: For a fixed amount of an ideal gas, if the pressure is kept constant, the volume (V) is directly proportional to its absolute temperature (T). This means if you increase the temperature, the volume increases, and vice versa.

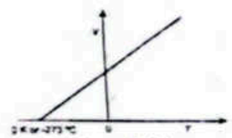


Fig 6.2

Mathematically:

$$V \propto T \text{ (at constant P)}$$

Or, $$\frac{V}{T} = \text{constant}$$

For two different states of the same gas at constant pressure:

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

Graphical Representation: A straight line passing through the origin (if temperature is in Kelvin) showing volume increasing with temperature.

Q What is Joseph Lussac's Law? State its mathematical form and graphical representation.

Statement: For a fixed amount of an ideal gas, if the volume is kept constant, the pressure (P) is directly proportional to its absolute temperature (T). This means if you increase the temperature, the pressure increases, and vice versa.

Mathematically:

$$P \propto T \text{ (at constant V)}$$

Or

$$\frac{P}{T} = \text{constant}$$

For two different states of the same gas at constant volume:

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

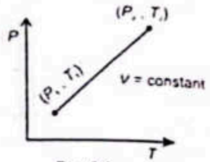


Fig. 6.3

Graphical Representation: A straight line passing through the origin (if temperature is in Kelvin) showing pressure increasing with temperature.

Q WHAT IS THERMAL EQUILIBRIUM? PROVIDE AN EXAMPLE.

THERMAL EQUILIBRIUM

Thermal equilibrium is a state where two objects or systems in contact have reached the same temperature. When this happens, there is no net flow of heat energy between them. They are "balanced" thermally.

Example: If you put a hot metal spoon into a cup of coffee:

1. Initially, the coffee is hotter than the spoon.
2. Heat flows from the hot coffee to the cooler spoon.
3. Eventually, the coffee and the spoon will both reach the same temperature. At this point, they are in thermal equilibrium, and heat stops flowing.

MULTIPLE CHOICE QUESTIONS

- **Thermodynamics primarily focuses on:**
  (a) The study of individual atoms and their motion.
  (b) The conversion of heat energy into other forms of energy.
  (c) The chemical reactions that produce heat.
  (d) The properties of light and sound.

Answer: (b) The conversion of heat energy into other forms of energy.

Explanation: As stated in the introduction, thermodynamics deals with relationships and conversions between heat and other forms of energy, especially at macroscopic scales.

- **Under which conditions do real gases behave most like ideal gases?**
  (a) High pressure and high temperature (b) Low pressure and low temperature
  (c) High pressure and low temperature (d) Low pressure and high temperature

Answer: (d) Low pressure and high temperature.

Explanation: At low pressure, gas molecules are far apart, making intermolecular forces negligible. At high temperature, molecules move very fast, so their kinetic energy is much greater than any small attractive forces. Both conditions minimize deviations from ideal gas assumptions.

- **The Boltzmann constant (kB) relates:**
  (a) Pressure and volume of a gas (b) The universal gas constant to Avogadro's number
  (c) The mass of a gas to its molar mass (d) The work done by a gas to its temperature.

Answer: (b) The universal gas constant to Avogadro's number.

Explanation: The Boltzmann constant is defined as $k_B = R/N_A$, where R is the universal gas constant and N_A is Avogadro's number (Equation 6.2).

- **When two objects are in thermal equilibrium, which of the following is true?**
  (a) Heat flows from one object to the other at a constant rate.
  (b) Their internal energies are necessarily equal.
  (c) There is no net transfer of heat between them.

  (d) One object is always hotter than the other.

Answer: (c) There is no net transfer of heat between them.

Explanation: Thermal equilibrium is defined as the state where objects in thermal contact have the same temperature, and consequently, there is no net heat flow between them. Their internal energies might not be equal if their masses or specific heat capacities are different.

- **For an ideal gas, its internal energy is primarily due to:**
  (a) Intermolecular forces.
  (b) Potential energy of its molecules.
  (c) Translational kinetic energy of its molecules.
  (d) Vibrational energy of its atoms.

Answer: (c) Translational kinetic energy of its molecules.

Explanation: For an ideal gas, intermolecular forces are negligible, meaning potential energy is zero. Its internal energy is mainly the kinetic energy associated with the straight-line motion (translation) of its molecules.

6.2 INTERNAL ENERGY

Q. What is Internal Energy? How is it related to the temperature of an ideal gas?

Ans

The **internal energy (U)** of a substance is the total energy of all its molecules. This includes:

- **Kinetic energy** of the molecules (due to their motion: translational, rotational, and vibrational).
- **Potential energy** due to the forces between molecules (if any).

For an **ideal gas**, the molecules are considered to have no forces between them (except during collisions). So, the potential energy is zero (P.E = 0). This means the internal energy of an ideal gas is mainly the **translational kinetic energy** of its molecules.

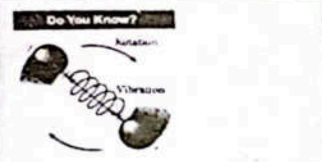
Relationship between Internal Energy and Temperature:

Since the temperature of a system is defined by the average kinetic energy of its molecules, for an ideal gas, its internal energy is directly proportional to its absolute temperature.

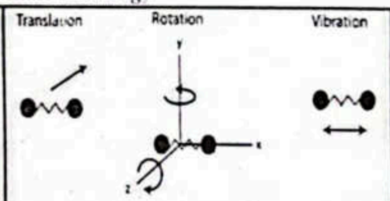
The average kinetic energy of gas molecules is given by:

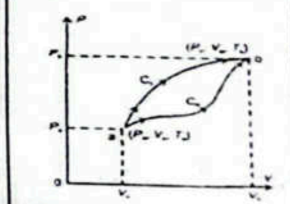
$$\langle K.E \rangle = \frac{2}{3} k_B T \quad \text{or} \quad \langle \frac{1}{2} m v^2 \rangle = \frac{2}{3} k_B T$$

This means if the temperature of an object rises, it's because the average kinetic energy of its particles has increased, leading to an increase in its internal energy.



A diatomic gas molecule has both translational and rotational energy. It has also vibrational energy associated with the spring like bond between its atoms.





$\Delta U_1 = \Delta U_2$ Internal Energy does not depend on path.

Do you know? (Page 121 Text Book):

- A diatomic gas molecule has both translational and rotational energy. It also has vibrational energy associated with the spring-like bond between its atoms.
- **Explanation:** Translational energy is movement of the molecule as a whole. Rotational energy is due to the molecule spinning around its axis. Vibrational energy is due to the atoms within the molecule oscillating relative to each other, like a spring.

Tidbit (Page 121 Text Book):

- Different processes can lead to changes in internal energy and temperature, such as heating (adding heat), adiabatic compression or expansion (no heat exchange), or phase changes (where heat energy changes the state of matter without changing temperature).
- **Explanation:** Internal energy can be changed by heat transfer (Q) or work done (W). Heating adds energy, increasing internal energy and typically temperature. Adiabatic processes involve work without heat exchange, changing internal energy and temperature. Phase changes involve latent heat, changing the state (e.g., solid to liquid) without changing temperature, but still altering internal energy.

Different processes can lead to changes in internal energy and temperature, such as heating (adding heat) adiabatic compression or expansion (no heat exchange), or phase changes (where heat energy changes the state of matter without changing temperature)

For your Information (Text Book Page 118):

- Internal energy is a function of state. Consequently, it does not depend on path but depends on initial and final states of the system. Thus, internal energy is similar to the gravitational P.E. So, like the potential energy, it is the change in internal energy and not its absolute value, which is important.
- **Explanation:** Being a "function of state" means its value is determined solely by the current state of the system (e.g., its temperature, pressure, volume), not by how that state was reached. Just as with potential energy, only the *change* in internal energy is measurable and physically significant, not an absolute value.

SLO BASED SHORT QUESTIONS & ANSWERS

- **How can we increase the internal energy? Explain. (RWP 2021 GI)**

Ans: By increasing the temperature of the system internal energy can be increased. **Reason:** Because the internal energy of an ideal gas is generally the translational K.E of its molecules, thus for an ideal gas system, the internal energy is directly proportional to its temperature. $U \propto T \propto \langle K.E \rangle$

- **Is it possible to convert internal energy into mechanical energy? Explain with an example. (RWP, GRW 2017) (LHR, DGK 2018 GI) (BWP 2018 GII) (SGD 2019 GI) (LHR 2021 GI) (GRW, FSD 2021 GII) (FSD, SGD, RWP 2022 GI) (SGD 2023 GI) (GRW, DGK 2023 GII)**

Ans: Yes, converting internal energy into mechanical energy is a very common process. In adiabatic expansion internal energy can be converted into mechanical energy. $-\Delta U = W$

Example: A classic example is a steam engine. In a steam engine, internal energy of the steam is used to run engine.

- **What is the similarity between internal energy and gravitational P.E.? (LHR 2017 GII)**

Ans: Internal energy and gravitational potential energy (GPE) share some similarities:

Stored Energy: Both represent stored, potential energy within a system.

State Functions: Neither internal energy nor GPE depends on the path taken. This means both depend only on the initial and final states.

Energy Transfer: Both can be converted into other forms of energy.

Difference

Source of the Stored Energy: Internal energy arises from the microscopic motions and interactions within a system, while GPE is due to the object's position in a gravitational field.

MULTIPLE CHOICE QUESTIONS

- Internal energy of ideal gas system is generally the
  (a) translational P.E (b) translational K.E (c) rotational P.E (d) rotational K.E
- The formula for internal energy is
  (a) 3/2(NKT) (b) 3/2(nRT) (c) ½(nRT) (d) Both a and b

- Joule is the unit of (D. G. Khan 11, Mirpur 16, Fsd 08, 16)
  (a) Kinetic energy (b) Potential energy (c) Heat energy (d) All of these
- Which is called the internal energy of an ideal gas? (Grw 2012, 2015)
  (a) Potential energy (b) Translational kinetic energy
  (c) Vibrational kinetic energy (d) All of these
- For an ideal gas system, the internal energy is directly proportional to (Mnt.17)
  (a) Pressure (b) Volume (c) Mass (d) Temperature
- The sum of all molecular energies of a substance is called: (GRW 2023 GII)
  (a) K.E (b) P.E (c) Internal energy (d) Chemical energy
- The internal energy of 2 mole of an ideal gas depends on: (DGK 2023 GI)
  (a) Volume (b) Pressure (c) Temperature (d) Potential energy

6.3 WORK AND HEAT

Q. What are Heat and Work in thermodynamics? Explain their sign conventions.

Ans

Both heat (Q) and work (W) are ways by which energy can be transferred into or out of a system. They are not properties stored within a system, but rather processes of energy transfer.

