TOPIC 1 Kinetic Theory and Ideal Gas Equation

SQ 6.1.1 What is thermodynamics?

Definition

Thermodynamics is the branch of physics that deals with the relationships and conversions between heat and other forms of energy.

Scope

It encompasses the principles governing the behaviour of systems at macroscopic scales, such as temperature, pressure and volume.

SQ 6.1.2 Why does thermodynamics play a key role in technology?

Reason

Almost all the raw energy available for our use is liberated in the form of heat. Thermodynamics tells us how this heat is converted into other useful forms of energy.

SQ 6.1.3 What is studied in the chapter of heat and thermodynamics?

Contents

In this chapter we study the behaviour of gases and the laws of thermodynamics, their significance and their applications.

SQ 6.1.4 What does the kinetic theory of gases explain?

Explanation

The kinetic theory of gases explains the behaviour of gases on the basis of the motion of their constituent particles.

Result

It gives a macroscopic understanding of gas properties such as pressure, temperature and volume.

SQ 6.1.5 In which branches of science is the kinetic theory of gases a fundamental theory?

Answer

The kinetic theory of gases is a fundamental theory in physics and chemistry.

SQ 6.1.6 What is the first assumption of the kinetic theory of gases?

Gas Particles are in Constant, Random Motion

Gas molecules are in perpetual, random motion. They move in straight lines until they collide with either another molecule or the walls of the container.

SQ 6.1.7 With what do the moving gas molecules collide?

Answer

The moving gas molecules collide either with another molecule or with the walls of the container.

SQ 6.1.8 Why is the volume of individual gas molecules considered negligible?

Negligible Volume of Gas Particles

The volume of the individual gas molecules is negligible as compared to the total volume of the gas. Therefore, the particles are considered point masses with no significant volume.

SQ 6.1.9 What is assumed about the forces between gas molecules?

No Intermolecular Forces

There are no attractive or repulsive forces between the gas molecules. The particles do not exert any force on each other except during collisions.

SQ 6.1.10 When do gas molecules exert force on one another?

Answer

Gas molecules do not exert any force on each other except during collisions.

SQ 6.1.11 What is meant by elastic collisions of gas molecules?

Elastic Collisions

The collisions between gas molecules, and with the walls of the container, are perfectly elastic. There is no net loss of kinetic energy during collisions and the total kinetic energy is conserved.

SQ 6.1.12 Why is a gas assumed to contain a large number of particles?

Large Number of Particles

A gas contains a large number of particles. This large number allows for the use of statistical methods to describe the properties of the gas.

SQ 6.1.13 How is the average kinetic energy of gas particles related to temperature?

Assumption

The average kinetic energy of gas particles is directly proportional to the absolute temperature of the gas.

Result

As the temperature increases, the speed of the gas particles also increases.

SQ 6.1.14 How does a gas exert pressure on the walls of its container?

Pressure due to Particle Collisions

The pressure exerted by a gas on the walls of its container is due to the collisions of gas particles with the walls. The force exerted by the particles during collisions generates pressure.

SQ 6.1.15 Why is the time of collision of gas particles neglected?

Time of Collisions is Negligible

The time interval of a collision between gas particles is extremely short compared to the time between collisions. This assumption simplifies the analysis of particle dynamics.

SQ 6.1.16 For which type of gas do the assumptions of the kinetic theory hold true?

Answer

The assumptions of the kinetic theory hold true for ideal gases only.

SQ 6.1.17 What are the limitations of the kinetic molecular theory?

Limitation

The assumptions of the kinetic theory hold true for ideal gases, but real gases exhibit deviations.

Reason

The deviations are due to intermolecular forces and finite molecular volume, especially at high pressures and low temperatures.

SQ 6.1.18 What does the kinetic theory of gases serve as a foundation for?

Answer

It serves as a foundational concept in understanding thermodynamics and statistical mechanics.

SQ 6.1.19 What is an ideal gas? Write the ideal gas equation.

Definition

A gas that obeys the kinetic theory of gases is termed as an ideal gas.

Formula

$PV = nRT$

Here P is pressure, V is volume, n is number of moles, R is universal gas constant and T is absolute temperature.

SQ 6.1.20 What is the value of the universal gas constant?

Value

$R = 8.3145\,\mathrm{J\,mol^{-1}K^{-1}}$

SQ 6.1.21 What does the ideal gas equation imply?

Implication

The product of pressure and volume is directly proportional to the absolute temperature for an ideal gas.

Formula

$PV \propto T$

SQ 6.1.22 What conditions must be satisfied for a real gas to behave like an ideal gas?

Condition

According to the kinetic theory a gas has no intermolecular interaction and its molecules are far apart from each other.

Result

The potential energy of the gas molecules must be negligible so that the molecules have only kinetic energy.

SQ 6.1.23 Write the relation for the number of moles of a gas.

Formula

$$n = \frac{\text{Mass of gas}}{\text{Molar mass of gas}} = \frac{m}{M}$$

SQ 6.1.24 Write the ideal gas equation in terms of mass and molar mass.

Formula

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

SQ 6.1.25 Show that the density of a gas depends on its pressure and temperature.

Derivation

Since density is

$$\rho = \frac{m}{V}$$

the ideal gas equation becomes

$$PM = \rho RT$$

Result

As R and M are constant, therefore $\rho \propto \dfrac{P}{T}$.

SQ 6.1.26 Why is the density of a gas low at low pressure and high temperature?

Reason

Since $\rho \propto \dfrac{P}{T}$, the density is low at low pressure and high temperature. The molecules then lie at large distances from each other.

SQ 6.1.27 Under what conditions does a real gas behave like an ideal gas?

Conditions

A real gas behaves like an ideal gas at low pressure and high temperature.

Reason

At low pressure and high temperature the density of the gas is low, so its molecules are at large distances and the intermolecular forces become negligible.

SQ 6.1.28 Define a mole in terms of Avogadro's number.

Definition

A mole is the number of atoms or molecules per unit Avogadro's number.

Formula

$$n = \frac{N}{N_A}$$

Here N is the number of atoms or molecules.

