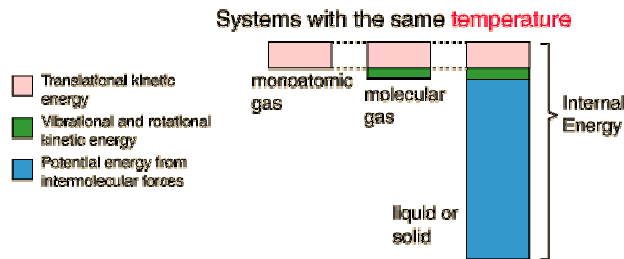


H2 THERMAL PHYSICS

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(a) Show an understanding that internal energy is determined by the state of the system and that can be expressed as the sum of a random distribution of kinetic and potential energies associated with the molecules of a system.

- Internal energy U of an object (solid, liquid or gas) is the sum of the (1) potential energy due to intermolecular forces, (2) translational kinetic energy and (3) vibrational and rotational kinetic energy. $U = \Sigma PE + \Sigma KE_{VR} + \Sigma KE_T$
- Internal energy U of an ideal monatomic gas is the sum of the (1) translational kinetic energy. $U = \Sigma KE_T$ only. (If ideal gas is not monatomic, $U = \Sigma KE_{VR} + \Sigma KE_T$)
- The useful diagram below is from <http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/inteng.html#c2>. Note that whether they are solid, liquid or gas, they have the same molecular translational kinetic energy as long as they are at the same temperature.



- **Keywords:** Internal energy U , Translational KE, Rotational KE, Ideal gas, Monoatomic, Intermolecular PE

(b) Relate a rise in temperature of a body to an increase in its internal energy.

- Temperature is a measure of an object's (solid, liquid or gas) internal energy. $U \propto T$.
- For an ideal gas, $U = \Sigma KE_T$ only. Since $KE_T = \frac{1}{2} m v^2$, the velocity of each molecule (of an ideal gas) is dependent on the temperature.
- Temperature can be measured in degrees Celsius (empirical scale) or Kelvin (thermodynamic or absolute scale).
- **Keywords:** Celsius, Kelvin, Empirical scale, Thermodynamic or Absolute scale.

(c) Show an understanding that regions of equal temperature are in thermal equilibrium.

- When ice ($T = 0^\circ\text{C}$ or 273.15 K) is added to water at room temperature (say $T = 30^\circ\text{C}$ or 303.15 K), there is heat transfer from the water (hotter body) to the ice (cooler body). If there is enough heat energy transferred, the ice can melt.
- When ice ($T = 0^\circ\text{C}$ or 273.15 K) is added to water at 0°C , there is no heat transfer from the water to the ice since they are at the same temperature ("just as hot"). The ice and the water are said to be in thermal equilibrium.
- **Keywords:** Thermal (or thermodynamic) equilibrium, Zeroth Law.

(d) Show an understanding that there is an absolute scale of temperature which does not depend on the property of any particular substance, i.e. the thermodynamic scale.

- Kinetic theory of ideal gases helps to develop the expression for gas pressure (out of syllabus). Combined this expression with the ideal gas equation, we get an expression for temperature.
- In empirical scale, we express temperature based on the thermal properties of a substance (eg. Mercury, Alcohol, Resistance, etc). These thermal properties are ASSUMED to vary proportionally with temperature after the quantities are measured at ice point ($T = 0^\circ\text{C}$ or 273.15 K) and boiling/steam point ($T = 100^\circ\text{C}$ or 373.15 K). Ice point and steam point are the fixed points in the empirical scale.
- Thermodynamic scale has only one fixed point, the triple point of water ($T = 273.16\text{ K}$ or 0.01°C).
- **Keywords:** Kinetic theory, Ideal gas equation ($pV = nRT$), Fixed points.

(e) Apply the concept that, on the thermodynamic (Kelvin) scale, absolute zero is the temperature at which all substances have a minimum internal energy.

- Intermolecular forces is determined by the intermolecular spacing. In the solid phase (which is the coolest phase compared to liquid and gas for a particular substance), the spacing is more or less fixed unlike the gaseous state where all gases can be compressed.

