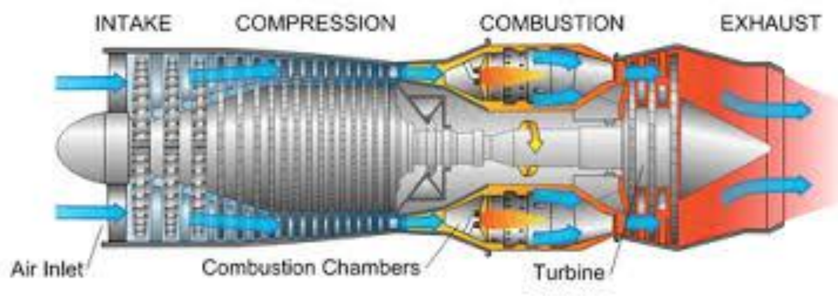
TIKRIT UNIVERSITY
COLLEGE OF ENGINEERING
MECHNICAL DEPARTMENT
INTERNAL COMBUSTION ENGINE



Chapter Three

Air Standard Cycles and their Analysis

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Assumptions of Thermodynamic Cycles Analysis

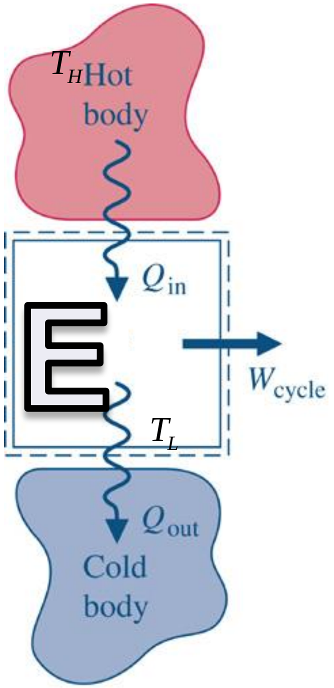
Air-standard analysis is a simplification of the real cycle that includes the following assumptions:

1) Working fluid consists of fixed amount of air (ideal gas)

2) Combustion process represented by heat transfer into and out of the cylinder from an external source.

3) Differences between intake and exhaust processes not considered (i.e. no pumping work)

4) Engine friction and heat losses not considered



Carnot Heat Engine

$$\eta_{th} = \frac{W_{cycle}}{Q_{in}} = \frac{Q_{in} - |Q_{out}|}{Q_{in}} = 1 - \frac{|Q_{out}|}{Q_{in}}$$

$$\eta_{th,Carnot} = \frac{W_{cycle}}{Q_{in}} = \frac{Q_{in} - |Q_{out}|}{Q_{in}} = 1 - \left(\frac{|Q_{out}|}{Q_{in}}\right)_{rev}$$

Carnot's Theoretical Model for Steam Engine

Kelvin and Rankine suggested that,

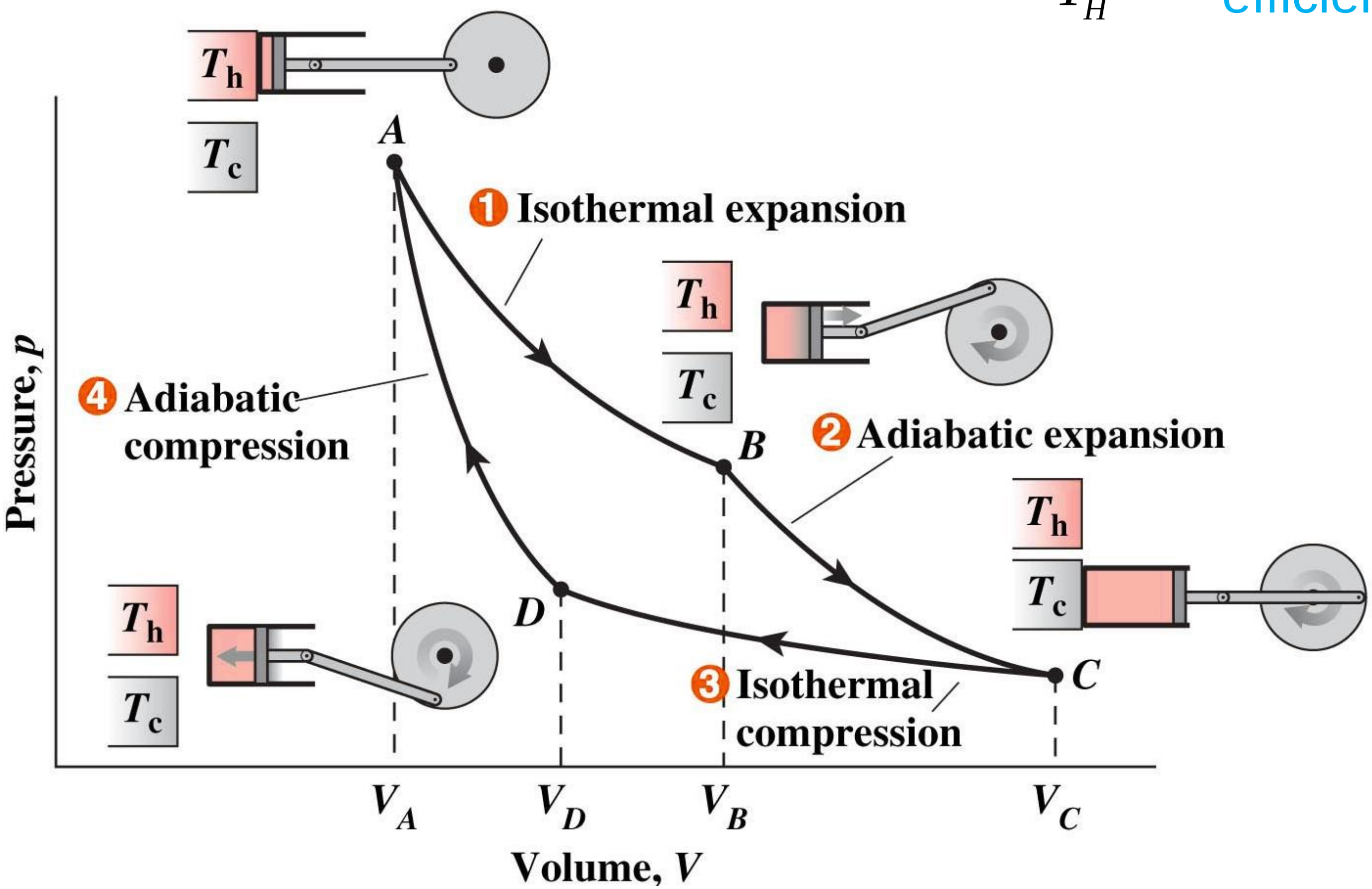
$$\left(\frac{|Q_{out}|}{Q_{in}}\right)_{rev} = \frac{T_L}{T_H}$$

Temperatures must be on the absolute scale!