Q What are the sign conventions for heat, work and internal energy?

Sign Conventions:

For energy transfers, we use specific signs.

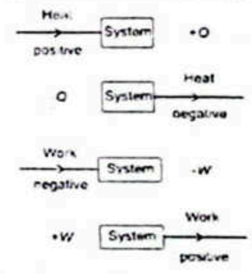
Heat (Q):

- **+Q (Positive):** Heat enters the system (system absorbs heat).
- **-Q (Negative):** Heat leaves the system (system releases heat).

Work (W):

- **+W (Positive):** Work is done **by** the system on its surroundings (e.g., expanding gas pushes a piston).
- **-W (Negative):** Work is done **on** the system by the surroundings (e.g., piston compresses gas).

For your information



HOW IS WORK DONE BY A GAS AT CONSTANT PRESSURE CALCULATED?

Imagine a gas in a cylinder with a movable piston. If the gas expands and pushes the piston up, it does work.

The work (W) done by the gas when its volume changes by ΔV at a constant pressure (P) is given by:

$$W = F\,\Delta Y = PA\,\Delta Y = P\,(A\Delta Y) = P\,\Delta V$$

$$\because P = \frac{F}{A} \Rightarrow F = PA$$

A gas is sealed in a cylinder by a weightless frictionless piston. The constant force F equals PA, and when the piston is displaced downward work is done on the gas.

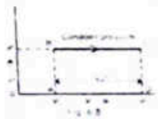
Where:

P = Constant pressure

ΔV = Change in volume $(V_{final} - V_{initial})$ = Area x Height = $A\,\Delta Y$

Q How is work done represented on a P-V Graph>

If you plot pressure (P) against volume (V) on a graph, the area under the curve between two points (initial and final volumes) represents the work done during that process. For a constant pressure process, this area is a rectangle.



SLO BASED SHORT QUESTIONS & ANSWERS

- **Explain the difference between "work done by a gas" and "work done on a gas" in terms of gas expansion/compression and energy transfer.**

Answer:

- **Work done by a gas:** Occurs when the gas expands and pushes against its surroundings (e.g., a piston moves outwards). The gas is transferring energy *out* of the system in the form of work. This is considered **positive work (+W)**.
- **Work done on a gas:** Occurs when the surroundings compress the gas (e.g., a piston pushes inwards). Energy is being transferred *into* the system in the form of work. This is considered **negative work (-W)**.

6.4 FIRST LAW OF THERMODYNAMICS

Q. State and explain the First Law of Thermodynamics. Provide an example.

Ans

The **First Law of Thermodynamics** is essentially the **Law of Conservation of Energy** applied to thermodynamic systems. It states that energy cannot be created or destroyed, only transferred or transformed from one form to another.

Statement of the First Law:

"In any thermodynamic process, when heat Q is added to a system, this energy appears as an increase in the internal energy (ΔU) stored in the system, plus the work W done by the system on its surroundings."

Mathematically:

$$Q = (U_2 - U_1) + W$$

Or, more simply:

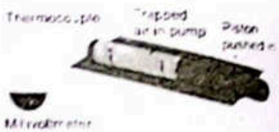
$$Q = \Delta U + W$$

Where:

Q = Heat added to the system

ΔU = Change in the internal energy of the system ($U_{final} - U_{initial}$)

W = Work done *by* the system on its surroundings



Examples:

i. **Bicycle Pump:** Consider a bicycle pump with a blocked outlet connected with thermocouple to monitor the air temperature. When piston is pushed rapidly, then push force does work on the air and thermometer shows a temperature rise. Thus internal energy of the air also increases.

$$\Delta U = W$$

ii. **Human Metabolism:** The process by which energy transformation occurs within an organism is called metabolism. Human beings and other animals require energy to do work when they walk, run or move heavy objects. This energy Q comes from the food. From first law of thermodynamics, we have,

$$\Delta U = Q - W$$

The work (W) done results in the decrease of internal energy.

Q. What are the key principles underlying the first law of thermodynamics?

1. **Conservation Principle:** The total energy in an isolated system always stays the same. If energy changes form (e.g., chemical to heat), the total amount remains constant.
2. **Wide Applicability:** This law applies to all kinds of energy transformations, whether in chemical reactions, electrical systems, or even biological processes like human metabolism.

Q. What are the main applications of the First Law of Thermodynamics?

Isothermal Process

Definition: A process where the temperature (T) of the system remains constant.

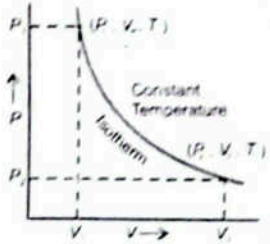
For an ideal gas: Since the internal energy (ΔU) of an ideal gas depends only on its temperature, if the temperature is constant, then the change in internal energy is zero ($\Delta U = 0$).

First Law becomes:

$$Q = W \qquad \text{since } \Delta U = 0$$

- **Isothermal Expansion:** In an isothermal expansion, all the heat added to the gas is converted into work done by the gas. For this to happen, the process must occur very slowly, allowing heat to flow in or out to maintain constant temperature.
- **Isothermal Compression**
  Conversely, if the gas is compressed very slowly by doing work 'W' on it, then an amount of heat Q must be allowed to leave the gas to produce isothermal compression. Hence, the first law of thermodynamics reduces to:

$$-Q = -W$$



GRAPH:

- The curve representing an isothermal process on a P-V diagram is called **an isotherm** (it's a hyperbola). Slope of Isotherm = -P/V
- As Boyle's law is applicable during isothermal change so, if P_1, V_1 are initial pressure and volume where, as P_2, V_2 are final pressure and volume, then:

$$P_1V_1 = P_2V_2$$

Q. What is an Adiabatic Process? How does the First Law apply to it? Give examples.

ADIABATIC PROCESS

Definition: A process where no heat (Q) enters or leaves the system. This happens either when the system is perfectly insulated or the process occurs very rapidly.

First Law becomes:

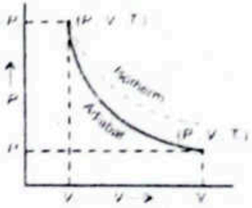
Since $Q = 0$, then $0 = \Delta U + W \Rightarrow W = -\Delta U$

Explanation:

- **Adiabatic Expansion:** If the gas **expands** (W is positive), it does work *by* using its own internal energy. This causes the internal energy to decrease, and thus the temperature of the gas falls. $W = -\Delta U$. Hence we can say adiabatic expansion causes cooling.
- **Adiabatic Compression:** If the gas is **compressed** (W is negative, meaning work is done *on* the gas), the work done increases its internal energy, causing the temperature of the gas to rise. $-W = \Delta U$

Examples:

- Rapid escape of air from a burst tire (air expands quickly, cools down).
- Rapid expansion and compression of air as a sound wave passes through it.
- Cloud formation in the atmosphere (rising air expands adiabatically and cools, leading to condensation).



Equation for Adiabatic Process:

For an adiabatic process, the relationship between pressure and volume is:

$$PV^{\gamma} = \text{constant}$$

Where γ (gamma) is the ratio of specific heats of the gas at constant pressure (C_p) to constant volume (C_v), i.e., $\gamma = C_p / C_v$ ($\gamma = E_s/E_T$ = Adiabatic Modulus of Elasticity/ Adiabatic Modulus of Elasticity)

GRAPH: The curve representing an adiabatic process on a P-V diagram is called an **adiabat**. An adiabat is steeper than an isotherm because the temperature also changes during an adiabatic process, leading to a faster drop in pressure for a given volume increase. Slope of Abiabat = $-\gamma P/V$

Brain teaser! (Text Book Page 121):

- **Why does the internal energy of an ideal gas remain constant during isothermal expansion?**

Ans For an ideal gas, internal energy is solely dependent on its temperature. In an isothermal process, the temperature is kept constant. Therefore, if the temperature does not change, the internal energy of an ideal gas also remains constant.

Brain teaser!
Why does the internal energy of an ideal gas remain constant during isothermal expansion?

For Your Information

Type of Gas	$C_p = \frac{\gamma R}{\gamma - 1}$	$C_v = \frac{R}{\gamma - 1}$	γ=Cp/Cv
Monoatomic	$\frac{5}{2}R$	$\frac{3}{2}R$	$\frac{5}{3} = 1.67$
Diatomic	$\frac{7}{2}R$	$\frac{5}{2}R$	$\frac{7}{5} = 1.4$
Polyatomic (Gases whose Atoms don't vibrate)	$\frac{9}{2}R$	$\frac{7}{2}R$	$\frac{9}{7} = 1.29$
Polyatomic	4 R	3 R	$\frac{4}{3} = 1.33$

MULTIPLE CHOICE QUESTIONS

- **In an isothermal process for an ideal gas, if 50 J of heat is supplied to the system, what is the work done by the system?**

(a) 0 J (b) 50 J (c) -50 J (d) 100

Answer: (b) 50 J.

Explanation: In an isothermal process for an ideal gas, the temperature remains constant, which means the internal energy (ΔU) remains constant (i.e., ΔU=0). According to the First Law of Thermodynamics (Q=ΔU+W), if ΔU=0, then Q=W. So, if 50 J of heat is supplied (Q=+50 J), then 50 J of work is done by the system (W=+50 J).

- **Which of the following is an example of an irreversible process?**

(a) Slow compression of a gas in a frictionless cylinder
(b) Melting of ice at 0°C
(c) An explosion
(d) Evaporation of water at its boiling point.

Answer: (c) An explosion

Explanation: An explosion is a rapid and highly dissipative process involving a sudden release of energy and a significant increase in disorder, making it impossible to reverse without leaving changes in the surroundings. The other options are considered practically reversible if performed slowly and ideally.

- **During an adiabatic compression, work of 250 J is done on system. What will be the change in internal energy?**

(a) +250 J (b) −250 J C. ±250 J D. 0 J

Solution:

In adiabatic compression work done is done on the system which is taken as negative so

$W \neq 250$ J $\Rightarrow W = -250$ J so $\Delta U = -W = -(-250) = +250$ J, system gains internal energy due to mechanical work being done on it.

