Topic 2 – Thermal Physics
Concepts and Definitions

	Thermal Concepts
0^{th} law of thermodynamics	When two systems are in thermal equilibrium, there is no net transfer of heat between them
1^{st} law of thermodynamics	Energy in a closed system will always remain constant In A/B heat transfer *:* $+Q_A = -Q_B$
Temperature	Measure of degree of hotness or coldness of an object
Internal Energy	Sum of random kinetic and potential energies of atoms and molecules in a system 1. KE : random translational and rotational motion of particles 2. PE : forces between molecules
Thermal Energy	Non-mechanical transfer of energy due to the temperature difference between bodies
Mole	Amount of substance that contains as many particles as atoms in 12g of pure C-12 Avogadro constant = 6.02 E^{23}
Molar Mass	Mass of 1 mole of a substance, in kg
	Thermal Properties
Thermal Capacity	Energy required to cause a unit rise in temperature of a body without a change in phase. (J K^{-1}) $Q = C\,\Delta T$
Specific Heat Capacity	Energy needed per unit mass of a substance to cause a unit rise in temperature without a change in phase. (J K^{-1} kg^{-1}) $Q = mc\,\Delta T$

Phase Differences

	Solid	**Liquid**	**Gas**
Structure	Regular	Irregular	Irregular
Spacing	Regular	Regular	Irregular
Particle Motion	Vibrational	Vibrational, Rotational, Translation	Rotational, Translational

Changes in Phase

Melting
1. Structure becomes irregular
2. Spacing increases slightly
3. Intermolecular bond weaken

Freezing
1. Structure becomes regular
2. Spacing decreases slightly
3. Intermolecular bonds strengthen

Evaporating
1. Energetic surface molecules with high KE overcome intermolecular forces and escape
2. Escaped molecules have irregular structure, large spacing
3. Average KE of remaining molecules fall

(Occurs at all temperatures, at liquid surface)

Boiling
1. Spacing increases significantly
2. Intermolecular bonds broken

(occurs at specific temperature, throughout liquid, bubbling observed)

	Condensing	1. Spacing decreases significantly 2. Intermolecular bonds formed

Temperature Constancy

1. During change in phase, KE of molecules remains constant
2. Intermolecular bonds either strengthened, weakened, broken or formed, causing change in PE of molecules

Specific Latent Heat of Fusion Energy required to change phase of a unit mass of substance from liquid to solid, without accompanying change in temperature (J kg^{-1})

$$Q = mL_F$$

Specific Latent Heat of Vaporization Energy required to change phase of a unit mass of substance from liquid to gas, without accompanying change in temperature (J kg^{-1})

$$Q = mL_V$$

Ideal Gas

Pressure Force per unit area (N m^{-2} = Pa)

Pressure in a Fluid Constant cross-sectional area A, at depth h under liquid surface, density ρ

$$\begin{aligned} P &= F/A \\ &= \rho Ahg/A \\ &= \rho hg \end{aligned}$$

Pressure Problems For gas-liquid interface to be static, pressure by liquid on gas = pressure by gas on liquid

Kinetic Model Gas consists of small particles that are in constant random motion and relatively high speeds

Assumptions of Model

Aspect of Model	Necessary assumptions
(1) No intermolecular forces : internal energy completely comprised of average kinetic energy	Increase distance between molecules (2) Particle size negligible compared to gas volume [ideal : low P, high T, high v]
Particles are moving in constant random motion, with constant average KE	(3) Collision time is negligible (4) Collisions are perfectly elastic

Real Gas Approximation

Pressure	Low	Greater distance between molecules, lower intermol F
Temperature	High	Greater KE, overcome intermol F
Density	Low	Greater v for same KE

Real gas should not readily condense / solidify

Origins of Pressure

1. Molecules hit wall of container, are deflected in opposite direction, momentum changes direction
2. By N2, molecule experiences force from wall
3. By N3, wall experiences equal and opposite force from molecule
4. Forces per unit area give rise to P

Temperature Statistical law, by Maxwell-Boltzmann distribution (monoatomic gas) :
* Temperature is not summative over all molecules in gas, but refers to specific kinetic energy molecule uniformly

