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SENIOR FIVE TERM 2

TOPIC 7/7: THERMODYNAMICS

Competency: The learner appreciates the behaviour of compressed gas systems in relation to their domestic and industrial applications.

Thermodynamics is the branch of physics that studies the relationships between heat, work, energy, and temperature, governed by four fundamental laws. It explains how energy is transferred and transformed in physical systems, from engines to living organisms

Core Concepts of Thermodynamics

- **System & Surroundings**: A system is the part of the universe under study; everything else is surroundings.
- **State Variables**: Properties like pressure, volume, temperature, and internal energy describe the system's condition.
- **Processes**: Changes in a system (isothermal, adiabatic, isobaric, isochoric) define how energy and matter interact.
- **Equilibrium**: A system is in thermodynamic equilibrium when macroscopic properties remain constant over time.

The Four Laws of Thermodynamics

Law	Statement	Key Implication
Zeroth Law	If two systems are each in thermal equilibrium with a third, they are in equilibrium with each other.	Defines **temperature** as a measurable property.
First Law	Energy cannot be created or destroyed, only transformed.	Basis of **energy conservation**.
Second Law	Entropy of an isolated system always increases.	Explains **irreversibility** and efficiency limits of engines.
Third Law	As temperature approaches absolute zero, entropy approaches a constant minimum.	Sets the **absolute zero scale**.

Applications of Thermodynamics

- **Engineering**: Design of heat engines, refrigerators, turbines, and power plants.
- **Chemistry & Biology**: Explains chemical reactions, metabolic processes, and energy transfer in cells.
- **Climate & Earth Science**: Models atmospheric processes, ocean currents, and energy balance of Earth.
- **Everyday Life**: Cooking, heating, cooling, and even the functioning of smartphones rely on thermodynamic principles.

Thermal equilibrium

This is a state of the body in which there is no net flow or exchange of heat within it or between it and its surroundings.

The Zeroth law of thermodynamic

It states that if two bodies are each in thermal equilibrium with a third body, then all the three bodies are in thermal equilibrium with each other.

The principle of conservation of energy

The principle of conservation of energy can be expressed mathematically by the equation

$\Delta Q = \Delta U + \Delta W$

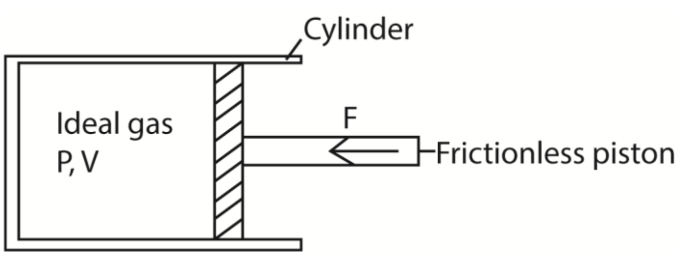
Where

ΔQ is the quantity of heat given to the system

ΔU is the rise in internal energy, the rise in internal energy is indicated by the rise in temperature

ΔW is the external work done by the system such as expansion against atmospheric pressure.

External work done by expanding gas.



Suppose the gas expands by dv so that the piston moves out through a small distance dx.

Work done by the gas, $dW = Fdx$

$= PAdx$

$= Pdv$

Total work done during expansion from v_1 to v_2 is given by

$$W = \int_{v_1}^{v_2} Pdv$$

Example 1

When 1.5kg of water is converted to steam at (100^0C) at standard pressure ($1.01 \times 10^5 Nm^{-2}$) 3.39MJ of heat is required. During the transformation from liquid to vapour, the increase in volume of water is $2.5m^3$.

(i) Calculate the work done against the external pressure during the process of evaporation.
From $\Delta W = P(V_2 - V_1)$
External work done = $1.01 \times 10^5 \times 2.5 = 2.53 \times 10^5$J

(ii) Explain what happens to the rest of the energy.
The difference in energy is the increase in internal energy of water molecules.
i.e. $3.39 \times 10^6 - 2.53 \times 10^5 = 3.24 \times 10^6$J = increase in internal energy of water molecules.

Molar Heat capacities

Definition

Molar heat capacity of a substance is the amount of heat required to raise the temperature of one mole of it by 1K. It is expressed in $Jmol^{-1}K^{-1}$.

Molar heat capacity at constant volume, c_v

Molar heat capacity at constant volume of a substance is the amount of heat required to raise the temperature of one mole of it by 1K at constant volume. It is expressed in $Jmol^{-1}K^{-1}$.

In a **constant volume (isochoric) process**, the volume of the system remains fixed, meaning the change in volume (ΔV) is zero. Consequently, **no work is done by the gas** because it cannot expand or contract to move its boundaries (like a piston). Any heat added to the system goes entirely into increasing its internal energy and temperature, which results in an increase in pressure.

Formula: $W = -P \times 0 = 0$

Real-world application of constant volume(isochoric)process (e.g., Gas cooker, welding gas cylinders):

- **Sealed gas cylinders** represent a nearly constant volume system. The high-pressure gas inside does no work until a valve is opened, allowing it to escape.
- When using a **gas cooker** heat added increases the temperature and pressure of the contents only with no work done until the valve is opened to allow expansion and escape of gases.