- **A fixed mass of an ideal gas slowly absorbs 1000 J of heat and as a result expands slowly, at a constant pressure of 2.0×10^4 Pa, from a volume of 0.050 m³ to a volume of 0.075 m³. What is the effect on the internal energy of the gas?**

A. It increases by 500J B. It increases by 1000J C. It decreases by 500J D. It remains same

Solution: $\Delta Q = 1000$ J, $P_1 = P_2 = P$ = constant $= 2 \times 10^4$ Pa

$\Delta V = V_2 - V_1 = 0.075 m - 0.050 m = 0.025 m$

∴ Applying 1st law of thermodynamics

$\Delta Q = \Delta U - W$

$\Delta U = \Delta Q - W = 1000 - P\Delta V = 1000 - (2 \times 10^4)(0.025) = 1000 - 0.05 \times 10^4 = 1000 - 5 \times 10^{-2} \times 10^4$

$= 1000 - 500 = 500$ J

- **Two blocks of ice when pressed together join to form one block because:**

(a) of heat produced during pressing (b) of cold produced during pressing
(c) melting point of ice increases with increase of pressure
(d) melting point of ice decreases with increase of pressure

Solution: When pressure increases, melting point decreases so ice in contact melts a bit to form a very thin layer / film between blocks of ice intact, now air in surrounding takes heat away from that thin film of water to convert it into ice again making two blocks a single one.

SLO BASED SHORT QUESTIONS & ANSWERS

- **Why does the temperature of air decrease when it rapidly escapes from a burst tire? What type of thermodynamic process is this?**

Ans: When air rapidly escapes from a burst tire, it undergoes an adiabatic expansion. This is because the expansion happens so quickly that there is very little time for heat to be exchanged between the air and its surroundings (ΔQ ≈ 0). As the air expands, it does work on the surroundings (pushes the outside air away). According to the First Law (W = −ΔU), this work is done at the expense of the air's own internal energy, causing its internal energy to decrease. Since the internal energy of a gas is directly related to its temperature, the temperature of the escaping air falls.

- **Why can't we use the vast heat content of the oceans to power ships indefinitely, even though the total energy is enormous?**

Ans: We cannot use the vast heat content of the oceans to power ships indefinitely because, according to the Second Law of Thermodynamics (Kelvin's statement), a heat engine requires a temperature difference to operate and produce work. While oceans contain a huge amount of thermal energy, there is no colder reservoir available to which heat can be rejected. Without a temperature difference, it's impossible to convert this heat entirely into useful mechanical work.

- **What is metabolism? How first law of thermodynamics explains it? (LHR 2019 GII) (FSD, BWP 2021) 21 (GRW 2017) (BWP, MTN, DGK 2018 GI)**

Ans: The process by which energy transformation occurs within an organism is called metabolism. Human beings and other animals require energy to do work when they walk, run or move heavy objects. This energy Q comes from the food. From first law of thermodynamics, we have:

$$\Delta U = Q - W$$

i.e. The work (W) done results in the decrease of internal energy.

- **What are isothermal and Adiabatic Processes? (SWL, RWP 2019) (SGD 2019 GI) (MTN 2019 GII) (GRW, BWP 2021) (GRW 2022 GI) (LHR 2022 GII) (SGD 2023 GII)**

Ans: **Isothermal Process:**

A process in which the temperature of the system remains constant while pressure and volume may change is called isothermal process. It is a slow process. In this process, the Boyle's law on the gas is applicable. Therefore, the product of pressure and volume of the gas remains constant during expansion or compression, i.e.,

$$PV = \text{Constant}$$

Adiabatic Process:

A process in which no heat enters or leaves the system while pressure and volume may change is called an adiabatic process. Experimentally, such a process can be achieved either by insulating the system from surrounding or by performing the process quickly.

$$Q = 0$$

- **As we know PV^{γ} = Constant. What do you know about "γ" (gamma) in this relation? (SGD 2023 GI)**

Ans: γ is the ratio of the molar specific heat of gas at constant pressure to the molar specific heat of gas at constant volume $\gamma = \frac{C_p}{C_v}$

Example: For monoatomic gas $\gamma = 1.67$, for diatomic gas $\gamma = 1.4$ and for polyatomic gas $\gamma = 1.33$

- **What would be the heat lost if internal energy decreases by 10 J and 20 J of work is done on the system simultaneously? (MTN 2018 GII) (BWP 2019 GII)**

Ans: ΔU: Change in internal energy (negative since it is decreasing) = -10 J
W: Work done on the system (negative since work is done on it) = -20 J
Q: Heat transfer (positive for heat entering the system, negative for heat leaving) = ?
Applying the first law:
$Q = \Delta U + W$
Substitute the known values:
$Q = (-10) + (-20) = -10 - 20$
$Q = -30$ J negative sign shows heat lost by the system.

- **Give two examples of adiabatic processes. (DGK 2019 GI) (MTN 2022 GI),(LHR 2016)**

Ans: **Example-1: The rapid escape of air from a punctured tyre** is an example of an adiabatic process.
Adiabatic Process: In an adiabatic process, there is no significant heat transfer between the system and its surroundings i.e., **Q = 0**
Rapid Escape = No Time for Heat Transfer: The rapid escape of air happens so quickly that there's minimum time for heat transfer between the escaping air and the surroundings. Therefore, the air pressure drops adiabatically as it expands. This can even cause a slight cooling sensation near the puncture due to the work done by the expanding air against the surrounding pressure.
Example-2: Cloud formation is an example of an adiabatic process:
Adiabatic Cooling: As air rises in the atmosphere, the pressure surrounding it decreases. This decrease in pressure allows the air to expand and it does work against the surrounding atmosphere. This work comes from the internal energy of the air itself, causing it to cool down (adiabatic cooling).
Cooler Air and Condensation: If the rising air cools enough due to this adiabatic process then the water vapor present in the air condenses around tiny particles like dust, forming visible cloud.

- **Prove that $W = -\Delta U$ for adiabatic expansion process. (SGD 2022 GII)**
- **In which process external work is done at the expense of the internal energy of the gas molecules? Explain it. (SWL 2023, GII 2018)**

Ans: Since we know that $Q = \Delta U + W$. In adiabatic process $Q = 0$ so $0 = \Delta U + W$. Shifting "ΔU" on left side we get $-\Delta U = W$ it shows that $W = -\Delta U$
Therefore, we have proved that $W = -\Delta U$ for an adiabatic expansion process. This means the work done on the surroundings by the system during the expansion (positive W) is equal to the decrease in internal energy of the system (negative ΔU). In simpler terms, the energy lost by the system as internal energy is equal to the work done by the system during the expansion.

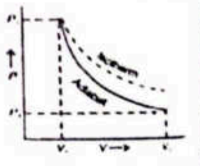
- **If PV^{γ} = constant; prove that $TV^{\gamma-1}$ = constant. (GRW 2022 GI)**

Ans: Since PV^{γ} = constant and $PV = nRT$ if $n = 1$(mole) then $PV = RT \Rightarrow P = \frac{RT}{V}$ so

$$\frac{RT}{V}V^{\gamma} = \text{constant}$$

$$TV^{\gamma-1} = \frac{\text{constant}}{R}$$

$$TV^{\gamma-1} = \text{constant}$$



- **Why adiabat is steeper than isotherm? Explain. (Lhr 2013 Group II)**

Ans: Since adiabatic process is faster or quick than isothermal process which is a slow process that is why PV diagram (adiabat) of adiabatic process is steeper (having more slope) than isotherm.

6.5 REVERSIBLE AND IRREVERSIBLE PROCESSES

Q. What is a reversible process? Describe its characteristics and provide Examples.

Ans

Definition: A process that can be perfectly reversed, meaning it can go back to its original state by retracing the exact same steps in reverse order, without causing any permanent change in the surroundings.

- A succession of events which brings the system back to its initial condition is called a cycle. A reversible cycle is the one in which all the changes are reversible.

Characteristics:

- It must occur very slowly (quasi-statically) so that the system is always in equilibrium.
- No energy is lost due to friction, resistance, or other dissipative forces.
- Thermal and mechanical effects are exactly reversed. If heat was absorbed in the forward process, it's released in the reverse, and vice versa.

Examples (idealized): Slow liquefaction and evaporation, very slow compression or expansion of a gas. In reality, perfectly reversible processes don't exist.

Note: No actual change is completely reversible.

Q. What is an Irreversible process? Describe its characteristics and provide examples.

Ans

Definition: A process that cannot be retraced in reverse to restore both the system and its surroundings to their initial states. There is always some energy dissipation or increase in disorder in the universe.

Characteristics:

- They occur naturally and spontaneously and suddenly.
- They often involve friction, heat conduction, convection, radiation, or rapid changes.

Examples: An explosion, burning fuel, mixing hot and cold water, a ball rolling to a stop due to friction, heat flowing from hot to cold. All real-world processes are irreversible.

Do you know?

First practical steam-engine was designed by John Braithwaite and John Ericsson in England around 1829.

6.6 HEAT ENGINE

Q. What is a Heat Engine? Explain its working principle.

Ans

A heat engine is a device that takes heat energy and converts some of it into mechanical work. It works in a cycle, meaning it returns to its original state after completing a series of steps.

WORKING PRINCIPLE OF A HEAT ENGINE

1. **Heat Absorption (Q_1):** The engine absorbs a quantity of heat (Q_1) from a **high-temperature reservoir** (also called the heat source, like a boiler with hot steam) at a temperature T_1.
2. **Work Output (W):** The engine uses some of this absorbed heat to perform useful mechanical work (W).
3. **Heat Rejection (Q_2):** The remaining heat (Q_2) that couldn't be converted into

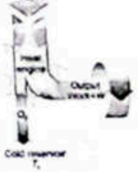


Fig 6.6

Schematic representation of a heat engine. The engine absorbs heat Q_1 from the hot reservoir, expels heat Q_2 to the cold reservoir and does work W.

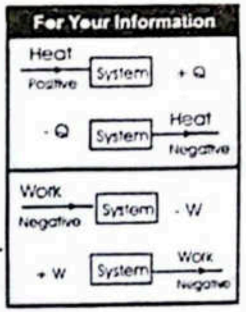
work is expelled to a **low-temperature reservoir** (also called the heat sink, like the atmosphere or a cooling pond) at a lower temperature T_2.

The net work done by the engine in one cycle is the difference between the heat absorbed and the heat rejected:

$$W = Q_1 - Q_2$$

The goal of a heat engine is to convert as much of Q_1 into W as possible.

For Your Information



EXPLANATION:
Heat entering a system is positive and leaving a system is negative. The work done by the system is positive and the work done on the system is negative, as shown in the figure.