$$KE = 3kT/2$$

RMS Velocity

$$v_{RMS} = \sqrt{3kT/m}$$

Ideal Gas Law	$PV = \text{nRT} = \text{NkT}$	
	Particle travels at velocity v perpendicular to a wall, collides elastically and is deflected in the opposite direction.	$\Delta\text{v} = 2\text{v}$ $F = \text{m}\Delta\text{v}/\Delta\text{t}$
	In a 1-dimensional box of length L, particle takes time Δt to travel between collisions	$\text{v} = 2\text{L}/\Delta\text{t}$ $\Delta\text{t} = 2\text{L}/\text{v}$
	Force on wall by particle, or by particle on wall, due to deflection	$\text{F} = \text{m}2\text{v}/\Delta\text{t}$ $= \text{mv}^2/\text{L}$
	Pressure in 1-dimension due to collision of N particles on area A of wall	$P_{1D} = \text{NF}/\text{A}$ $= \text{Nmv}^2/\text{AL}$ $= \text{Nmv}^2/\text{V}$
	Pressure in 2-dimensions due to collision of N particles on area A of wall	$P = P_{1D}/3$ $= \text{Nmv}^2/3\text{V}$
	Using statistically defined relation between kinetic energy and temperature	$\text{PV} = \text{Nmv}^2/3$ $= \text{N}(2/3)(\text{mv}^2/2)$ $= \text{N}(2/3)(3/2)\text{kT}$
	Ideal gas law, where N : number of molecules / n : number of moles	$\text{PV} = \text{NkT}$ $= \text{nRT}$
Pressure-Velocity Relation	$\text{P} = \rho v^2/3$	
	3-dimensional pressure is a third of 1-dimensional pressure, as molecules are equally likely to deflect off three times as many directions	$P_{3D} = P_{1D}/3$ $= \text{NF}/3A$
	Change in momentum 2Nmv when N particles at speed v deflect off a wall	$P_{3D} = 2\text{Nmv}/3A\Delta t$ $v = 2\text{NL}/\Delta t$ $P_{3D} = \text{Nmv}^2/3AL$
	Density is total mass of all molecules N, divided by the volume occupied	$P_{3D} = \text{Nmv}^2/3V$ $= (1/3)(\text{Nm/V})\,\text{v}^2$ $= (1/3)\rho\text{v}^2$
	Thermodynamic Scale	
Fixed Points of Kelvin Scale	1. Absolute zero : no movement possible (0K) 2. Triple point of water : water can exist in stable equilibrium in solid, liquid, and gaseous states (273.16K)	
Celsius / Kelvin	$T/\text{K} = t/\text{C} + 273.15$	
Pressure-Temperature Graphs	**Ideal Gas** - Linear - Uniform P/T gradient - Intersection : (-273.16, 0)	**Real Gas** - Linear - Differing P/T gradient - Differing condensation points - Extrapolate to intersection
Thermometer Requirements	Physical property must have unique value for each temperature	

Topic 2 – Thermal Physics
Questions

Thermal Properties

1 Liquid X has a specific heat capacity Cx. It is mixed with an equal mass of liquid Y with specific heat capacity Cy. The initial temperature of X, Tx is initially greater than that of Y, Ty.

a. Express the ratio of the temperature rise of X over that of Y in terms of the Cx and Cy.
b. Express the equilibrium temperature of the substance in terms of Cx, Cy, Tx and Ty.

[Cy/Cx , T = (CxTx + CyTy) / (Cx + Cy)]

2 A metal piece of mass m and 0C is placed in contact with another metal piece of mass 4m at 100C. Their equilibrium temperature is 75C.

a. What is the ratio of their specific heat capacities?
b. What is the ratio of their thermal capacities?

[4/3 , 1/3]

3 A 1kg ice chunk is removed from a -3C fridge and placed on a table in a 28C room.
(c, ice = 2100 J K^{-1} kg^{-1}) (L_F, water = 330 kJ kg^{-1}) (c, water = 4200 J K^{-1} kg^{-1})

a. At equilibrium, how much heat energy has been lost by the air in the room to the water/ice?
b. If the system takes 3hours to reach equilibrium, water is the average power loss of the air in the room to the water/ice?
c. If the power transfer occurs at a constant rate, what is the instantaneous rate of temperature rise when the ice is at -2C?
d. If the power transfer occurs at a constant rate, what is the instantaneous rate of temperature rise when the water is at 20C?
e. What is the average rate of temperature rise? Explain why this is smaller than both answers (b) and (c).

[450000J / 42W / 0.020 Ks^{-1} / 0.010 Ks^{-1} / 0.0029 Ks^{-1}]

4 In another universe, another temperature (K') and energy (J') scale are defined, where :
The freezing point of water is 25K' and the boiling point of water is 100K'
J' is the heat that must be added to one gram of water to raise its temperature by 1 K'.
What is the specific heat capacity in K', J', and g?

[1 J' K'^{-1} g^{-1}]

5 As altitude increases, does the L_V of water increase or decrease, and why?

[decreases]

6 A certain rise in temperature is secured when 500g of water passes through a heater in 60s. The power dissipated in the element is 210W. The same rise in temperature is secured when 300g passes through the heater in 180s, and the power dissipated is 50W. In both cases, assume that the rate of power loss to the surroundings is constant.

a. What is the rise in temperature in both cases?
b. What is the rate of power loss to the surroundings?

[5.71K, 10W]

7 100g of ice at 0C is mixed with 100g of water at 100C. Draw, on the same axes, the temperature-time graphs of the two substances.

8 A solar furnace of area 0.4 m^2 supplies energy to substance Y at a rate of 1400 Jm^{-2}. Substance Y has a melting point of -2C, a boiling point of 98C, c of liquid Y = 3000 J kg^{-1}. What is the minimum time needed for 1kg of solid substance Y at 2C to be heated to 98C? Assume that no heat is lost to the surroundings.