SQ 6.1.29 What is the value of Avogadro's number?

Value

$N_A = 6.02 \times 10^{23}$

SQ 6.1.30 Define Boltzmann constant and give its value.

Definition

Boltzmann constant is the ratio of the universal gas constant to Avogadro's number.

Formula

$k_B = \frac{R}{N_A}$

Value

$k_B = 1.38 \times 10^{-23}\,\mathrm{JK^{-1}}$

SQ 6.1.31 Write the ideal gas equation in terms of Boltzmann constant.

Formula

$PV = Nk_BT$

Here N is the number of molecules of the gas and k_B is Boltzmann constant.

SQ 6.1.32 Derive the ideal gas equation in the form $PV = Nk_BT$.

Derivation

From the ideal gas equation

$PV = nRT$

and since

$n = \frac{N}{N_A}$

we get

$PV = \frac{N}{N_A}RT$

Substitution

The term $\frac{R}{N_A}$ is termed as Boltzmann constant k_B, therefore:

Formula

$PV = Nk_BT$

SQ 6.1.33 Why is Boltzmann constant obtained by dividing R by Avogadro's number?

Reason

The universal gas constant R applies to one mole of a gas. Dividing it by Avogadro's number gives the constant per molecule, which is Boltzmann constant.

SQ 6.1.34 One mole of an ideal gas is at 300 K. Calculate its volume at a pressure of 1 atm.

Data

Here

$n = 1\,\mathrm{mol}$

$T = 300\,\mathrm{K}$

and

$P = 101325\,\mathrm{Pa}$

Solution

Using

$PV = Nk_BT$

the volume is

$V = \frac{Nk_BT}{P}.$

Result

$V = 0.0245\,\mathrm{m^3}$

SQ 6.1.35 How does the behaviour of real gases differ from an ideal gas at high pressure?

Difference

At high pressure the molecules come close together, so their finite volume is no longer negligible compared with the volume of the gas.

Reason

The intermolecular forces can no longer be neglected, therefore the gas deviates from ideal behaviour.

SQ 6.1.36 How does the behaviour of real gases differ from an ideal gas at low temperature?

Difference

At low temperature the average kinetic energy of the molecules is small, so the attractive intermolecular forces become significant.

Reason

The kinetic theory assumes no intermolecular forces, hence the real gas deviates from ideal behaviour.

SQ 6.1.37 Under what conditions do real gases approach ideal behaviour?

Conditions

Real gases approach ideal behaviour under low pressure and high temperature.

SQ 6.1.38 What is meant by perpetual random motion of gas molecules?

Meaning

Gas molecules never come to rest and move continuously in all directions without any preferred direction, colliding with one another and with the walls of the container.

TOPIC 2 Gas Laws

SQ 6.2.1 What are gas laws?

Definition

The laws that mutually relate the state variables of an ideal gas are termed as gas laws.

SQ 6.2.2 Name the state functions which describe the quantity of a gas.

State Functions

Pressure P, volume V and temperature T describe the quantity of a gas.

Behaviour

With a change in one variable the second variable changes while the third is kept constant.

SQ 6.2.3 State Boyle's law.

Statement

For a fixed mass of an ideal gas, the pressure P exerted by a gas varies inversely with the volume V occupied by the gas at constant temperature.

Mathematically

$P \propto \frac{1}{V}$

$PV = \text{constant}$

SQ 6.2.4 Write Boyle's law for two different states of a gas.

Formula

$P_1V_1 = P_2V_2$

SQ 6.2.5 Who introduced Boyle's law and when?

Introduction

Boyle's law was introduced by Robert Boyle in 1662. It provides a relationship between the pressure and volume of a gas at constant temperature.

SQ 6.2.6 State Charles' law.

Statement

The volume of a given mass of gas at constant pressure is directly proportional to the absolute temperature.

Mathematically

$V \propto T$

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

SQ 6.2.7 Write Charles' law for two different states of a gas.

Formula

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

SQ 6.2.8 Who formulated Charles' law and when?

Formulation

Charles' law was formulated in 1870 by the French physicist Jacques Charles. It relates the volume and temperature of a fixed mass of an ideal gas at constant pressure.

SQ 6.2.9 State Joseph Gay-Lussac's law.

Statement

For a fixed mass of an ideal gas, the pressure exerted by a gas varies directly with the absolute temperature of the gas at constant volume.

Mathematically

$P \propto T$

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

SQ 6.2.10 Write Gay-Lussac's law for two different states of a gas.

Formula

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

SQ 6.2.11 What does the graph of Charles' law show?

Graph

The graph of volume against absolute temperature is a straight line. When it is extended backward, it meets the temperature axis at 0 K or −273 °C.

SQ 6.2.12 Which quantity is kept constant in each of the three gas laws?

Boyle's Law	Charles' Law	Gay-Lussac's Law
Temperature is kept constant.	Pressure is kept constant.	Volume is kept constant.
It relates pressure and volume.	It relates volume and temperature.	It relates pressure and temperature.

SQ 6.2.13 Which gas law is applied when a gas changes at constant temperature?

Answer

Boyle's law is applied, because it holds for a fixed mass of an ideal gas at constant temperature.

SQ 6.2.14 A gas occupies 6.0 L at a pressure of 12 atm. Find its volume when the pressure is increased by 2.0 atm at constant temperature.

Data

Here

$V_1 = 6.0\,\text{L}$

$P_1 = 12\,\text{atm}$

and

$P_2 = 14\,\text{atm}$

Solution

Using Boyle's law

$P_1V_1 = P_2V_2$

we get

$V_2 = \frac{P_1V_1}{P_2}.$

Result

$V_2 = 5.14\,\text{L}$

TOPIC 3 Thermal Equilibrium and Internal Energy

SQ 6.3.1 What is meant by thermal equilibrium?

Definition

When two bodies are at the same temperature, the thermal energy of each body is equal. As a result there is no driving force for heat transfer between them and they remain in thermal equilibrium.

SQ 6.3.2 To what is thermal energy of a body related?

Answer

Thermal energy of a body is related to the kinetic energy of its particles.

