RAFFLES INSTITUTION
YEAR 5-6 PHYSICS DEPARTMENT

Tutorial 9 FIRST LAW OF THERMODYNAMICS

Self-Check Questions

S1 Define *specific heat capacity*, and outline the main principles of its determination for

(i) a solid, **(ii)** a liquid.

S2 Define *specific latent heat*, and outline the main principles of its determination for

(i) fusion, **(ii)** vaporization.

S3 Explain, using the kinetic model of matter, why

(i) melting and boiling take place without a change in temperature,

(ii) the specific latent heat of vaporisation is higher than specific latent heat of fusion for the same substance,

(iii) cooling effect accompanies evaporation.

S4 Explain what is meant by the internal energy U of

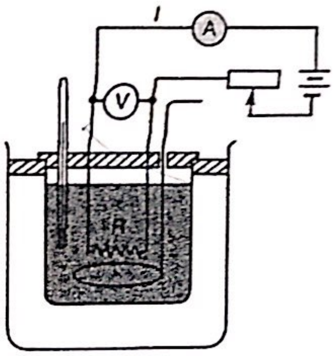
(i) a system, **(ii)** an ideal gas.

S5 State the *first law of thermodynamics* and explain how it is an application of the principle of conservation of energy.

S6 State how the internal energy of a body is related to its temperature.

Self-Practice Questions

SP1 The figure shows the apparatus used in the determination of the specific heat capacity of a liquid. The total heat capacity of the calorimeter, the heater, the stirrer and the thermometer was 107 J K^{-1}. The mass of liquid in the calorimeter was 0.241 kg, and the ammeter and voltmeter readings were 3.40 A and 12.2 V respectively. When the temperature of the liquid was equal to that of the surroundings, its value was found to be increasing at the rate of 46.3×10^{-3} K s^{-1}.



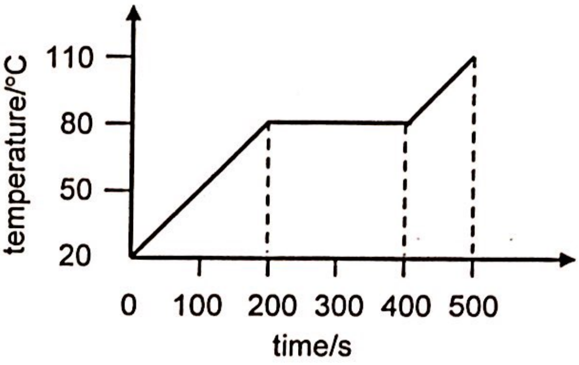
(a) Determine a value for the specific heat capacity of the liquid.

(b) State the advantage of measuring the rate of rise of temperature of the liquid when its temperature is equal to that of the surroundings rather than measuring the rise of temperature taking place in a given length of time.

SP2 A certain solid X is heated in an insulated container at a constant rate. The temperature of the material varies as shown in the graph. If the specific heat capacity of the solid is 1800 J kg^{-1} K^{-1}, calculate

(a) the specific latent heat of fusion of the solid,

(b) the specific heat capacity of liquid X.



SP3 A thermally insulated tube through which a gas may be passed through at constant pressure contains an electric heater and thermometers for measuring the temperature of the gas as it enters and as it leaves the tube. 3.0×10^{-3} m^3 of the gas of density 1.8 kg m^{-3} flows into the tube in 90 s and, when electrical power is supplied to the heater at a rate of 0.16 W, the temperature difference between the outlet and inlet is 2.5 K.

(a) Calculate the specific heat capacity of the gas at constant pressure.

(b) Explain the features of the constant-flow method that makes it particularly suitable for the accurate determination of the specific heat capacities of fluids.

SP4 An ideal gas contained within a piston-cylinder assembly is compressed. 500 J of work is done and 200 J of heat is lost. Calculate the increase in the internal energy of the gas.

SP5 A 1.00 mol sample of argon gas is heated at constant pressure from 300 K to 420 K. Assuming that the gas is ideal, calculate

(a) the work done on the gas,

(b) the increase in its internal energy and

(c) the energy transferred to the gas by heat.

