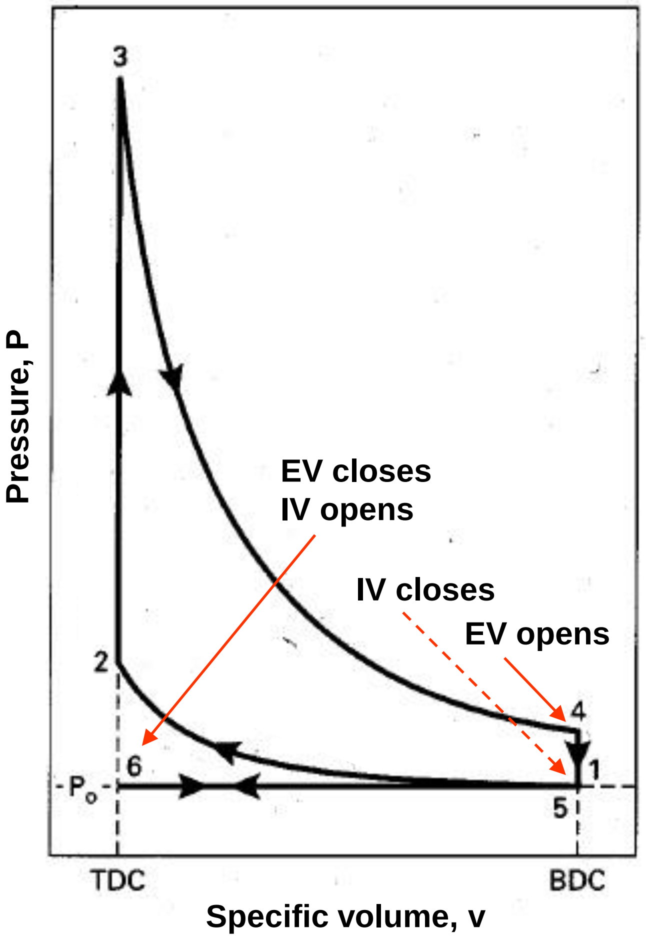
Ideal Intake and Exhaust Strokes

In the ideal four-stroke cycle the exhaust process is modeled as constant volume heat extraction and does not consider the actual gas flow.



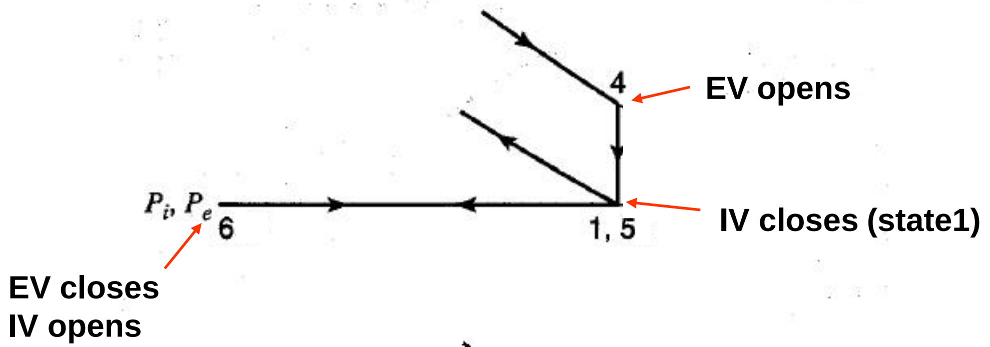
At WOT the intake exhaust processes are often shown as a constant pressure processes, e.g., 5→6 and 6→5 where states 1 and 5 are the same.

Process 5-6 indicates a decrease in specific volume which is incorrect since as the cylinder volume decreases so does the mass →specific volume remains the same!

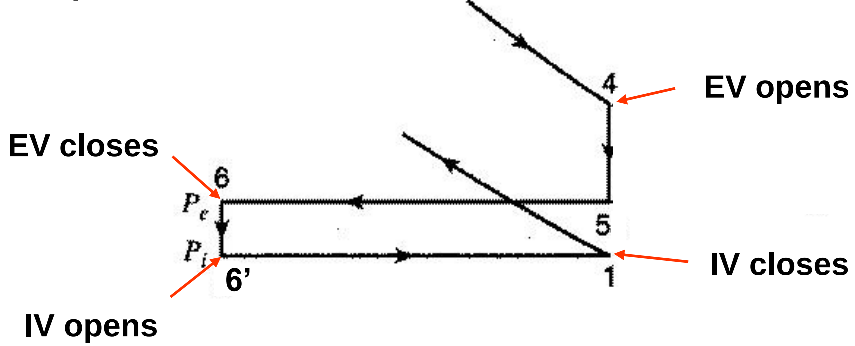
This inconsistency results from treating an open system problem with a closed system model

Valves operate instantaneously, intake and exhaust process are adiabatic and constant pressure.

