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# 10.2 Thermodynamics & Engines

XVIII

# Engineering Physics

## AQA A Level Revision Notes

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# A Level Physics AQA

## 11.2 Thermodynamics & Engines

**CONTENTS**



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11.2.1 The First Law of Thermodynamics

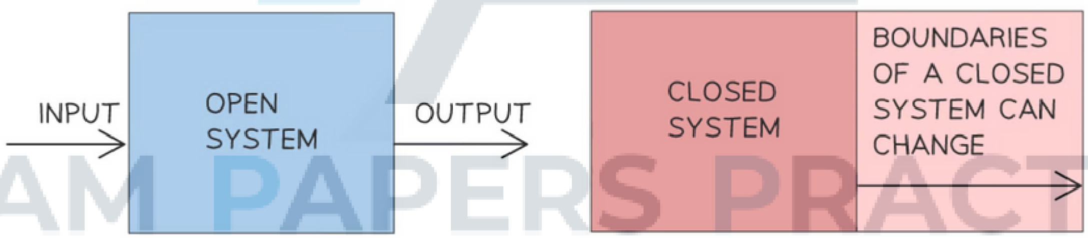
## The First Law of Thermodynamics

- The first law of thermodynamics is based on the principle of conservation of energy
  - This applies to heating, cooling and work done
- The first law can be expressed in different ways, depending on the sign convention used
- For AQA, the first law of thermodynamics is therefore defined as:

$$Q = \Delta U + W$$

- Where:
  - $\Delta U$ = increase in internal energy (J)
  - $Q$ = energy supplied to the system by heating (J)
  - $W$ = work done by the system (J)
- The 'system' is a region of space containing a quantity of gas
- The system is **open** if gas or vapour flows into and out of the region
  - Examples include a gas expanding through the nozzle of an aerosol can or steam passing through a turbine
- The system is **closed** if gas or vapour remains within the region, although the boundary can expand or contract with changes in the volume of the gas
  - Examples include gas expanding in a cylinder by moving a piston or air in a balloon being heated

Open and closed systems




***An open system is where gas can flow in and out, whilst in a closed system, gas can only remain within the boundary***

- In both systems, work can 'cross' the boundary

- The first law of thermodynamics applies to **all** situations, not just to gases
  - There is an important sign convention used for this equation

- Amount of heat transfer Q is:
  - **Positive** if heat energy is **added**
  - **Negative** if heat energy is **removed**
- The change in internal energy $\Delta U$ is:
  - **Positive** if the internal energy **increases**
  - **Negative** if the internal energy **decreases**
- The work done, $W$ is: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- **Positive** if work is done **by** the gas (the gas expands)
- **Negative** if the work is done **on** the gas (the gas is compressed)

## Worked Example

The volume occupied by 1.00 mol of a liquid at 50°C is $2.4 \times 10^{-5}$ m$^3$. When the liquid is vaporised at an atmospheric pressure of $1.03 \times 10^5$ Pa, the vapour occupies a volume of $5.9 \times 10^{-2}$ m$^3$.

The latent heat to vaporise 1.00 mol of this liquid at 50°C at atmospheric pressure is $3.48 \times 10^4$ J.

For this change of state, determine the increase in internal energy $\Delta U$ of the system.

**Answer:**

**Step 1: List the known quantities**

- Thermal energy, $Q = 3.48 \times 10^4$ J
- Atmospheric pressure, $p = 1.03 \times 10^5$ Pa
- Initial volume = $2.4 \times 10^{-5}$ m$^3$
- Final volume = $5.9 \times 10^{-2}$ m$^3$

**Step 2: Calculate the work done $W$**

- The work done by a gas at constant pressure is

$$W = p\Delta V$$

- Where the change in volume is:

$$\Delta V = \text{final volume} - \text{initial volume} = (5.9 \times 10^{-2}) - (2.4 \times 10^{-5}) = 0.059 \text{ m}^3$$

- Since the volume of the gas decreases (it is compressed), the work done is negative

$$W = (1.03 \times 10^5) \times 0.059 = 6077 = 6.08 \times 10^3 \text{ J}$$

$$W = -6.08 \times 10^3 \text{ J}$$

**Step 3: Substitute the values into the equation for the first law of thermodynamics**

- From the first law of thermodynamics:

$$\Delta U = Q + W$$

$$\Delta U = (3.48 \times 10^4) + (-6.08 \times 10^3) = 28\,720$$

- Increase in internal energy: $\Delta U = 28\,700$ J (3 s.f.)



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**Exam Tip**

The sign convention is **very** important for AQA, make sure you understand how it is used from the worked example.

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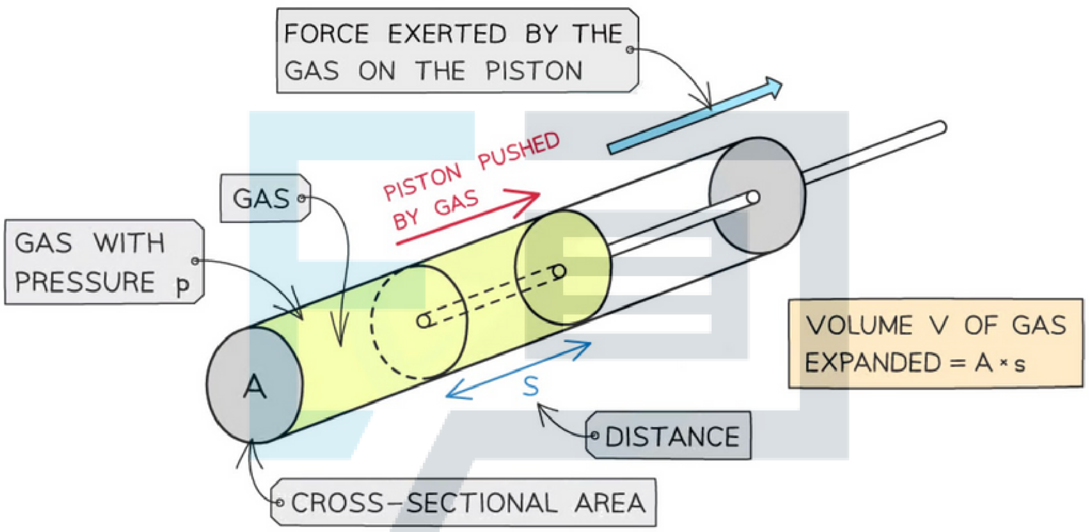
11.2.2 p-V Diagrams

## p–V Diagrams

- When a gas **expands**, it **does work** on its surroundings by exerting pressure on the walls of the container it's in
- For a gas inside a piston, the force exerted by the gas pushes the piston outwards
  - As a result, work is done **by** the gas when the piston expands the volume of the gas
- Alternatively, if an external force is applied to the piston, the gas will be **compressed**
  - In this case, work is done **on** the gas when the piston compresses the gas

Gas pushed in a piston




***The expansion of the gas does work on the piston by exerting a force over a distance, s***

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- The work done when the volume of a gas changes at constant pressure is:

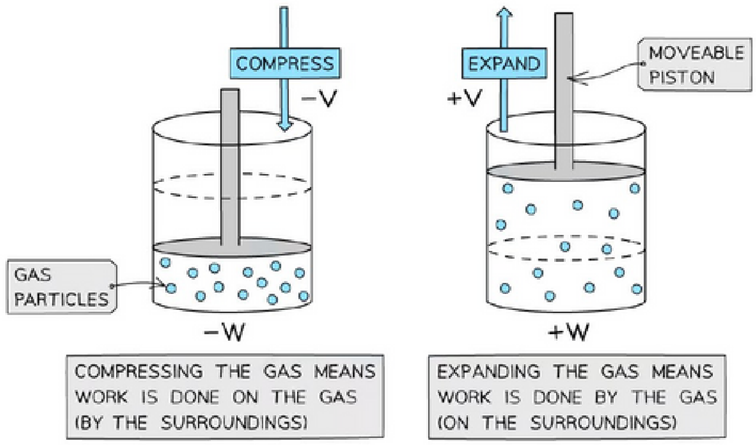
$$W = p\Delta V$$

- Where:
  - $W$ = work done (J)
  - $p$ = pressure of the gas (Pa)
  - $\Delta V$ = change in the volume of the gas ($m^3$)
- This equation assumes that the surrounding pressure does not change as the gas expands
  - This is true if the gas is expanding against the pressure of the atmosphere, which changes very slowly

## p-V diagrams

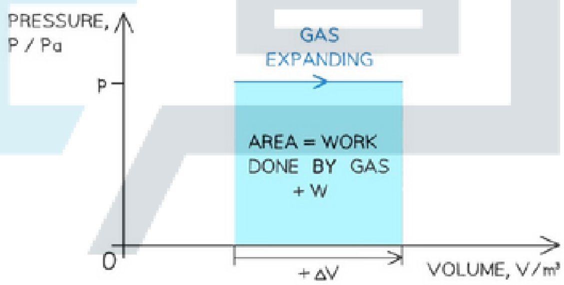
- Pressure-volume ($p$-$V$) diagrams are often used to represent changes in the **state of a gas** in thermodynamic processes

Gas expanding and compressing in a cylinder by a piston




***Positive or negative work done depends on whether the gas is compressed or e***

- The **area under** a $p$–$V$ diagram tells us how much work is done
- When a gas **expands** (at constant pressure) ***work done is positive***
  - Volume increases $+\Delta V$
  - Work is done **by** the gas $+W$

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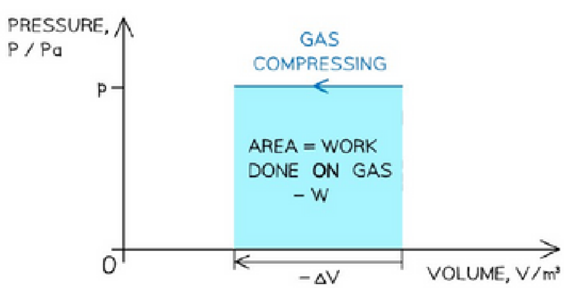
- When a gas is **compressed** (at constant pressure) ***work done W is negative***
  - Volume decreases $-\Delta V$
  - Work is done **on** the gas $-W$




- When both the volume and pressure of gas **changes**

**The work done can be determined from the area under a p–V diagram**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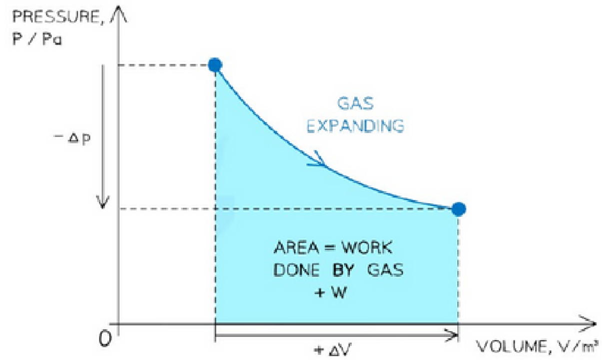


- In the context of engines, these are referred to as **indicator diagrams**

## Worked Example

When a balloon is inflated, its rubber walls push against the air around it.