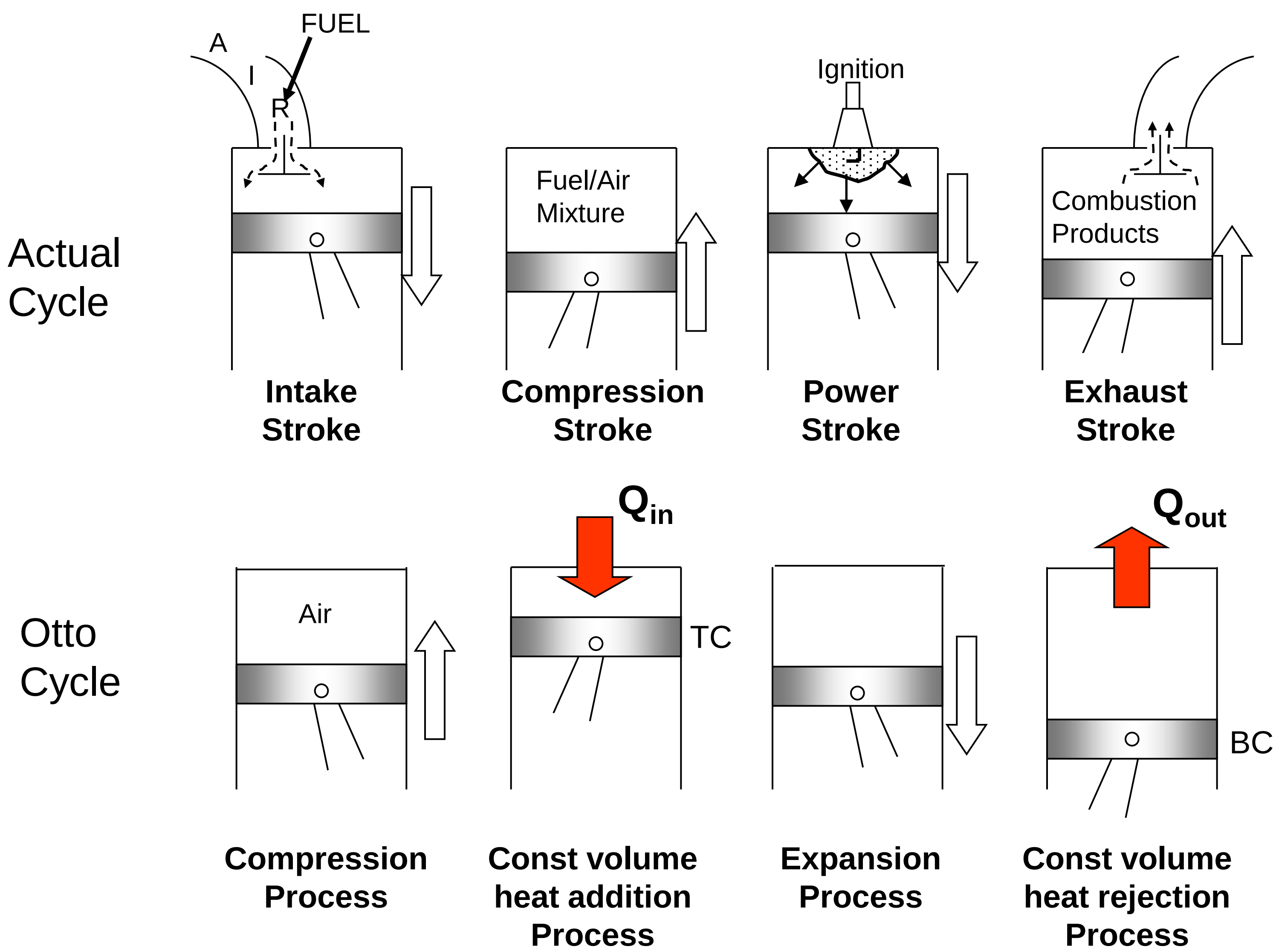
Therefore, the thermal efficiency of a Carnot Heat Engine is,

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$$

This is the **maximum** efficiency of a heat engine!



SI Engine Cycle vs Air Standard Otto Cycle

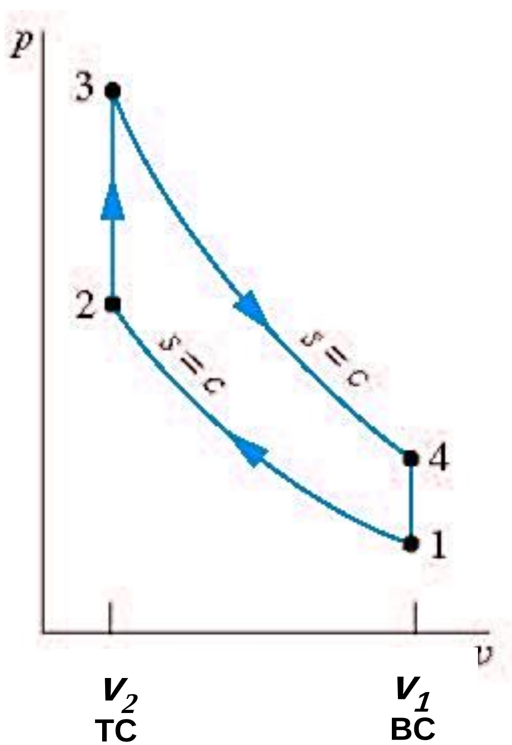


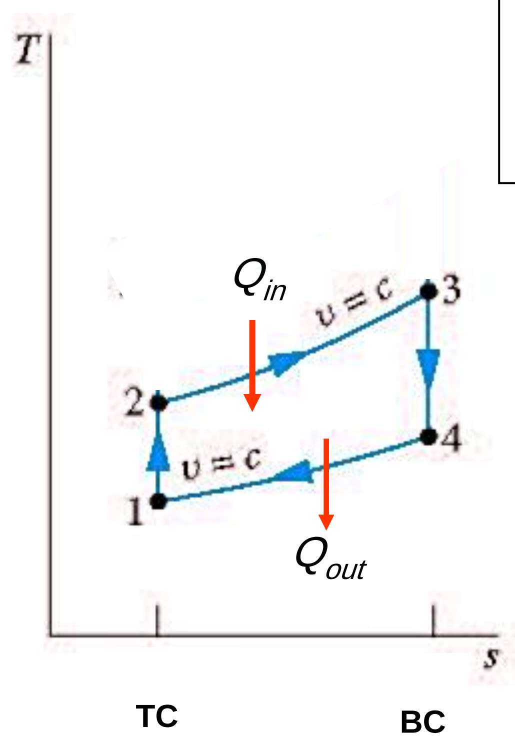
Air-Standard Otto cycle

1. Process 1→ 2 Isentropic compression
2. Process 2 → 3 Constant volume heat addition
3. Process 3 → 4 Isentropic expansion
4. Process 4 → 1 Constant volume heat rejection