SLO BASED SHORT QUESTIONS & ANSWERS

- **Energy can be added to a system when no heat transfer takes place. Is this statement true? Support your response with an example. (SGD 2022 GI)**

Ans: That statement is true. Energy can be added to a system without heat transfer by work done on the system.
Example: when a thermo flask is shaken rapidly then temperature of milk inside the flask rises due to the work done in shaking process. Work ∝ < K.E > ∝ T ∝ U

- **Justify! Work and heat are similar. (LHR 2019 GI) (LHR 2019 GII)**

Ans: Work and heat are similar, but not quite the same. Work ∝ < K.E > ∝ U ∝ Q
Similarities:
Energy Transfer: Both work and heat are mechanisms for transferring energy from one system to another. They are not forms of energy themselves but ways to transfer it.
Path Functions: The amount of work or heat transferred depends on the specific process or path taken, not just the initial and final states of the system.
Effect on Internal Energy: Both work and heat can change the internal energy of a system, which is the total kinetic and potential energy of its molecules.

- **A heat engine works between 327°C and 27°C. Find its efficiency. (FSD 2022 GI) (See Numerical 11.7)**

Ans: Temperature of source, T_1 = 327 C° + 273 = 600 K and Temperature of sink, T_2 = 27 C° + 273 = 300 K

Using the relation, $\eta = \left(1 - \frac{T_2}{T_1}\right) \times 100 \Rightarrow \eta = \left(1 - \frac{300}{600}\right) \times 100 \Rightarrow \eta = \left(1 - \frac{1}{2}\right) \times 100 = 50\%$ $\boxed{\eta = 50\% \text{ Ans}}$

- **How can the efficiency of a practical heat engine be increased? (SGD 2018 GII)**

Ans: Efficiency of a heat engine can be increased by increasing the temperature difference between source and sink. **Reason:** $\eta = \left(1 - \frac{T_2}{T_1}\right) \times 100 = \frac{T_1 - T_2}{T_1} \times 100$

- **What will be the efficiency of an engine if it performs 100J of work and rejects 400J of heat energy to the cold reservoir? (MTN 2023 GI)**
- **An engine absorbs heat of 10 J and rejects 5 J heat, what is the heat being used by the engine? (LHR 2019 GII)**

Ans: Since we know that $W = Q_1 - Q_2$ so W = 10 - 5 = 5 J is the heat being used by engine

MULTIPLE CHOICE QUESTIONS

- **An ideal gas heat engine operates in a Carnot cycle which works between the temperatures 227°C and 127°C. It absorbs 6 kcal at the higher temperature. The amount of heat (in kcal) converted into work is equal to:**

(a) 4.89 (b) 3.5 (c) 1.6 (d) 1.2

Solution: $\therefore \frac{W}{Q_1} = 1 - \frac{T_2}{T_1} \therefore \frac{W}{6} = 1 - \frac{400}{500} \therefore \frac{W}{6} = 1 - \frac{4}{5} \Rightarrow \frac{W}{6} = \frac{1}{5} \Rightarrow w = \frac{6}{5}K_{cal} = 1.2K_{cal}$

6.7 SECOND LAW OF THERMODYNAMICS

Q. State and explain the Second Law of Thermodynamics (Lord Kelvin's Statement).

Ans

The First Law tells us that energy is conserved, but it doesn't say anything about the *direction* of energy flow or the *conditions* under which heat can be converted into work. That's where the **Second Law of Thermodynamics** comes in.

Lord Kelvin's Statement (based on Heat Engines):
"It is impossible to devise a process which may convert heat, extracted from a single reservoir, entirely into work without leaving any change in the working system." or we can say a heat engine without sink is not possible.

Explanation
let us analyze briefly the operation of an engine. The engine or the system absorbs a quantity of heat Q_1, from the heat source at temperature T_1. It does work W and expels heat Q_2, to low temperature reservoir at temperature T_2. Hence, for the working of heat engine there must bea source of heat at a high temperature and a sink at low temperature to which heat may be rejected.

Example:
It has been observed that petrol engines convert roughly 25% and diesel engines 35 to 40% available heat energy into work remaining is wasted due to friction between parts of engines.

WHAT ARE THE SIGNIFICANCE OF LORD KELVIN'S STATEMENT OF THE SECOND LAW OF THERMODYNAMICS?

- You cannot build a perfect heat engine that takes heat from *just one* hot source and turns *all* of it into useful work.
- To get work from heat, you **must** have a temperature difference. Heat must flow from a higher temperature to a lower temperature. Some heat will always be rejected to the colder reservoir.
- This is why oceans and the atmosphere, despite containing vast amounts of heat, cannot be used to produce useful work unless there's a colder place to reject heat.

Tidbits (Text Book Page 123):

- **According to the Kelvin statement of the second law of thermodynamics, the process pictured here is impossible. Heat from a source at a single temperature cannot be converted entirely into work. (Accompanied by an "IMPOSSIBLE" diagram).**

Explanation: This emphasizes a core limitation of heat engines: you cannot achieve 100% efficiency by extracting heat from a single reservoir and converting it entirely into work. Some heat must always be rejected to a colder reservoir.

According to the Kelvin statement of the second law of thermodynamics, the process pictured here is impossible. Heat from a source at a single temperature cannot be converted entirely into work.

6.8 CARNOT ENGINE ANS CARNOT'S THEOREM

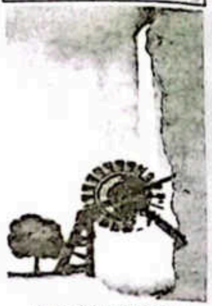
Q. What is a Carnot Engine? Describe the Carnot Cycle and state Carnot's Theorem.

Ans

CARNOT ENGINE

The **Carnot engine** is a theoretical, ideal heat engine that operates in a perfectly **reversible cycle (called the Carnot cycle).** It is the most efficient engine possible operating between two given temperatures. While it is an ideal concept and cannot be built in reality, it sets the maximum possible efficiency for any heat engine.

Interesting information



A waterfall analogy for the heat engine

DESCRIBE THE FOUR STEPS OF THE CARNOT CYCLE.

The Carnot cycle uses an ideal gas as its working substance and consists of four reversible processes:

1. **Isothermal Expansion (A to B):** The gas expands slowly at a constant high temperature (T_1), absorbing heat (Q_1) from the hot reservoir.
2. **Adiabatic Expansion (B to C):** The gas continues to expand, but now without any heat exchange. As it expands, it does work, and its temperature drops from T_1 to T_2.
3. **Isothermal Compression (C to D):** The gas is slowly compressed at a constant low temperature (T_2), releasing heat (Q_2) to the cold reservoir.
4. **Adiabatic Compression (D to A):** The gas is compressed again, without heat exchange. Work is done on the gas, and its temperature rises from T_2 back to T_1, returning the gas to its initial state.

Q How is the efficiency of a Heat Engine defined and calculated?

The efficiency of any heat engine is defined as the ratio of the useful work output to the heat energy input:

$$\eta = \frac{\text{Output(Work)}}{\text{Input(Energy)}}$$

$$\eta = \frac{W}{Q_1}$$

Since $W = Q_1 - Q_2$, we can write:

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

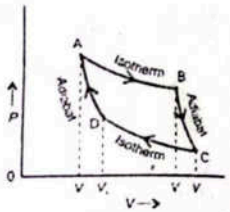


Fig 6.9

For a Carnot engine, the efficiency can be expressed solely in terms of the absolute temperatures of the hot (T_1) and cold (T_2) reservoirs:

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

To get the percentage efficiency, multiply by 100:

Percentage efficiency $\eta = (\frac{T_1 - T_2}{T_1}) \times 100\% = (1 - \frac{T_2}{T_1}) \times 100\%$

Significance: The efficiency of a Carnot engine only depends on the temperature difference between the hot and cold reservoirs. A larger temperature difference means higher efficiency. However, efficiency can never be 100% (or 1) unless the cold reservoir is at absolute zero (T_2=0 K), which is practically impossible. Therefore, all real heat engines are less efficient than the ideal Carnot engine due to unavoidable energy losses like friction.

Interesting information (Text Book Page 124):
A waterfall analogy for the heat engine.
Explanation: Just as water flows from a higher elevation to a lower elevation, doing work (e.g., turning a turbine), heat flows from a high-temperature reservoir to a low-temperature reservoir, and some of

CARNOT THEOREM

STATE CARNOT'S THEOREM.

1. "No heat engine can be more efficient than a Carnot engine operating between the same two temperatures."

2. "All Carnot engines operating between the same two temperatures have the same efficiency, irrespective of the nature of the working substance."

Q. What is the Key Takeaway regarding the efficiency of a carnot engine?

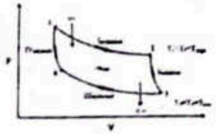
Efficiency of a Carnot Engine

The efficiency of a Carnot engine only depends on the temperature difference between the hot and cold reservoirs. A larger temperature difference means higher efficiency. However, efficiency can never be 100% (or 1) unless the cold reservoir is at absolute zero (T_2 = 0 K), which is practically impossible. Therefore all real heat engines are less efficient than the ideal Carnot engine due to unavoidable energy losses like friction.

SLO BASED SHORT QUESTIONS

- **Draw PV-diagram which show four steps of Carnot engine. (DGK 2021 GI) (GRW 2023 GI) (FSD 2023 GII)**

Ans:



- **What is the effect on efficiency of Carnot engine, if the temperature of the sink only be decreased? (LHR 2019)**

Ans: If the temperature of the sink (cold reservoir) in a Carnot engine is decreased while keeping the temperature of the source (hot reservoir) constant, the efficiency of the Carnot engine will **increase**.
Reason: the formula for the efficiency of a Carnot engine is

$\%\eta = (1 - \frac{T_2}{T_1}) \times 100 = (\frac{T_1 - T_2}{T_1}) \times 100 \Rightarrow \eta \propto T_1 - T_2$ Since efficiency is a ratio, it depends on the difference between the hot and cold reservoir temperatures ($T_1 - T_2$). So when T_2 is deceased then $T_1 - T_2$ also increases and hence efficiency increases.

- **Under what circumstances the efficiency of a Carnot engine will be 100%? It is possible? (BWP 2017) (BWP 2018 GII) (MTN 2023 GII)**

Ans: But it can be 100% or one unless cold reservoir is at absolute zero temperature (i.e. T_2 = 0 K). Since cold reservoir at absolute zero temperature is not possible, hence the maximum efficiency is always less than one. Reason:

$$\eta\% = (1 - \frac{T_2}{T_1}) \times 100 = (\frac{T_1 - T_2}{T_1}) \times 100 \text{ Now if } T_2 = 0 \Rightarrow \eta = (1 - \frac{0}{T_1}) \times 100 = 100\%$$

- **Carnot cycle provides the basis to define a temperature scale that is independent of material properties. Explain. (BWP 2019)**

Ans: The Carnot cycle plays an important role in defining a thermodynamic temperature scale which is independent of the material properties of a thermometer. Because the Carnot cycle operates on the principle that the efficiency of a heat engine depends only on the absolute temperatures of the hot and cold reservoirs and not on the working substance. This concept led to the development of the Kelvin scale, the standard thermodynamic temperature scale. The Kelvin scale assigns a zero temperature to the point where a Carnot engine operating with an ideal gas would have zero efficiency (absolute zero). Un known temperature is determined by

$$T = 273.16 \frac{Q}{Q_3} K$$

Q and Q_3 be the quantities of heat absorbed or rejected by the system.