Calculate the work done when the balloon is blown up from 0.015 $m^3$ to 0.030 $m^3$.

Atmospheric pressure = $1.0 \times 10^5$ Pa.

**Answer:**

- The work done by a gas is equal to

$$W = p\Delta V$$

- Where the change in volume is

$$\Delta V = \text{final volume} - \text{initial volume} = 0.030 - 0.015 = 0.015 \text{ m}^3$$

- Therefore, work done is

$$W = (1.0 \times 10^5) \times 0.015 = 1500 \text{ J}$$

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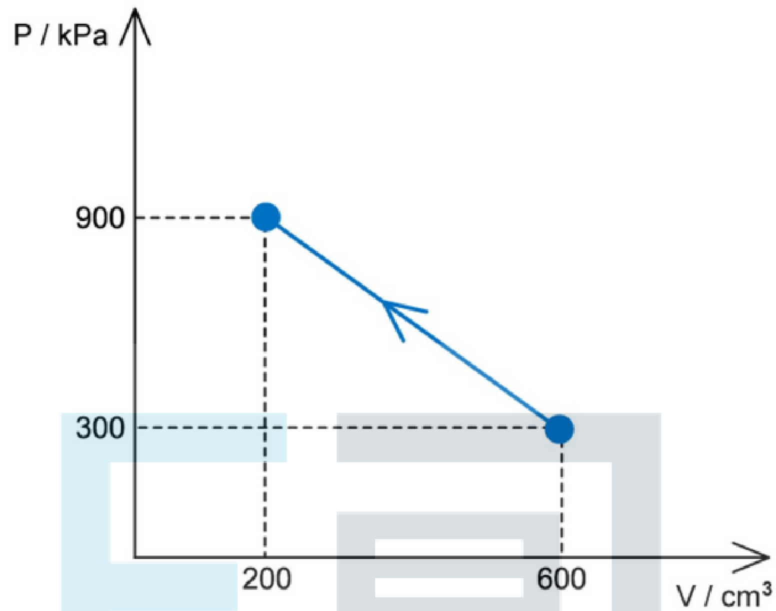
## Worked Example

An ideal gas is compressed, as shown on the graph below.




(a)

For this change, state and explain whether work is done on the gas or by the gas

(b)

Determine the value of the work done and state whether it is positive or negative

**Answer:**

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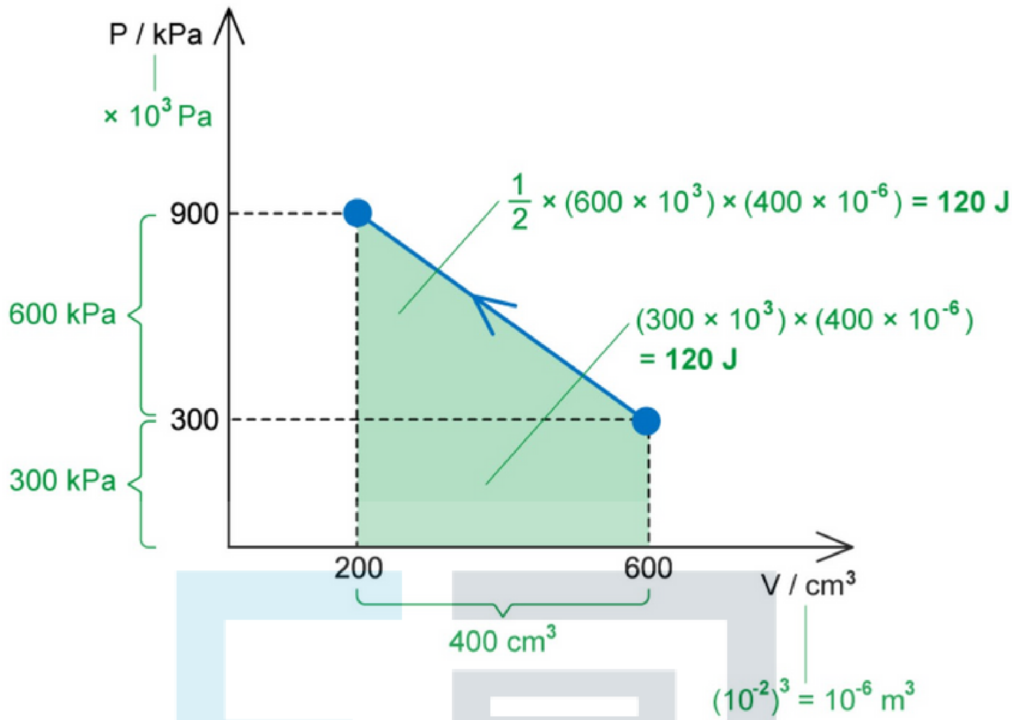
**(a)**

- The volume decreases, therefore, work is done **on the gas**

**(b)**

- The work done is equal to the area under the p-V diagram




$$W = \frac{1}{2}(600\times10^3)(400\times10^{-6}) + (300\times10^3)(400\times10^{-6})$$

Work done on the gas, $W$ = 240 J

**Exam Tip**

Interpreting $p$-$V$ diagrams is a very important part of Thermodynamics. Questions linked to the ideal gas equation, $PV = nRT$ or $\frac{pV}{T}$ = constant might also be involved.

11.2.3 Thermodynamic Processes

## Thermodynamic Processes

- The four main thermodynamic processes are
  - Constant volume ($W = 0$)
  - Constant pressure ($\Delta p = 0$)
  - Isothermal ($\Delta T = 0$)
  - Adiabatic ($\Delta Q = 0$)

# Constant pressure

- An **isobaric** (constant pressure) process is defined as:

**A process in which no change in pressure occurs**

- This occurs when gases are allowed to expand or contract freely during a change in temperature
- When there is a change in volume $\Delta V$ at a constant pressure $p$, work done $W$ is equal to

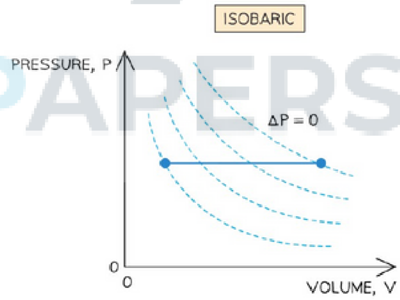
$$W = p\Delta V$$

- From the first law of thermodynamics:

$$Q = \Delta U + W$$

$$Q = \Delta U \pm p\Delta V$$

- The ± sign reflects whether work has been done on or by the gas as a result of the change in volume




***The solid blue line represents an isobaric process at constant pressure on a p-V diagram***

# Constant volume

- An **isovolumetric** (constant volume) process is defined as:

**A process where no change in volume occurs and the system does no work**

- If there is no change in volume, then there is no work done on or by the gas, so $W = 0$
- Therefore, from the first law of thermodynamics:

$$Q = \Delta U + W = \Delta U + 0$$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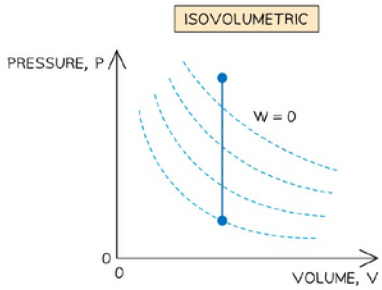
$$Q = \Delta U$$




***The solid blue line represents an isovolumetric process at constant volume on a p-V diagram***

## Constant temperature (isothermal)

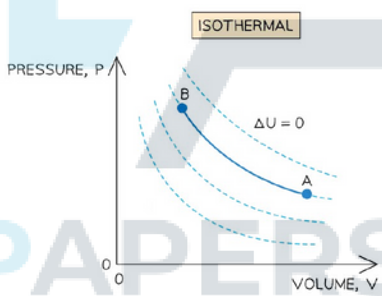
- An **isothermal** process is defined as:

**A process in which no change in temperature occurs**

- If the temperature does not change, then the internal energy of the gas will not change, so $\Delta U = 0$
- Therefore, from the first law of thermodynamics:

$$Q = \Delta U + W = 0 + W$$

$$Q = W$$




***The solid blue line represents an isothermal process with constant temperature on a p-V diagram***

## Constant thermal energy (adiabatic)

- An **adiabatic** process is defined as:

**A process where no heat is transferred into or out of the system**

- If there is no heat entering or leaving the system then $Q = 0$
- Therefore, from the first law of thermodynamics:

$$Q = \Delta U + W = 0$$

$$W = -\Delta U$$

- This means that all the work done is at the expense of the system's internal energy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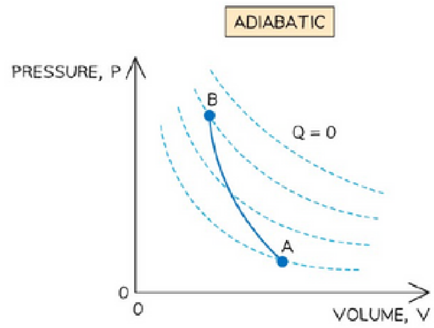
- Hence, an adiabatic process will usually be accompanied by a change in temperature




***The solid blue line represents an adiabatic process with constant thermal energy on a p-V diagram***

## Adiabatic Processes

- Adiabatic processes in ideal gases can be modelled by the equation

$$pV^{\gamma} = constant$$

- Where:
  - $p$ = pressure of the gas (Pa)
  - $V$ = volume occupied by the gas ($m^3$)
- This equation can be used for calculating changes in pressure, volume and temperature, e.g. for monatomic ideal gases, where $\gamma = \frac{5}{3}$

$$p_1 V_1^{\frac{5}{3}} = p_2 V_2^{\frac{5}{3}}$$

- Where:
  - $p_1$ = initial pressure (Pa)
  - $p_2$ = final pressure (Pa)
  - $V_1$ = initial volume ($m^3$)
  - $V_2$ = final volume ($m^3$)

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## Worked Example

A quantity of energy Q is supplied to three ideal gases **X**, **Y** and **Z**.

Gas **X** absorbs Q isothermally, gas **Y** isovolumetrically and gas **Z** isobarically.