Compression ratio:

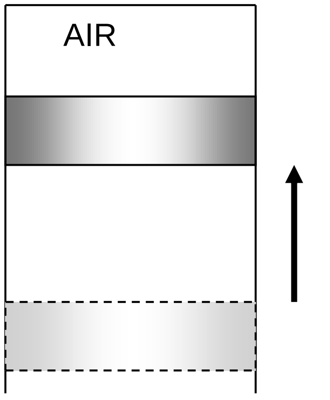
$$r = \frac{v_1}{v_2} = \frac{v_4}{v_3}$$





First Law Analysis of Otto Cycle

1→2 <u>Isentropic Compression</u>



$$(u_2 - u_1) = \frac{\cancel{Q}}{m} - \left(-\frac{W_{in}}{m}\right)$$

$$\boxed{\frac{W_{in}}{m} = (u_2 - u_1)}$$

dE=Q-W

$$\boxed{\frac{v_2}{v_1} = \frac{1}{r}}$$

$$R = \frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \rightarrow \boxed{\frac{P_2}{P_1} = \frac{T_2}{T_1} \cdot \frac{v_1}{v_2}}$$

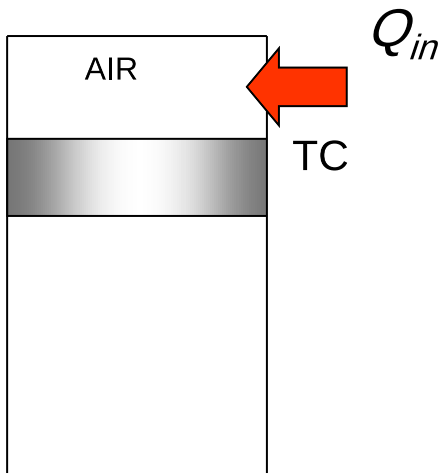
First Law Analysis of Otto Cycle

2→3 <u>Constant Volume Heat Addition</u>

$$(u_3 - u_2) = (+\frac{Q_{in}}{m}) - \cancel{\frac{W}{m}}$$

$$\boxed{\frac{Q_{in}}{m} = (u_3 - u_2)}$$

$$v = \frac{P_2}{RT_2} = \frac{P_3}{RT_3} \rightarrow \boxed{\frac{P_3}{P_2} = \frac{T_3}{T_2}}$$

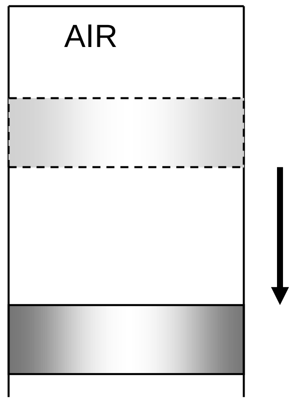


First Law Analysis of Otto Cycle

3 → 4 <u>Isentropic Expansion</u>

$$(u_4 - u_3) = \frac{\cancel{Q}}{m} - (+\frac{W_{out}}{m})$$

$$\boxed{\frac{W_{out}}{m} = (u_3 - u_4)}$$



$$\boxed{\frac{v_4}{v_3} = r}$$

$$\frac{P_4 v_4}{T_4} = \frac{P_3 v_3}{T_3} \rightarrow \boxed{\frac{P_4}{P_3} = \frac{T_4}{T_3} \cdot \frac{v_3}{v_4}}$$

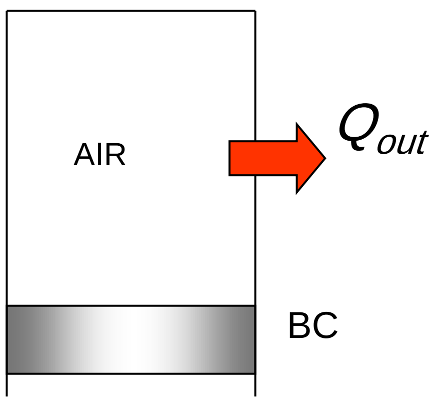
First Law Analysis of Otto Cycle

4 → 1 Constant Volume Heat Removal

$$(u_1 - u_4) = (-\frac{Q_{out}}{m}) - \frac{\cancel{W}}{m}$$

$$\boxed{\frac{Q_{out}}{m} = (u_4 - u_1)}$$

$$v = \frac{P_4}{RT_4} = \frac{P_1}{RT_1} \rightarrow \boxed{\frac{P_4}{T_4} = \frac{P_1}{T_1}}$$



First Law Analysis

Net cycle work:

$$W_{cycle} = W_{out} - W_{in} = m(u_3 - u_4) - m(u_2 - u_1)$$

Cycle thermal efficiency:

$$\eta_{th} = \frac{W_{cycle}}{Q_{in}} = \frac{W_{out} - W_{in}}{Q_{in}} = \frac{(u_3 - u_4) - (u_2 - u_1)}{(u_3 - u_2)}$$

$$\eta_{th} = \frac{(u_3 - u_2) - (u_4 - u_1)}{u_3 - u_2} = 1 - \frac{u_4 - u_1}{u_3 - u_2}$$

Cold Air-Standard Analysis

• For a cold air-standard analysis the specific heats are assumed to be constant evaluated at ambient temperature values ($k = c_p/c_v = 1.4$).