SQ 6.3.3 Give an example of thermal equilibrium.

Example

When a metal spoon is put into a hot cup of coffee, initially the coffee is hotter than the spoon.

Process

Over time heat flows from the coffee to the spoon. Eventually both reach the same temperature and there is no net heat flow, so they are in thermal equilibrium.

SQ 6.3.4 When is thermal equilibrium achieved between coffee and a spoon?

Answer

Thermal equilibrium is achieved at the point where the coffee and the spoon reach the same temperature and there is no net heat flow between them.

SQ 6.3.5 What is internal energy?

Definition

The sum of all forms of molecular energies (kinetic and potential) of a substance is termed as its internal energy.

SQ 6.3.6 Which substance is usually considered as the working substance in thermodynamics?

Answer

In the study of thermodynamics, usually an ideal gas is considered as the working substance.

SQ 6.3.7 Why is the internal energy of an ideal gas only translational kinetic energy?

Reason
The molecules of an ideal gas are mere mass points which exert no forces on one another. Therefore, the internal energy of an ideal gas system is generally the translational kinetic energy of its molecules.

SQ 6.3.8 How is temperature of a system defined in the kinetic theory?

Definition
The temperature of a system is defined as the average kinetic energy of its molecules.

SQ 6.3.9 How is the internal energy of an ideal gas related to its temperature?

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

SQ 6.3.10 Write the expression for average kinetic energy of gas molecules.

Formula

$$\langle KE \rangle = \frac{3}{2} k_B T$$

$$\left\langle \frac{1}{2} m v^2 \right\rangle = \frac{3}{2} k_B T$$

Here k_B is Boltzmann constant.

SQ 6.3.11 What does a rise in temperature of an object reflect?

Answer
The rise in temperature of an object reflects an increase in the internal kinetic energy of its particles.

SQ 6.3.12 How does absorption of heat increase the temperature of an object?

Explanation
The increase in internal energy occurs due to the absorption of heat energy, which raises the average kinetic energy of the particles and thus increases the temperature of the object.

SQ 6.3.13 Why is internal energy called a function of state?

Reason
Internal energy is a function of state, so it does not depend on the path but depends only on the initial and final states of the system.

SQ 6.3.14 How is internal energy similar to gravitational potential energy?

Similarity
Internal energy is similar to gravitational potential energy. Like potential energy, it is the change in internal energy and not its absolute value that is important.

SQ 6.3.15 Which processes can change the internal energy of a system?

Processes
Heating (adding heat), adiabatic compression or expansion (no heat exchange), and phase changes.

SQ 6.3.16 Does temperature change during a phase change?

Answer
No. In a phase change the heat energy changes the state of matter without changing temperature.

SQ 6.3.17 What energies does a diatomic gas molecule possess?

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

SQ 6.3.18 Why does the internal energy of an ideal gas depend only on its temperature?

Reason
The molecules of an ideal gas exert no forces on one another, so their potential energy is zero. The internal energy is therefore only the kinetic energy of the molecules, which depends on temperature alone.

TOPIC 4 Heat and Work

SQ 6.4.1 What do heat and work correspond to?

Answer
Both heat and work correspond to the transfer of energy by some means.

SQ 6.4.2 To what was the idea of heat in and work out first applied?

Answer
The idea was first applied to the steam engine, where it was natural to transfer heat in and get work out.

SQ 6.4.3 Why are heat in and work out taken as positive quantities?

Reason
In the steam engine it was natural to transfer heat in and get work out. Consequently, it made sense to define both heat in and work out as positive quantities.

SQ 6.4.4 What sign convention is used for work in thermodynamics?

Convention
Work done by the system on its environment is considered positive, while work done on the system by the environment is taken as negative.

SQ 6.4.5 **What happens when an amount of heat enters a system?**

Explanation

If an amount of heat Q enters the system, it could appear either as an increase in internal energy, or as a resulting quantity of work performed by the system on the surroundings, or both.

SQ 6.4.6 **Describe the arrangement used to express work in measurable variables.**

Arrangement

A gas is enclosed in a cylinder with a moveable, frictionless piston of cross-sectional area A.

Equilibrium

In equilibrium the system occupies volume V and exerts a pressure P on the walls of the cylinder and its piston.

SQ 6.4.7 **Derive the expression for work done by an expanding gas.**

Derivation

The force exerted by the gas on the piston of area A is

$F = PA$

As the piston moves up through a small distance Δy, the work done by the gas is

$W = F\Delta y = PA\Delta y$

Since $A\Delta y$ is equal to the change in volume ΔV, the work done by the gas becomes as under.

Formula

$W = P\Delta V$

SQ 6.4.8 **Why must the gas expand slowly while calculating work done?**

Reason

The gas is assumed to expand through ΔV very slowly, so that it remains in equilibrium throughout the process.

SQ 6.4.9 **How is work done represented on a P-V graph?**

Answer

The work done can be calculated by the area under the P-V graph.

SQ 6.4.10 **Show that the area under a P-V graph is equal to the work done.**

Proof

For a change at constant pressure the work done is

$W = P\Delta V$

On a P-V graph the height of the strip is the pressure P and its base is the change in volume ΔV, so the area of the strip is $P\Delta V$.

Result

Hence the area under the P-V graph is equal to the work done.

SQ 6.4.11 **How is work done (i) by a gas (ii) on a gas?**

Work Done by a Gas

When the gas expands and the piston is displaced upward, work is done by the gas and it is taken as positive.

Work Done on a Gas

When the gas is compressed and the piston is displaced downward, work is done on the gas and it is taken as negative.

SQ 6.4.12 **What are the laws of thermodynamics?**

Definition

The general principles which deal with heat energy and its transformation into mechanical energy are known as the laws of thermodynamics.

TOPIC 5 First Law and Thermodynamic Processes

SQ 6.5.1 **What happens when heat is added to a system?**

Effects

When heat is added to a system there is an increase in the internal energy due to the rise in temperature, an increase in pressure, or a change in the state.