Complete the table by inserting the words 'positive', 'zero' or 'negative' for the work done *W*, the change in internal energy *ΔU* and the temperature change *ΔT* for each gas.

| | $W$ | $\Delta U$ | $\Delta T$ |
|---|---|---|---|
| **X** | | | |
| **Y** | | | |
| **Z** | | | |

**Answer:**

- **X**: Isothermal = constant temperature, no change in internal energy
  - Temperature: $\Delta T = 0$
  - Internal energy: $\Delta T \propto \Delta U$, so, $\Delta U = 0$
  - Work done: $Q = \Delta U + W \Rightarrow Q = +W$
- **Y**: Isovolumetric = constant volume, no work done
  - Work done: $W \propto \Delta V$, so, $W = 0$
  - Internal energy: $Q = \Delta U + W \Rightarrow Q = +\Delta U$
  - Temperature: $\Delta T \propto \Delta U$, so, $\Delta T > 0$
- **Z**: Isobaric = constant pressure
  - Work done: $\Delta p = 0$, so $W = p\Delta V$, so $W > 0$
  - Internal energy: $Q = \Delta U + W$, so $\Delta U > 0$
  - Temperature: $\Delta T \propto \Delta U$, so $\Delta T > 0$

| | $W$ | $\Delta U$ | $\Delta T$ |
|---|---|---|---|
| **X** | positive | 0 | 0 |
| **Y** | 0 | positive | positive |
| **Z** | positive | positive | positive |

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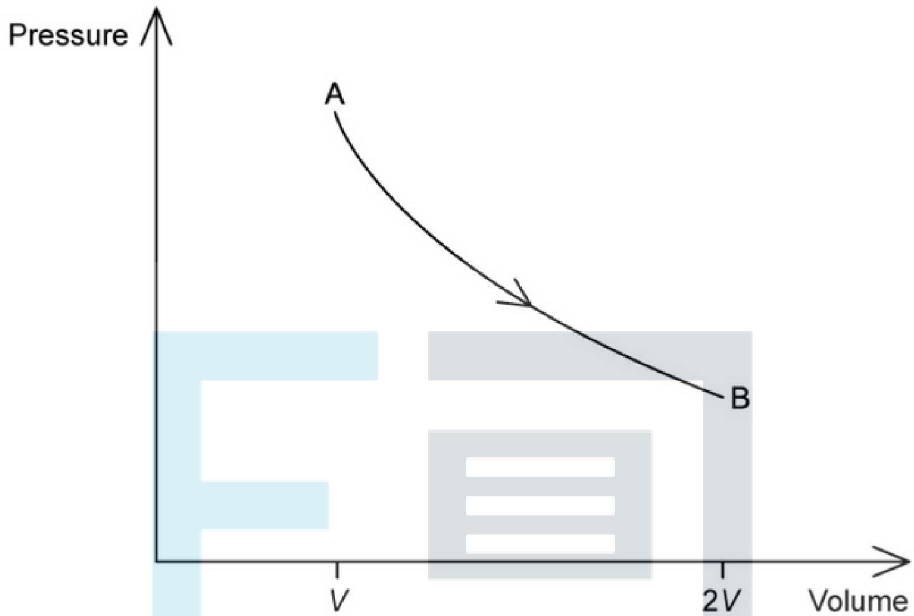
## Worked Example

A heat engine operates on the cycle shown in the pressure-volume diagram. One step in the cycle consists of an isothermal expansion of an ideal gas from state A of volume $V$ to state B of volume $2V$.




On the graph, complete the cycle ABCA by drawing curves to show

- a change at constant volume from state B to state C
- an adiabatic compression from state C to state A

**Answer:**

- **Constant volume** = no work done
- Next step is a compression (where pressure increases), so this step should involve a **pressure drop**
  - Hence, B to C: line drawn vertically down
- **Adiabatic** = no heat supplied or removed, **compression** = work is done on the gas, volume decreases
  - Hence, C to A: line curves up to meet A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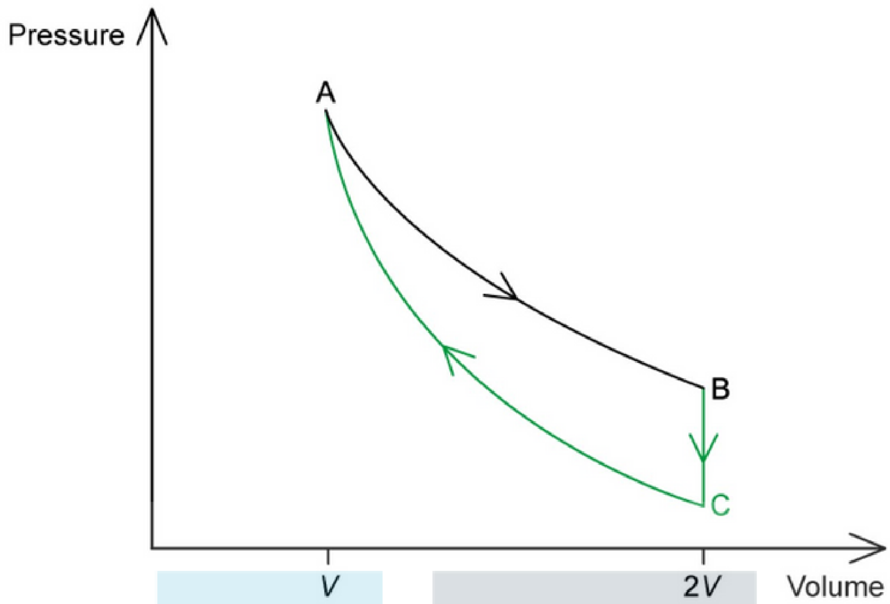


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## Worked Example

An ideal monatomic gas $\left(\gamma = \frac{5}{3}\right)$ expands adiabatically from a state with pressure $7.5 \times 10^5$ Pa and volume $1.8 \times 10^{-3}$ m$^3$ to a state of volume $4.2 \times 10^{-3}$ m$^3$.

Calculate the new pressure of the gas.

**Answer:**

- For an ideal monatomic gas undergoing an adiabatic change:

$$pV^{\frac{5}{3}} = C$$

$$p_1 V_1^{\frac{5}{3}} = p_2 V_2^{\frac{5}{3}}$$

- Where:
  - Initial pressure, $p_1 = 7.5 \times 10^5$ Pa
  - Final pressure = $p_2$
  - Initial volume, $V_1 = 1.8 \times 10^{-3}$ m$^3$
  - Final volume, $V_2 = 4.2 \times 10^{-3}$ m$^3$

$$p_2 = p_1 \left(\frac{V_1}{V_2}\right)^{\frac{5}{3}}$$

$$p_2 = (7.5 \times 10^5) \times \left(\frac{1.8 \times 10^{-3}}{4.2 \times 10^{-3}}\right)^{\frac{5}{3}}$$

New pressure: $p_2 = 1.8 \times 10^5$ Pa

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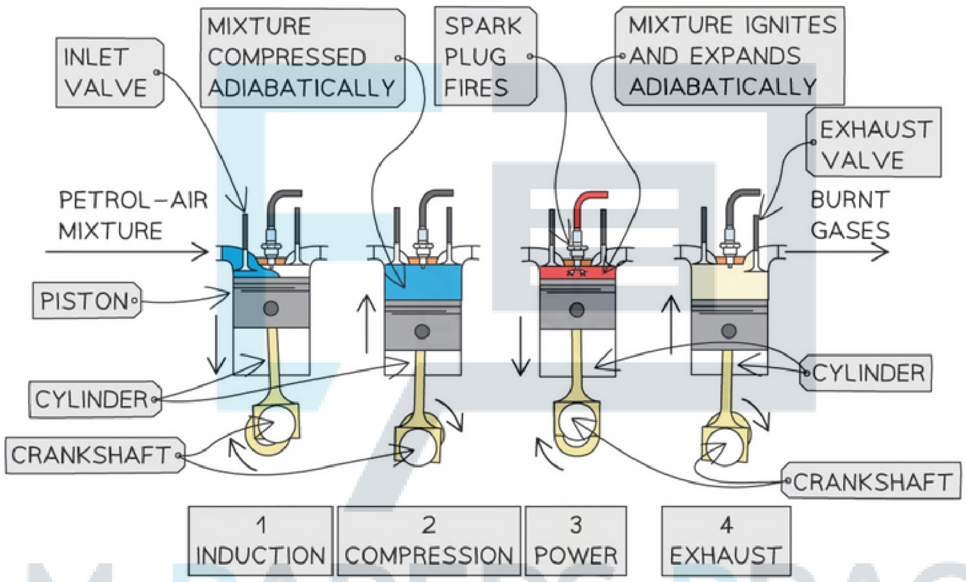
11.2.4 The Otto Cycle

## The Otto Cycle

# The Four-Stroke Petrol Engine Cycle

- A heat engine is a device that extracts energy from its environment in the form of heat and converts it into useful work
- A four-stroke engine is an internal combustion engine that burns fuel **once** every 4 strokes of the piston
  - This is commonly used in ordinary cars
- Inside the engine, a piston moves easily up and down in a cylinder
  - Each movement of the piston up or down is a 'stroke'

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***The four 'strokes' of the petrol engine cycle***

- For the full 4 strokes, this requires **2** revolutions of the crankshaft (used to move the piston up and down)

## Induction

- The piston moves down the cylinder, increasing the volume of the petrol-air mixture which is drawn into the cylinder by the inlet valve
- The pressure in the cylinder remains constant, just below atmospheric pressure

## Compression

- The inlet valve is closed and the piston moves back up, doing work on the gas
- This compresses the gas, causing its **volume** to **decrease** and **pressure** to **increase**
  - This process is done adiabatically
- Almost at the end of the piston's stroke, the petrol-air mixture is ignited by a spark at the spark plug

- The temperature and pressure of the gas increase rapidly, at an almost constant volume

## Power

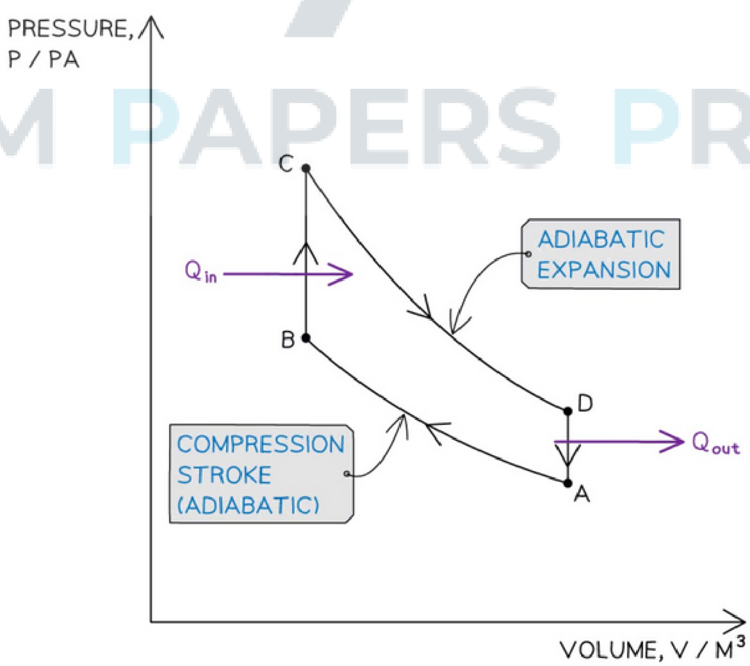
- The high pressure forces the piston back down the cylinder, so work is done by the expanding gas
- The exhaust valve opens when the piston is very near the bottom of the stroke, and the pressure reduces almost to atmospheric pressure

