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To understand engine cycles, you must first ensure that you understand the systems and processes involved.

Systems
A system can be defined as region in space which contains gas or vapour. An open system is one in which the gas flows into, out of, or through the region. A closed system is one in which the gas or vapour remains within the boundary of the region, although the boundary (and size) of the region may alter. The gas may contract or expand, for example with the movement of a piston. In both open and closed systems heat and work may be transferred across the boundary.

The First Law of Thermodynamics Applied to Systems
$Q = \Delta U + W$ where Q is energy supplied
ΔU is the change in internal energy
and W is the work done by gas

When a gas expands, work is done by the gas and the work done W is positive. If a gas is compressed then work is done on the gas and W is negative. The energy supplied or removed, Q is done by heat transfer and if Q is negative then the gas is cooled (that is energy is removed from the system).

An isothermal change is one that occurs at a constant temperature. The internal energy does not change, so ΔU is zero.
Boyle's Law is obeyed: pV = constant or $p_1V_1 = p_2V_2$

An adiabatic change is one which occurs at constant heat, i.e. no heat passes into or out of the gas and so Q is zero. For example, during the compression stroke of an internal combustion engine no heat enters or leaves the system and so ΔU = minus W. Work is done on the gas, the internal energy rises and so the temperature increases.

The relevant law is pV^Y = constant and so $p_1V_1^Y = p_2V_2^Y$

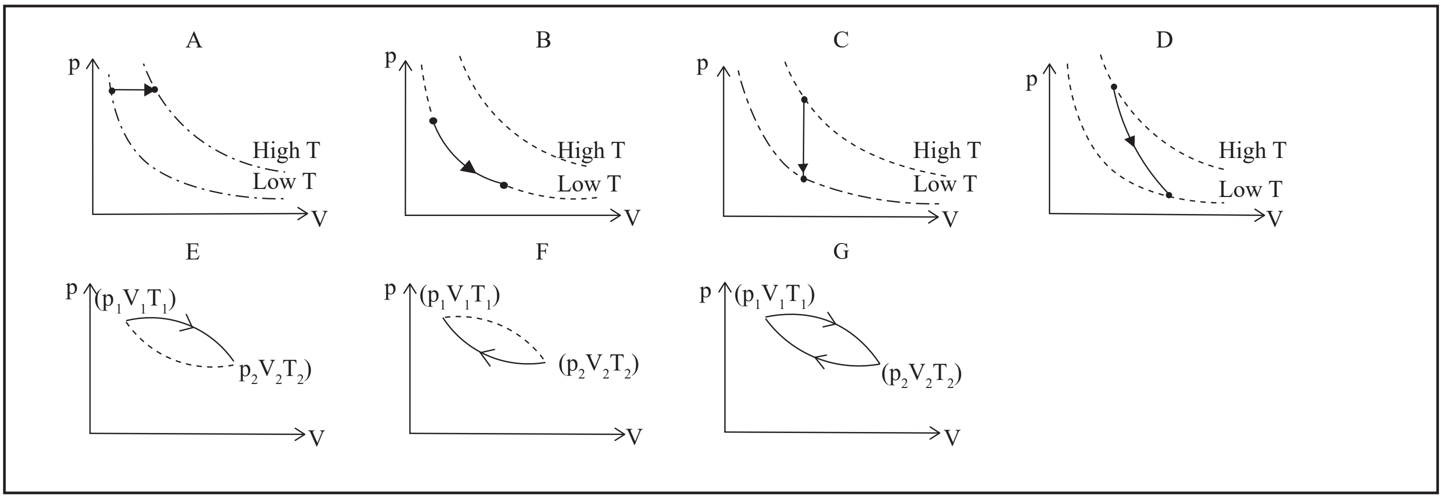
Processes
Processes are the changes in pressure, volume or temperature. They are governed by the ideal gas equation; pV = nRT.
For a closed system, that is one involving non-flow processes,

n is constant and so $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$

The formula can be applied for isothermal and adiabatic changes and for constant volume and constant pressure changes.

Indicator Diagrams
An engine cycle can be represented by an **indicator diagram**. An indicator diagram is a graph of cylinder pressure plotted against volume for the complete cycle (or for the power stroke) of an engine. These variations of pressure and volume are cyclic because a fluid is performing a work cycle in the engine. The area of the indicator diagram represents the work done during the each cycle.