SQ 6.5.2 **State the first law of thermodynamics.**

Statement

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

$Q = \Delta U + W$

SQ 6.5.3 **Write the first law of thermodynamics in terms of change in internal energy.**

Formula

$\Delta U = U_2 - U_1 = Q - W$

Here U_1 and U_2 are the internal energies of the first and second states.

SQ 6.5.4 **Why is the change in internal energy the same for all processes concerning the state?**

Reason

The change in internal energy

$\Delta U = U_2 - U_1$

is defined by the initial and final states only. Since it is the same for all processes concerning the state, the first law can be stated in a general form.

SQ 6.5.5 **Which conservation principle underlies the first law of thermodynamics?**

Conservation Principle

The underlying principle of the first law is the conservation of energy. Energy can change from one form to another, but the total energy in an isolated system remains constant over time.

SQ 6.5.6 **Give an example of energy changing from one form to another.**

Example

Energy can change from chemical potential energy into thermal energy, but the total energy in an isolated system remains constant over time.

SQ 6.5.7 **What is meant by the wider applicability of the first law of thermodynamics?**

Wider Applicability

Beyond mechanical systems, the first law applies universally to all forms of energy and all types of processes, including chemical reactions, electrical systems and nuclear reactions.

SQ 6.5.8 **What does the first law allow scientists and engineers to do?**

Answer
It provides a foundational understanding that allows scientists and engineers to predict and understand energy transformations in various contexts.

SQ 6.5.9 **How does the first law express the law of conservation of energy?**

Explanation
The first law affirms that energy is a conserved quantity in isolated systems.
Framework
It provides a framework to understand how energy is transferred and transformed within systems, without violating the principle that energy can neither be created nor be destroyed.

SQ 6.5.10 **Explain the bicycle pump as an example of the first law of thermodynamics.**

Explanation
When the handle of a bicycle pump with a blocked outlet is pumped rapidly, it becomes hot due to the mechanical work done on the gas.
Result
The push force does work on the air, thereby increasing its internal energy, which is shown by the rise in temperature of the air.

SQ 6.5.11 **How is the air temperature monitored in the bicycle pump experiment?**

Arrangement
A thermocouple connected through the blocked outlet allows the air temperature to be monitored.
Sensitivity
A thermocouple thermometer can detect a minute variation of temperature.

SQ 6.5.12 **Why do human beings and other animals need energy?**

Reason
Human beings and other animals do work when they walk, run or move, and work requires energy.
Growth
Energy is also needed for growth, to make new cells and to replace old cells that have died.

SQ 6.5.13 **How does human metabolism illustrate energy conservation?**

Metabolism
The energy transforming processes that occur within an organism are named as metabolism.
Application
Applying
$\Delta U = Q - W$
to the human body, work done results in a decrease in internal energy, and this internal energy is maintained by the food we eat.

SQ 6.5.14 **A gas at a pressure of 8000 N m^{-2} pushes a piston of area 0.10 m^2 through 4.0 cm. Find the work done.**

Solution
The work done by the gas is
$W = P\Delta V = PA\Delta y$
Calculation
$W = 8000 \times 0.10 \times 4.0 \times 10^{-2}$
Result
$W = 32\,\mathrm{J}$

SQ 6.5.15 **If 42 J of heat is transferred to a gas which does 32 J of work, find the change in internal energy.**

Solution
From the first law of thermodynamics
$\Delta U = Q - W$
Calculation
$\Delta U = 42\,\mathrm{J} - 32\,\mathrm{J}$
Result
$\Delta U = 10\,\mathrm{J}$

SQ 6.5.16 **A gas absorbs 500 J of heat and performs 300 J of work on its surroundings. Find the change in internal energy.**

Solution
From the first law of thermodynamics
$\Delta U = Q - W$
Calculation
$\Delta U = 500\,\mathrm{J} - 300\,\mathrm{J}$
Result
$\Delta U = 200\,\mathrm{J}$

SQ 6.5.17 **What is an isothermal process?**

Definition
It is a process which is carried out at constant temperature, so the condition for the application of Boyle's law on the gas is fulfilled.

SQ 6.5.18 **What remains constant during an isothermal change?**

Answer
When a gas expands or compresses isothermally, the product of its pressure and volume remains constant during the process.
Formula
$P_1V_1 = P_2V_2$

SQ 6.5.19 **Why does the first law reduce to Q = W for an isothermal process?**

Reason
In an ideal gas the potential energy associated with its molecules is zero, so its internal energy depends only on temperature. In an isothermal change the temperature remains constant, therefore
$\Delta U = 0$
Result
$Q = W$

SQ 6.5.20 What must be supplied to a gas during an isothermal expansion?

Answer

If the gas expands and does external work W, an amount of heat Q has to be supplied to the gas in order to produce the isothermal change.

SQ 6.5.21 Why must an isothermal change take place slowly?

Reason

Transfer of heat from one place to another requires time. Hence, to keep the temperature of the gas constant, the expansion or compression must take place slowly.

SQ 6.5.22 What is an isotherm?

Definition

The curve representing an isothermal process on a P-V diagram is called an isotherm.

SQ 6.5.23 What is an adiabatic process?

Definition

An adiabatic process is the one in which no heat enters or leaves the system, so

$\Delta Q = 0$

Mathematically

$W = -\Delta U$

SQ 6.5.24 Why does the temperature of a gas fall during adiabatic expansion?

Reason

If the gas expands and does external work, it is done at the expense of the internal energy of its molecules. Hence the temperature of the gas falls.

SQ 6.5.25 Why does adiabatic compression raise the temperature of a gas?

Reason

An adiabatic compression causes the temperature of the gas to rise because of the work done on the gas, which increases its internal energy.

SQ 6.5.26 When does an adiabatic change occur?

Condition

Adiabatic change occurs when the gas is expanded or compressed rapidly, particularly when the gas is contained in an insulated cylinder.

SQ 6.5.27 Give three examples of adiabatic processes.

Examples

The rapid escape of air from a burst tyre.

The rapid expansion and compression of air through which a sound wave is passing.

Cloud formation in the atmosphere.