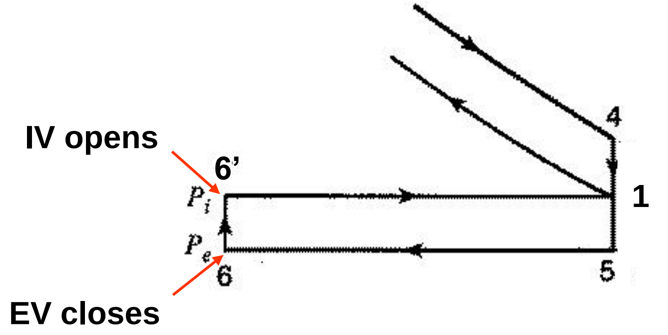
Unthrottled: $P_i = P_e = 1$ atm



Throttled: $P_i < P_e$

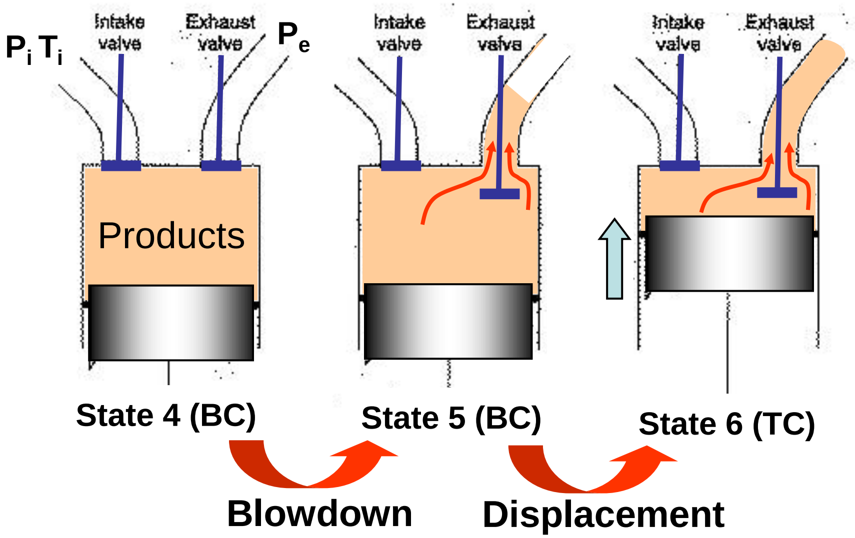


Supercharged: $P_i > P_e$



Actual Exhaust Strokes

The actual exhaust process consists of two phases:

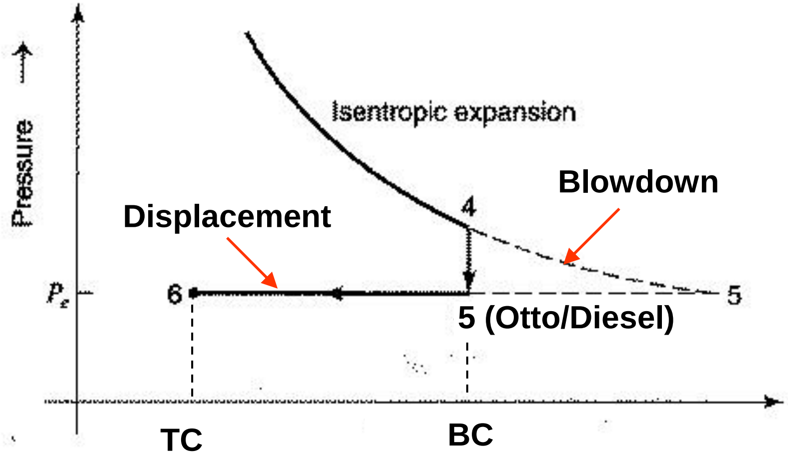


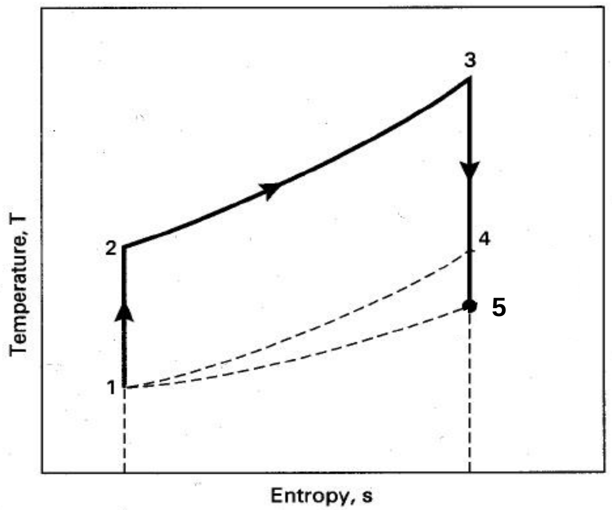
Blowdown – At the end of the power stroke when the exhaust valve opens the cylinder pressure is much higher than the exhaust manifold pressure which is typically at 1 atm ($P_4 > P_e$), so the cylinder gas flows out through the exhaust valve and the pressure drops to P_e.

Displacement – Remaining gas is pushed out of the cylinder by the piston moving to TC.

Blowdown

- During the blowdown the gas remaining in the cylinder undergoes an isentropic expansion process (neglecting heat transfer)





- State 5 at the end of blowdown is a fictitious state corresponding to no actual piston location

$$P_5 = P_e$$

$$T_5 = T_4 \left(\frac{P_5}{P_4} \right)^{k-1/k} = T_4 \left(\frac{P_e}{P_4} \right)^{k-1/k}$$

Residual Gas

The gas remaining in the cylinder when the piston reaches TC is called **residual gas** which mixes with intake gas (fuel-air for SI and air for CI)

The residual gas temperature T_6 is equal to T_5

The **Residual gas fraction *f*** is defined as the ratio of the mass of residual gas to the mass of the fuel-air (assume ideal gas *Pv = RT*)

$$f = \frac{m_6}{m_1} = \frac{m_6}{m_4} = \frac{V_6 / v_6}{V_4 / v_4} = \frac{1}{r}\frac{v_4}{v_6} = \frac{1}{r}\frac{T_4}{T_6}\frac{P_6}{P_4} = \frac{1}{r}\frac{T_4}{T_5}\frac{P_6}{P_4}$$

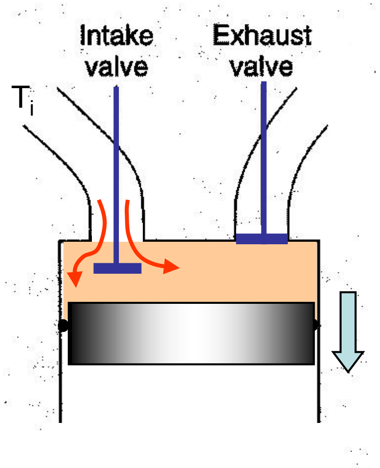
$$\text{since} \qquad \frac{T_5}{T_4} = \left(\frac{P_5}{P_4}\right)^{k-1/k}$$

$$\boxed{f = \frac{1}{r}\left(\frac{P_5}{P_4}\right)^{\frac{1}{k}} = \frac{1}{r}\left(\frac{P_e}{P_4}\right)^{\frac{1}{k}}}$$

Typically values of *f* are in the range 3% to 12%, lower in Diesels (larger r)

Intake Stroke 6→ 1

When the intake valve opens the fresh gas with mass m_i mixes with the hotter residual gas with mass m_R so the gas temperature at the end of the intake stroke T_1 will be greater than the inlet temperature T_i.



Applying conservation of mass:

$$m_i = m_1 - m_R = m_1 - m_6$$

Applying conservation of energy (open system):

$$U_1 - U_6 = \cancel{Q}_{6-1} - W_{6-1} + m_i h_i$$

$$m_1 u_1 - m_6 u_6 = -P_i (V_1 - V_6) + m_i h_i$$

$$m_1 (h_1 - P_1 v_1) - m_6 (h_6 - P_6 v_6) = -P_i (V_1 - V_6) + (m_1 - m_6) h_i$$

$$\boxed{h_1 = \frac{m_6}{m_1}\left[h_6 + \left(\frac{m_1}{m_6} - 1\right) h_i + (P_1 - P_6) v_6\right]}$$

Intake Gas Temperature (T_1)

Recall $m_6 = m_1 f$ and assuming ideal gas $P_6 v_6 = RT_6$ and $h = c_p T$

$$h_1 = (1-f)h_i + fh_6 - \left(1 - \frac{P_1}{P_6}\right) fRT_6$$

$$T_1 = (1-f)T_i + fT_6\left[1 - \left(1 - \frac{P_1}{P_6}\right)\left(\frac{k-1}{k}\right)\right]$$