• For the two isentropic processes in the cycle, assuming ideal gas with constant specific heat using $Pv^k = const.$ $Pv = RT$ yields:

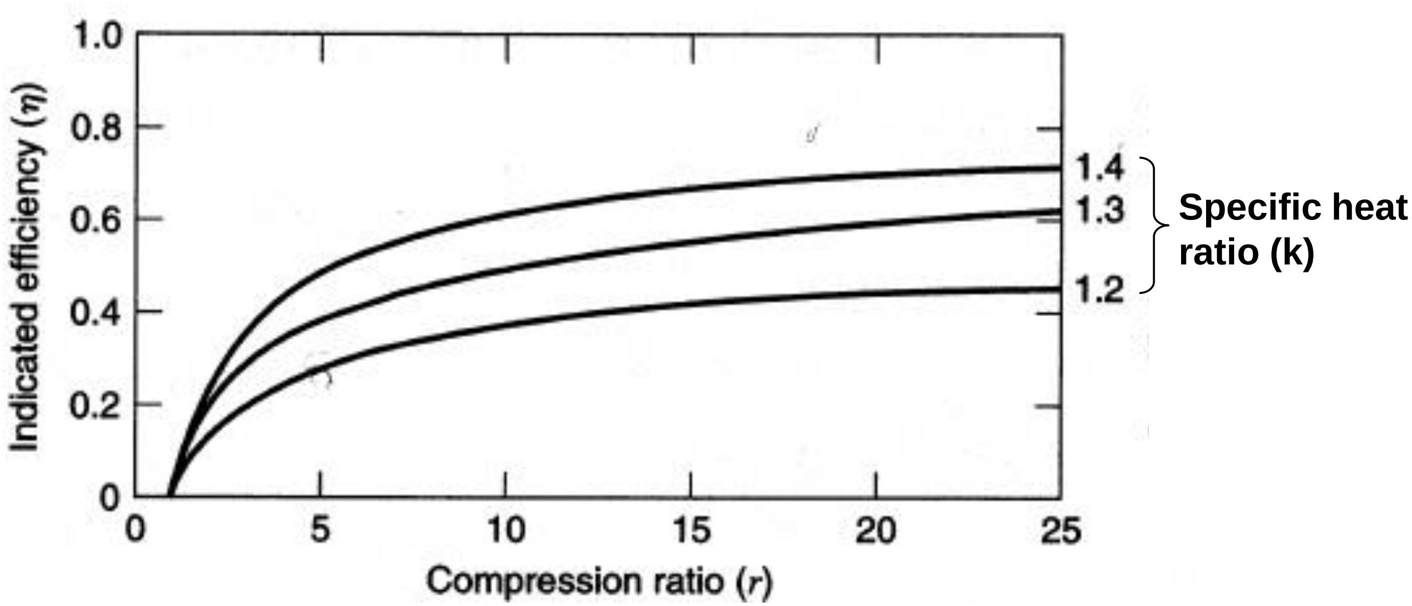
1 → 2 : $$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} = r^{k-1} \qquad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

3 → 4 : $$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{k-1} = \left(\frac{1}{r}\right)^{k-1} \qquad \frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{k-1}{k}}$$

$$\eta_{th_{const\ c_V}} = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)} = 1 - \frac{T_1}{T_2} = \boxed{1 - \frac{1}{r^{k-1}}}$$

Effect of Specific Heat Ratio

$$\eta_{th_{const\ c_V}} = 1 - \frac{1}{r^{k-1}}$$

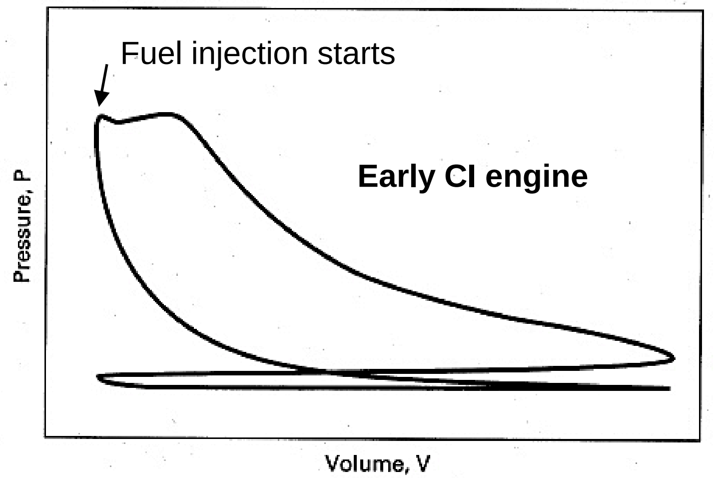


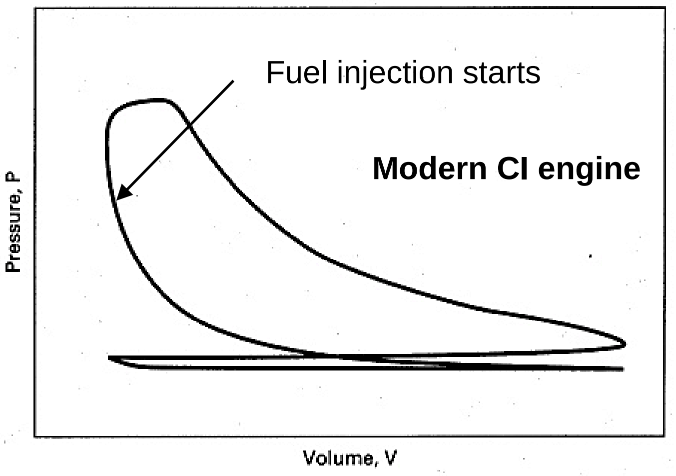
Cylinder temperatures vary between 20K and 2000K where 1.2 < k < 1.4

Thermodynamic Cycles for CI engines

- In early CI engines the fuel was injected when the piston reached TDC and thus combustion lasted well into the expansion stroke.