SQ 6.5.28 Write the relation for an adiabatic process and define gamma.

Formula

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

Here γ is the ratio of the molar specific heat of the gas at constant pressure to the molar specific heat at constant volume, i.e.

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

SQ 6.5.29 Why is $PV^\gamma = \text{constant}$ used instead of $PV = \text{constant}$ for an adiabatic change?

Reason

In an adiabatic change the temperature of the gas does not remain constant, so Boyle's law cannot be applied.

Result

It has been seen that in this case

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

SQ 6.5.30 What is an adiabat?

Definition

The curve representing an adiabatic process on a P-V diagram is called an adiabat.

SQ 6.5.31 Why is an adiabat steeper than an isotherm?

Isotherm

For an isothermal change

$PV = \text{constant}$

so the pressure falls only in inverse proportion to the volume.

Adiabat

For an adiabatic change

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

and since $\gamma > 1$ the pressure falls more rapidly with volume.

Result

Therefore the adiabat is steeper than the isotherm.

SQ 6.5.32 Differentiate between an isothermal and an adiabatic process.

Isothermal Process	Adiabatic Process
It is carried out at constant temperature.	No heat enters or leaves the system.
The change in internal energy is zero, so $Q = W$.	The heat exchanged is zero, so $W = -\Delta U$.
It obeys $PV = \text{constant}$.	It obeys $PV^\gamma = \text{constant}$.
The process must take place slowly.	The process takes place rapidly.

SQ 6.5.33 What happens to the temperature and pressure of a gas expanding adiabatically?

Temperature

The gas does external work at the expense of the internal energy of its molecules, so its temperature falls.

Pressure

Since the volume increases and

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

therefore the pressure of the gas decreases.

SQ 6.5.34 **How is the first law of thermodynamics applied to an isothermal process?**

Application

For an ideal gas the internal energy depends only on temperature, which remains constant, so
$\Delta U = 0$

Result

The first law
$Q = \Delta U + W$
reduces to
$Q = W$.

SQ 6.5.35 **How is the first law of thermodynamics applied to an adiabatic process?**

Application

In an adiabatic process no heat enters or leaves the system, so
$\Delta Q = 0$

Result

The first law gives
$W = -\Delta U$.

SQ 6.5.36 **What is the sign convention for heat in the first law of thermodynamics?**

Convention

Heat added to the system is taken as positive and heat removed from the system is taken as negative.

TOPIC 6 Reversible and Irreversible Processes

SQ 6.6.1 **What is a reversible process?**

Definition

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

SQ 6.6.2 **What happens in the reverse of a reversible process?**

Explanation

The working substance passes through the same stages as in the direct process, but the thermal and mechanical effects at each stage are exactly reversed.

Result

The working substance is restored to its original condition.

SQ 6.6.3 **What happens to the heat absorbed in the direct process during the reverse process?**

Answer

If heat is absorbed in the direct process, it will be given out in the reverse process.

SQ 6.6.4 **What happens to the work done in the reverse of a reversible process?**

Answer

If work is done by the substance in the direct process, then work will be done on the substance in the reverse process.

SQ 6.6.5 **What is a cycle and a reversible cycle?**

Cycle

A succession of events which brings the system back to its initial condition is called a cycle.

Reversible Cycle

A reversible cycle is the one in which all the changes are reversible.

SQ 6.6.6 **Is any actual change completely reversible?**

Answer

No actual change is completely reversible. However, some processes may be made practically reversible by performing them slowly.

SQ 6.6.7 **Give examples of practically reversible processes.**

Examples

The processes of liquefaction and evaporation of a substance, performed slowly, are practically reversible.
The slow compression of a gas in a cylinder is also reversible.

SQ 6.6.8 **How can the slow compression of a gas in a cylinder be reversed?**

Answer

The compression can be changed to expansion by slowly decreasing the pressure on the piston to reverse the operation.

SQ 6.6.9 **What is an irreversible process?**

Definition

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

SQ 6.6.10 **Which changes are irreversible?**

Irreversible Changes

All changes which occur suddenly, or which involve friction or dissipation of energy through conduction, convection or radiation, are irreversible.

SQ 6.6.11 **Give an example of a highly irreversible process.**

Example

An explosion is an example of a highly irreversible process, because it occurs suddenly and cannot be retraced.

SQ 6.6.12 **Differentiate between reversible and irreversible processes.**

Reversible Process	Irreversible Process
It can be retraced in exactly the reverse order.	It cannot be retraced in the backward direction.
It produces no change in the surroundings.	It changes the surroundings permanently.
It is carried out slowly, as in slow compression of a gas.	It occurs suddenly or involves friction, as in an explosion.

TOPIC 7 Heat Engine

SQ 6.7.1 **What is a heat engine?**

Definition

A heat engine is a device which converts some thermal energy into mechanical work.

SQ 6.7.2 From where does the heat supplied to a heat engine usually come?

Answer
Usually the heat comes from the burning of a fuel.

SQ 6.7.3 Which was the earliest heat engine?

Answer
The steam engine was the earliest heat engine.

SQ 6.7.4 On which observation was the steam engine developed?

Observation
When water is boiled in a vessel covered with a lid, the steam inside tries to push the lid off, showing the ability to do work. This observation helped to develop the steam engine.

SQ 6.7.5 Who developed the first heat engines and when?

Answer
Heat engines were first developed in England around 1828 by John Braithwaite and John Ericsson.

SQ 6.7.6 State the working principle of a heat engine.

Principle
The working principle of a heat engine involves the cyclic transfer of heat energy from a high temperature reservoir to a low temperature reservoir, with the objective of converting as much heat as possible into mechanical work.

SQ 6.7.7 Through what kind of process does a heat engine operate?

Answer
A heat engine operates through a cyclic process, in which the working substance eventually returns to its initial state.

SQ 6.7.8 Why is the net work done by a heat engine equal to the net heat absorbed?

Reason
The working substance goes through a cyclic process and eventually returns to its initial state, so the change in internal energy is zero.

Result
From the first law of thermodynamics,
$W = Q_1 - Q_2$.