SP6 **(a)** Explain what is meant by an isothermal change.

(b) How is an isothermal compression of a gas achieved in practice?

(c) Explain why, in the isothermal compression of an ideal gas, the internal energy remains the same even though mechanical work is done on the system.

SP7 A cylinder fitted with a frictionless piston contains 5.0×10^{-4} m^3 of an ideal gas at a pressure of 1.0×10^5 Pa and temperature of 300 K.

The gas is then

(i) heated at constant pressure to 450 K, and then

(ii) cooled at constant volume to the original temperature of 300 K. The heat extracted in this stage is 63 J.

(a) Illustrate theses changes on a p-V diagram labelled with the appropriate values of pressure and volume.

(b) Determine the work done by the gas in stage **(i)**.

(c) Calculate the total heat input in stage **(i)**.

Discussion Questions

Specific heat capacity of water	4190 J kg^{-1} K^{-1}
Specific latent heat of fusion of water	3.33×10^5 J kg^{-1}
Specific latent heat of vaporisation of water	2.26×10^6 J kg^{-1}
Specific heat capacity of ice	2050 J kg^{-1} K^{-1}
Specific heat capacity of Copper (for the calorimeter)	380 J kg^{-1} K^{-1}

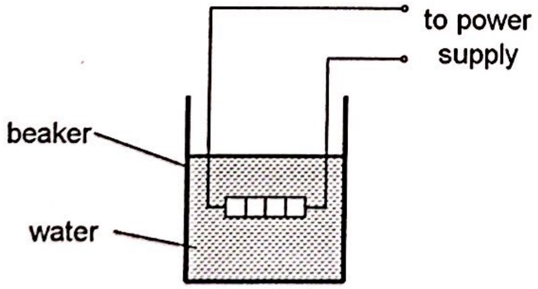
D1 A thermally isolated beaker contains 1.000 kg of water at 20 °C. A mass M of ice at −20 °C is dropped into it. When the system reaches thermal equilibrium, a mass m of ice remains unmelted. Show that $m = 1.123M - 0.252$, where m and M are measured in kg. (Assume that the heat transferred to the beaker is negligible.) [2]

D2 A well-lagged calorimeter of mass 120 g contains 200 g of water and 50 g of ice, initially at 0 °C. A jet steam is blown through the water until the temperature reaches 30 °C. Calculate the mass of the steam that must have condensed. [3]

D3 100 g of ice cubes at a temperature of −15 °C are dropped into 200 g of water at a temperature of 25 °C in a glass. Determine the final temperature of the drink. [3]

D4 A student carries out an experiment to determine the specific latent heat of vaporisation of water. Water is boiled in a beaker by means of an electric heater, as shown in the figure. The power supplied to the heater is measured when the water is boiling at a constant rate. The mass m of water evaporated in 5.0 minutes is determined.

Data for the power P and the mass m for two different values of P are shown.



P /W	m /g
140	14.1
95	8.2

(a) Suggest why, in order to obtain a reliable result for the specific latent heat, the mass m is determined for two different values of P. [1]

(b) Calculate the value for the specific latent heat of vaporisation. [3]

(N10/III/1-part)

D5 In a space, such as a swimming pool enclosure, water at 30 °C and water vapour, also at 30 °C, coexist.

(a) Compare the pattern of movement and the speed of molecules in water and water vapour at the same temperature. [4]

(b) State what is meant by the *internal energy* of a system. [2]

(c) Using your answer in (b), compare the internal energy per unit mass of water and water vapour at the same temperature. [3]

(d) Explain, in terms of internal energy, why the specific latent heat of vaporisation of a substance is greater than its specific latent heat of fusion. [2]

(N06/III/2-part)

D6 **(a)** **(i)** A car tyre has a fixed internal volume of 0.0120 m^3. On a day when the temperature is 25 °C, the pressure in the tyre has to be increased from 2.62×10^5 Pa to 3.23×10^5 Pa. Assuming the air is an ideal gas, calculate the amount of air in moles which has to be supplied at constant temperature. [3]