- However, at the lowest temperature, we can assume that this is where translational, rotational and vibrational K.E.s are zero.
- Therefore, at 0 K (the absolute zero) the internal energy of any substance is made up purely of intermolecular P.E.

(f) Convert temperatures measure in Kelvin to degrees Celsius: $T/K = T/^{\circ}\text{C} + 273.15$.

EXAMPLES

Convert 200 K to degrees Celsius.

$$T/K = T/^{\circ}\text{C} + 273.15$$

$$\rightarrow 200 = T/^{\circ}\text{C} + 273.15$$

$$\rightarrow T/^{\circ}\text{C} = 200 - 273.15 = -73.15\text{ }^{\circ}\text{C}$$

Convert 100 $^{\circ}\text{C}$ to Kelvin.

$$T/K = T/^{\circ}\text{C} + 273.15$$

$$\rightarrow T/K = 100 + 273.15$$

$$\rightarrow T/K = 100 + 273.15 = 373.15\text{ K}$$

(g) Define and use the concept of specific heat capacity, and identify the main principles of its determination by electrical methods.

- Calorimetry is a method where quantities of heat energy transfers are measured.
- Heat capacity C of an object is the amount of heat energy required to raise its temp by 1 K (without a change in phase). Unit: J.
- Specific heat capacity c is the amount of heat energy required to raise a substance of 1 kg by 1 K (without a change in phase). Unit: J kg^{-1} .
- Main problem in calorimetry is accounting for heat lost to the surrounding. The continuous flow method minimizes the errors in heat loss significantly.
- **Keywords:** Heat capacity C, Specific heat capacity c, Calorimetry, Constant flow method.

EXAMPLES

How many joules are required to raise the temperature of 0.5 kg ice at $-15\text{ }^{\circ}\text{C}$ to $-10\text{ }^{\circ}\text{C}$?

$$\text{Heat required} = mc\Delta T = (0.5)(2100)(-10 - (-15)) = 5250\text{ J}$$

(h) Define and use the concept of specific latent heat, and identify the main principles of its determination by electrical methods.

- Basic idea: Heat supplied = Heat absorbed (Principle of Conservation of Energy).
- Heat energy supplied by a heating coil = power x time = $Pt = IVt$

EXAMPLES

0.2 kg of water at room temperature (say $T = 27\text{ }^{\circ}\text{C}$) is placed in a covered styrofoam cup. A heating coil supplied with a constant current of 3 A at a potential difference of 2 V is submerged into the water for 15 minutes. Assuming no heat lost to the surrounding, calculate the final temperature of the water.

$$\text{Heat supplied} = \text{Heat absorbed}$$

$$\rightarrow IVt = mc\Delta T$$

$$\rightarrow (3)(2)(15 \times 60) = (0.2)(4200)(T_f - 27)$$

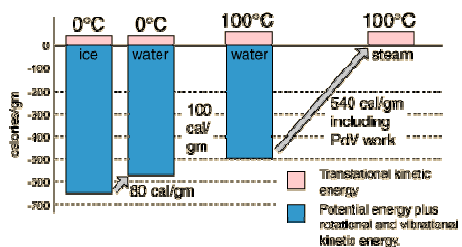
$$\rightarrow T_f = 33.4\text{ }^{\circ}\text{C}$$

(i) Explain using a simple kinetic model for matter why

i. Melting and boiling take place without a change in temperature,

ii. The specific latent heat of vaporization is higher than specific latent heat of fusion for the same substance,

- Again, HyperPhysics provides another useful illustration in what happens to the internal energy of a substance when it changes phase.



from HyperPhysics

- Note: Intermolecular P.E. causes the sum of P.E. and rotational and vibrational K.E.s to be negative. This implies that intermolecular forces, in this case, are attractive in nature and therefore negative. It's contribution in the solid and liquid state is also very significant.
- Note: Translational K.E. quantities at the same temperature (although, different phase) is the same. Compare KE_T for ice (solid) and water (liquid) at 0°C and KE_T for water (liquid) and steam (gas) at 100°C .
- When a substance changes state from solid to liquid, large amount of energy is used to break the solid intermolecular bonds. In liquid state, the molecules have lesser intermolecular force between them. In this change, the translational K.E. is not changed leaving the temperature unchanged (latent means hidden, unobservable).
- As compared to solid to liquid phase change, much larger energy is required to pull the molecules far apart resulting in insignificant intermolecular forces between the molecules. That is the reason for why the latent heat of vaporization is much larger than the latent heat of fusion.
- **Keywords:** Latent heat of vaporization, Specific latent heat of vaporization, Latent heat of fusion, Specific latent heat of fusion,

iii. Cooling effect accompanies evaporation.

