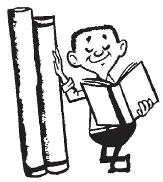
Internal Combustion Engines

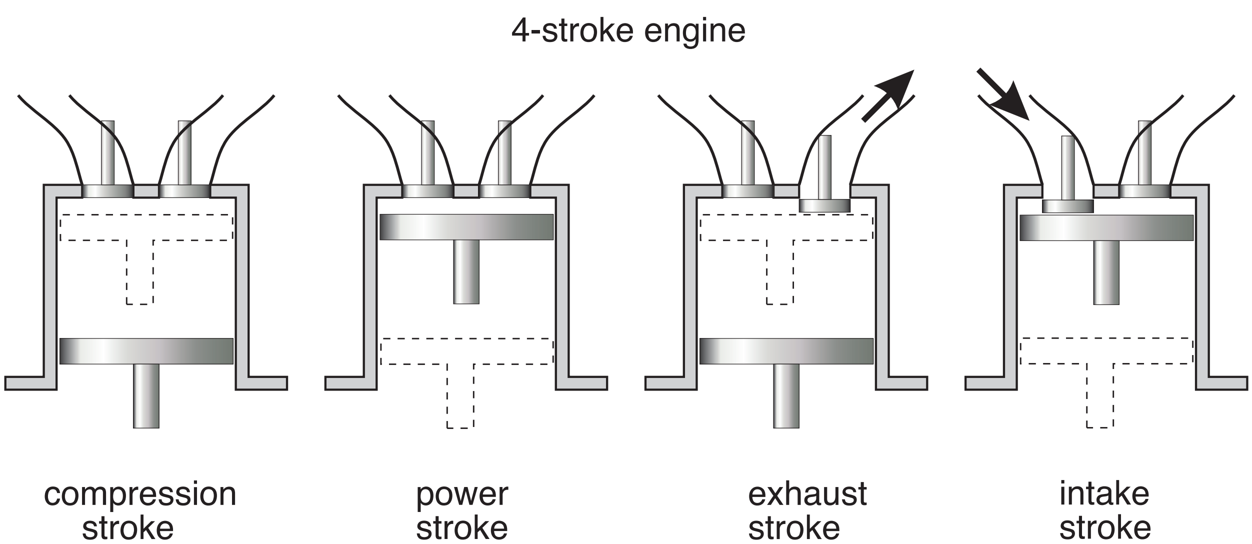


Reading	Problems
8-3 → 8-7	8-35, 8-45, 8-52

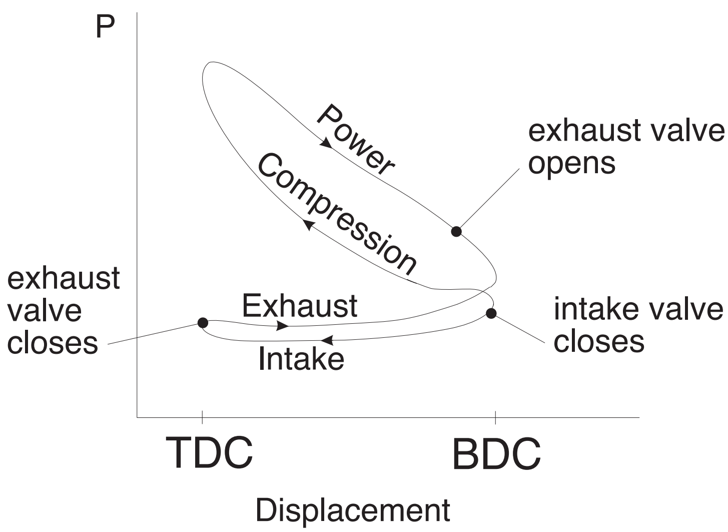
Definitions

1. **spark ignition**:
   - a mixture of fuel and air is ignited by a spark plug
   - applications requiring power to about 225 kW (300 HP)
   - relatively light and low in cost
2. **compression ignition engine**:
   - air is compressed to a high enough pressure and temperature that combustion occurs when the fuel is injected
   - applications where fuel economy and relatively large amounts of power are required

The Gasoline Engine



- conversion of chemical energy to mechanical energy
- can obtain very high temperatures due to the short duration of the power stroke



Air Standard Cycle

ASSUMPTIONS:

- air is an ideal gas with constant c_p and c_v
- no intake or exhaust processes
- the cycle is completed by heat transfer to the surroundings
- the internal combustion process is replaced by a heat transfer process from a TER
- all internal processes are reversible
- heat addition occurs instantaneously while the piston is at TDC