- **How efficiency of Carnot engine increases practically?**

Ans: The efficiency of Carnot engine can be increased practically by increasing the temperature difference between hot and cold reservoir.

Reason: $\%\eta = (1 - \frac{T_2}{T_1}) \times 100 = (\frac{T_1 - T_2}{T_1}) \times 100 \Rightarrow \eta \propto T_1 - T_2$

MULTIPLE CHOICE QUESTIONS

- **If the temperature of source equals the sink, the efficiency of Carnot engine**
  (a) Increases (b) Remains constant (c) Decreases **(d) Becomes zero**

Solution: If "$T_1 = T_2$" then no heat transfer takes place or efficiency becomes zero.

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

$$\%\eta = \left(1 - \frac{1}{1}\right) \times 100 = (1-1) \times 100 = 0$$

$\%\eta = 0$

- **The efficiency of all reversible heat engines working between same hot and cold reservoirs**
  (a) Is same (b) Depends on pressure (c) Depends on fuel used (d) Depends on volume
- **The efficiency of a cannot engine can be made 100% if**
  (a) Low temperature reservoir is at 0°C
  (b) When both the reservoirs are of the same temperature
  (c) Low temperature reservoir is at 0 K
  D Low temperature reservoir is 0°F

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

$T_2 = 0\,K$ then

$\%\eta = (1 - 0) \times 100 = 100\%$

- **The turbine in a steam power plant takes heat from a boiler at 427°C and exhausts into low temperature reservoir at 77°C. The efficiency is:**
  (a) 25% **(b) 50%** (c) 75% (d) 100%

Solution: $T_1 = 427°C + 273 = 700\,K$

$T_2 = 77°C + 273 = 350\,K$

$$\%\eta = \left(1 - \frac{T_2}{T_1}\right) \times 100 = \left(1 - \frac{350}{700}\right) \times 100$$

$\%\eta = (1 - 0.50) \times 100 = 0.5 \times 100 = 50\%$

- **In a Carnot cycle, heat is given to the system, its temperature will:**
  (a) Increase (b) Decrease **(c) Remain constant** (d) Zero

Solution: In a Carnot cycle when heat is given to a system then it only be an isothermal expansion, so,"T" must remain same.

- **In a Carnot cycle, heat is neither given nor taken out of the system, its temperature:**
  (a) Increases (b) Decreases (c) Remains constant **(d) May rise or fall**

Solution: On contrary to previous question, if no heat is provided or taken away from system during a Carnot cycle it must be either adiabatic expansion (resulting in decrease in "T" or "U") or it may be an adiabatic contraction (resulting in increase in "T" or "U")

- **A Carnot engine works between a hot reservoir at temperature T_1 and a cold reservoir at temperature T_2, to increase its efficiency**
  (a) T_1 and T_2 both should be increased
  (b) T_1 should be decreased and T_2 should be increased
  (c) T_1 and T_2 both should be decreased
  (d) T_1 should be increased and T_2 should be decreased

Solution: $\eta \propto 1 - \frac{T_2}{T_1}$ which means it depends upon the ratio of "$\frac{T_2}{T_1}$", smaller this ratio, T_2 (Temperature of sink) must be decreased and T_1(Temperature of source) must be increased.

- **For which combination of working temperatures the efficiency of Carnot's engine is highest?**
  (a) 100 K, 80 K (b) 80 K, 60 K **(c) 40 K, 20 K** (d) 60 K, 40 K
- **%η will be highest for one for whom $\frac{T_2}{T_1}$ is minimum.**

(a) $\frac{T_2}{T_1} = \frac{80}{100} = 0.8$ (b) $\frac{T_2}{T_1} = \frac{60}{80} = 0.75$ (c) $\frac{T_2}{T_1} = \frac{20}{40} = 0.50$ (d) $\frac{T_2}{T_1} = \frac{40}{60} = 0.66$

So clearly (C. option has minimum value for $\frac{T_2}{T_1}$ to given us maximum %η.

- **In a Carnot heat engine 8000 J of heat is absorbed from a source at 400 K and 6500 J of heat is rejected to the sink. The temperature of the sink is:**
  (a) 325 K (b) 100 K (c) 0 K (d) 273 K

Solution: $Q_1 = 8,000\,J, Q_2 = 6500\,J, T_1 = 400\,K, T_2 = ?$

$$\therefore \frac{T_2}{T_1} = \frac{Q_2}{Q_1} \Rightarrow T_2 = \frac{Q_2}{Q_1} \times T_1 = \frac{6500}{8999} \times 400 \quad T_2 = \frac{65}{8} \times 40 = 325k$$

- **A Carnot engine takes 300 cal of heat at 500 K and rejects 150 cal of heat to the sink. The temperature of the sink is:**
  (a) 1000 K (b) 750 K **(c) 250 K** (d) 125 K

Solution: $Q_1 = 300\,cal, T_1 = 500K$

$Q_2 = 150\,cal, T_2 = ?$

$$\frac{Q_2}{Q_1} = \frac{T_2}{T_1} \text{ it gives } T_2 = \frac{Q_2}{Q_1} \times T_1 = \frac{150}{300} \times 500 = 50 \times 5 = 250K$$

6.9 REFRIGERATOR

Q. What is a Refrigerator? Explain its working principle.

Ans

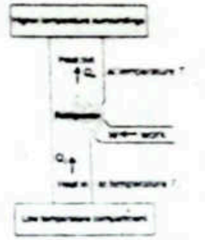


Fig. 6.19

REFRIGERATOR

A refrigerator is a device that works opposite to a heat engine. Its main job is to keep a cold space (like the inside of your fridge) at a temperature lower than its surroundings.

WORKING:

A refrigerator operates in a cyclic process, but in reverse of a heat engine.

1. **Heat Absorption (Q_c):** It absorbs heat (Q_c) from the **low-temperature reservoir (LTR)** (the cold compartment inside the fridge) at temperature T_c.
2. **Work Input (W):** To move heat from a colder place to a warmer place (which doesn't happen naturally), external work (W) must be done *on* the system (usually by a compressor).
3. **Heat Rejection (Q_H):** This absorbed heat plus the work done is then released as heat (Q_H) to the **high-temperature reservoir (HTR)** (the warmer surroundings outside the fridge) at temperature T_H.
   The heat rejected to the hot reservoir (Q_H) is: $Q_H = Q_c + W$
   So, the work input required is: $W = Q_H - Q_c$

Coefficient of Performance (COP) of a Refrigerator

The efficiency of a refrigerator is measured by its Coefficient of Performance (COP). It's the ratio of the heat removed from the cold reservoir to the work done to remove it:

$$E = \frac{\text{Heat Removed From Cold Reservior}}{\text{Work Done of Refrigerator}} = \frac{Q_c}{W}$$

Substituting $W = Q_H - Q_C$

$$E = \frac{\text{Heat Removed From Cold Reservior}}{\text{Work Done of Refrigerator}} = \frac{Q_c}{Q_H - Q_c}$$

For an ideal refrigerator (Carnot refrigerator), the COP can be expressed in terms of absolute temperatures:

$$E = \frac{T_1}{T_2 - T_1} \text{ since } Q \propto T$$

A higher COP means the refrigerator is more efficient, removing more heat from the cold space for less work input.

MULTIPLE CHOICE QUESTIONS

- **A refrigerator's coefficient of performance (COP) is a measure of: .**
  (a) How much work it produces.
  (b) How much heat it generates.
  (c) How effectively it removes heat from the cold reservoir for a given work input.
  (d) Its overall energy consumption.

Answer: (c) How effectively it removes heat from the cold reservoir for a given work input.

Explanation: The COP of a refrigerator is defined as the ratio of the heat removed from the cold reservoir (Qc) to the work done (W) to remove it (E=Qc/W). A higher COP means more efficient cooling.

SLO BASED SHORT QUESTIONS & ANSWERS

- **In what fundamental way does a refrigerator operate in reverse compared to a heat engine, and what is required for this reverse operation?**

Ans: A heat engine converts heat flow from hot to cold into work. A refrigerator operates in reverse by forcing heat to flow from a colder body to a hotter body. This reverse operation is not spontaneous and requires an input of external work (e.g., from an electric motor) to move the heat against its natural direction of flow.

6.10 ENTROPY

Q. What is Entropy? How is its change defined?

Ans

ENTROPY (S)

It is a thermodynamic quantity that measures the **degree of disorder or randomness** in a system. It is a way to quantify the Second Law of Thermodynamics.

The concept of entropy was introduced by Rudolph Clausius in 1856. It is a state function

CHANGE IN ENTROPY

When a system absorbs a quantity of heat (ΔQ) at a constant absolute temperature (T) in a reversible process, the change in entropy is:

$$\Delta S = \Delta Q / T$$

- **Positive ΔS:** When heat is added to a system, its disorder increases, so entropy increases.
- **Negative ΔS:** When heat is removed from a system, its disorder decreases, so entropy decreases.

Suppose that an amount of heat Q flows from a hot reservoir at temperature T_1 through a conducting rod to a cold reservoir at temperature T_2.

As the hot reservoir loses heat, so decrease in entropy of hot reservoir = $\frac{Q}{T_1}$

As the cold reservoir gains heat, so increase in entropy of cold reservoir = $\frac{Q}{T_2}$

Also $T_1 > T_2$, thus $\frac{Q}{T_2} > \frac{Q}{T_1}$

Hence, net change in entropy = $\frac{Q}{T_2} - \frac{Q}{T_1}$

That is positive. Thus we conclude that change in entropy is positive when heat is added and negative when heat is removed from the system.

SECOND LAW OF THERMODYNAMICS IN TERMS OF ENTROPY.

"If a system undergoes a natural process, it will go in the direction that causes the entropy of the system plus the environment to increase."

This means that in any spontaneous or natural process, the total disorder of the universe (system + surroundings) always increases or stays the same (for ideal reversible processes). It never decreases.

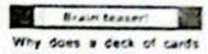
RELATIONSHIP BETWEEN ENTROPY AND DISORDER

Natural processes always tend towards a state of greater disorder.