## Exhaust

- The piston moves up the cylinder, forcing the burnt gases through the open exhaust valve and out of the cylinder
- The pressure in the cylinder remains at just above atmospheric pressure

# Indicator Diagrams

- Indicator diagrams are p-V diagrams for engines
  - They are used to calculate the output power and efficiency
- The **theoretical** indicator diagram produced from a four-stroke petrol engine uses the following assumptions:
  - The same gas / air is constantly moving through the cycle repeatedly
  - The pressure and temperature can change instantaneously
  - The expansion and compression happens adiabatically
  - The engine experiences no friction
  - The heat source is external
- This theoretical diagram would look like this:




***Theoretical indicator diagram for a four-stroke petrol engine***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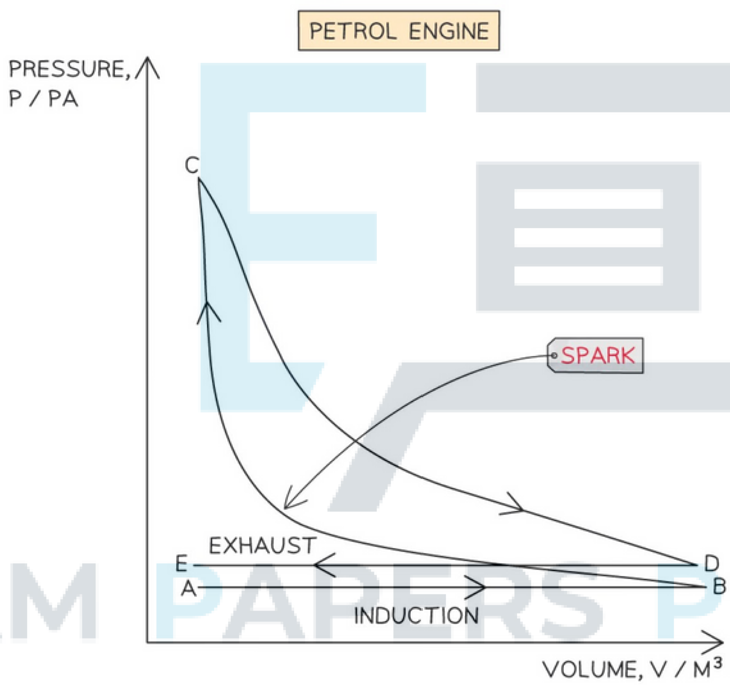
- From **A** to **B**:
  - The gas is compressed adiabatically
- From **B** to **C**:
  - **Heat** is supplied and the volume is kept constant
  - Ignition for the spark occurs
- From **C** to **D**:
  - The gas expands adiabatically (cooling)
- From **D** to **E**:
  - The system is cooled at a constant volume (heat leaves the system)

- The four-stroke petrol engine cycle is sometimes referred to as the Otto cycle

- The **actual** indicator diagram is formed using recorded data, using a pressure sensor and transducer in the cylinder, and looks slightly different:




***Actual indicator diagram for a four-stroke petrol engine***

- From **A** to **B** is:
  - The induction (intake of air)
- From **B** to **C** is:
  - The compression
- From **C** to **D** is:
  - The expansion
- From **D** to **E** is:
  - The exhaust (expelling of the air)
- The **work done** on the gas during the compression stroke is given by the area **underneath** the compression curve (**B–C**), and the work done by the gas during the expansion stroke is given by the area underneath the expansion curve (**C–D**)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  - Therefore the net work done by the air is given by the area enclosed by the loop (**B**–**C**–**D**) on the *p*-*V* diagram
  - For this actual cycle, the **area** (and therefore work done) enclosed by the loop in the diagram is always **less** than the theoretical loop

## Comparing Actual and Theoretical Indicator Diagrams

- The key **differences** between the actual and theoretical indicator diagrams are:
  - In the actual diagram, the corners of the graph. are rounded
    - This is because the valve takes a finite time to open and close (the combustion is not instantaneous)
  - The heating and cooling cannot occur at a constant volume
    - For this, the temperature and pressure increase to be instantaneous or the piston would have to stop at the top of the stroke
  - In reality, the expansion and compression are not adiabatic
    - There is some heat transfer taking place to cool the gas during these strokes
  - In a real engine, some exhaust gas or fuel vapour is often present, not pure air
  - The fuel may not be completely burnt at the end of the cycle
  - The induction and exhaust strokes (the horizontal lines in the ideal diagram) are usually omitted from the theoretical diagram
    - In the exhaust stroke, heat $Q_{out}$ is ejected into the environment. In a real engine, the gas leaves the engine and is replaced by a new mixture of air and fuel

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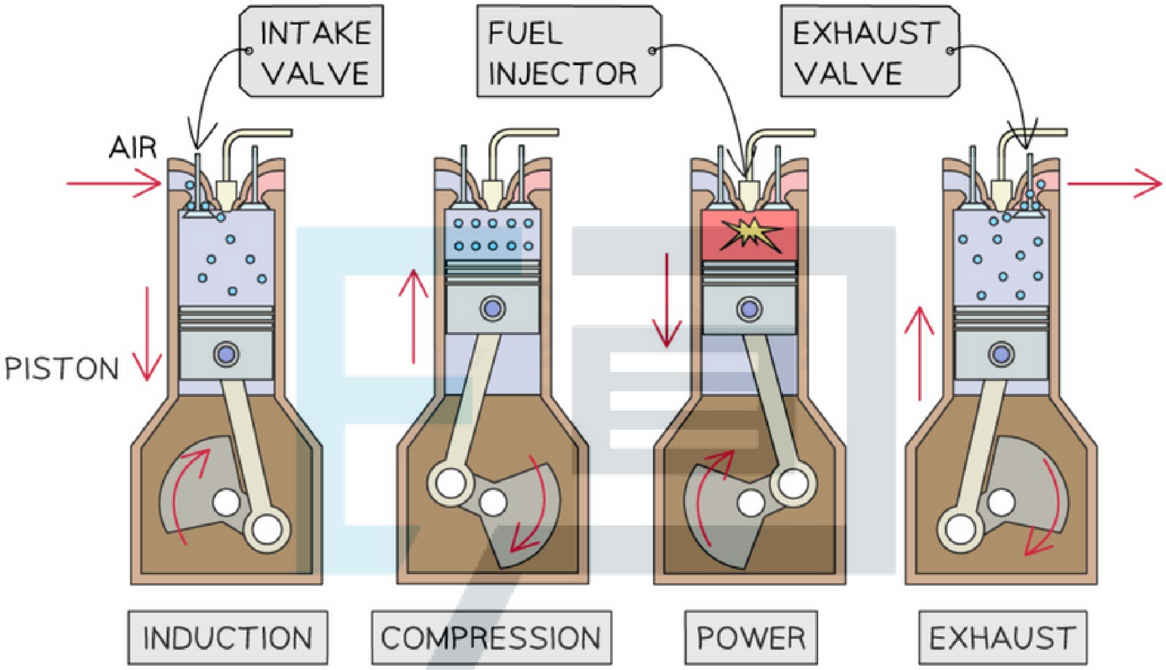
## Diesel Engine Cycle

# The Diesel Engine Cycle

- A diesel engine cycle is not that different from a petrol engine cycle
- It still consists of 4 strokes, but they work differently

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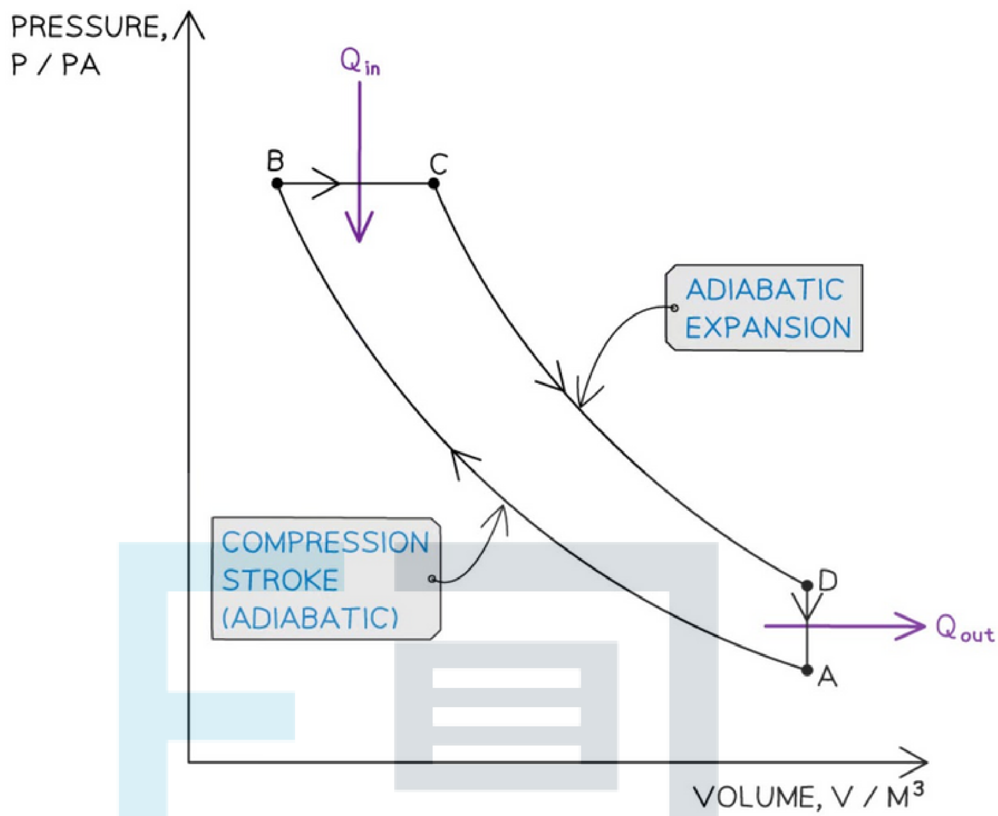
***The four 'strokes' of the diesel engine cycle***

- In the induction (or intake) stroke, only **air** is drawn into the cylinder (compared to a petrol-air mixture in the petrol engine)
  - This means there is no **fuel** in the cylinder during compression
- During the compression stroke, the air is compressed at a high temperature which vapourises and ignites the **diesel fuel** (as a fine spray) pumped directly into the cylinder through an injector
- The expansion and exhaust stages are similar