In terms of inlet and exhaust conditions $P_1 = P_i$, $P_6 = P_e$, $T_6 = T_e$

$$\boxed{T_1 = (1-f)T_i + fT_e\left[1 - \left(1 - \frac{P_i}{P_e}\right)\left(\frac{k-1}{k}\right)\right]}$$

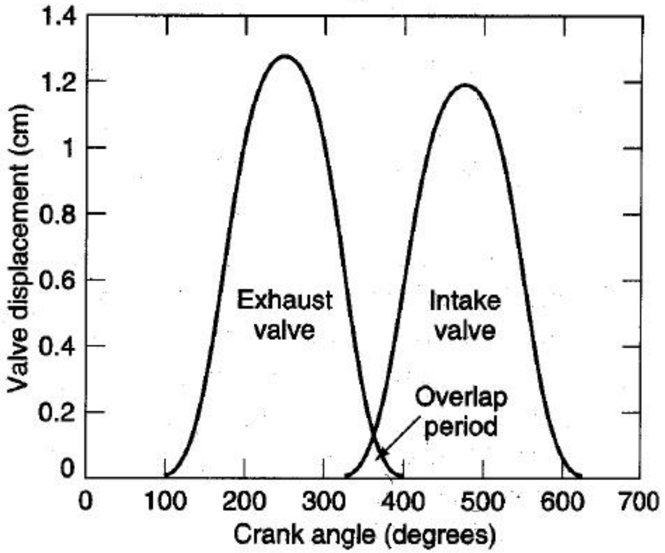
Valve Overlap

In real engines valves don’t open and close instantaneously.

In order to ensure that the valve is fully open during a stroke for volumetric efficiency, the valves are open for longer than 180º.

The exhaust valve opens before TC and closes after BC and the intake valve opens before TC and closes after BC.

At TC there is a period of **valve overlap** where both the intake and exhaust valves are open.



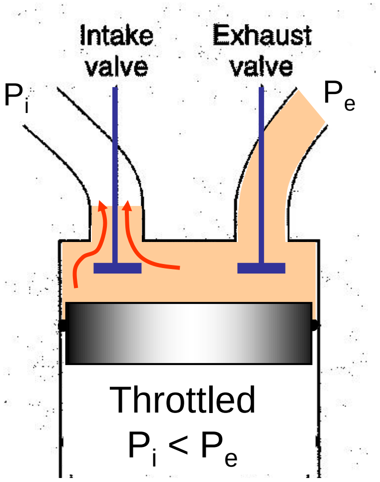
Valve overlap

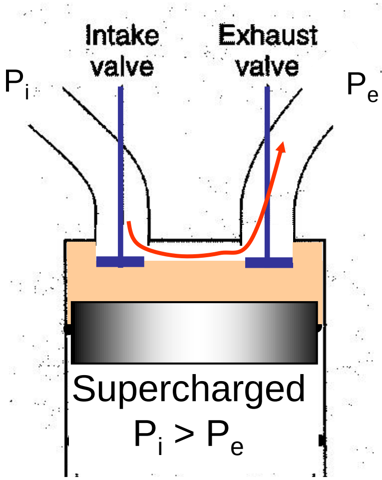
When the intake valve opens the cylinder pressure is at P_e

Part throttle ($P_i < P_e$): residual gas flows into the intake port. During intake stroke the residual gas is first returned to the cylinder then fresh gas is introduced. Residual gas reduces part load performance.