(ii) A portable supply of air used to inflate tyres has a volume of 0.0108 m^3 and is filled with air at a pressure of 8.72×10^5 Pa. Show that at 25 °C, there is more than enough air in it to supply four tyres as in **(i)**, without the pressure falling below 3.23×10^5 Pa. [2]

(b) **(i)** Show that the internal energy of a molecule of air at a temperature of 25°C is 6.17×10^{-21} J. Assume the air behaves as an ideal gas. [2]

(ii) Hence calculate the internal energy of one mole of air at a temperature of 25 °C [1]

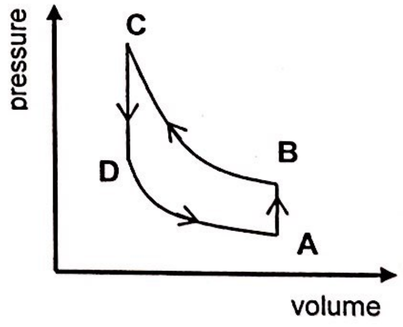
(iii) Calculate the increase in the internal energy of the air in the tyre in **(a)(i)** as a result of increasing its pressure. [2]

(N07/III/6-part)

D7 An ideal gas contained within a piston-cylinder assembly has a pressure of 100 kPa. 800 J of heat is transferred to the gas such that the gas undergoes an isobaric expansion from a volume of 0.030 m^3 to 0.035 m^3. Determine the increase in the internal energy of the gas. [2]

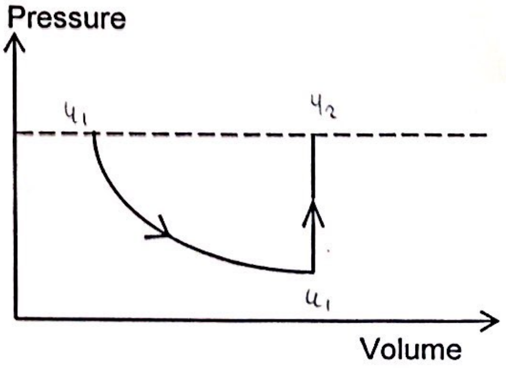
D8 An ideal gas undergoes the following cyclic process ABCDA as shown. Use the first law of thermodynamics to complete the following table.

Process	Q /J	W /J	ΔU /J
AB	280		
BC	20	170	
CD	− 400		
DA		− 70	



[4]

D9 A sample of an ideal gas initially having internal energy U_1 is allowed to expand adiabatically by doing external work W. Heat Q is then supplied to it, keeping the volume constant at its new value, until the pressure rises to its original value.
The internal energy is then U_2.
Determine the total increase in internal energy in terms of Q and W.



[2]

Challenging Questions

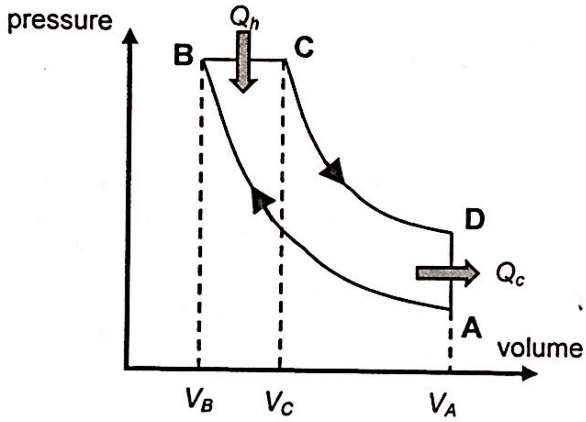
C1 A multicylinder gasoline engine in an airplane, operating at 2500 rev min^{-1}, takes in energy 7.89×10^3 J and exhaust 4.58×10^3 J for each revolution of the crankshaft.

(a) How many litres (L) of fuel does it consume in 1 hour of operation if the heat of combustion is 4.03×10^7 J L^{-1}?

(b) What is the mechanical power output of the engine? Ignore friction.

(c) What power must the exhaust and cooling system transfer out of the engine?