# Indicator Diagrams

- This theoretical diagram would look like this:




***Theoretical indicator diagram for a four-stroke diesel engine***

- From **A** to **B**:
  - The gas is compressed adiabatically
- From **B** to **C**:
  - Heat is supplied and the **pressure** is kept constant
- From **C** to **D**:
  - The gas expands adiabatically (cooling)
- From **D** to **E**:
  - The system is cooled at a constant volume

- The **actual** indicator diagram looks like: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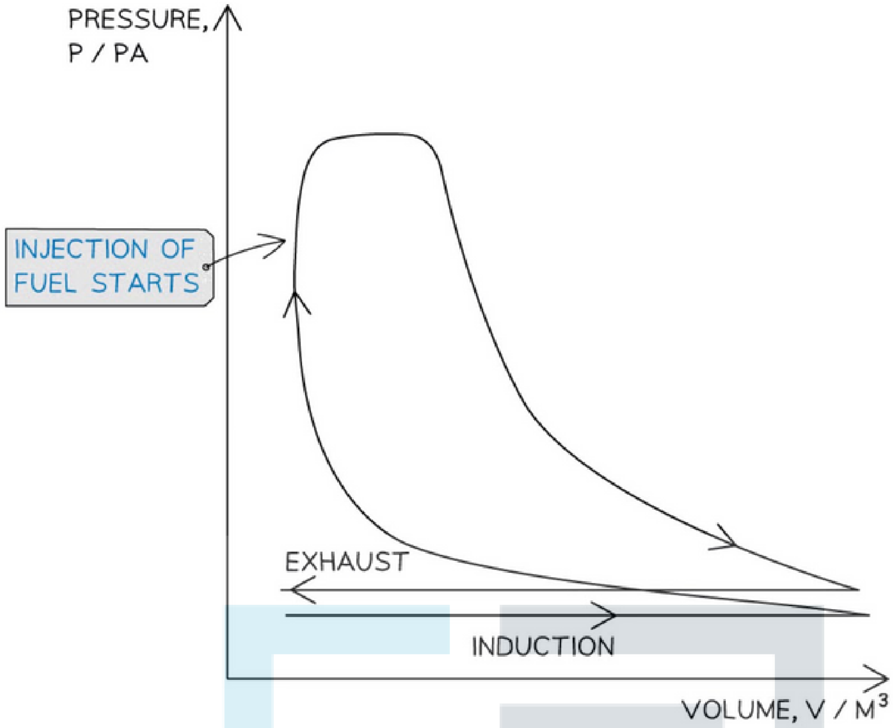


- The biggest difference is from **B** to **C** – there is **no** sharp peak at the start of the expansion stroke

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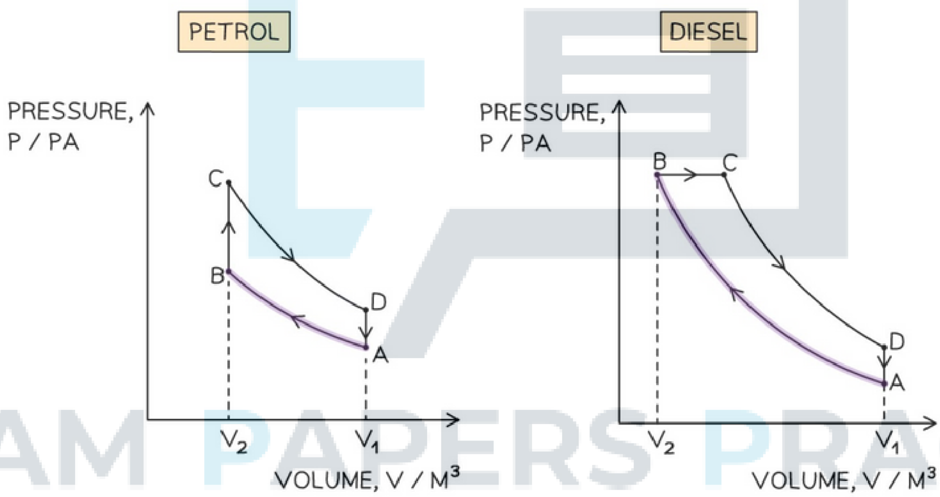
11.2.6 Comparing Petrol & Diesel Engines

## Comparing Petrol & Diesel Engines

- Diesel engines are more efficient than petrol engines, and this can be seen from their indicator diagrams
- Efficiency is directly proportional to the **compression ratio** of an engine, which is defined as:

$$\frac{\text{volume enclosed at the beginning of compression stroke}}{\text{volume enclosed at the end of the compression stroke}}$$

- The compression stroke of the engine is when the volume of the gas decreases, as the piston moves **upwards**
  - This is when work is done **on** the gas
- On an indicator diagram, this is the ratio $\frac{V_1}{V_2}$




- The area under this line is the **work done on the gas**
- A diesel engine can achieve a much **higher** compression ratio, typically 16, whilst a petrol engine is about 10
  - This is an indication that diesel engines are more efficient
- Diesel engines require this higher compression ratio to get the pressure and temperature of the air high enough for the diesel fuel to self-ignite
  - The petrol-air mixture in a petrol engine is ignited by a **spark** at lower pressures (and temperatures)
- Petrol engines are limited in their compression ratio
  - If the compression ratio is too high, the petrol-air mixture could self-ignite **before** the spark (pre-ignition), due to the higher temperatures and pressures
  - This can also happen if there has been a build-up of carbon in the cylinder (from burnt oil accidentally inside). This can also ignite the petrol-air mixture before the spark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- The disadvantage of diesel engines is that they operate at **higher working pressures**, which makes them more expensive to produce as they have to be more robust and stable
- They have a lower power-to-weight ratio
- Petrol engines produce more carbon monoxide, hydrocarbons and carbon dioxide than diesel engines
    - This can be improved using a catalytic converter, which oxidised the pollutants and reduces the harmful emissions
    - However, they are still not reduced below the levels of a diesel engine

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## 11.2.7 Power Output of an Engine

# Power Output of an Engine

- An engine's efficiency depends on its **power output**
- This is determined by the **fuel**

## Input Power

- The **calorific value** of fuel is the amount of energy fuel stores per unit volume (or per unit mass)
  - For **liquid** fuel, this is measured in **J kg$^{-1}$**
  - For a **gas**, this is measured in **J m$^{-3}$**
- The **flow rate** of fuel is the volume (or mass) that flows per second
  - For **liquid** fuel, this is measured in **kg s$^{-1}$**
  - For a **gas**, this is measured in **m$^3$ s$^{-1}$**
- The product of these gives the input power of the engine:

$$Input\ power\ =\ calorific\ value\ \times\ fuel\ flow\ rate$$

## Indicated Power

- The indicated power is the power developed in the **cylinder** of an engine
- This depends on the number of cycles (strokes) per second

$$Number\ of\ cycles\ per\ second\ =\ \frac{1}{time\ for\ one\ cycle}$$

- In a four-stroke engine, 1 cycle is equal to **2** revolutions

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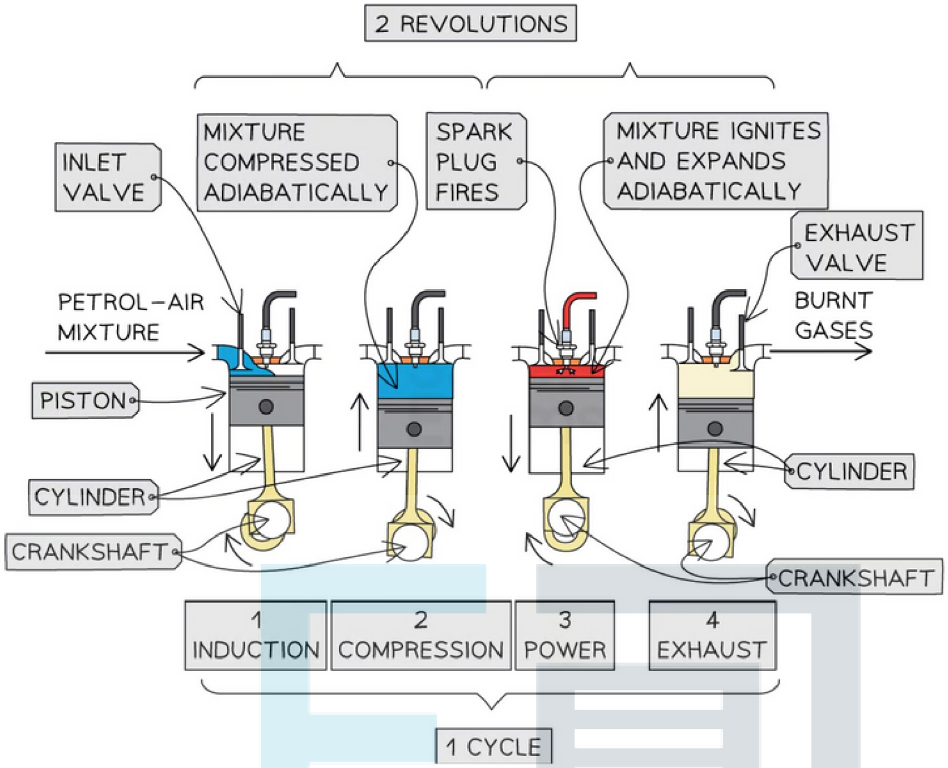
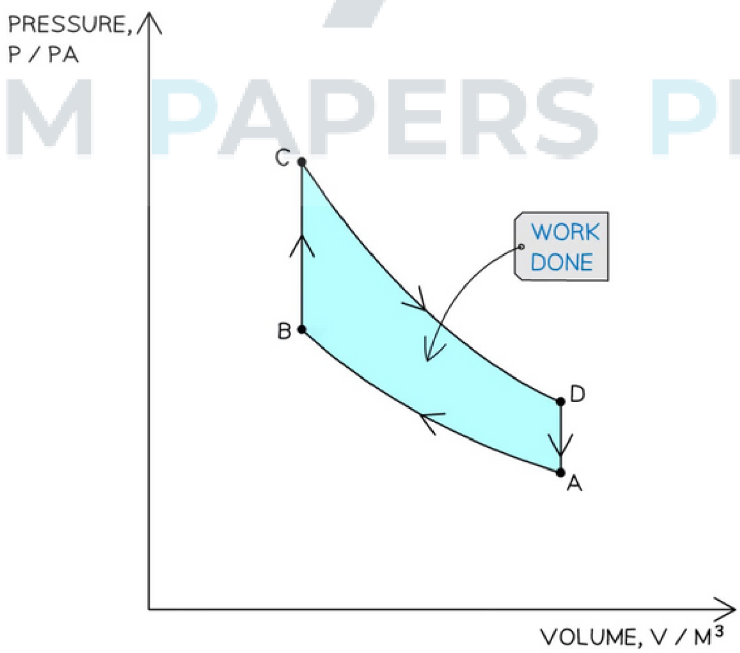