Figure 1 Indicator diagrams



Quick Question 1: Which of the indicator diagrams represent processes and which represent a cycle?
Answer: Diagrams A, B, C and D represent processes. Diagrams E, F and G represent a cycle.

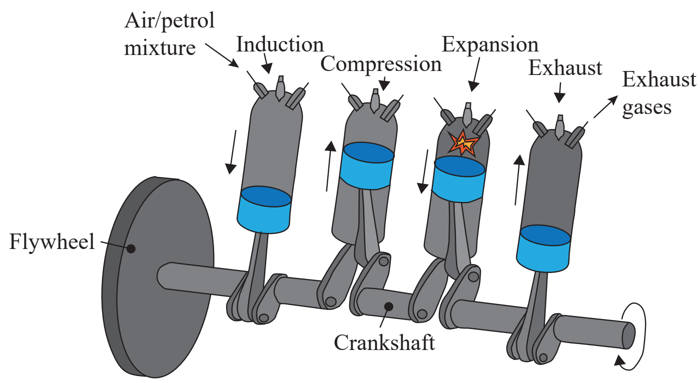
Quick Question 2: Name each of the processes shown.
Answer: A is an isobaric process (p is constant); B is an isothermal process (pV is constant); C is an isovolumetric process (V is constant); D is an adiabatic process (pV^γ is constant).

Quick Question 3: Which of the indicator diagrams represents: work done on a gas, net work done by gas, work done by gas?
Answer: F is work done on a gas (area between solid curve and x axis), G is net work done by gas (area contained within cycle), and E is work done by gas (area between solid curve and x axis).

Cycle of a Four Stroke Petrol Engine

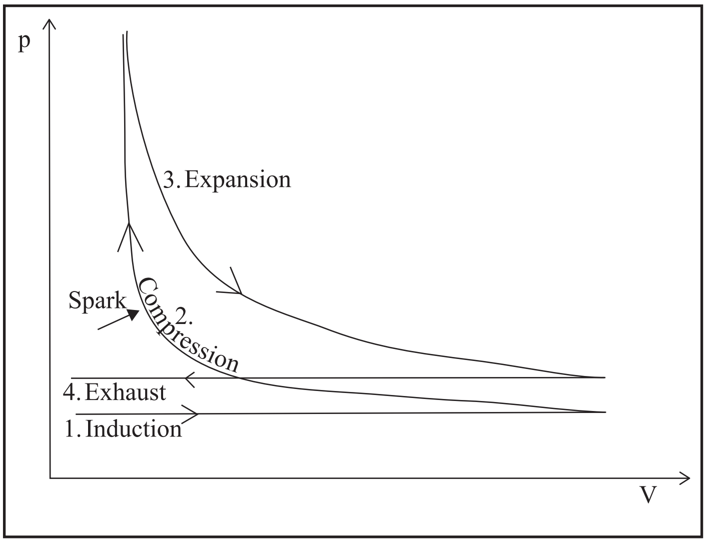
The diagram below shows the basic structure of a Four Stroke Petrol Engine.

Figure 2 Four stroke petrol engine



1. Induction. The piston begins at the top of the cylinder and travels down. The air and petrol mixture is drawn into the cylinder through the open inlet valves at constant pressure.
2. Compression. The inlet valves are closed and the piston travels up compressing the air petrol mixture. As the top of the piston nearly reaches the top of the cylinder, the spark plug ignites the mixture, giving an almost instantaneous increase in pressure and temperature (the volume remaining nearly constant).
3. Expansion. The gas expands rapidly forcing the piston down. There is a net output of work done by the gas.
4. Exhaust. The exhaust valve is opened and the piston moves upwards expelling the burnt gases through the open exhaust valve.

Figure 3 Indicator diagram: Four stroke petrol engine cycle



The **work done per cycle is equal to the area of the loop**. **Work** is **done by the gas** during the expansion = **area under the expansion curve**. **Work** is **done on the gas** during the compression = **area under the compression curve**.