- **Heat flow:** When hot and cold substances mix, heat flows from hot to cold, increasing the overall disorder because the organized separation of hot and cold regions is lost.
- **Gas expansion:** When a gas expands into a larger volume, its molecules have more space to move around, increasing their randomness and thus increasing entropy.

Brain teaser! (Text Book Page 128):

Why does a deck of cards become more disordered when shuffled?


Brain teaser!
Why does a deck of cards become more disordered when shuffled?

Ans: Shuffling a deck of cards increases the number of possible arrangements of the cards. A perfectly ordered deck (e.g. sorted by suit and rank) has only one specific arrangement. Shuffling introduces randomness, leading to a vast number of possible disordered arrangements, making it highly improbable to return to the original ordered state spontaneously. This increase in the number of possible microstates corresponds to an increase in entropy.

ENTROPY AS DEGRADATION OF ENERGY:

When heat flows from a body at higher temperature where more energy is available to low temperature where low or no heat is available then energy is degraded.

An increase in entropy means that energy becomes "degraded" or less available for doing useful work. For example, when hot and cold water mix, the total energy remains the same (First Law), but you can no longer use that mixed warm water to run a heat engine as effectively as you could with separate hot and cold sources. The energy hasn't been lost, but its quality (its ability to do work) has decreased. This concept is sometimes referred to as the **"heat death of the universe,"** suggesting that eventually, the entire universe will reach a state of maximum entropy (uniform temperature and maximum disorder), where no more useful work can be done.

Entropy as times arrow:

In all real processes, the energy available for doing useful work will decrease. When all the systems are taken together as the universe, the entropy of the universe always increases. So it is regarded as Time Arrow.

Law of increase of Entropy

Entropy of the universe during any process either remains constant or increase. $\Delta S_{universe} \geq 0$

SLO BASED SHORT QUESTIONS & ANSWERS

- **What does the concept of "degradation of energy" imply in terms of entropy?**

An: The "degradation of energy" implies that as entropy increases in natural processes, the quality of energy decreases. While the total amount of energy remains conserved (First Law), it becomes less available for doing useful work. For example, when hot and cold substances mix, the energy is still present, but the temperature difference (which drives useful work) is lost, meaning the energy has been "degraded" to a less useful form. This leads towards a state of maximum disorder where no more work can be extracted.

- **What is negative entropy? Give example and its unit. (GRW 2019)**

Ans: In strict sense of thermodynamics, there is no such thing as negative entropy. Entropy is a measure of disorder in a system that can only increase or remains constant over time in a closed system (according to the second law of thermodynamics). However, the term "negative entropy" is sometimes used in the departure from randomness or decrease in randomness or how close a system is to a perfect order. It's not a negative value of entropy but rather a measure of how far a system's entropy is from its maximum possible value. $\Delta S = -\frac{\Delta Q}{T} < 0$

Examples:
Melting of ice is an example of increase in entropy. However, when heat is taken out from water and it converts into ice then we can say that entropy change is negative.
Units: Entropy itself is measured in units like **Joules per Kelvin (J/K)**. Negative entropy, as a measure of departure from randomness, has no specific unit as it is a relative measure.

- **Does entropy of a system increases or decrease due to friction? (LHR 2017 GI) (SGD 2017) (SGD 2018 GI) (BWP 2018 GII) (SWL 2019) (MTN 2019 GI) (BWP 2019 GII) (MTN 2022 GI) (LHR 2022 GII) (MTN, DGK 2023 GI) (MTN, LHR, SGD, RWP 2023 GII)**

Ans: Due to friction, the entropy of a system always increases. $\Delta S = +\frac{\Delta Q}{T} > 0$

Increased Disorder: Due to friction the randomness or disorder within the system increases.
Energy Dissipation: Friction also leads to the dissipation of mechanical energy into thermal energy (heat). Since heat is a more disordered form of energy compared to organized mechanical energy. This conversion also produces overall increase in entropy.
Examples:
Rubbing our hands together: The friction between our hands increases the random motion of molecules, making them feel warm (increased thermal energy and entropy).

- **Give an example of a natural process that involves an increase in entropy. (AJK 2019) (MTN 2019 GI) (GRW 2019 GII) (BWP 2022 GI) (SGD, GRW 2022 Gil) (SWL 2023 GII)**

Ans: Melting ice is an example of entropy increase. Ice has a very ordered structure, while liquid water has more freedom of movement for its molecules, making it a more disordered state. This increase in disorder reflects the natural tendency of entropy to increase in a closed system.

- **Why the entropy of the universe always increases?**

Ans: Because according to Law of increase in entropy "Entropy of the universe during any process either remains constant or increase".

$$\Delta S_{universe} \geq 0$$

- **A system absorb 200 J heat at an absolute temperature 200K. Calculate the change in entropy.(DGK 2019 GII)(DGK 2021)**

Ans. $\Delta S = +\frac{\Delta Q}{T} = +\frac{200}{200+273} = \frac{200}{473} = +0.423 J K^{-1}$

- **What is a negative entropy? Give example and Define entropy. Write its SI Unit (Fsd 2012)**

Ans. Negative entropy indicates the decrease in disorderness in the system or more order in the system. Entropy itself cannot be negative. However, negative entropy is a concept used to describe the **departure from randomness** in a system. It is a measure of how much order is present in a system compared to a random distribution.

Example

(i) If the heat of the system is increasing then the entropy of the system will be positive and entropy change is positive.

(ii) If the heat of the system is decreasing then the entropy change is negative.

Definition

Entropy is the measure of disorder of the system. It can be expressed as $\Delta S = \frac{\Delta Q}{T}$

The SI unit of entropy is $J K^{-1}$.

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TEXT BOOK EXERCISE WITH SOLUTION

MULTIPLE CHOICE QUESTIONS

6.1 In an isothermal change, internal energy:
(a) decreases (b) increases
(c) remains the same (d) becomes zero
Explanation: For an ideal gas, internal energy depends only on temperature. In an isothermal process, the temperature is kept constant, so the internal energy of the ideal gas also remains constant.

6.2 First law of thermodynamics is based upon law of conservation of:
(a) mass **(b) energy**
(c) momentum (d) charge
Explanation: The First Law of Thermodynamics is a direct statement of the principle of conservation of energy, asserting that energy cannot be created or destroyed, only transformed.

6.3 A device which converts mechanical energy into heat energy is called:
(a) heat engine (b) Carnot engine
(c) refrigerator (d) turbine
Explanation: A heat engine is the general term for any device that takes heat energy and converts a portion of it into mechanical work through a cyclic process. A Carnot engine is a specific, ideal type of heat engine.

6.4 When two objects are made in thermal contact having same temperature, then they are at:
(a) thermal Equilibrium
(b) chemical Equilibrium
(c) mechanical Equilibrium
(d) physical Equilibrium
Explanation: Thermal equilibrium is the state where two objects in contact have reached the same temperature, resulting in no net flow of heat between them.

6.5 When the system is expanded by adding heat energy, then the work done will be:
(a) positive and on the system
(b) negative and on the system
(c) positive and by the system
(d) negative and by the system
Explanation: When a system expands, it pushes against its surroundings, meaning it does work on the surroundings. By convention, work done by the system is considered positive.

6.6 Entropy of a system in reversible process:
(a) decreases (b) increases
(c) is Infinite **(d) is zero**
Explanation: For a truly reversible process, the net change in entropy of the system and its surroundings combined is zero. The entropy of the system itself can change, but if the process is reversible, the change in entropy of the system is exactly balanced by the change in entropy of the surroundings, leading to a net change of zero for the universe.

6.7 What happens to internal energy of an object when its temperature:
(a) decreases (b) remains Constant
(c) increases (d) fluctuates
Explanation: The Boltzmann constant (kB) is a fundamental physical constant relating the average kinetic energy of particles in a gas with the thermodynamic temperature of the gas. Its value is 1.38×10^{-23} Joules per Kelvin.

6.8 The value of Boltzmann constant is:
(a) $1.38 \times 10^{-23} J K^{-1}$ (b) $1.38 X 10^{23} J K^{1}$
(c) $1.38 X 10^{24} J K^{-1}$ (d) $1.38 \times 10^{-23} J^{-1} K^{-1}$
Explanation: An adiabatic process is defined by the condition that no heat energy enters or leaves the system ($\Delta Q = 0$). Temperature, internal energy, and work done can all change in an adiabatic process.

6.9 In an adiabatic process, there is no:
(a) change in temperature
(b) exchange of heat
(c) change in internal energy
(d) work done
Explanation: For an ideal gas (and generally for most substances), internal energy is directly related to temperature. As temperature increases, the average kinetic energy of the molecules increases, leading to an increase in the object's internal energy.

6.10 Thermodynamics mostly deals with:
(a) Measurement of quantity of heat
(b) Transfer of quantity of heat
(c) Change of state
(d) Conversion of heat to other forms of energy
Explanation: Thermodynamics is the branch of physics that specifically studies the relationships between heat and other forms of energy, and how heat can be converted into mechanical work or vice versa. While it involves measuring and transferring heat, its core focus is on these energy transformations.

SHORT ANSWER QUESTIONS

6.1 What is meant by thermal equilibrium? Explain briefly.

Ans: (Two or more than two bodies are said to be in thermal equilibrium if they have same temperature.

- They all have same thermal energy which is associated with the kinetic energy of the particles. So there is no driving force to transfer heat among them and they remain in thermal equilibrium.)

For Example, when we put a metal spoon into a hot cup of coffee. Initially, the coffee is hotter than the spoon. Overtime, heat flows from the coffee to the spoon. Eventually, the coffee and spoon reach the same temperature. At this point no heat transfer between coffee and spoon and they are said to be in thermal equilibrium.

6.2 What is meant by internal energy? How is it related to temperature of an ideal gas?

Ans: Internal energy is the total energy contained within a system due to the motion and interaction of its molecules. It includes the kinetic energy (translational, rotational, and vibrational) and potential energy (due to intermolecular forces) of the molecules.

For an ideal gas, there are no intermolecular forces, so its potential energy is considered zero. Therefore, the internal energy of an ideal gas is solely due to the translational kinetic energy of its molecules. Since temperature is a measure of the average kinetic energy of molecules, the internal energy of an ideal gas is directly proportional to its absolute temperature. If the temperature increases, the internal energy increases, and vice versa.

$$U \propto \langle K.E \rangle$$

6.3 State 2nd law of thermodynamics in two different forms.

Ans: **Lord Kelvin's statement**

It is impossible to devise a process which may convert heat, extracted from a single reservoir, entirely into work without leaving any change in the working system.