- In modern engines the fuel is injected before TDC (about 20º)

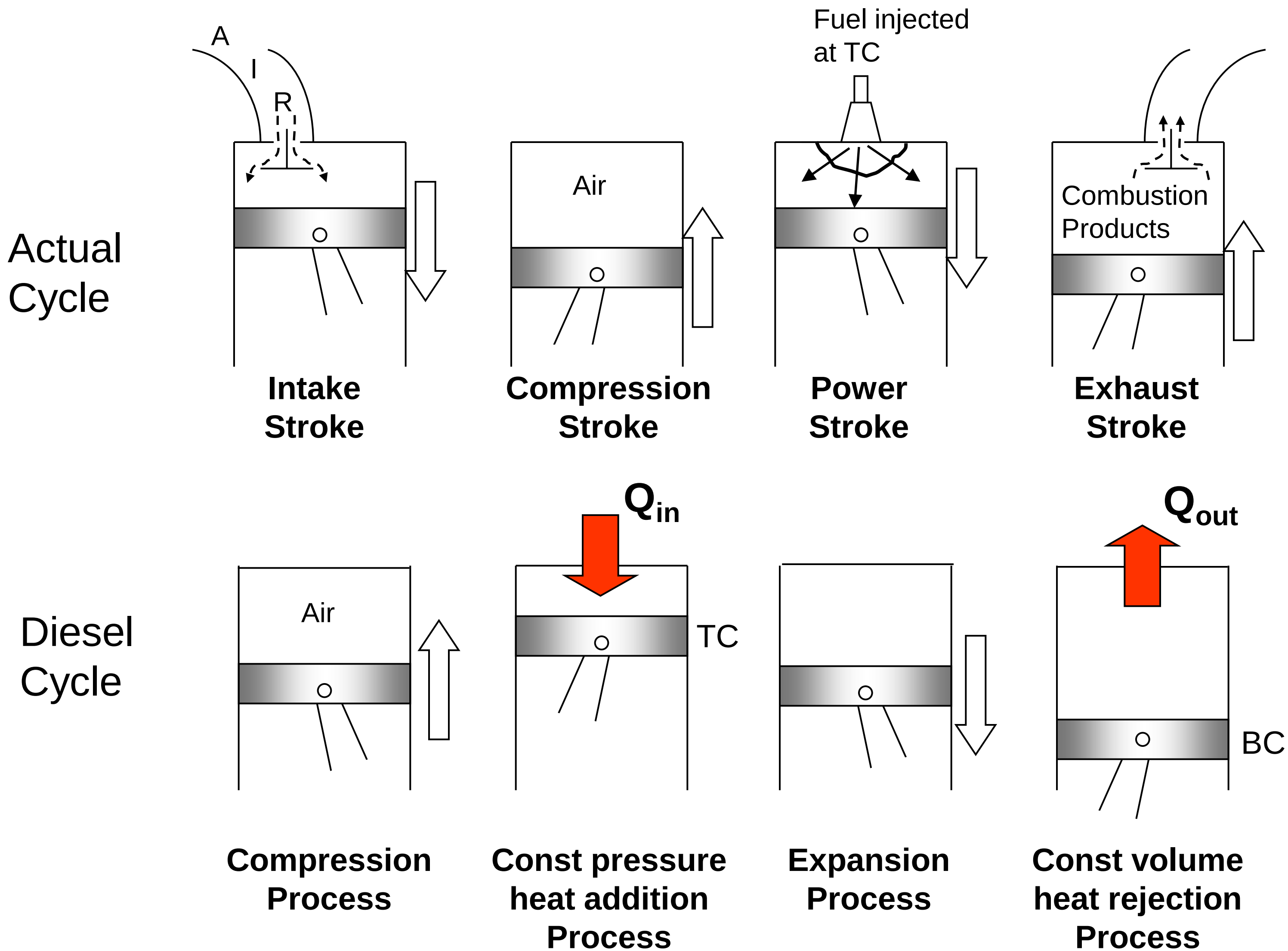




- The combustion process in the early CI engines is best approximated by a constant pressure heat addition process → **Diesel Cycle**

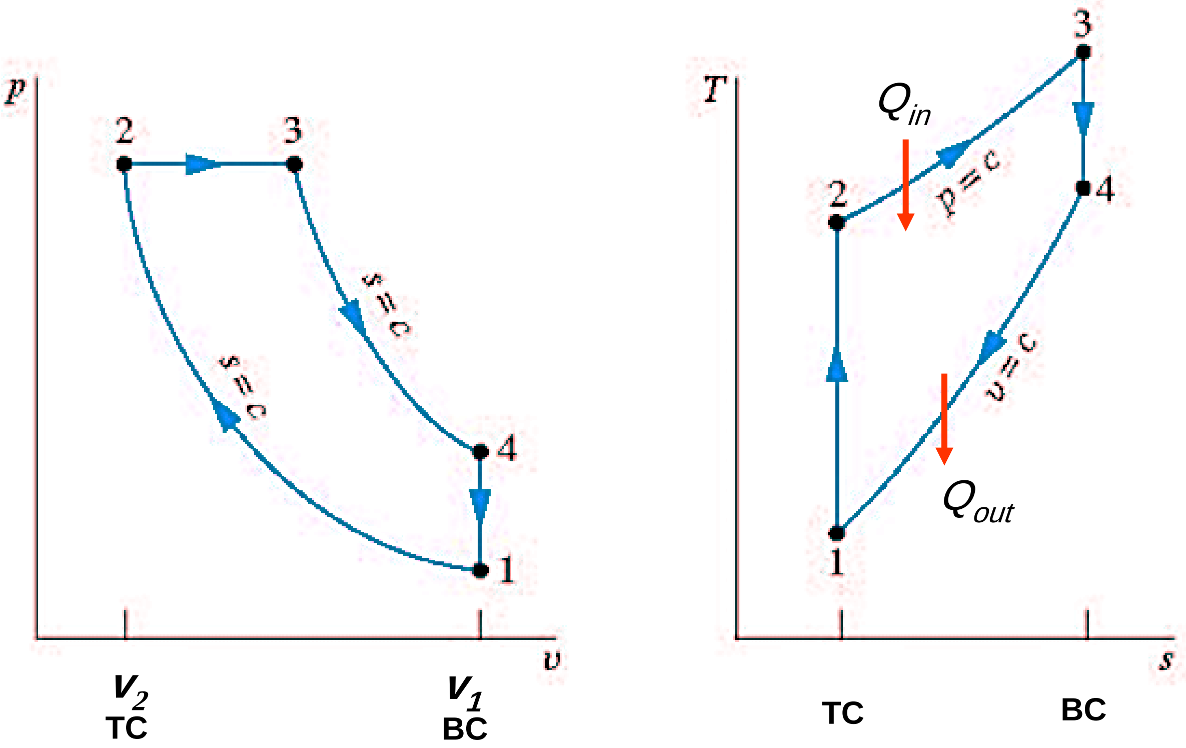
- The combustion process in the modern CI engines is best approximated by a combination of constant volume & constant pressure → **Dual Cycle**

Early CI Engine Cycle vs Diesel Cycle



Air-Standard Diesel Cycle

Process 1→ 2 Isentropic compression
Process 2 → 3 Constant pressure heat addition
Process 3 → 4 Isentropic expansion
Process 4 → 1 Constant volume heat rejection