Molar heat capacity at constant pressure, c_p

Molar heat capacity at constant pressure of a substance is the amount of heat required to raise the temperature of one mole of it by 1K at constant pressure. It is expressed in $Jmol^{-1}K^{-1}$.

In a **constant pressure (isobaric) process**, the pressure of the system remains constant, but the volume is free to change. In this scenario, **work is done by the gas** as it expands or work is done *on* the gas as it is compressed. Part of any heat added is used for this expansion work, and the rest changes the internal energy of the gas.

Formula: $W = -P\Delta V$ (where P is pressure and ΔV is the change in volume)

Real-world application constant pressure (isobaric) process (e.g., Compressors for refrigerators/ACs):

- **Refrigerators and air conditioners** work is done by the **compressor** *on* the refrigerant gas to decrease its volume and increase its pressure as part of cooling cycle.
- Inflation of a balloon does work against external atmospheric pressure
- Gas cylinder, work is done when filling gas cylinders because it involves compression/decrease in volume of a gas but increase in pressure.
- **Gas compressors** do work when the turn a gas into a liquid which involves a descrease in volume but increase in pressure

The relationship between the principal molar heat capacities C_p and C_v for an deal gas.

From dQ = dU + dW……………. (i)
But dQ = C_pdT, dU = C_vdT and dW= PdV = RdT
Substituting in (i)

C_pdT = C_vdT + RdT
$\therefore C_p - C_v = R$
Where R is the universal gas constant per unit mass.

Example 2

The temperature of 1mole of helium gas at a pressure of 1.0 x 10^5Pa increases from 20^0C to 100^0C when the gas is compressed adiabatically.

Find the final pressure of the gas. (Take $^{C_p}/_{C_v}$ =γ =1.67) (04 marks)

$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$
$$but\ V = \frac{nRT}{P} => \frac{P_1T_1^{\gamma}}{P_1} = \frac{P_2T_2^{\gamma}}{P_2}$$
$$=> \frac{T_1^{\gamma}}{P_1^{\gamma-1}} = \frac{T_2^{\gamma}}{P_2^{\gamma-1}}$$
$$\frac{(293)^{1.67}}{(1.0\ x\ 10^5)^{0.67}} = \frac{(373)^{1.67}}{(P)^{0.67}}$$
$$P = 1.87\ x\ 10^5 Pa$$

Example 3

Nitrogen gas is trapped in a container by a movable piston. If the temperature of the gas is raised from 0^0C to 50^0C at constant pressure of 4.0 x 10^5Pa and the total heat added is 3.0 x 10^4J, calculate the work done by the gas. [The molar heat capacity of nitrogen at constant pressure is 29.1Jmol^{-1}K^{-1}, C_p/C_v= 1.4]

ΔQ = ΔU + Δw …………………… (i)

Cv = $\frac{C_p}{1.4} = \frac{29.1}{1.4}$ = 20.79Jmol^{-1}

ΔQ = $nC_p\Delta T$

n = $\frac{\Delta Q}{C_p \Delta T} = \frac{3 \, x \, 10^4}{29.1 \, x \, 50} = 20.62$

From equation (i)

3 x 10^4 = 20.62 x 20.79 (50-0) + Δw

Δw = 8.57 x 10^3J

Example 4

Ten moles of a gas, initially at 27^0C are heated at constant pressure of 1.01 x 10^5Pa and volume increased from 0.25m^3 to 0.375m^3. Calculate the increase in internal energy.

[Assume C_p = 28.5Jmol^{-1}K^{-1}] (06marks)

T_1 = 27^0C = 300K

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

$\frac{0.250}{300} = \frac{0.375}{T_2}$; T_2 = 450K

$\Delta T = 450 - 300 = 150K$

ΔQ = ΔU + Δw

$nC_p\Delta T = nC_v\Delta T + nR\Delta T$

$nC_v\Delta T = nC_p\Delta T - nR\Delta T$

= 10 x 28.5 x 150 – 10 x 8.31 x 150

= 3.03 x 10^4J

Example 5

An ideal gas at 18^0C is compressed adiabatically until the volume is halved. Calculate the final temperature of the gas. [Assume specific heat capacities of the gas at constant pressure and volume are 2100Jkg^{-1}K^{-1} and 1500Jkg^{-1}K^{-1}] respectively. (04marks)

$T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1}$

$\gamma = \frac{2100}{1500} = 1.40$

⇨ $291(V)^{1.4-1} = T_2\left(\frac{V}{2}\right)^{1.4-1}$

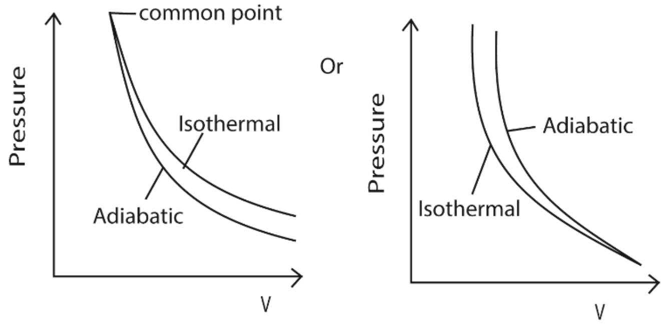
T_2 = 384K

Isothermal and adiabatic changes

Isothermal expansion takes place at constant temperature.