C2 An idealized diesel engine operates in a cycle known as the air-standard diesel cycle as shown below. Fuel is sprayed into the cylinder at the point of maximum compression, B. Combustion occurs during the expansion B → C, which is modeled as an isobaric process. Processes A → B and C → D are adiabatic processes.



Show that the efficiency of an engine operating in this idealized diesel cycle is

$$e = 1 - \frac{1}{\gamma}\left(\frac{T_D - T_A}{T_C - T_B}\right)$$

Additional information given for C2:

1. The *principal molar heat capacity* of a gas at *constant pressure*, C_P, is the amount of heat needed to raise the temperature of one mole of the gas by 1 K at constant pressure.
2. The *principal molar heat capacity* of a gas at *constant volume*, C_V, is the amount of heat needed to raise the temperature of one mole of the gas by 1 K at constant volume.
3. For an adiabatic change (or process), pV^{γ} = constant, where $\gamma = \frac{C_P}{C_V}$
4. $C_P - C_V = R$, the ideal gas constant.
5. The efficiency of a heat engine is defined as $e = \frac{\text{net work done in 1 cycle}}{\text{heat supplied in 1 cycle}}$

Discussion Questions Answers:

D2	0.0194 kg	**D6**	0.296 mol; 3710 J; 1100 J
D4	2.30×10^6 J kg^{-1}	**D8**	300 J

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Self-Check Questions Suggested Solutions

S1 Refer to notes Pg 3-4 **S2** Refer to notes Pg 10-11 **S3** Refer to notes Pg 8

S4 **(i)** The internal energy U of a system can be expressed as the sum of all the microscopic kinetic and potential energies of the molecules within the system.

(ii) For an ideal gas, the assumption is that the molecules have negligible interactions with each other. Thus, the potential energy associated with ideal gas molecules is zero. The internal energy of an ideal gas is therefore the sum of all the microscopic kinetic energies of the gas molecules.

S5 The first law of thermodynamics states that the internal energy of a system depends only on its state; the increase in the internal energy of a system is the sum of the work done on the system and the heat supplied to the system.

The principle of conservation of energy states that energy cannot be created or destroyed, but can be changed from one form to another.

- Since the internal energy is the sum of the microscopic kinetic and potential energies of the molecules within the system, it cannot increase unless there is energy of other forms entering the system.
- In a thermodynamic system, the energy that enters a system can be either in the form of heat supplied or work done on the system or both and these are transformed into internal energy of the system, and so internal energy increases.

S6 The internal energy of a body $U = \frac{3}{2}NkT = \frac{3}{2}nRT$

Self-Practice Questions Suggested Solutions

SP1 **(a)** In one second,

Energy supplied = Energy gained

$$IV(1) = C_{\text{apparatus}}\Delta T + m_{\text{liquid}}c_{\text{liquid}}\Delta T$$

$$c_{\text{liquid}} = \frac{IV - C_{\text{apparatus}}\Delta T}{m_{\text{liquid}}\Delta T}$$

$$= \frac{(3.40)(12.2)-(107)\left(46.3\times10^{-3}\right)}{(0.241)\left(46.3\times10^{-3}\right)}$$

$$= 3273.4$$

$$= 3.27\times10^{3} \text{ kg (3 s.f.)}$$

(b) When the temperature of the liquid is equal to that of the surroundings, the apparatus is neither losing nor gaining heat from the surroundings. There is no need to take into account the heat gain from or loss to the surroundings.

SP2 Since power is constant,

$$P = mc\frac{\Delta T}{\Delta t} = m(1800)\left(\frac{80-20}{200-0}\right) = 540m$$

(a) X takes 200 s to melt.

$$\begin{aligned} Pt &= ml_f \\ (540m)(200) &= ml_f \\ l_f &= 108000 \\ &= 1.08 \times 10^{-5}\ \text{J kg}^{-1} \end{aligned}$$

(b) The temperature of X increases over 100 s.

$$\begin{aligned} Pt_2 &= mc_l(\Delta T)_2 \\ (540m)(100) &= mc_l(110-80) \\ c_l &= 1800\ \text{J kg}^{-1}\ \text{K}^{-1} \end{aligned}$$

SP3 **(a)** Assuming no heat loss to the surroundings,

Electrical energy supplied = heat transferred to gas

$I\,V\,t = m\,c\,(T_{out} - T_{in})$

$0.16 \times 90 = (3.0 \times 10^{-3}) \times 1.8 \times c \times (2.5)$

$c = 1070\ \text{J kg}^{-1}\ \text{K}^{-1}$

(b) Measurements are only taken when the inlet and outlet temperatures have stabilised (i.e. the system has reached steady state). As such, the heat capacity of the apparatus can be ignored.