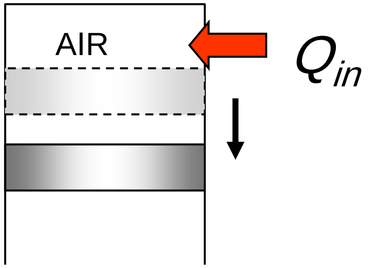
Cut-off ratio:

$$r_c = \frac{v_3}{v_2}$$

First Law Analysis of Diesel Cycle

Equations for processes 1→2, 4→1 are the same as those presented for the Otto cycle

2→3 Constant Pressure Heat Addition



$$(u_3 - u_2) = (+\frac{Q_{in}}{m}) - \frac{P_2(V_3 - V_2)}{m}$$

$$\frac{Q_{in}}{m} = (u_3 + P_3 v_3) - (u_2 + P_2 v_2)$$

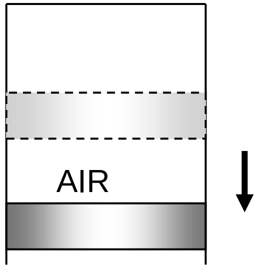
$$\boxed{\frac{Q_{in}}{m} = (h_3 - h_2)}$$

$$P = \frac{RT_2}{v_2} = \frac{RT_3}{v_3} \rightarrow \boxed{\frac{T_3}{T_2} = \frac{v_3}{v_2} = r_c}$$

3 → 4 Isentropic Expansion

$$(u_4 - u_3) = \frac{\cancel{Q}}{m} - \left(+\frac{W_{out}}{m}\right)$$

$$\boxed{\frac{W_{out}}{m} = (u_3 - u_4)}$$



Note that $v_4 = v_1$, so: $$\frac{v_4}{v_3} = \frac{v_4}{v_2}\cdot\frac{v_2}{v_3} = \frac{v_1}{v_2}\cdot\frac{v_2}{v_3} = \frac{r}{r_c} \rightarrow \boxed{\frac{v_4}{v_3} = \frac{r}{r_c}}$$

$$\frac{P_4 v_4}{T_4} = \frac{P_3 v_3}{T_3} \rightarrow \boxed{\frac{P_4}{P_3} = \frac{T_4}{T_3}\cdot\frac{r_c}{r}}$$

Thermal Efficiency

$$\eta_{\substack{Diesel\\cycle}} = 1 - \frac{Q_{out}/m}{Q_{in}/m} = 1 - \frac{u_4 - u_1}{h_3 - h_2}$$

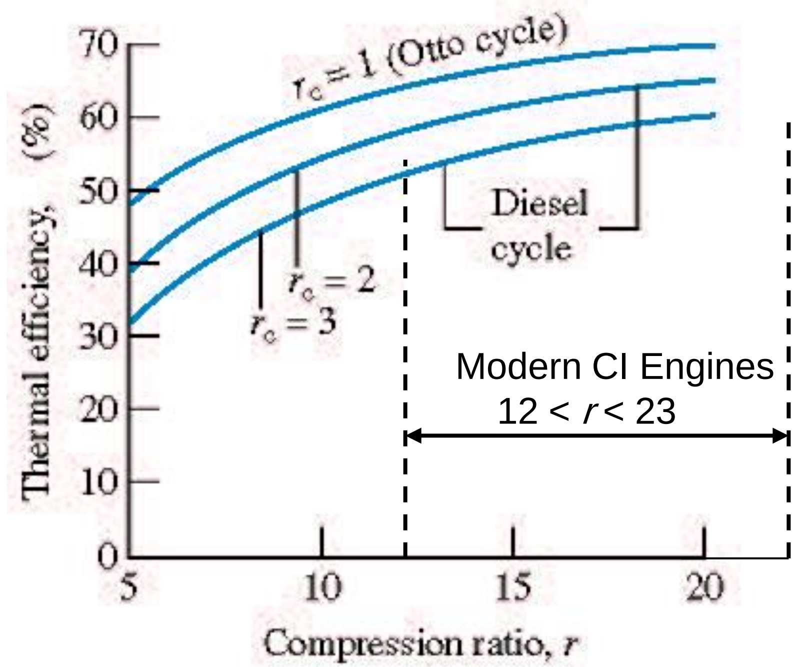
For cold air-standard the above reduces to:

$$\eta_{\substack{Diesel\\const\ c_V}} = 1 - \frac{1}{r^{k-1}}\left[\frac{1}{k}\cdot\frac{\left(r_c^{\,k} - 1\right)}{\left(r_c - 1\right)}\right] \quad \text{recall,} \quad \eta_{Otto} = 1 - \frac{1}{r^{k-1}}$$

Note the term in the square bracket is always larger than one so for the same compression ratio, *r*, the Diesel cycle has a *lower* thermal efficiency than the Otto cycle

When r_c ($=v_3/v_2$)$\rightarrow$1 the Diesel cycle efficiency approaches the efficiency of the Otto cycle