The exhaust and induction strokes may appear as a single line. However, any area that appears between them can be taken from the area of the loop (as negative work) if it is significant.

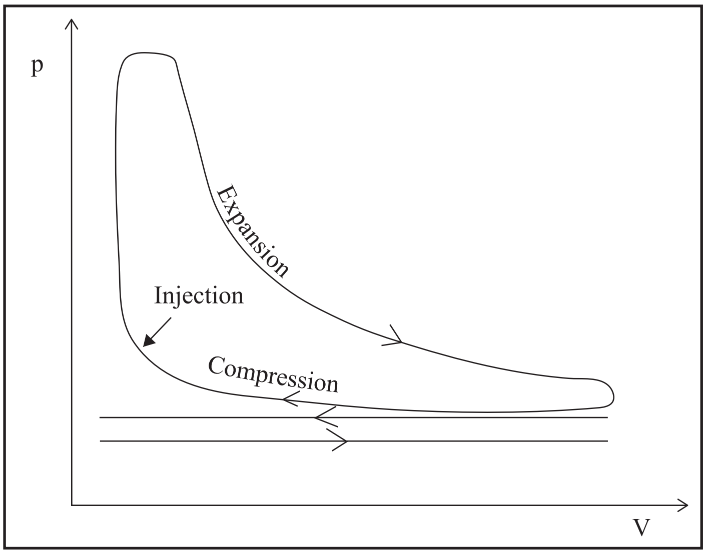
Cycle of a Four Stroke Diesel Engine

A Four Stroke Diesel Engine is similar in structure to a Four Stroke Petrol Engine but what happens in the cycle is slightly different.

1. Induction. Only air is pulled into the cylinder.
2. Compression. The air is compressed until it reaches a temperature high enough to ignite diesel fuel. Diesel fuel is injected into the cylinder and ignites.

3. Expansion. The gas expands rapidly forcing the piston down. There is a net output of work done by the gas.
4. Exhaust. The exhaust valve is opened and the piston moves upwards expelling the burnt gases through the open exhaust valve.

Figure 4 Indicator diagram for a Four Stroke Petrol Engine Cycle



The **net work done per cycle is equal to the area enclosed by the loop on the indicator diagram.**
The **indicated power = the net work done divided by the time taken for one cycle**.
Thus **indicated power = net work done multiplied by number of cycles per second.**
For vehicles with more than one cylinder, **indicated power = net work done multiplied by the number of cycles per second, multiplied by the number of cylinders.**
Input power = calorific value of fuel ($J\ kg^{-1}$) × fuel flow rate ($kg\ s^{-1}$)

Output or Brake Power

The brake power is defined as the useful power output at the crankshaft of the engine.
For a linear system the work done = force x displacement = $\boldsymbol{F s}$

For a system which rotates the displacement is given by $\boldsymbol{s} = r\,\boldsymbol{\theta}$ where $\boldsymbol{\theta}$ is the angular displacement in radians.
The work done = $\boldsymbol{F}\, r\, \boldsymbol{\theta}$
The torque $\boldsymbol{T} = \boldsymbol{F}\, r$

Therefore the work done in joules is given by $W = \boldsymbol{T}\,\boldsymbol{\theta}$
Power, P is the rate of work done = $\Delta w \div \Delta t$

Thus Power in watts

$$P = \frac{XW}{\Delta t} = \frac{\Delta T\theta}{\Delta t} = T\omega$$

where ω is the angular velocity in radians per second
Brake power (in Watts) $P = T\omega$

where ω is the angular velocity of the crankshaft in rad s^{-1} and T is the engine torque in Nm.

Note: There may be frictional torque, and this will oppose the motion, power will be used to overcome this.
This will give a net torque $T_{net} = T_{applied} - T_{fraction}$

The friction power is given by:
friction power = indicated power – brake power

Efficiency

Overall efficiency of an engine = $\dfrac{\text{Brake power}}{\text{Input power}}$

Note: The Second Law of Thermodynamics is obeyed by all engines and it states that the efficiency of any process which converts heat into work cannot equal 100%. An ideal engine which obeys both the first and second laws of thermodynamics, converting heat into energy, has a heat source and a sink into which it must reject some energy.