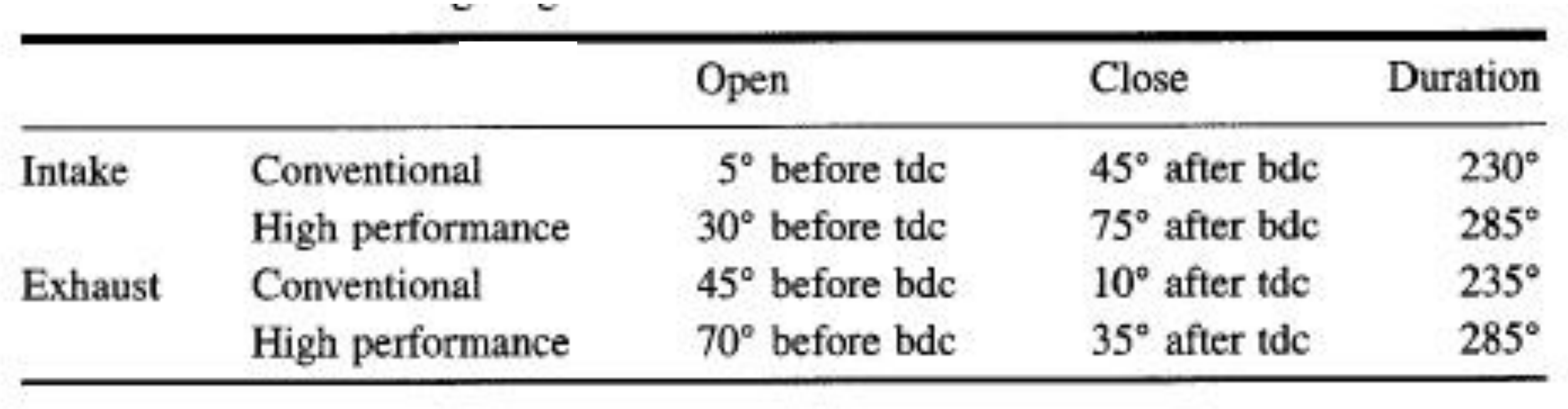
WOT ($P_i = P_e$): some fresh gas can flow out the exhaust valve reducing performance and increasing emissions.

Supercharged ($P_i > P_e$): fresh gas can flow out the exhaust valve





Valve Timing



		Open	Close	Duration
Intake	Conventional	5° before tdc	45° after bdc	230°
	High performance	30° before tdc	75° after bdc	285°
Exhaust	Conventional	45° before bdc	10° after tdc	235°
	High performance	70° before bdc	35° after tdc	285°

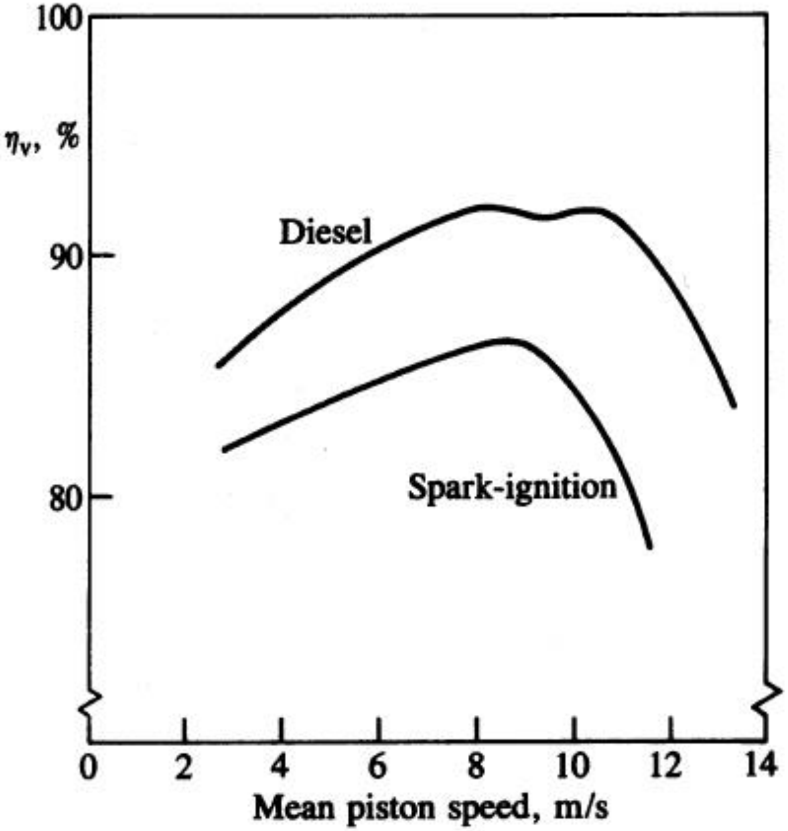
Conventional engines operate at low rpms, with idle and part load important
High performance engines operate at high rpms at WOT, with power and volumetric efficiency important

At high engine speeds less time available for fresh gas intake so need more crank angles to get high volumetric efficiency → large valve overlap

At low engine speed and part throttle valve overlap is minimized by reducing the angle duration for valves staying open.

Volumetric Efficiency

$$\eta_v = \frac{m_a}{\rho_{a,o} V_d}$$



Volumetric efficiency is affected by :

i) Fuel evaporation
ii) Mixture temperature
iii) Pressure drop in the intake system
iv) Gas dynamic effects

Note: <u>piston speed is proportional to air flow velocity</u>

Factors affecting η_v as a function of speed