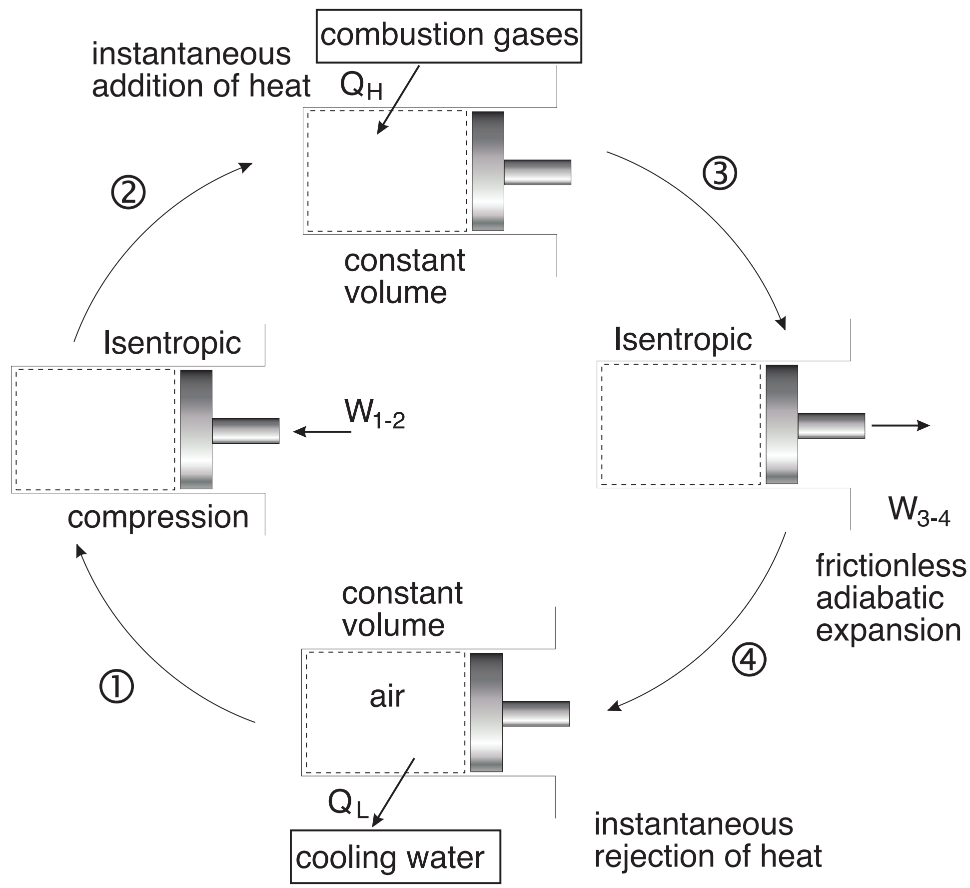
Definitions

Mean Effective Pressure (MEP): The theoretical constant pressure that, if it acted on the piston during the power stroke would produce the same *net* work as actually developed in one complete cycle.

$$MEP = \frac{\text{net work for one cycle}}{\text{displacement volume}} = \frac{W_{net}}{V_{BDC} - V_{TDC}}$$

The mean effective pressure is an index that relates the work output of the engine to it size (displacement volume).

Otto Cycle



- the theoretical model for the gasoline engine
- consists of four internally reversible processes
- heat is transferred to the working fluid at constant volume

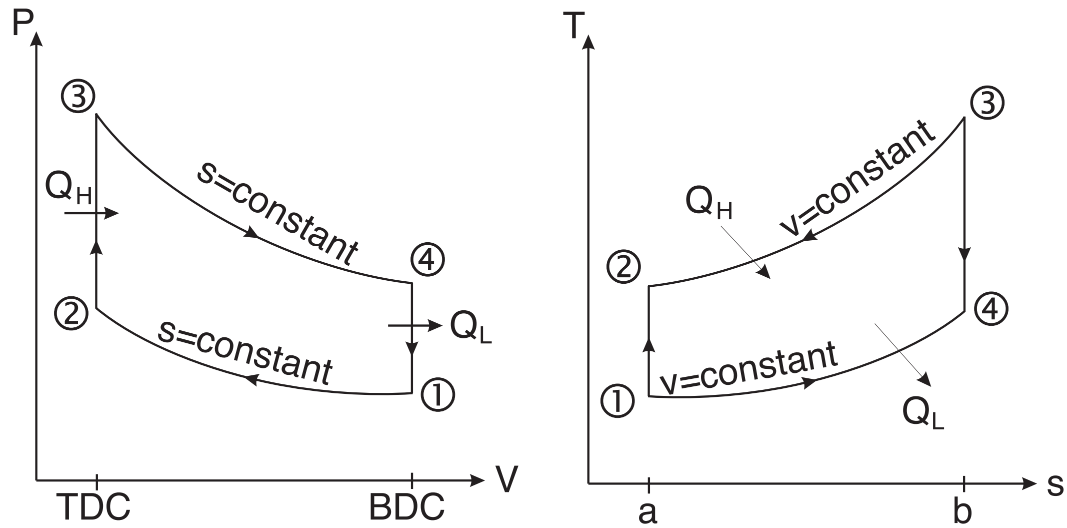
The **Otto cycle** consists of four internally reversible processes in series