TOPIC 8 Second Law of Thermodynamics

SQ 6.8.1 Why was the second law of thermodynamics needed?

Reason
The first law tells us that heat energy can be converted into an equivalent amount of work, but it is silent about the conditions under which this conversion takes place.

SQ 6.8.2 With what is the second law of thermodynamics concerned?

Answer
The second law is concerned with the circumstances in which heat can be converted into work, and with the direction of flow of heat.

SQ 6.8.3 Describe the actual operation of a heat engine.

Operation
The engine 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 the low temperature reservoir at temperature T_2.

SQ 6.8.4 What is the efficiency of practical petrol and diesel engines?

Observation
It has been observed that petrol engines convert roughly 25% and diesel engines 35 to 40% of the available heat energy into work.

SQ 6.8.5 What does a petrol engine of a motor car do with the heat of the burning fuel?

Answer
The petrol engine extracts heat from the burning fuel, converts a part of this energy into mechanical energy or work, and expels the rest to the atmosphere.

SQ 6.8.6 State Lord Kelvin's statement of the second law of thermodynamics.

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.

SQ 6.8.7 Can a single heat reservoir be made to perform work?

Answer
No. A single heat reservoir, no matter how much energy it contains, cannot be made to perform any work.

SQ 6.8.8 Why can the heat contents of the oceans and atmosphere not be used to do work?

Reason
The oceans and atmosphere contain a large amount of heat energy, but there is no reservoir at a temperature lower than either of them to which heat may be expelled.

SQ 6.8.9 What is essential for the working of a heat engine?

Requirement
As a consequence of the second law, two bodies at different temperatures are essential for the conversion of heat into work.

Source and Sink
There must be a source of heat at a high temperature and a sink at a low temperature to which heat may be expelled.

SQ 6.8.10 Can a cyclic reversible heat engine absorb heat at constant temperature and convert it completely into work?

Answer
No, it is not possible.

Reason
According to Lord Kelvin's statement, heat extracted from a single reservoir cannot be converted entirely into work. Some heat must always be rejected to a low temperature reservoir.

TOPIC 9 Carnot Engine and Carnot Theorem

SQ 6.9.1 What is a Carnot engine?

Definition

Sadi Carnot in 1824 described an ideal engine using only isothermal and adiabatic processes.

Result

He showed that a heat engine operating in an ideal reversible cycle between two heat reservoirs at different temperatures would be the most efficient engine.

SQ 6.9.2 Who described the ideal heat engine and in which year?

Answer

Sadi Carnot described the ideal engine in 1824.

SQ 6.9.3 Which processes are used in a Carnot cycle?

Answer

A Carnot cycle uses only isothermal and adiabatic processes, and it uses an ideal gas as the working substance.

SQ 6.9.4 Name the four steps of the Carnot cycle.

Steps

The gas expands isothermally at temperature T_1, absorbing heat Q_1 from the hot reservoir.
The gas expands adiabatically until its temperature drops to T_2.
The gas is compressed isothermally at temperature T_2, rejecting heat Q_2 to the cold reservoir.
The gas is compressed adiabatically to restore its initial state at temperature T_1.

SQ 6.9.5 Describe the first step of the Carnot cycle.

Isothermal Expansion

The gas is allowed to expand isothermally at temperature T_1, absorbing heat Q_1 from the hot reservoir. The process is represented by the curve AB.

SQ 6.9.6 Describe the second step of the Carnot cycle.

Adiabatic Expansion

The gas is then allowed to expand adiabatically until its temperature drops to T_2. The process is represented by the curve BC.

SQ 6.9.7 Describe the third step of the Carnot cycle.

Isothermal Compression

The gas at this stage is compressed isothermally at temperature T_2, rejecting heat Q_2 to the cold reservoir. The process is represented by the curve CD.

SQ 6.9.8 Describe the fourth step of the Carnot cycle.

Adiabatic Compression

Finally the gas is compressed adiabatically to restore its initial state at temperature T_1. The process is represented by the curve DA.

SQ 6.9.9 Why is each process of the Carnot cycle perfectly reversible?

Reason

Thermal and mechanical equilibrium is maintained all the time, so that each process is perfectly reversible.

SQ 6.9.10 Why is the change in internal energy zero in a Carnot cycle?

Reason

The working substance returns to its initial state at the end of one cycle, so there is no change in its internal energy, i.e. $\Delta U = 0$

SQ 6.9.11 How is the net work done in one Carnot cycle determined?

Answer

The net work done during one cycle equals the area enclosed by the path ABCDA of the P-V diagram. It can also be estimated from the net heat absorbed in one cycle.

Formula

$W = Q_1 - Q_2$

SQ 6.9.12 Define the efficiency of a heat engine.

Definition

The efficiency of a heat engine is the ratio of the output energy to the input energy.

Formula

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

SQ 6.9.13 Write the expression for the efficiency of a Carnot engine.

Formula

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

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

SQ 6.9.14 Why can the efficiency of a Carnot engine be written in terms of temperature?

Reason

The energy transfer in an isothermal expansion or compression turns out to be proportional to the kelvin temperature.

Result

Hence Q_1 and Q_2 are proportional to T_1 and T_2, therefore $\eta = 1 - \frac{T_2}{T_1}$.

SQ 6.9.15 Write the expression for percentage efficiency of a Carnot engine.

Formula

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

SQ 6.9.16 In which unit must the reservoir temperatures be taken in the efficiency formula?

Answer

Both reservoir temperatures must be taken in kelvin, because the energy transfer is proportional to the kelvin temperature.

SQ 6.9.17 **On what factors does the efficiency of a Carnot engine depend?**

Dependence
The efficiency of a Carnot engine depends on the temperatures of the hot and cold reservoirs. It is independent of the nature of the working substance.

SQ 6.9.18 **What is the effect of the temperature difference of the two reservoirs on efficiency?**

Effect
The larger the temperature difference of the two reservoirs, the greater is the efficiency of the Carnot engine.