Thermal Efficiency

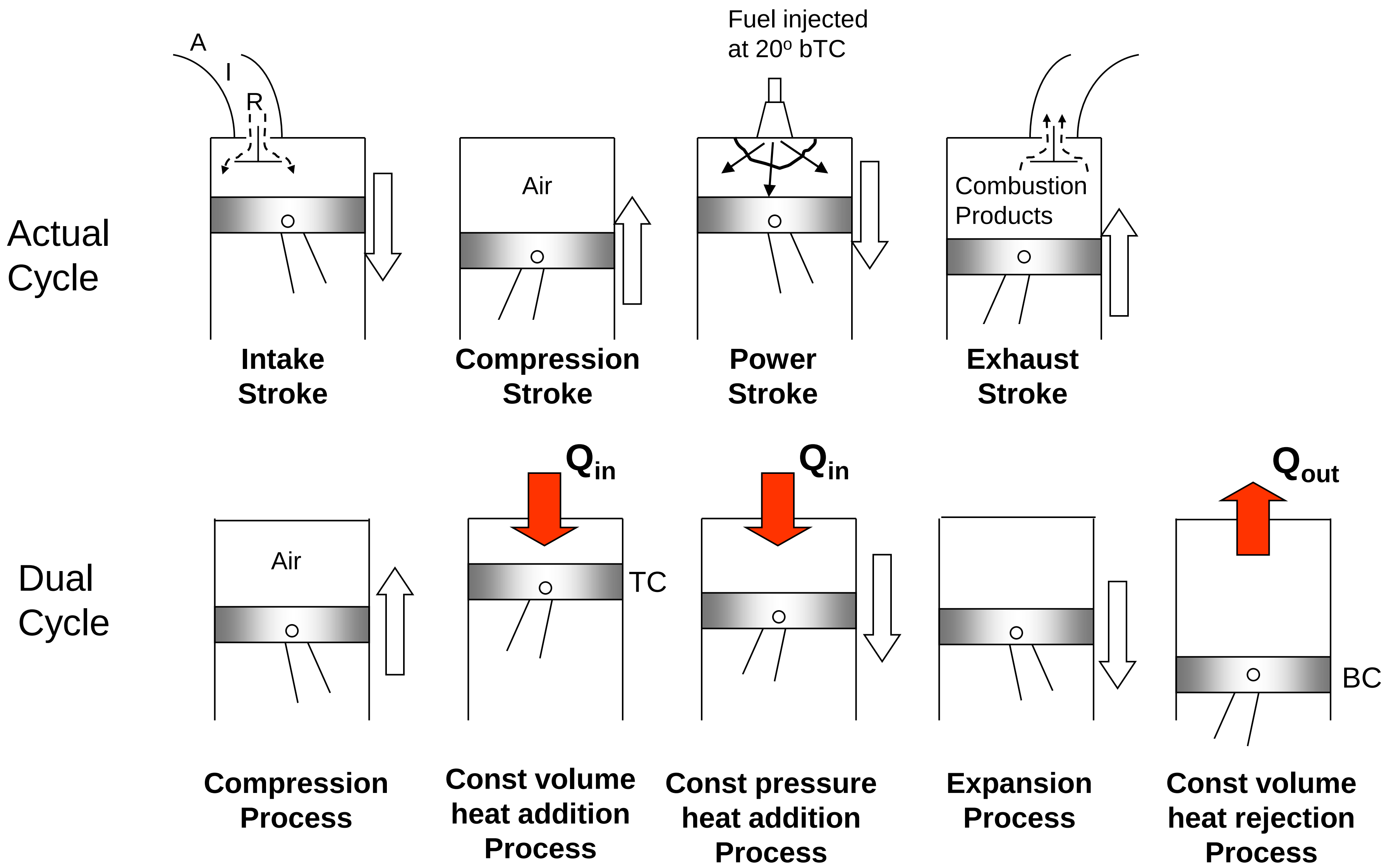


The cut-off ratio is not a natural choice for the independent variable
A more suitable parameter is the heat input, the two are related by:

$$r_c = 1 - \frac{k-1}{k}\left(\frac{Q_{in}}{P_1 V_1}\right)\frac{1}{r^{k-1}}$$

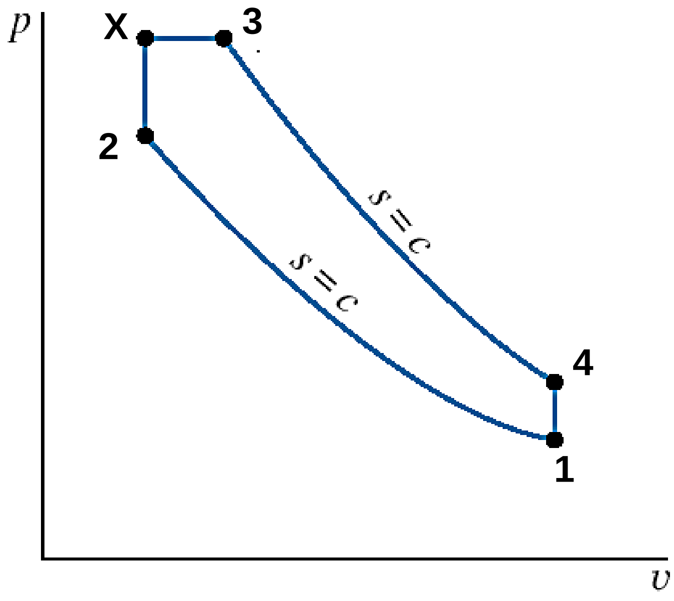
as $Q_{in} \rightarrow 0$, $r_c \rightarrow 1$ and $\eta \rightarrow \eta_{Otto}$

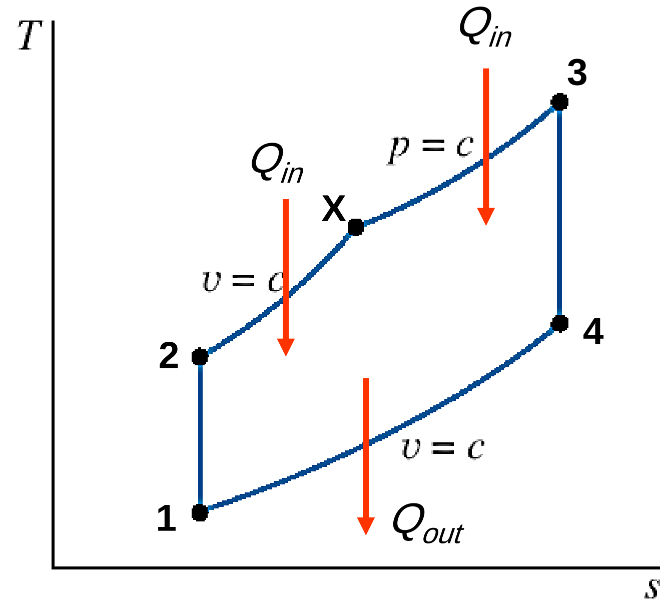
Modern CI Engine Cycle vs Dual Cycle



Dual Cycle

Process 1 → 2 Isentropic compression
Process 2 → X Constant volume heat addition
Process X → 3 Constant pressure heat addition
Process 3 → 4 Isentropic expansion
Process 4 → 1 Constant volume heat rejection





Thermal Efficiency

$$\eta_{\substack{Dual \\ cycle}} = 1 - \frac{Q_{out}/m}{Q_{in}/m} \qquad \eta_{\substack{Dual \\ cycle}} = 1 - \frac{u_4 - u_1}{(u_x - u_2) + (h_3 - h_x)}$$

For cold air-standard the above reduces to:

$$\boxed{\eta_{\substack{Dual \\ const\, c_v}} = 1 - \frac{1}{r^{k-1}} \left[\frac{\alpha r_c^k - 1}{(\alpha - 1) + \alpha k (r_c - 1)} \right]}$$

$$\text{where } r_c = {}^{v_3}\!/_{v_x} \text{ and } \alpha = {}^{p_3}\!/_{p_2}$$