The heat loss to the surroundings can be eliminated by repeating the experiment again with a different flow rate and adjusting the power of the heating coil, such that the inlet and outlet temperatures remain at the same values as that of the first experiment.

SP4 $\Delta U = Q + W = (-200) + 500 = 300\ \text{J}$

SP5 **(a)**

$$\begin{aligned} W &= -p(\Delta V) = -nR(\Delta T) \\ &= -1.00(8.31)(420-300) = -997\ \text{J} \end{aligned}$$

(b)

$$\begin{aligned} \Delta U &= \frac{3}{2}nR(T_2 - T_1) \\ &= \frac{3}{2}(1.00)(8.31)(420-300) = 1500\ \text{J} \end{aligned}$$

(c) First law of thermodynamics,

$\Delta U = Q + W$

$Q = \Delta U - W = 1495.8 - (-997.2) = 2493 = 2490\ \text{J}\quad (3sf)$

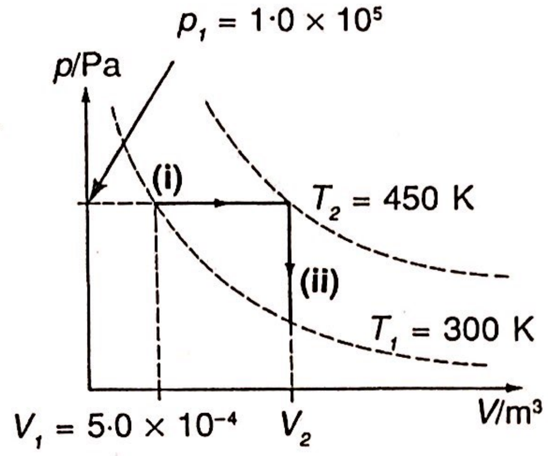
Heat energy transferred to the gas is 2490 J.

SP6 **(a)** Isothermal change refers to the change in pressure and volume of a gas under a constant temperature condition, i.e. $\Delta T = 0$.

(b) Isothermal compression of a gas can be achieved in practice by keeping the gas in a thin-walled, and good conducting vessel placed in a temperature bath. The compression is done slowly, in small steps, to allow for heat flow out of the gas to maintain a constant temperature.

(c) For isothermal compression, the rate of work done on the gas is the same as the rate at which heat is extracted from the gas; hence there is no change in the internal energy.

SP7 **(a)**



(b) $W = p_1\Delta V = p_1(V_2 - V_1)$

Using $\dfrac{V_1}{T_1} = \dfrac{V_2}{T_2}$ at constant p,

$$V_2 = \frac{T_2}{T_1}V_1 = \frac{450}{300}\times V_1$$

$$W = p_1(V_2 - V_1)$$

$$= (1.0\times10^5)\left(\frac{450}{300}V_1 - V_1\right)$$

$$= (1.0\times10^5)\left(\frac{450}{300} - 1\right)(5.0\times10^{-4})$$

$$= 25 \text{ J}$$

(c) From stage **(ii)**, for a constant volume process, applying the First Law of Thermodynamics:

$\Delta U' = Q' + W' = Q' = -63 + 0 = -63$ J

Since ΔU only depends on ΔT for an ideal gas, there is no change in ΔU at the end of stage **(ii)** since the final temperature is the same as the initial temperature.

For stage **(i)**, $\Delta U = +63$ J

$$\Delta U = Q + W$$

$$63 = Q + (-25)$$

$$Q = 63 + 25 = 88 \text{ J}$$

Hence, stage **(i)** has a heat gain of 88 J.