Clausius statement:

It is impossible to construct a device that transfer heat from cold to hot region by a cyclic process without the expenditure of energy.

6.4 Is it possible to construct a heat engine of 100% efficiency? Explain.

Ans: The efficiency of heat engine cannot be 100% according to second law of thermodynamics.

The efficiency of heat engine is

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

Here T_1 is the temperature of source and T_2 is the temperature of sink.

For 100% efficiency $T_2 = 0$ K or $T_1 = \infty$, which is not possible to achieve. so, it is impossible for heat engines to achieve 100% thermal efficiency.

6.5 Differentiate between reversible and irreversible processes.

Ans: **Reversible Process**

(A reversible process is one which can be retraced in exactly reverse order, without producing any change in the surroundings.)

For example

Liquification and evaporation of a substance performed slowly, are practically reversible. Similarly, the slow compression of a gas in a cylinder is reversible process as the compression can be changed to expansion by slowly decreasing the pressure on the piston to reverse the operation.

Irreversible Process:

(If a process cannot be retraced in the backward direction by reversing the controlling factors, it is an irreversible process.)

For example

All changes which occur suddenly or which involve friction or dissipation of energy through conduction, convection or radiation are irreversible. An example of highly irreversible process is an explosion.

6.6 Why adiabat is steeper than isotherm? Explain.

Ans: In both process PV diagram represent their respective relationships among pressure, volume, and temperature.

The adiabatic equation for an ideal gas is given by PV^{γ} = constant and for isothermal process

PV = constant., where γ is the heat capacity ratio and it is greater than 1.

The steeper slope of the adiabatic curve compared to the isothermal curve on a PV graph shows the greater sensitivity of pressure changes to volume changes in adiabatic processes.

~~Since~~ (the temperature ~~also~~ falls during an adiabatic expansion but the pressure drops more rapidly than it would in an isothermal expansion for the same volume change. This makes the adiabat curve appear steeper than the isotherm on a P-V diagram)

6.7 A refrigerator transforms heat from cold to hot body. Does this violate the second law of thermodynamics? Justify your answer.

Ans: No, a refrigerator does not violate the second law of thermodynamics. It is in accordance with the second law of thermodynamics which is stated as the heat cannot flow from a cold body to a hot body without the expenditure of external energy. the refrigerator demonstrates this by using electric energy for the flow of heat against its natural flow.

6.8 Explain briefly heat death of universe in terms of entropy.

Ans: The "heat death of the universe" is a theoretical concept based on the Second Law of Thermodynamics. The Second Law states that the total entropy (disorder) of an isolated system (like the universe) always tends to increase. This implies that over an extremely long time, all energy in the universe will eventually spread out uniformly, and all temperature differences will disappear. When everything reaches the same temperature and maximum disorder, there will be no more available energy to do useful work, and no more spontaneous processes will occur. The universe would effectively reach a state of thermal equilibrium, a "heat death," where no further change is possible.

6.9 Is it possible for a cyclic reversible heat engine to absorb heat at constant temperature and transforms it completely into work without rejecting some heat at low temperature? Explain.

Ans: No, it is impossible to construct a heat engine that will not expel heat into the atmosphere.

If heat engine don't expel heat into atmosphere it will become 100% efficient that is against second law of thermodynamics.

$$\eta = 1 - \frac{Q_2}{Q_1} \times 100\%$$

If $Q_2 = 0$ then $\eta = 100\ \%$

6.10 How does behavior of real gases differ from ideal gas at high pressure and low temperature? Identify the reasons behind these differences based on kinetic theory of gases.

Ans: Real gases deviate from ideal behavior at high pressure and low temperature due to two main reasons which violate ideal gas assumptions:

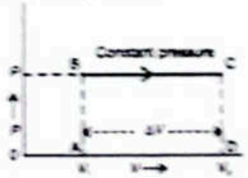
- **Intermolecular Forces:** Ideal gases assume no forces between molecules. However, at high pressure (molecules are closer) and low temperature (less kinetic energy), attractive forces between real gas molecules become significant, reducing the observed pressure.
- **Volume of Gas Particles:** Ideal gases assume negligible particle volume. At high pressure, the actual volume occupied by the gas molecules themselves becomes a substantial portion of the container's total volume, reducing the "free space" available for molecular movement.

6.11 Show that area under P - V graph is equal to work done.

Ans: Consider a gas enclosed in a cylinder with a movable piston. If the gas expands by a small volume ΔV at a constant pressure P, the work done by the gas is W = PΔV

On a P-V graph, if pressure P is on the y-axis and volume V is on the x-axis, then PΔV represents the area of a rectangle with height P and width ΔV.

Therefore, the area under the P-V graph represents the total work done by (or on) the gas during a thermodynamic process.



6.12 How is work done (i) by a gas (ii) on a gas? Calculate.

Ans: Work is done by a gas when it expands, and it is done on a gas when it is compressed. Both involve a change in volume and pressure, and the work done can be calculated using the formula $W = \sum P\,dV$

(i) **Work done by a gas:** When a gas expands, then work is done by a gas against external pressure or on surroundings and volume of the gas increases.

It is calculated as by constant pressure and taken as negative

$$W = -P\Delta V$$

(ii) **Work done on a gas:** When a gas compresses, then work is done on a gas by external forces and the volume of the gas decreases.
It is calculated as by constant external pressure and taken as positive.

$$W = + P\Delta V$$

CONSTRUCTED RESPONSE QUESTIONS

6.1 Explain how thermodynamics relates to the concept of energy conservation.

Ans: The law of conservation of energy and first law of thermodynamics are entangled with each other. The first law of thermodynamics basically a specific application of the law of conservation of energy to thermodynamic processes.
The first law specifically applies to thermodynamics systems, where energy can be transferred from heat to work or other form of energy as heat and work. The internal energy (ΔU) of a system is equal to the heat added to the system (ΔQ) minus the work done by the system on its surroundings (ΔW).

i.e $\Delta U = \Delta Q - W$

6.2 Explain how thermodynamics applies to biological systems, such as human body.

Ans: Human metabolism also provides an example of energy conservation. Human beings and other animals need energy for their growth and to do work. During their growth new cells are formed to replace old dead cell. The process of energy transformation within organism is called metabolism. The first law of thermodynamics ($\Delta U = Q - W$) can be applied to organism of the human body. Work done will result in the decrease in internal energy of the body. Consequently, the body temperature or in other words internal energy is maintained by the food we eat.

6.3 A gas is expanding adiabatically. Explain what happens to temperature and pressure of the gas.

Ans: When a gas expands adiabatically, it means there is no heat exchange with its surroundings ($\Delta Q = 0$). According to the First Law of Thermodynamics ($Q = \Delta U + W$), if $Q = 0$, then $W = -\Delta U$.

- **Temperature:** As the gas expands, it does positive work ($W > 0$) on its surroundings. Since this work is done without any heat input, the energy for this work must come from the gas's own internal energy (ΔU becomes negative). As the internal energy of an ideal gas is directly proportional to its temperature, a decrease in internal energy leads to a decrease in the temperature of the gas.
- **Pressure:** Because the gas is expanding (volume increases) and its temperature is simultaneously decreasing, the pressure of the gas will decrease significantly. The combined effect of increased volume and decreased temperature causes a more rapid drop in pressure than in an isothermal expansion, which is why an adiabat is steeper than an isotherm on a P-V diagram.

6.4 A coffee cup is left on a table, and overtime coffee cup cools down. Explain thermodynamics processes occurring during this process.

Ans:

- **Heat Transfer (Conduction, Convection, Radiation):** Heat energy from the hot coffee is transferred to the cooler surroundings (the table, the air, and the room) through:
  - Conduction: Heat flows directly from the coffee to the cup and then to the table.
  - Convection: The hot coffee heats the air directly above it, making the air less dense. This warm air rises, and cooler air moves in to take its place, creating convection currents that carry heat away.
  - Radiation: The hot coffee and cup emit thermal radiation (infrared waves) to the cooler surroundings.
- **Internal Energy Change:** As the coffee loses heat, its internal energy decreases, which is reflected in its decreasing temperature.
- Entropy Increase: This is an irreversible process. Heat flows spontaneously from a region of higher temperature (coffee) to regions of lower temperature (surroundings). This natural flow increases the overall disorder (entropy) of the universe, as the energy becomes more spread out and less available for useful work. The decrease in entropy of the coffee is more than compensated by the increase in entropy of the surroundings.
- No Work Done (negligible): In this simple cooling process, there is no significant mechanical work being done by or on the coffee system.

6.5 How we can explain different weather patterns through thermodymical processes like wind, rain, etc.

Ans: Weather patterns are driven by thermodynamic principles.

- **Wind** results from uneven solar heating, causing warm air to rise (convection) and cooler air to move in and replace it.
- **Rain** involves water evaporation (absorbing heat), moist air rising and cooling adiabatically (due to expansion at lower atmospheric pressure), leading to water vapor condensation into clouds (releasing latent heat), and finally precipitation.
- **Cloud Formation** occurs as moist air cools adiabatically while rising, causing water vapor to condense around tiny particles.

All these atmospheric phenomena involve continuous energy transfers and entropy changes, governed by the laws of thermodynamics.

COMPREHENSIVE QUESTIONS

6.1 What are the postulates of kinetic theory of gases? Derive a relation for ideal gas equation in the form $PV = NkT$ from general gas equation.

6.2 State and explain various gas laws.

6.3 Explain first law of thermodynamics in detail. Give an example in support of your explanation. Give its two applications.

6.4 What is a refrigerator? Explain its working. Derive an expression for its co-efficient of performance.

6.5 What is Carnot engine? Describe Carnot cycle. State Carnot theorem and derive an expression for efficiency of Carnot engine.

6.6 Define and explain the term "Entropy".

SOLVED EXAMPLES

EXAMPLE 6.1: One mole of an ideal gas is at a temperature of 300 K. If the Boltzmann constant is 1.38×10^{-23} J K^{-1}, calculate the volume of the gas at a pressure of 1 atm. [1 atm=101325 Pa]

Given:

Number of moles, $n = 1$ mol
Temperature, $T = 300$ K
Boltzmann constant, $kB = 1.38\times10^{-23}$ J K^{-1}
Pressure, $P = 1$ atm $= 101325$ Pa
Avogadro's number, $N_A = 6.02\times10^{23}$ mol^{-1} (needed to find R if not given directly, or to use $PV = Nk_BT$)

Required:

Volume of the gas, V

Formula:

We can use the ideal gas equation $PV = nRT$
We know that $R = N_A \times k_B$.
So, $PV = n(N_Ak_B)T$.
Rearranging to find V

$$V = P/nN_Ak_BT$$

Calculation:

$V = 101325$ Pa(1 mol)$\times$(6.02$\times$1023 mol^{-1}) $\times$ (1.38×10^{-23} J K^{-1}) $\times$ (300 K)
$V = 1013256.02 \times 1.38 \times 300$ m^3
$V = 1.013252493.48$ m^3
$V = 0.0246$ m^3 (rounded to three significant figures)

Answer: The volume of the gas would be approximately 0.0246 m^3

EXAMPLE 6.2: A gas is enclosed in a container fitted with a piston of cross-sectional area 0.10 m^2. The pressure of the gas is maintained at 8000 N m^{-2}. When heat is slowly transferred, the piston is pushed up through a distance of 4.0 cm. If 42 J heat is transferred to the system during the expansion, what is the change in internal energy of the system?