Note, the Otto cycle ($r_c=1$) and the Diesel cycle ($\alpha=1$) are special cases:

$$\eta_{Otto} = 1 - \frac{1}{r^{k-1}} \qquad \eta_{Diesel} = 1 - \frac{1}{r^{k-1}} \left[\frac{1}{k} \cdot \frac{(r_c^k - 1)}{(r_c - 1)} \right]$$

Comparison between Otto, Diesel and Dual cycles

The use of the Dual cycle requires information about either:

i) the fractions of constant volume and constant pressure heat addition
(common assumption is to *equally* split the heat addition), or

ii) maximum pressure p_3.

iii) Transformation of r_c and α into more natural variables yields

$$r_c = 1 - \frac{k-1}{\alpha k}\left[\left(\frac{Q_{in}}{p_1 V_1}\right)\frac{1}{r^{k-1}} - \frac{\alpha - 1}{k-1}\right] \qquad \alpha = \frac{1}{r^k}\frac{p_3}{p_1}$$

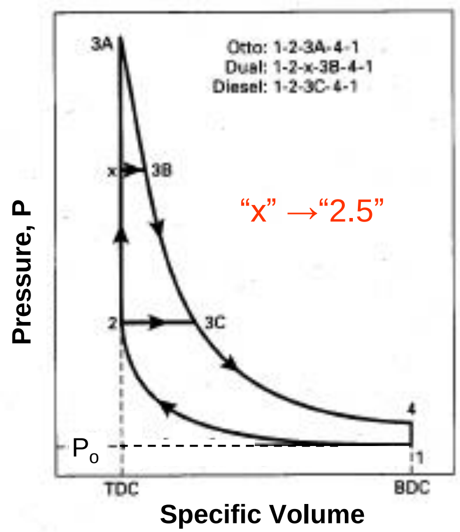
For the same inlet conditions p_1, V_1 and the same compression ratio:

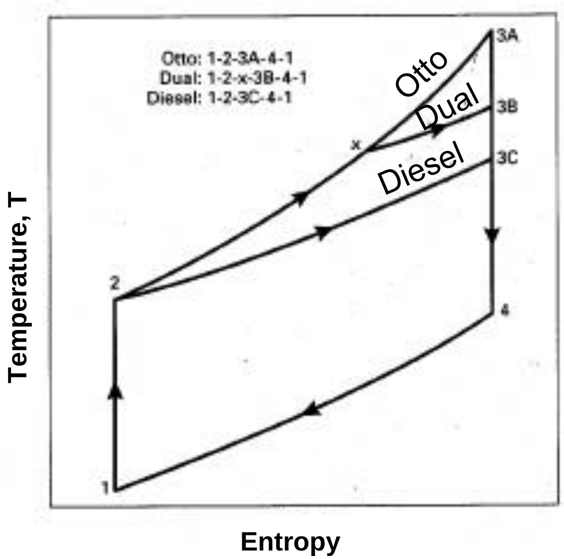
$$\eta_{Otto} > \eta_{Dual} > \eta_{Diesel}$$

For the same inlet conditions p_1, V_1 and the same peak pressure p_3 (actual design limitation in engines):

$$\eta_{Diesel} > \eta_{Dual} > \eta_{otto}$$

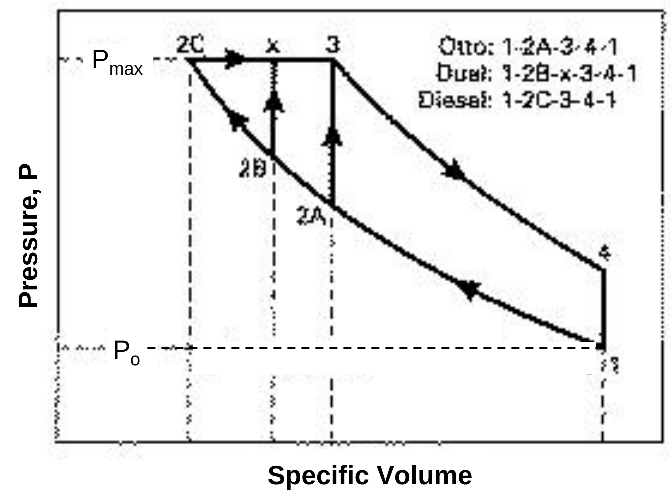
For the *same compression ratio* & p_{1}, V_{1}:

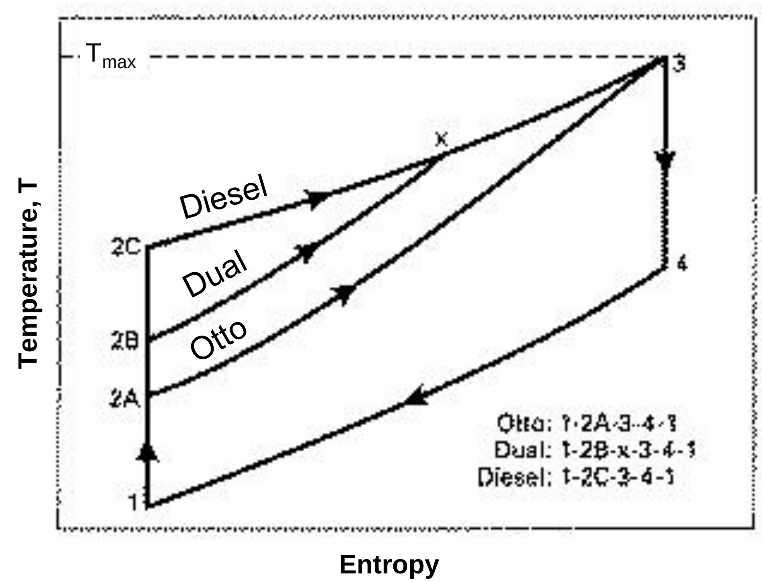




$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{\int_{4}^{1} T ds}{\int_{2}^{3} T ds}$$

For the *same peak pressure* p_{3} & p_{1}, V_{1}:





Type of Fuel Vs Combustion Strategy

- Highly volatile with High self Ignition Temperature: Spark Ignition. Ignition after thorough mixing of air and fuel.

- Less Volatile with low self Ignition Temperature: Compression Ignition , Almost simultaneous mixing & Ignition.