- When part of a liquid is allowed to evaporate on the surface, there will be molecules (at the surface) which have enough KE_T (the more energetic ones) to escape. When the more energetic molecules escape, the average KE_T of the liquid decreases. This results in a lower internal energy.
- Recall that $U \propto T$. Therefore, lower U means a lowered T (cooling).

(j) Recall and use first law of thermodynamics expressed in terms of the change in internal energy, the heating of the system and the work done on the system.

- First Law of Thermodynamics: The increase in internal energy (ΔU) of a system is the sum of the heat supplied (Q) to the system and the work done (W) on the system. $\Delta U = Q + W$.

EXAMPLES

An ideal gas in an insulated piston is compressed. The work done on the gas due to the compression is 50J. What is the increase in its internal energy? What happens to its temperature?

$$\Delta U = Q + W$$

$$\rightarrow \Delta U = 0 + 50 = +50 \text{ J}$$

Since $U \propto T$, there is an increase in its temperature.

An ideal gas in a piston is allowed to expand. The work done by the gas due to the expansion is 50J. At the same time 50 J of heat was supplied to the gas. What is the increase in its internal energy? What happens to its temperature?

$$\Delta U = Q + W$$

$$\rightarrow \Delta U = 50 + (-50) = 0 \text{ J}$$

Since $U \propto T$, there is no change in its temperature.

(k) Recall and use the ideal gas equation $pV = nRT$, where n is the amount of gas in moles.

EXAMPLES

A sample of oxygen gas is placed in an insulated piston at a temperature of 300 K. The pressure of the gas is 2 Pa and the volume is 0.050 m^3 . ($R = \text{universal gas constant} = 8.31 \text{ J/mol K}$). Calculate the number of moles of oxygen.

Assume the oxygen gas is an ideal one.

$$pV = nRT$$

$$\rightarrow (2)(0.050) = n(8.31)(300)$$

$$\rightarrow n = 4.01 \times 10^{-5} \text{ moles}$$

- (l) Show an understanding of the significance of the Avogadro constant as the number of atoms in 0.012 kg of carbon-12.
 (m) Use molar quantities where one mole of any substance is the amount containing a number of particles equal to the Avogadro constant.

- The mass of one mole of carbon-12 is 0.012 kg. There are 6.02×10^{23} atoms in one mole of carbon-12 sample.
- There are 6.02×10^{23} atoms in one mole of any sample.

EXAMPLES

How many atoms are there in 0.004 kg of oxygen?

Assume oxygen sample is a diatomic ideal gas, the mass of one mole is 0.032 kg.

0.004 kg of oxygen is equivalent to 0.125 mole of oxygen.

Therefore, number of oxygen atoms = $(0.125)(6.02 \times 10^{23})$

Estimate the intermolecular spacing in solids and liquids. (challenging question)

Use a familiar substance as an example, say, water of density 1 g cm^{-3}

Mass of 1 mole of water = $16 + 1 + 1 = 18 \text{ g}$ (A water molecule is made up of two Hydrogen atoms and one Oxygen atom)

Therefore, 1 cm^3 of water contains $1/18$ mole of water or $(1/18) \times 6.02 \times 10^{23}$ molecules.

Intermolecular spacing = $\{1 / [(1/18)(6.02 \times 10^{23})]\}^{1/3} = 2.8 \times 10^{-6} \text{ cm}$

Intermolecular spacing of any substance in solid or liquid state is in the region of $\sim 10^{-8}$ to $\sim 10^{-9} \text{ m}$

- (n) Recall and apply the relationship that the mean kinetic energy of a molecule of an ideal gas is proportional to the thermodynamic temperature to new situations or to solve related problems.

- $KE_{\text{ave}} \propto T$
- $v_{\text{rms}} \propto \sqrt{T}$

EXAMPLES

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