Given:

Cross-sectional area of piston, $A = 0.10$ m^2
Pressure of gas, $P = 8000$ N m^{-2}
Distance piston is pushed up, $\Delta y = 4.0$ cm $= 0.04$ m (converted to meters)
Heat transferred to the system, $Q = 42$ J (positive because heat is transferred to the system)

Required:

Change in internal energy, ΔU

Formulas:

1. Work done by the gas: $W = P\Delta V$
2. Change in volume: $\Delta V = A\,\Delta y$
3. First Law of Thermodynamics
$Q = \Delta U + W \Rightarrow \Delta U = Q - W$

Calculation:

First, calculate the change in volume
$\Delta V = A \times \Delta y = (0.10\ m^2) \times (0.04\ m) = 0.004\ m^3$
Next, calculate the work done by the gas:
$W = P \times \Delta V = (8000\ N\ m^{-2}) \times (0.004\ m^3) = 32$ J
Finally, calculate the change in internal energy using the First Law:

$$\Delta U = Q - W = 42\ J - 32\ J = 10\ J$$

Answer: The change in internal energy of the system is 10 J.

EXAMPLE 6.3: The turbine in a steam power plant takes steam from a boiler at 427 °C and exhausts into a low temperature reservoir at 77°C. What is the maximum possible efficiency?

Given:

High temperature reservoir (boiler), $T_H = 427$ °C
Low temperature reservoir (exhaust), $T_c = 77$ °C

Required:

Maximum possible efficiency (η)
Important Note: For efficiency calculations, temperatures must always be in Kelvin (K).
Convert Celsius to Kelvin: $T(K) = T(°C) + 273$
$T_H = 427 + 273 = 700$ K
$T_c = 77 + 273 = 350$ K

Formula:

The maximum possible efficiency is that of a Carnot engine:

$\eta = 1 - T_c/T_H$

Calculation:

$\eta = 1 - 350\,K/700\,K$

$\eta = 1 - 0.5$

$\eta = 0.5$

To express as a percentage:

Percentage efficiency $= 0.5 \times 100 = 50\%$

Answer: The maximum possible efficiency is 50%.

EXAMPLE 6.4: A refrigerator has a coefficient of performance 8. If temperature in the freezer is -23 °C, then what is the temperature at which it rejects the heat?

Given:

Coefficient of performance, E = 8

Temperature of cold reservoir (freezer), $T_c = -23\,°C$

Required:

Temperature of hot reservoir (where heat is rejected), $T_H = ?$

Important Note: Convert Celsius to Kelvin

$T_c = -23 + 273 = 250\,K$

Formula:

For the coefficient of performance of a refrigerator in terms of temperature:

$$E = \frac{T_C}{T_H - T_C}$$

Calculation:

Substitute the given values into the formula:

$$8 = \frac{T_C}{T_H - T_C} = \frac{250K}{T_H - 250K}$$

Now, solve for T_H:

$8 \times (T_H - 250\,K) = 250\,K$

$T_H - 250\,K = 31.25\,K$

$T_H - 250\,K = 31.25\,K$

$T_H = 250\,K + 31.25\,K$

$T_H = 281.25\,K$

To convert back to Celsius (optional, but good for understanding):

$T_H = 281.25 - 273 = 8.25\,°C$

Answer: The temperature at which the refrigerator rejects heat is 281.25 K (or 8.25 °C).

EXAMPLE 6.5: Calculate the entropy change when 1.0 kg ice at 0 °C melts into water at 0 °C. Latent heat of fusion of ice $L_f = 3.36 \times 10^5\,J\,kg^{-1}$.

Given:

Mass of ice, m=1.0 kg

Temperature, T=0 °C

Latent heat of fusion of ice, $L_f = 3.36 \times 105\,J\,kg^{-1}$

Required:

Entropy change, ΔS

Important Note: Convert Celsius to Kelvin.

$T = 0 + 273 = 273\,K$

Formulas:

1. Heat absorbed during melting (phase change): $\Delta Q = mL_f$
2. Change in entropy: $\Delta S = \Delta Q/T$

Calculation:

First, calculate the heat absorbed:

$\Delta Q = (1.0\,kg) \times (3.36\times10^5\,J\,kg^{-1}) = 3.36\times10^5\,J$

Next, calculate the entropy change:

$\Delta S = 3.36 \times 10^5\,J/273\,K$

$\Delta S \approx 1230.77\,J\,K^{-1} = 1.23 \times 10^3\,K/K$

Answer: The entropy change when 1.0 kg of ice melts is approximately $1.23\times10^3\,J\,K^{-1}$.

NUMERICAL PROBLEMS

6.1 A gas occupies 6.0L of volume at a pressure of 12 atm. What will be the volume of gas if the pressure is increased by 2.0 atm, assuming that temperature remains constant.

Given:

Initial Volume of gas = V_1 = 6.0 L

Initial Pressure of gas = P_1 = 12 atm

Final pressure of gas = $P_2 = 12 + 2.0 = 14$ atm

Final Volume of gas = V_2 = ?

Solution:

By applying boyle's law

$P_1V_1 = P_2V_2$

$6 \times 12 = 14 \times V_2$

$V_2 = 5.14\,L$

6.2 In a vacuum chamber which is connected to a cryogenic pump, pressure as low as 1.00 nPa is being attained. Calculate the number of molecules in 1.00 m³ vessel at this pressure and temperature of 300 K.

Pressure in vacuum chamber = P = 1.00 nPa $= 1 \times 10^{-9}$ Pa

Volume of vessel = V = 1.00 m³

Temperature of vessel = T = 300 K

Boltzmann constant $= k_B = 1.38 \times 10^{-23}\,J\,K^{-1}$

Number of molecules = N = ?

Solution

By using general gas constant in terms of Boltzmann constant

$PV = Nk_BT$

$1 \times 10^{-9} \times 1 = N \times 1.38 \times 10^{-23} \times 300$

$1 = N \times 4.14 \times 10^{-23+11}$

$1 = N \times 4.14 \times 10^{-12}$

$N = 0.241 \times 10^{12}$

$N = 2.41 \times 10^{11}$ molecules

6.3 A gas undergoes a thermodynamic process where it absorbs 500 J of heat energy and performs 300 J work on its surroundings. Calculate the change in internal energy of the gas.

Given Heat absorbed = 500 J

Work done = W = 300 J

Change in internal energy = ΔU = ?

Solution

By applying first law of thermodynamics

$Q = \Delta U + W$

$\Delta U = Q - W$

$\Delta U = 500 - 300 = 200\,J$

6.4 A Carnot engine is operating between a high temperature reservoir at 600K and a low temperature reservoir at 300K. Calculate:

(i) The maximum possible efficiency

(ii) The amount of work output if the engine absorbs 500 J of heat from the high temperature reservoir

Given Temperature of hot reservoir = T_1 = 600 K

Temperature of cold reservoir = T_2 = 300 K

(i) efficiency = η = ?

(ii) heat absorbed = Q_1 = 500 J

work done = W = ?

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

$\eta = \left(1 - \frac{300}{600}\right) \times 100 = 50\%$

(ii) Now by using

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

$\frac{Q_2}{500} = \frac{300}{600}$

$Q_2 = \frac{300}{600} \times 500 = 250\,J$

$W = Q_1 - Q_2$

$W = 500 - 250 = 250\,J$

6.5 A refrigerator extracts 1200 J of heat from its interior (the cold reservoir and releases 1800 J of heat to the surrounding environment) (the hot reservoir) during each cycle. Calculate:

(i) the work input required per cycle.

(ii) the co-efficient of performance(COP) of the refrigerator.

Given $Q_c = 1200\,J$

$Q_H = 1800\,J$

(i) Work input = W = ?

(ii) Coefficient of performance = E = ?

(i) $W = Q_H - Q_c$

$W = 1800 - 1200 = 600\,J$

(ii) $E = \frac{Q_c}{W}$

$E = \frac{1200}{600} = 2$

6.6 Calculate the entropy change when 1.0mole of ice at 0°Cmelts to form liquid water at the same temperature. (Heat of fusion of ice per mole $= 6.01\times10^3$ J)

Given: No of mole of ice = 1 mole

Temperature of ice = T = 0 °C = 273 K

Latent Heat of fusion for ice, $L_f = 6.01 \times 10^3\,J/mole$

To Find:

Change in entropy, ΔS = ?

Total heat removed from water, ΔQ = ?

Calculation:

$\Delta Q = n \times L_f$

$\Delta Q = 1 \times 6.01 \times 10^3 J = 6.01 \times 10^3 J$

Since heat is taken out from water to freeze into ice, hence entropy of ice decreases. So

$$\Delta S = \frac{\Delta Q}{T}$$

$$\Delta S = \frac{6.01\times 10^3\,J}{273\,K} = 22\,J\,K^{-1} = 22\,J\,K^{-1}$$

6.7 A gas occupies 400ml at 20°C. What volume will it occupy at 80°C, assuming constant pressure?

Given Volume of gas = V_1 = 400 mL

Temperature of gas = T_1 = 20 °C = 20 + 273 = 293 K

Temperature of gas = T_2 = 80 °C = 80 + 273 = 353 K

Volume of gas = V_2 = ?

Solution

By applying Charles law

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

$\frac{V_2}{353} = \frac{400\,mL}{293}$

$V_2 = \frac{400\,mL}{293} \times 353 = 482\,mL$

6.8 A gas has a pressure of 2 atm at 300 K. What pressure will it have at 450 K, assuming constant volume?

Given pressure of gas = P_1 = 2 atm

Temperature of gas = T_1 = 300 K

Temperature of gas = T_2 = 450 K

pressure of gas = P_2 = ?

Solution

By applying Gay lussac's law

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

$\frac{P_2}{450} = \frac{2}{300}$

$P_2 = \frac{2}{300} \times 450 = 3\,atm$