Adiabatic expansion takes place at constant heat.

Sketch graphs of pressure versus volume for fixed mass of a gas undergoing isothermal and adiabatic changes.



Condition necessary for realization of an isothermal change

(i) The gas must be held in thin-walled and highly conducting vessel
(ii) The process must take place slowly so that heat pass into the gas to maintain constant temperature.
(iii) The gas vessel must be surrounded by a constant temperature bath.

Conditions for adiabatic change

(i) The gas must be held in a thick walled and poorly conducting vessel
(ii) The process must be carried out rapidly to minimize heat linkage through the walls.

Relationship between volume, pressure and temperature

(i) For reversible isothermal change
PV = nRT where n is the number of mole of gas, R = gas constant
(ii) For reversible adiabatic change
Pv^{γ} = constant
$TV^{\gamma-1}$ = constant

Example 6

Ten moles of a gas, initially at 27^0C are heated at constant pressure of 1.01 x 10^5Pa and volume increased from 0.25m^3 to 0.375m^3. Calculate the increase in internal energy.
[Assume C_p = 28.5$Jmol^{-1}K^{-1}$] (06marks)

$T_1 = 27^0C = 300K$

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

$\frac{0.250}{300} = \frac{0.375}{T_2}$; T_2 = 450K

$\Delta T = 450 - 300 = 150K$

ΔQ = ΔU + Δw

$nC_p\Delta T = nC_v\Delta T + nR\Delta T$

$nC_v\Delta T = nC_p\Delta T - nR\Delta T$

= 10 x 28.5 x 150 – 10 x 8.31 x 150

$= 3.03 \times 10^4 J$

Example 7

An ideal gas at 18^0C is compressed adiabatically until the volume is halved. Calculate the final temperature of the gas. [Assume specific heat capacities of the gas at constant pressure and volume are $2100Jkg^{-1}K^{-1}$ and $1500Jkg^{-1}K^{-1}$] respectively. (04marks)

$$T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1}$$

$$\gamma = \frac{2100}{1500} = 1.40$$

$$\Rightarrow \; 291(V)^{1.4-1} = T_2\left(\frac{V}{2}\right)^{1.4-1}$$

$T_2 = 384K$

Example 8

State the first law of thermodynamics and use it to distinguish between Isothermal and adiabatic changes in a gas. (05marks)

$$\Delta Q = \Delta U + \Delta W = nC_v\Delta T + \Delta W$$

During isothermal expansion, $\Delta T = 0$. Therefore all the energy supplied is equal to the work done by the gas during expansion.

In adiabatic expansion, no heat enters or leaves the gas. Therefore $\Delta Q = 0$ and $\Delta U = -\Delta W$.

In adiabatic expansion, work s done at the expense of its internal energy. Therefore the gas cools.

Example 9

(a) (i) What is meant by isothermal process and adiabatic process? (02marks)

Isothermal process is the expansion or compression of a gas at constant temperature.

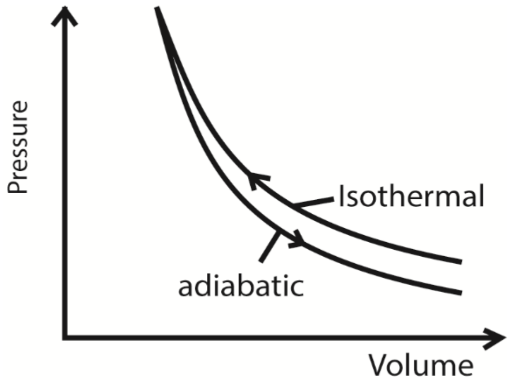
Adiabatic process is the expansion or compression of a gas where there is no heat loss or gain into the gas.

(ii) Explain why adiabatic expansion of a gas causes cooling (03marks)

During an adiabatic expansion of a gas, no heat is supplied to the gas. Molecules strike the receding piston and bounce off with reduced velocities and hence lower kinetic energy. Since kinetic energy is proportional to temperature, the gas cools during the expansion

(b) A gas at a temperature of 17^0C and pressure 1.0×10^5Pa compressed isothermally to half its original volume. It is then allowed to expand adiabatically to its original volume

(i) Sketch a P-V curve the above process (02marks)



(ii) If the specific heat capacity at constant pressure is 2100Jmol^{-1}K^{-1} and at constant volume is 1500Jmol^{-1}K^{-1}, find the final temperature of the gas (04marks)

$\gamma = \frac{2100}{1500} = 1.4$

$T_2 V_2^{\gamma-1} = T_3 V_3^{\gamma-1}$

$290\left(\frac{V}{2}\right)^{0.4} = T_3 V^{0.4}$

$T_3 = 219.8K$

Thank you
Dr. Bbosa Science