***A four-stroke engine has 2 revolutions of the crankshaft in one cycle***

- The power developed is the **work done** each second, which is the area of the main *p-V* loop of the indicator diagram




***Area of p–V loop for a diesel engine***

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- The indicated power is defined by the equation:

$$Indicated\ power = (area\ of\ p - V\ loop) \times (number\ of\ cycles\ per\ second) \times (number\ of\ cylinders\ in\ engine)$$

## Output (Brake) Power

- The brake power is the power output by the engine and is the same as the rotational power

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## Friction Power

- Part of the indicated power must be used to overcome frictional forces within the engine
  - Due to this, this means the brake power is **lower** than the indicated power
- It is defined as:

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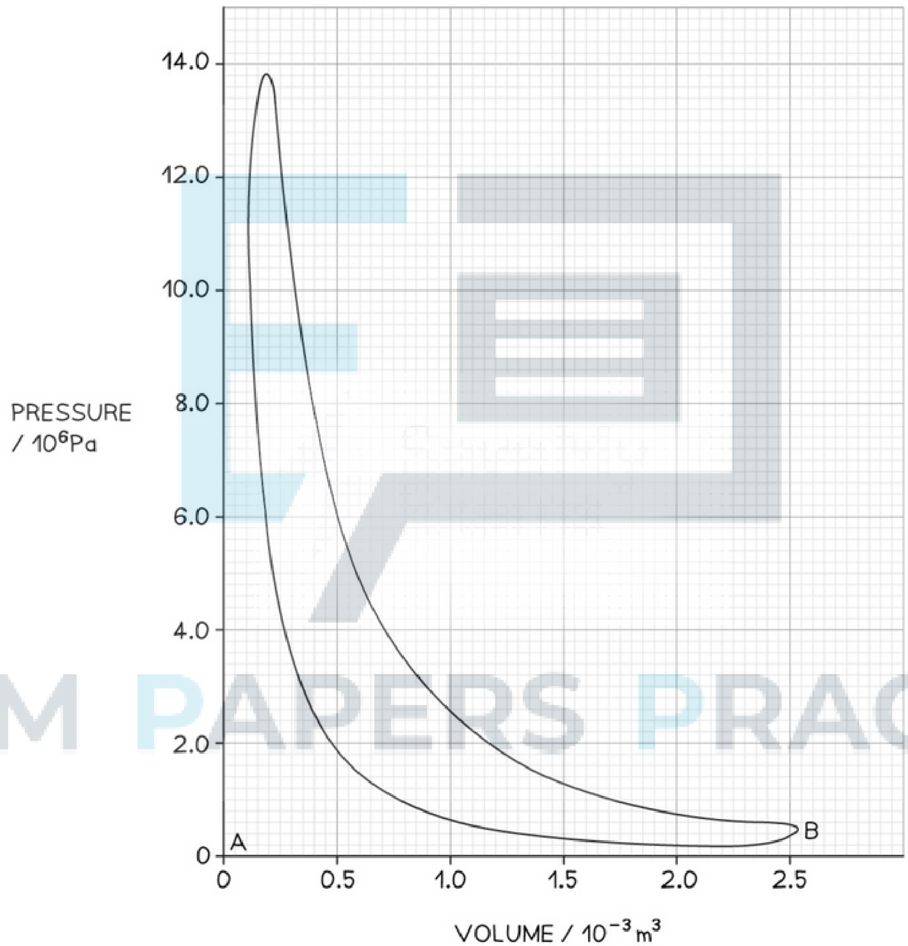
## Worked Example

A four-stroke diesel engine with three cylinders is running at constant speed on a test bed. An indicator diagram for one cylinder is shown in the figure below and other test data are given below:

- measured output power of engine (brake power) = 75.0 kW
- fuel used in 150 seconds = 0.284 litre
- calorific value of fuel = 38.6 MJ litre$^{-1}$
- engine speed = 3500 rev min$^{-1}$




(a) Determine the indicated power of the engine, assuming all cylinders give the same power

(b) Calculate the input power of the engine.

**Answer**

(a)

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Step 1: State the indicated power equation

$$\text{Indicated power} = (\text{area of } p - V \text{ loop}) \times (\text{number of cycles per second}) \times (\text{number of cylinders})$$

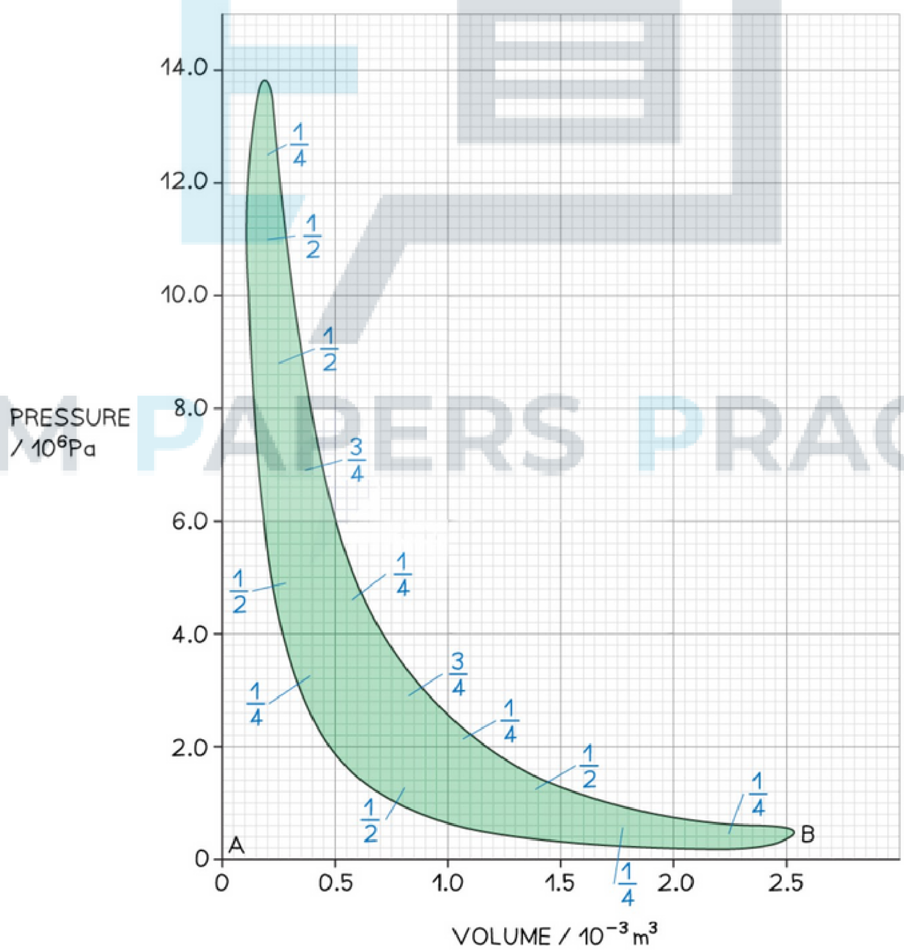
**Step 2: Calculate the number of cycles per second**

- The engine speed is 3500 rev $\text{min}^{-1}$
  - This is $\frac{3500}{60}$ rev $s^{-1}$
  - 1 revolution = 2 cycles
  - Therefore, the number of **cycles** per second is

$$\left(\frac{3500}{60}\right) \times \frac{1}{2}$$

**Step 3: Calculate the area of the *p–V* loop**

- It is easier to use the big squares
- 1 big square = volume of $(0.5 \times 10^{-3}) \times (2.0 \times 10^{6}) = 1000 \text{ m}^3 \text{ Pa}$




- Splitting up the graph into squares gives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$$\left(6 \times \frac{1}{4}\right) + \left(5 \times \frac{1}{2}\right) + \left(2 \times \frac{1}{4}\right) = 4.5 \text{ squares}$$

- This gives an area of

$$4.5 \times 1000 = 4500$$

- The indicated power is therefore:

$$Indicated\ power = 4500 \times \left(\frac{3500}{60} \times \frac{1}{2}\right) \times 3 = 394 \text{ kW}$$

(b)

**Step 1: State the input power equation**

$$Input\ power = calorific\ value \times fuel\ flow\ rate$$

**Step 2: Calculate the fuel rate**

- Fuel used in 150 seconds = 0.284 litres

$$Fuel\ rate = \frac{0.284}{150} = 0.0019 \text{ litres s}^{-1}$$

**Step 3: Calculate the input power**

$$Input\ power = (38.6 \times 10^6) \times 0.0019 = 73340 = 7.3 \times 10^4 \text{ W}$$

Exam Tip

There are a lot of equations here. These are all given in your data sheet, so you must be confident with how to **use** them.

For input power, make sure the calorific value and flow rate are in the **same units**. For example, if one is in terms of mass, the other must also be in terms of mass.

Sometimes, the engine may not have cylinders. Not all engines will require cylinders to function, depending on their type. In this case, this part of the indicated power equation can be omitted. Make sure you use the number of cycles **per second** instead of the time for one cycle!

Being able to find areas from graphs by counting the squares is a **very** important skill to have in A level physics. The mark scheme will allow a wide range of answers, so don't worry if you're approximations are slightly out, as the accepted answers will adjust for these

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## 11.2.8 Engine Efficiency

# Engine Efficiency

- The efficiency of an engine can be measured in three different ways: overall, thermal and mechanical
- The **overall** efficiency of an engine is:

$$overall\ efficiency = \frac{brake\ power}{input\ power}$$

- This is also the product of the thermal and mechanical efficiencies
- The **thermal** efficiency of an engine is:

$$thermal\ efficiency = \frac{indicated\ power}{input\ power}$$

- This tells us how well the engine transforms the chemical energy in the fuel into useful power (and work) in the engine cylinders
- The **mechanical** efficiency engine is:

$$mechanical\ efficiency = \frac{brake\ power}{indicated\ power}$$

- This depends on the amount of energy lost due to moving parts of the engine (due to friction)

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## Worked Example

An engine consumes fuel at the rate of 0.90 kg per second. The calorific value of the fuel is 44 MJ $kg^{-1}$.

The indicated power of the engine is 4720 kW. Because of the high speed of the air in the engine, there is significant frictional heating amounting to a power loss of 230 kW.

Calculate the overall efficiency of the engine.