SQ 6.9.19 **Why can the efficiency of a Carnot engine never be 100%?**

Reason
The efficiency can be one or 100% only if the cold reservoir is at absolute zero temperature
$(T_2 = 0\,\mathrm{K})$
Such reservoirs are not available, hence the maximum efficiency is always less than one.

SQ 6.9.20 **What does the Carnot cycle establish?**

Answer
The Carnot cycle establishes an upper limit on the efficiency of all heat engines.

SQ 6.9.21 **State Carnot's theorem.**

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

SQ 6.9.22 **State the extended form of Carnot's theorem.**

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

SQ 6.9.23 **How can the efficiency of a practical heat engine be increased?**

Answer
In most practical cases the cold reservoir is near room temperature. So the efficiency can only be increased by raising the temperature of the hot reservoir.

SQ 6.9.24 **Why are all real heat engines less efficient than a Carnot engine?**

Reason
No practical heat engine can be perfectly reversible and energy dissipation is inevitable. All real heat engines are less efficient than a Carnot engine due to friction and other heat losses.

SQ 6.9.25 **A steam turbine takes steam at 427 °C and exhausts at 77 °C. Find its maximum possible efficiency.**

Data
Here
$T_1 = 427 + 273 = 700\,\mathrm{K}$
and
$T_2 = 77 + 273 = 350\,\mathrm{K}$

Solution
$$\eta = \frac{T_1 - T_2}{T_1} = \frac{700 - 350}{700}$$

Result
$\eta = 0.5 \quad \text{or} \quad 50\%$

SQ 6.9.26 **A Carnot engine operates between 600 K and 300 K. Find its maximum possible efficiency.**

Solution
$$\eta = 1 - \frac{T_2}{T_1} = 1 - \frac{300}{600}$$

Result
$\eta = 0.5 \quad \text{or} \quad 50\%$

SQ 6.9.27 **A Carnot engine of 50% efficiency absorbs 500 J of heat from the hot reservoir. Find its work output.**

Solution
Since
$$\eta = \frac{W}{Q_1}$$
therefore
$W = \eta Q_1$

Calculation
$W = 0.5 \times 500\,\mathrm{J}$

Result
$W = 250\,\mathrm{J}$

SQ 6.9.28 **Is it possible to construct a heat engine of 100% efficiency?**

Answer
No, it is not possible.

Reason
For
$\eta = 1$
the cold reservoir must be at
$T_2 = 0\,\mathrm{K}$
Such reservoirs are not available, hence the maximum efficiency is always less than one.

TOPIC 10 Refrigerator

SQ 6.10.1 **What is a refrigerator?**

Definition
A refrigerator is a device which maintains the temperature of a body below that of its surroundings.

SQ 6.10.2 **How does a refrigerator operate compared with a heat engine?**

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

SQ 6.10.3 **From where does a refrigerator absorb heat and where does it give it off?**

Answer
A refrigerator absorbs heat from a cold reservoir and gives it off to a hot reservoir.

SQ 6.10.4 How does a refrigerator differ from a heat engine?

Refrigerator	Heat Engine
Work is done on the system.	Work is done by the system.
It absorbs heat from a cold reservoir and gives it off to a hot reservoir.	It absorbs heat from a hot reservoir and rejects heat to a cold reservoir.
It is a heat engine operating in reverse.	It converts thermal energy into mechanical work.

SQ 6.10.5 On which statement of the second law does a refrigerator work?

Answer
A refrigerator works on the basis of the Clausius statement of the second law of thermodynamics, i.e. a heat engine operating in reverse.

SQ 6.10.6 Which part of a refrigerator draws heat from the low temperature reservoir?

Answer
Heat Q_2 is drawn from the Low Temperature Reservoir by the compressor and is thrown into the High Temperature Reservoir with the help of external work done.

SQ 6.10.7 Write the relation for heat rejected by a refrigerator to the hot reservoir.

Formula
$Q_2 + W = Q_1$
$W = Q_1 - Q_2$
Here Q_2 is the heat drawn from the low temperature reservoir and Q_1 is the heat rejected to the high temperature reservoir.

SQ 6.10.8 What is the main purpose of a refrigerator?

Purpose
The main purpose of a refrigerator is to extract as much heat Q_2 as possible from the low temperature reservoir with the expenditure of as little work as possible.

SQ 6.10.9 Define the coefficient of performance of a refrigerator.

Definition
The ratio of heat removed from the low temperature reservoir (Q_2) to the work done (W) is called the coefficient of performance of a refrigerator.

Formula
$$\text{C.O.P} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}$$

SQ 6.10.10 Write the coefficient of performance in terms of temperature.

Formula
$$\text{C.O.P} = \frac{T_2}{T_1 - T_2}$$

SQ 6.10.11 What makes one refrigerator better than another?

Answer
A better refrigerator will remove a greater amount of heat from inside the refrigerator for the expenditure of a smaller mechanical work or electrical energy.

SQ 6.10.12 A refrigerator transfers heat from a cold to a hot body. Does this violate the second law of thermodynamics?

Answer
No, it does not violate the second law.

Reason
Heat does not flow by itself from the cold body to the hot body. It is drawn from the low temperature reservoir and thrown into the high temperature reservoir with the help of external work done on the system.

SQ 6.10.13 A refrigerator has a coefficient of performance 8 and its freezer is at −23 °C. Find the temperature at which it rejects heat.

Data
Here
$\text{C.O.P} = 8$
and
$T_2 = -23 + 273 = 250\,\text{K}$

Solution
Using
$$\text{C.O.P} = \frac{T_2}{T_1 - T_2}$$
we get
$8(T_1 - 250) = 250$

Result
$T_1 = 281.25\,\text{K} = 8.25\,^{\circ}\text{C}$

SQ 6.10.14 A refrigerator extracts 1200 J of heat and releases 1800 J to the surroundings. Find the work done on it.

Solution
Using
$W = Q_1 - Q_2$
where Q_1 is heat rejected and Q_2 is heat extracted.

Calculation
$W = 1800\,\text{J} - 1200\,\text{J}$

Result
$W = 600\,\text{J}$

SQ 6.10.15 A refrigerator extracts 1200 J of heat with a work input of 600 J. Find its coefficient of performance.