[1000s]

9 A liquid is boiled in an insulated container using an electric heater. A current of 3A is used, passing through a potential difference of 6V. If the mass of the liquid decreases by 100g in 9 minutes, what is the L_V of the liquid?

[97.2 kJ kg^{-1}]

10 Two experiments are set up to determine the L_V of a liquid. In experiment 1, 5A current is passed through 75V for 20min. The mass of the liquid decreases by 517g. In experiment 2, 2A current is passed through 100V for 15min. The mass of the liquid decreases by 191g. Assume that the power loss to the surroundings is constant over time and in the two experiments.

a. What is the L_V of the liquid?
b. What is the power loss from the liquids to the surroundings?
c. Explain why the experiment had to be conducted twice to find L_V.

[800 kJ kg^{-1}, 30 Js^{-1}]

Ideal Gas

1 The graphs of PV against P are plotted for the same sample of gas at three different temperatures. At a certain pressure, the 0C sample has PV-value a, the 100C sample has PV-value c, and the last sample has PV-value b. Express in terms of a, b and c the temperature of the last sample.

[373.15 b/c]

2 Flasks X and Y are connected by a tube of negligible volume and the system is filled with an ideal gas. X has volume 2L and temperature 200K, while Y has volume 1L and temperature 400K. What is the ratio of the mass of gas in X, to that in Y?

[1/4]

3 A sample of ideal gas at temperature T exists. Each particle has mass m and root-mean-square speed v. If the temperature of the gas is raised by 10K, express the fractional increase in v in terms of m, v, T and k.

[$\sqrt{1 + 10/T} - 1$]

4 The density of Helium at 273K and 100kPa is 0.178 kg m^{-3}. What is the root-mean-square speed of its particles?

[1300 m s^{-1}]

5
a. Draw 3 P-V graphs for an ideal gas at 3 different temperatures, labelled $T_1 > T_2 > T_3$.
b. Draw 3 P-T graphs for an ideal gas at 3 different volumes, labelled $V_1 > V_2 > V_3$.
c. Draw 3 T-V graphs for an ideal gas at 3 different pressures, labelled $P_1 > P_2 > P_3$.

6 A container with a volume of 3.5 10^{-3} contains Nitrogen gas at a pressure of 2.18 10^{6} Pa and a temperature of 33C. Nitrogen gas has a molar mass of 0.028g.

a. Find the number of Nitrogen molecules in the container.
b. Find the average kinetic energy of a Nitrogen molecule.
c. Oxygen gas has a molar mass of 0.032kg. Using the answer from (b), find its root-mean-square speed at 33C.

[1.81 10^{24}, 6.33 10^{-21}, 488 m s^{-1}]

7 A container contains a mixture of neon and oxygen gases at equilibrium, at a temperature of 100C. Assume that both are ideal gases.

a. What is the average kinetic energy of the molecules of each of the gases?
b. A neon atom is 3.3 10^{-26} kg in mass. What is its root-mean-square speed?
c. An oxygen atom has 1.6 times the mass of a neon one. Using the answer to (b), find the root-mean-square of the oxygen molecules.

[7.72 10^{-21}, 679 m s^{-1}, 537 m s^{-1}]

8 In a specific waterfall, water falls through a distance of 20m. The mass of one mole of water molecules is 0.018kg.

a. What is the change in gravitational potential energy of a water molecule after the fall?
b. Assume that all the potential energy is converted to thermal energy. The specific heat capacity of water is 4200 J kg^{-1} K^{-1}. Using this, calculate the rise in temperature of the water after it falls.
c. Assume that all the potential energy is converted to random kinetic energy. Using $EK = (3/2)\ kT$, calculate the rise in temperature of the water after it falls.
d. Explain the difference between answers (b) and (c), as well as which method of calculation is more reasonable.

[5.87 10^{-23}, 0.0467K, 0.283K]

9 One mole of molecular oxygen has a mass of 0.032kg. 96g of oxygen gas is placed in a container of volume 0.0035m^3. The temperature of the gas is 295C.

a. What is the pressure of the gas?
b. What is the average random kinetic energy of the molecules?

c. What is the root-mean-square speed of the molecules?
d. The gas now expands such that its volume doubles and its pressure is quartered. What is the root-mean-square speed of the molecules now?

[4.05 10^6 Pa, 1.17 10^{-20}, 666 m s^{-1}, 942 m s^{-1}]

10 A closed bulb on one end of a u-shaped liquid column contains a mass of gas Y. The other side of the liquid column is open to the atmosphere. 0.013mol of air is trapped in a volume of 300 cm^3 at a temperature of 20C. Atmospheric pressure is 101000 Pa.

a. Determine the pressure exerted by the gas on the liquid column.
b. The height of the interface between gas Y and the liquid is lower than that between the atmosphere and the liquid. If the liquid has a density of 14000 kg m^{-3}, find this height difference.

[105628 Pa, 0.0337m]