**Answer:**

**Step 1: State the overall efficiency equation**

$$Overall\ efficiency = \frac{brake\ power}{input\ power}$$

**Step 2: Calculate the brake power**

$$Friction\ power = indicated\ power - brake\ power$$

$$Brake\ power = indicated\ power - friction\ power$$

$$Brake\ power = 4720 - 230 = 4490\ \text{kW}$$

**Step 3: Calculate the input power**

$$Input\ power = calorific\ value \times fuel\ flow\ rate$$

$$Input\ power = (44 \times 10^6) \times 0.90 = 3.96 \times 10^7\ \text{W}$$

**Step 4: Calculate the overall efficiency**;

$$Overall\ efficiency = \frac{4490 \times 10^3}{3.96 \times 10^7} = 0.11\,(11\%)$$

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## Exam Tip

These formulas are **not** given on your data sheet, so make sure to remember these!

You can see from the worked example that it's very important to understand how and when to use the power equations!

Exam questions may be set on other theoretical cycles of other engines, which you don't need to know the working knowledge of. Therefore, the questions will be interpretive, so you should be confident in finding the area under a *p*-*V* loop for different engines or their efficiency.

You will also be examined on how well you understand what is going on in the engine based on the information given (they will not stray too far from diesel and petrol)



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11.2.9 The Second Law of Thermodynamics

## Second Law of Thermodynamics

- A heat engine is a system that converts heat to usable energy which is then used to do mechanical work
- The second law of thermodynamics states that

**A heat engine requires a source and a sink to operate**

- A **source** is a high-temperature reservoir
  - It has a high temperature $T_H$ and the heat energy from it is $Q_H$
- A **sink** is a low-temperature reservoir
  - It has a low temperature $T_C$ and the heat energy going into it is $Q_C$

- Another way of stating the second law is:

**Thermal energy cannot spontaneously transfer from a region of lower temperature to a region of higher temperature**

Or:

**When extracting energy from a heat reservoir, it is impossible to convert it all into work**

- If the engine reached the temperature of the source, **no heat would flow** as they would have reached thermal equilibrium
  - Therefore, no **work** would be done
- This means it is impossible for a heat engine to work solely on the First Law of Thermodynamics
- If a heat engine **only** obeyed the First Law (there is no friction), the source-sink diagram would look like:

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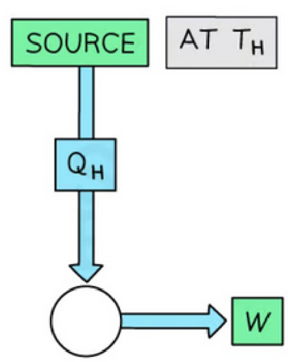
# Source-Sink Diagrams




***Source-sink diagram that obeys only the First Law of Thermodynamics***

- It is assumed that $T_H$ remains at a constant temperature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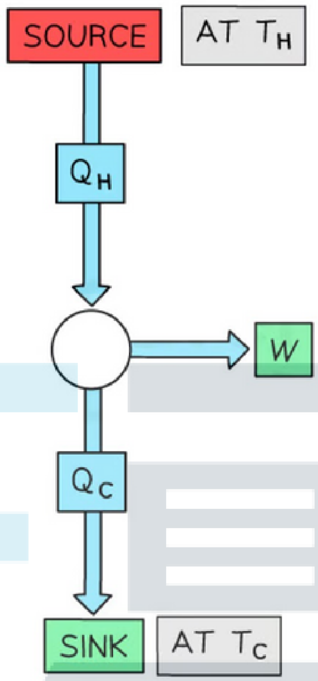
- This engine is 100% efficient however, it is **not** possible to make this type of engine, due to frictional losses in real life
- Therefore, all engines obey the Second Law of Thermodynamics, and a source-sink diagram for an actual heat engine is




***Actual source-sink diagram for a heat engine that obeys the First and Second Law of Thermodynamics***

- Heat energy ($Q_H$) is transferred from the source at temperature $T_H$
- Some of this energy is transferred into work, $W$
- The remaining energy ($Q_C$), is transferred to the sink at temperature $T_C$

## Exam Tip

Remember that heat can only flow from a **hot** place to **cold**. Therefore, if you're sketching source-sink diagrams, take care with the arrows and make sure you have all the components included (especially the work done, otherwise, the engine wouldn't work!).

Take care of your terminology:

- Heat **engines** convert thermal energy into mechanical work (as above)
- Heat **pumps** transfer heat energy from low temperature to high temperature (this is explored later)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## 11.2.10 Heat Engines

### Efficiency of a Heat Engine

- The goal of a heat engine is to transfer thermal energy into useful mechanical work as efficiently as possible
- The efficiency of a heat engine can, therefore, be calculated using

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efficiency =
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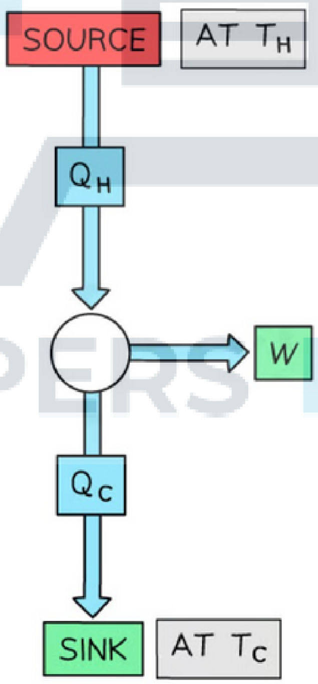
- Where:
  - $W$ = useful work output (J)
  - $Q_H$ = energy transferred from the source (J)
  - $Q_C$ = energy transferred to the sink (J)




***Source-sink diagram for a heat engine***

- Since the efficiency of a heat engine can never be 0 (otherwise there would no work!) this means **no heat engine can completely convert heat into work**

## Worked Example

Which is a correct statement about an ideal heat engine?

**A** The efficiency is 75% when the kelvin temperature of the hot source is four times the kelvin temperature of the cold sink

**B** The maximum efficiency depends on the *p-V* cycle fo the engine

**C** The efficiency is decreased when the kelvin temperature of the hot source and the cold sink are decreased by equal amounts

**D** The efficiency is 25% when the kelvin temperature of the hot source is four times the kelvin temperature of the cold sink

**Answer: A**

- If the hot source is four times the kelvin temperature of the cold sink, then $Q_H = 4Q_C$
- In the efficiency equation, this is

$$\frac{Q_H - Q_C}{Q_H} = \frac{4Q_C - Q_C}{4Q_C} = \frac{3Q_C}{4Q_C} = \frac{3}{4} = 0.75$$

- This efficiency is 75 %

## Exam Tip

This equation is given on your data sheet. Make sure all the variables are in the **same** units i.e. J or kJ. You must convert these into the same units before you do your calculation.

If the efficiency is asked for as a percentage instead of a decimal, remember to × 100

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## Maximum Theoretical Efficiency

- As the efficiency of a thermodynamic system increases, the **difference** between the temperatures of the source and sink increases
- The maximum theoretical efficiency of a heat engine is:

$$\text{Maximum theoretical efficiency} = \frac{T_H - T_C}{T_H}$$

- Where:
  - $T_C$ = temperature in the sink (cold reservoir) (K)
  - $T_H$ = temperature in the source (hot reservoir) (K)
- This equation can be used if an **ideal gas** is used as a substance for the engine
- Therefore, to make an engine as efficient as possible, the source temperature must be as high as possible, and the sink temperature as low as possible
- The maximum theoretical efficiency is 100% only if the sink temperature is at 0 K

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## Worked Example

An engineer designs a heat engine that has an inlet temperature of 500 K and an outlet temperature of 300 K. The engineer claims that 100 kJ of thermal energy flows out of the source and 25 kJ of thermal energy flows into the sink.

Determine, with reference to the second law of thermodynamics, whether this engine is thermodynamically possible.

**Answer:**

**Step 1: Determine the efficiency of the proposed engine**

- The efficiency of this engine would be

$$efficiency = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H}$$

- Where:
  - Heat transferred in, $Q_H$ = 100 kJ
  - Heat transferred out, $Q_C$ = 25 kJ

$$\text{Efficiency} = \frac{100 - 25}{100} = 0.75 = 75\%$$

**Step 2: Determine the maximum theoretical efficiency of the proposed engine**

- A Carnot engine operating between the same temperatures would have an efficiency of

$$\text{Maximum theoretical efficiency} = \frac{T_H - T_C}{T_H}$$

- Where:
  - Inlet temperature, $T_H$ = 500 K
  - Outlet temperature, $T_C$ = 300 K

$$\text{Maximum theoretical efficiency} = \frac{500 - 300}{500} = 0.4 = 40\%$$

**Step 3: Discuss the proposed engine in relation to the second law**

- The second law of thermodynamics states that it is impossible for heat to flow from a cooler body to a hotter body without performing work
- This law sets an upper limit on the maximum possible efficiency of the transfer of thermal energy to mechanical energy in a heat engine
- The maximum possible efficiency of the proposed engine is 40%, but the engineer is proposing an efficiency of 75% i.e. an efficiency greater than the efficiency of the engine


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- This violates the second law, hence **the proposed engine is impossible**

### Exam Tip

This equation is valid for **all** idealised reversible engines, irrespective of the particular cycle and the particular working substance. You may be given unfamiliar cycles in the exam (such as the Carnot cycle) to apply this to.

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## 11.2.11 Limitations of Real Heat Engines

### Limitations of Real Heat Engines

- Practical engines have a much **lower efficiency** than their theoretical equivalent

### Limitations of Real Heat Engines

1. **Work done** to overcome frictional forces within the engine
    - An engine is made up of multiple parts (such as crankshafts and pistons) all in contact with each other which will naturally cause friction
    - There is also a transfer of energy out of the system by the heating of the cylinder walls that make up the engine
2. The **fuel** is not completely burnt in the process, so **the temperature rise isn't as high as expected**
    - The higher the difference in the temperature between the source and sink, the higher the efficiency
3. The **power** is used to drive internal components, such as pumps and motors
    - This power is therefore not used for useful work
4. The petrol-air mixture is **not** an ideal gas
    - It is actually a mixture of polyatomic molecules, which will sometimes be under high temperatures and pressures
5. **Imperfect** combustion
    - The heat energy in the compression stroke is taken not entirely at the single temperature $T_H$ and not entirely rejected at the single temperature $T_C$
    - In reality, the heat is usually taken in over a range of temperatures and rejected also over a range of temperatures
    - The maximum temperature is therefore not always obtained
6. The processes that form the engine cycle are **irreversible**
    - Energy is dissipated out of the system
    - There is no equilibrium with the surroundings as the processes are too quick
    - The inlet and exhaust values take a finite time to open and close (this gave the 'curved' edges in the actual $p$-$V$ diagram for the petrol engine)
    - The pistons are always moving, so the heating is not always at a constant volume
    - The compression and expansion strokes are not truly adiabatic, as heat energy is lost from the system