Solution
$$\text{C.O.P} = \frac{Q_2}{W} = \frac{1200\,\text{J}}{600\,\text{J}}$$

Result
$\text{C.O.P} = 2$

SQ 6.10.16 In which direction does a refrigerator transfer heat and why is work needed?

Direction
A refrigerator transfers heat from a low temperature reservoir to a high temperature reservoir.

Reason
Heat cannot flow in this direction by itself, so external work must be done on the system.

TOPIC 11 Entropy

SQ 6.11.1 **Who introduced the concept of entropy and why?**

Introduction
The concept of entropy was introduced into the study of thermodynamics by Rudolph Clausius in 1856 to give a quantitative basis for the second law.

SQ 6.11.2 **What does entropy provide in the description of a system?**

Answer
Entropy provides another variable to describe the state of a system, to go along with pressure, volume, temperature and internal energy.

SQ 6.11.3 **Define entropy and write its mathematical form.**

Definition
If a system undergoes a reversible process during which it absorbs a quantity of heat ΔQ at absolute temperature T, then the increase in the state variable called entropy S is given by:

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

SQ 6.11.4 **What is the SI unit of entropy?**

Unit
Since entropy is heat divided by absolute temperature, its unit is joule per kelvin, i.e. $\mathrm{J\,K^{-1}}$.

SQ 6.11.5 **When is the change in entropy positive and when is it negative?**

Answer
The change in entropy is positive when heat is added to the system and negative when heat is removed from the system.

SQ 6.11.6 **Why is the change in entropy important rather than entropy itself?**

Reason
Like potential energy or internal energy, it is the change in entropy of the system which is important, and not its absolute value.

SQ 6.11.7 **Show that heat flow from a hot to a cold reservoir increases entropy.**

Explanation
If heat Q flows from a reservoir at T_1 to a reservoir at T_2 where $T_1 > T_2$, the hot reservoir loses entropy Q/T_1 and the cold reservoir gains entropy Q/T_2.

Result
Since $T_1 > T_2$, therefore $Q/T_2 > Q/T_1$, and the net change in entropy $\frac{Q}{T_2} - \frac{Q}{T_1}$ is positive.

SQ 6.11.8 **What follows from the fact that heat flow always increases entropy?**

Answer
It follows that in all natural processes, where heat flows from one system to another, there is always a net increase in entropy. This is another statement of the second law of thermodynamics.

SQ 6.11.9 **State the second law of thermodynamics in terms of entropy.**

Statement
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.

SQ 6.11.10 **Towards which state does a natural process tend to proceed?**

Answer
A natural process tends to proceed towards a state of greater disorder. Thus there is a relation between entropy and molecular disorder.

SQ 6.11.11 **Why does an irreversible heat flow increase disorder?**

Reason
An irreversible heat flow from a hot to a cold substance increases disorder, because the molecules are initially sorted out in hotter and cooler regions. This order is lost when the system comes to thermal equilibrium.

SQ 6.11.12 **Why does the addition of heat to a system increase its entropy?**

Reason
Addition of heat increases the average molecular speeds and therefore the randomness of molecular motion, which increases the disorder of the system.

SQ 6.11.13 **Why does free expansion of a gas increase its entropy?**

Reason
Free expansion of a gas increases its disorder, because the molecules have greater randomness of position after expansion than before.

SQ 6.11.14 **Which processes are probable in terms of entropy?**

Answer
Only those processes are probable for which the entropy of the system increases or remains constant.

SQ 6.11.15 **What happens to entropy in reversible and irreversible processes?**

Reversible Process
The process for which entropy remains constant is a reversible process.

Irreversible Process
For all irreversible processes, the entropy of the system increases.

SQ 6.11.16 **What is lost every time the entropy of a system increases?**

Answer
Every time entropy increases, the opportunity to convert some heat into work is lost.

SQ 6.11.17 What happens when hot and cold water are mixed?

Explanation

There is an increase in entropy when hot and cold waters are mixed. Finally the warm water cannot be separated into a hot layer and a cold layer.

Energy

There has been no loss of energy, but some of the energy is no longer available for conversion into work.

SQ 6.11.18 What is meant by degradation of energy?

Meaning

Increase in entropy means degradation of energy from a higher level, where more work can be extracted, to a lower level at which less or no useful work can be done.

Result

The energy is degraded, going from a more orderly form to a less orderly form, eventually ending up as thermal energy.

SQ 6.11.19 What happens to the energy available for useful work in all real processes?

Answer

In all real processes where heat transfer occurs, the energy available for doing useful work decreases and eventually the entropy increases.

SQ 6.11.20 What happens to the entropy of the universe?

Answer

Even if the temperature of some system decreases, thereby decreasing its entropy, it is at the expense of a net increase in entropy of some other system. When all the systems are taken together as the universe, the entropy of the universe always increases.

SQ 6.11.21 Explain the heat death of the universe in terms of entropy.

Explanation

In every natural process the energy available for doing useful work decreases and the entropy of the universe always increases.

Heat Death

Energy is continuously degraded from a more orderly form to a less orderly form, eventually ending up as thermal energy, until no useful work can be extracted anywhere.

SQ 6.11.22 Calculate the entropy change when 1.0 kg of ice at 0 °C melts into water at 0 °C.

Data

Here

$m = 1\,\mathrm{kg}$

$T = 0\,^\circ\mathrm{C} = 273\,\mathrm{K}$

and

$L_f = 3.36 \times 10^5\,\mathrm{J\,kg^{-1}}$

Solution

Since

$\Delta Q = mL_f$

therefore

$$\Delta S = \frac{mL_f}{T}.$$

Result

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

SQ 6.11.23 What does the increase in entropy measure when ice melts into water?

Answer

The increase in entropy is a measure of the increase in the disorder of the water molecules that change from the solid to the liquid state.

SQ 6.11.24 Why is an increase in temperature said to increase the disorder of a system?

Reason

An increase in temperature increases the average molecular speeds, and therefore the randomness of molecular motion. This greater randomness means greater disorder, so the entropy of the system increases.