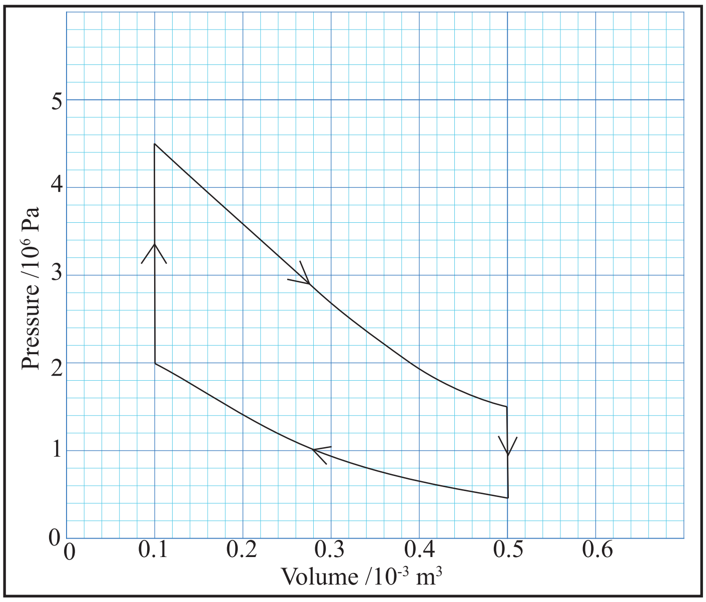
Thermal efficiency of an engine = $\dfrac{\text{Indicated power}}{\text{Input power}}$

Mechanical effeciency of an engine = $\dfrac{\text{Brake power}}{\text{Indicated power}}$

Quick Question 4: The overall efficiency of an engine is 46%. The input power is 112 kW and the indicated power is 90kW. Find the mechanical efficiency of the engine.

Answer: Using the equation for overall efficiency,
the brake power = 46% × 112000 = 51520 J.
Using the equation for mechanical efficiency,
the mechanical efficiency = 51520 ÷ 90000 = 57% (to 2 s.f.)

Calculating the work done in one engine cycle from the indicator diagram



The work done in one cycle is given by the area of the loop of the theoretical indicator diagram. Each small square represents 0.1×10^6 Pa × 0.01×10^{-3} m^2 = 1J. The number of small squares is approximately 660. Work done is 1J x 660 = 660 J in each cycle.

The **indicated power** is given by area of the loop on the p-V diagram in joules multiplied by the number of cycles per second (s^{-1}) multiplied by the number of cylinders.

Practice Exam Style Questions

1. An engine crankshaft rotates at a frequency of 30 cycles per second. The torque is 250 Nm. Find the output power of this engine. (2 marks)
2. When an engine with four cylinders is being operated at 35 cycles per second, the area of the loop of an indicator diagram for one of the cylinders gives a value of 85 J. The brake power of the engine is stated to be 8500 W. Find the friction power of the engine. (2 marks)
3. Why does an engine have a crankshaft? (1 mark)
4. Explain the term *adiabatic compression of a gas.* (1 mark)
5. The temperature falls during the adiabatic expansion of a gas. Use the first law of thermodynamics to explain why this occurs. (4 marks)

Answers to Practice Exam Style Questions

1. Angular velocity of crankshaft, $\omega = 2\pi f\omega 2 \times \pi \times 30 = 188.5$ rad s^{-1}.
   The output power is given by $P = Tw$ (1 mark)
   substituting gives P = 250 × 188.5 = 47124W = 47 kW. (1 mark)
2. Indicated power = 85 × 35 × 4 = 11900 W. (1 mark). Substituting into the equation for friction power gives 11900 × 8500 = 3400 W = 3.4 kW. (1 mark)
3. The pistons move up and down. A crankshaft converts this to rotatory motion. (1 mark)
4. A decrease in volume of the gas with no heat transfer from the gas. (1 mark)
5. The first law of thermodynamics states Q = ΔU + W. For an adiabatic process Q, the heat transfer is zero. (1 mark)
   Thus work done W = - ΔU. (change in internal energy of the gas) (1 mark).
   The work done is positive and so ΔU is negative. (1 mark)
   The internal energy is related to the temperature and thus the temperature will fall. (1 mark)

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