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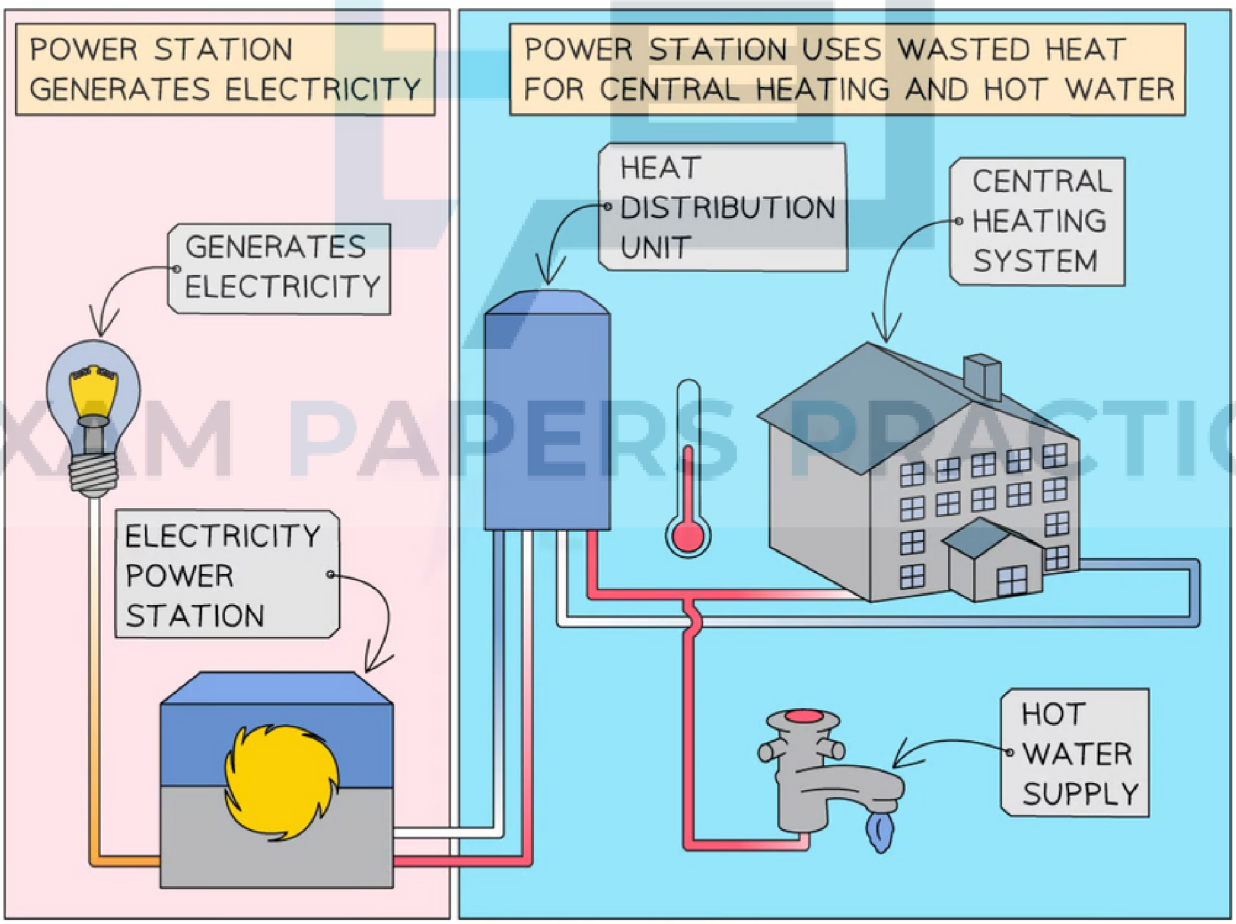
## Combined Heat & Power (CHP) Schemes

- In heat engines, the useful work output (*W*) is usually less than the heat energy transferred to the sink ($Q_C$)
- Combined heat and power (CHP) schemes are used to maximise the useful work output (and hence, power output) and the energy transferred to the **source** ($Q_H$)
- Conventional power stations that use heat engines are in reality, about 35% efficient
  - Their maximum theoretical efficiency is around 61%
- They transfer large amounts of energy to their surroundings through cooling towers or a local river or sea
- Instead of removing this heat through cooling, this heat could then be used to **heat homes and businesses** which are close by
  - This is used in CHP power stations which are much more heat and energy-efficient
- In the UK, most power plants are naturally positioned far away from homes and businesses so the heat would have cooled down by the time it has reached them, so they are not as popular

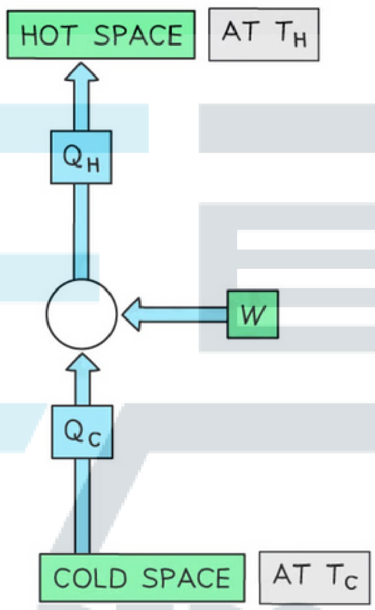



***A CHP system in a power plant can generate some electricity, but the huge amount of wasted heat energy is useful for other supplying heat to water or buildings***

## 11.2.12 Reversed Heat Engines

### Heat Pumps & Refrigerators

- A **reversed** heat engine is one that transfers heat energy from a cold space (sink, at a low temperature) to a hot space (source, at a higher temperature) by **inputting work**
  - Work needs to be done because heat energy naturally flows from a warmer to a colder space (like in heat engines)
- Reversed heat engines are used for:
  - **Refrigerators** or **air-conditioning**
  - **Heat pumps** (an engine used to heat a building)
- The source-sink diagram looks like this:

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***Source-sink diagram for a reversed heat engine, notice the direction of all arrows are reversed from the normal source-sink diagram***

- Where:
  - $Q_C$ = energy extracted from the cold space (J)
  - $Q_H$ = energy delivered to the hot space (J)
  - $W$ = work inputted (J)
- $Q_H$ is sometimes referred to as $Q_{out}$ and $Q_C$ as $Q_{in}$
- $Q_H$ will always be **greater** than $Q_C$ for this to work
- Applying the First Law of Thermodynamics means that:

$$Q_H = Q_C + W$$

- Efficiency is **not** calculated the same way as a heat engine, because its effectiveness depends on the device and its function
- A **refrigerator extracts** as much energy as possible from the **cold** space per joule of work done


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  - A refrigerator wants to stay **cold**, so it is taking the heat **out** of the system
  - The **inside** of the fridge is the **cold** space and the outside is the **hot** space
- A **heat pump** (e.g. to heat a house) **provides** as much energy as possible to the **hot** space per joule of work done
  - A heat pump wants to make a room **warm**, so it puts heat **into** the system
  - The outside of the house is the **cold** space and the inside is the **hot** space
- They are both identical in principle, and it is possible to use one to fulfil the function of the other, but it wouldn't work as well
  - This is because a domestic refrigerator keeps the contents inside it cool, but simultaneously acts as a heater, as it warms up the room it is placed in

### Exam Tip

When answering qualitative questions, be careful to **define** terms precisely. Be wary of terms such as 'input energy' and 'output energy' without clarifying it further. 'Input energy' could refer to energy input to a **room** or hot space, or energy input to the **device** from the cold space, or even energy input in the form of work. Always say where the energy is **coming from** and **going to**, so this is clear.

You only need to know the basic principles of heat pumps and refrigerators (that they're reversed heat engines). A knowledge of practical heat pumps or refrigerator cycles and devices is not required for your exam.

The 'source' in the exam question may be referred to as the 'hot space' or 'hot reservoir' instead of 'source' - look out for this different terminology, they mean the same thing

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## 11.2.13 Coefficients of Performance

### Coefficients of Performance

- As mentioned in Heat Pumps & Refrigerators, the efficiency of a reversed heat engine depends on its **purpose**
- Therefore a **coefficient of performance (COP)** is used to measure their effectiveness instead
  - It is **not** a measure of efficiency, as it can be greater than 1
- The COP is a measure of how **effective** a reversed heat engine is at transferring heat **per unit of work done**
  - E.g. A COP of 7 is 7 J of heat energy is transferred per 1 J of work done
- The COP of a refrigerator is defined by:

$$COP_{ref} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C} = \frac{T_C}{T_H - T_C}$$

- Where:
  - $Q_C$ = energy extracted from the cold space (J)
  - $Q_H$ = energy delivered to the hot space (J)
  - $W$ = work inputted (J)
  - $T_H$ = temperature of hot space (K)
  - $T_C$ = temperature of the cold space (K)
- The COP of a heat pump is defined by:

$$COP_{hp} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C} = \frac{T_H}{T_H - T_C}$$

- Since $Q_H = Q_C + W$, the COPs could be written in terms of each other:

$$WCOP_{hp} = WCOP_{ref} + W$$

$$COP_{hp} = COP_{ref} + 1$$

- Because the COP is a **ratio** it has **no units**
- Since $Q_H < Q_C$, this means

$$COP_{hp} > COP_{ref}$$

- Heat pumps are used instead of conventional electric or gas heaters for large-scale buildings because the energy transferred by a heat pump **exceeds** the work done on the pump
  - An electric or gas heater will at most convert 1 J of energy per 1 J of work done, so would be far more expensive to run on large scales


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## Worked Example

An ideal heat engine has an efficiency of 0.25.

The same engine works in reverse as an ideal refrigerator between the same hot and cold spaces.

Determine the coefficient of performance $COP_{ref}$ of the refrigerator.

**Answer**:

**Step 1: State the First Law of Thermodynamics (for reversed heat engine)**

$$Q_H = Q_C + W$$

**Step 2: Determine $Q_H$ in terms of $W$**

$$efficiency\ of\ heat\ engine = \frac{W}{Q_H} = 0.25$$

$$Q_H = \frac{W}{0.25} = 4W$$

**Step 3: Substitute into the First Law to determine at equation for $Q_C$**

$$Q_C = Q_H - W$$

$$Q_C = 4W - W = 3W$$

**Step 4: State the equation for $COP_{ref}$**

$$COP_{ref} = \frac{Q_C}{W}$$

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**Step 5: Substitute the values**

$$COP_{ref} = \frac{3W}{W} = 3$$

## Exam Tip

The COP equations in terms of Q and *W* are included in your data sheet, but **not** the equation with $T_H$ and $T_C$. For these values, you can assume the engine is running at maximum theoretical efficiency.

When defining the COP, make sure not to use the words 'heat input' without specifying where the heat is being input to, as this is too vague and will not be accepted by the examiner.



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