

The Kinetic Theory of Gases (Summary)

Key Terms

Avogadro's number	N_A , the number of molecules in one mole of a substance; $N_A = 6.02 \times 10^{23}$ particles/mole
Boltzmann constant	k_B , a physical constant that relates energy to temperature and appears in the ideal gas law; $k_B = 1.38 \times 10^{-23} \text{ J/K}$
critical temperature	T_c at which the isotherm has a point with zero slope
Dalton's law of partial pressures	physical law that states that the total pressure of a gas is the sum of partial pressures of the component gases
degree of freedom	independent kind of motion possessing energy, such as the kinetic energy of motion in one of the three orthogonal spatial directions
equipartition theorem	theorem that the energy of a classical thermodynamic system is shared equally among its degrees of freedom
ideal gas	gas at the limit of low density and high temperature
ideal gas law	physical law that relates the pressure and volume of a gas, far from liquefaction, to the number of gas molecules or number of moles of gas and the temperature of the gas
internal energy	sum of the mechanical energies of all of the molecules in it
kinetic theory of gases	theory that derives the macroscopic properties of gases from the motion of the molecules they consist of
Maxwell-Boltzmann distribution	function that can be integrated to give the probability of finding ideal gas molecules with speeds in the range between the limits of integration
mean free path	average distance between collisions of a particle
mean free time	average time between collisions of a particle
mole	quantity of a substance whose mass (in grams) is equal to its molecular mass
most probable speed	speed near which the speeds of most molecules are found, the peak of the speed distribution function
partial pressure	pressure a gas would create if it occupied the total volume of space available
peak speed	same as "most probable speed"
pV diagram	graph of pressure vs. volume
root-mean-square (rms) speed	square root of the average of the square (of a quantity)
supercritical	condition of a fluid being at such a high temperature and pressure that the liquid phase cannot exist
universal gas constant	R , the constant that appears in the ideal gas law expressed in terms of moles, given by $R = N_A k_B$
van der Waals equation of state	equation, typically approximate, which relates the pressure and volume of a gas to the number of gas molecules or number of moles of gas and the temperature of the gas

vapor pressure

partial pressure of a vapor at which it is in equilibrium with the liquid (or solid, in the case of sublimation) phase of the same substance

Key Equations

Ideal gas law in terms of molecules	$pV = Nk_B T$
Ideal gas law ratios if the amount of gas is constant	$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$
Ideal gas law in terms of moles	$pV = nRT$
Van der Waals equation	$[p + a(\frac{n}{V})^2](V - nb) = nRT$
Pressure, volume, and molecular speed	$pV = \frac{1}{3} N m \bar{v}^2$
Root-mean-square speed	$v_{rms} = \sqrt{\frac{3RT}{M}} = \sqrt{\frac{3k_B T}{m}}$
Mean free path	$\lambda = \frac{V}{4\sqrt{2}\pi r^2 N} = \frac{k_B T}{4\sqrt{2}\pi r^2 p}$
Mean free time	$\tau = \frac{k_B T}{4\sqrt{2}\pi r^2 p v_{rms}}$

The following two equations apply only to a monatomic ideal gas:

Average kinetic energy of a molecule	$\bar{K} = \frac{3}{2} k_B T$
Internal energy	$E_{int} = \frac{3}{2} N k_B T$
Heat in terms of molar heat capacity at constant volume	$Q = n C_V \Delta T$
Molar heat capacity at constant volume for an ideal gas with d degrees of freedom	$C_V = \frac{d}{2} R$
Maxwell-Boltzmann speed distribution	$f(v) = \frac{4}{\sqrt{\pi}} \left(\frac{m}{2k_B T} \right)^{3/2} v^2 e^{-mv^2/2k_B T}$
Average velocity of a molecule	$\bar{v} = \sqrt{\frac{8}{\pi} \frac{k_B T}{m}} = \sqrt{\frac{8}{\pi} \frac{RT}{M}}$
Peak velocity of a molecule	$v_p = \sqrt{\frac{2k_B T}{m}} = \sqrt{\frac{2RT}{M}}$

Summary

2.2 Molecular Model of an Ideal Gas

- The ideal gas law relates the pressure and volume of a gas to the number of gas molecules and the temperature of the gas.
- A mole of any substance has a number of molecules equal to the number of atoms in a 12-g sample of carbon-12. The number of molecules in a mole is called Avogadro's number N_A ,

$$N_A = 6.02 \times 10^{23} \text{ mol}^{-1}.$$

- A mole of any substance has a mass in grams numerically equal to its molecular mass in unified mass units, which can be determined from the periodic table of elements. The ideal gas law can also be written and solved in terms of the number of moles of gas:

$$pV = nRT,$$

where n is the number of moles and R is the universal gas constant,

$$R = 8.31 \text{ J/mol} \cdot \text{K}.$$

- The ideal gas law is generally valid at temperatures well above the boiling temperature.
- The van der Waals equation of state for gases is valid closer to the boiling point than the ideal gas law.

- Above the critical temperature and pressure for a given substance, the liquid phase does not exist, and the sample is “supercritical.”

2.3 Pressure, Temperature, and RMS Speed

- Kinetic theory is the atomic description of gases as well as liquids and solids. It models the properties of matter in terms of continuous random motion of molecules.
- The ideal gas law can be expressed in terms of the mass of the gas’s molecules and \bar{v}^2 , the average of the molecular speed squared, instead of the temperature.
- The temperature of gases is proportional to the average translational kinetic energy of molecules. Hence, the typical speed of gas molecules v_{rms} is proportional to the square root of the temperature and inversely proportional to the square root of the molecular mass.
- In a mixture of gases, each gas exerts a pressure equal to the total pressure times the fraction of the mixture that the gas makes up.
- The mean free path (the average distance between collisions) and the mean free time of gas molecules are proportional to the temperature and inversely proportional to the molar density and the molecules’ cross-sectional area.

2.4 Heat Capacity and Equipartition of Energy

- Every degree of freedom of an ideal gas contributes $\frac{1}{2}k_B T$ per atom or molecule to its changes in internal energy.
- Every degree of freedom contributes $\frac{1}{2}R$ to its molar heat capacity at constant volume C_V .
- Degrees of freedom do not contribute if the temperature is too low to excite the minimum energy of the degree of freedom as given by quantum mechanics. Therefore, at ordinary temperatures, $d=3$ for monatomic gases, $d=5$ for diatomic gases, and $d\approx 6$ for polyatomic gases.

2.5 Distribution of Molecular Speeds

- The motion of individual molecules in a gas is random in magnitude and direction. However, a gas of many molecules has a predictable distribution of molecular speeds, known as the Maxwell-Boltzmann distribution.
- The average and most probable velocities of molecules having the Maxwell-Boltzmann speed distribution, as well as the rms velocity, can be calculated from the temperature and molecular mass.

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