1 ⟶ 2 isentropic compression or air as the piston moves from BDC to TDC

2 ⟶ 3 constant volume heat addition to the fuel/air mixture from an external source while the piston is at TDC (represents the ignition process and the subsequent burning of fuel)

3 ⟶ 4 isentropic expansion (power stroke)

4 ⟶ 1 constant volume heat rejection at BDC



The Otto cycle efficiency is given as

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{V_2}{V_1}\right)^{k-1} = 1 - \left(\frac{V_1}{V_2}\right)^{1-k}$$

If we let

$$r = \frac{V_1}{V_2} = \frac{V_4}{V_3} = compression\ ratio$$

Then

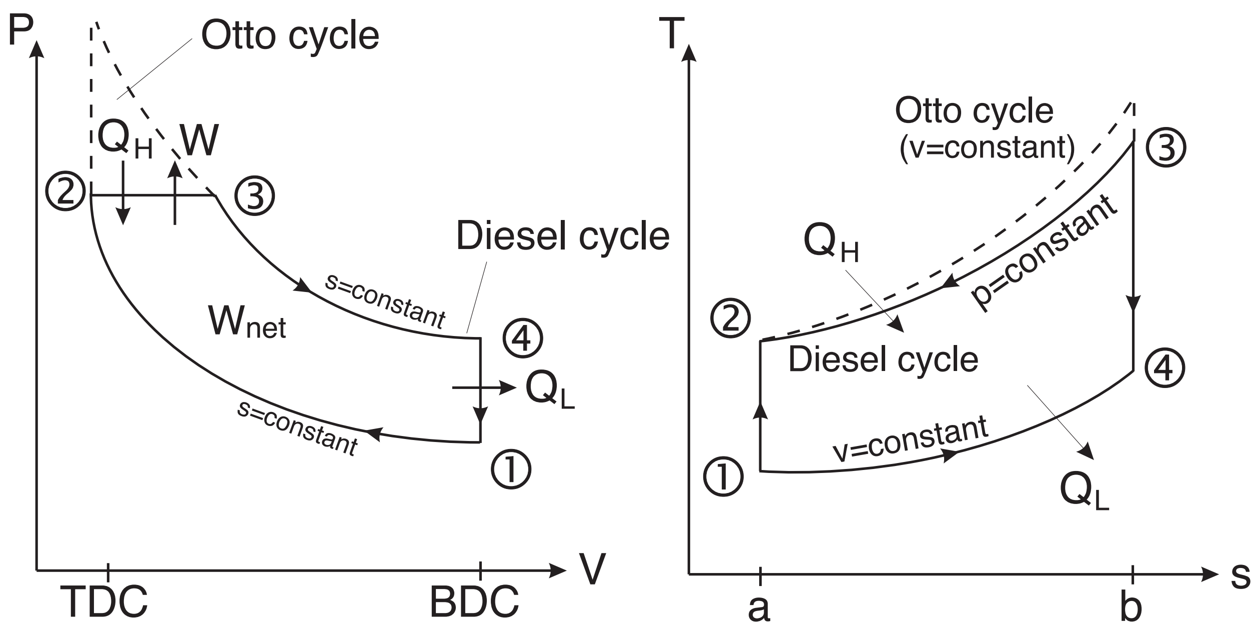
$$\boxed{\eta_{Otto} = 1 - r^{1-k}}$$

Why not go to higher compression ratios?

- there is an increased tendency for the fuel to detonate as the compression ratio increases
- the pressure wave gives rise to engine knock
- can be reduced by adding tetraethyl lead to the fuel
- not good for the environment

Diesel Cycle

- an ideal cycle for the compression ignition engine (diesel engine)
- all steps in the cycle are reversible
- heat is transferred to the working fluid at constant pressure
- heat transfer must be just sufficient to maintain a constant pressure



If we let

$$r = \frac{V_1}{V_2} = compression\,ratio = \frac{V_4}{V_2}$$

$$r_v = \frac{V_3}{V_2} = cutoff\,ratio \rightarrow \; injection\,period$$

then the diesel cycle efficiency is given as

$$\boxed{\eta_{Diesel} = 1 - \frac{1}{r^{k-1}}\left(\frac{1}{k}\right)\left(\frac{r_v^k - 1}{r_v - 1}\right)}$$

Where we note

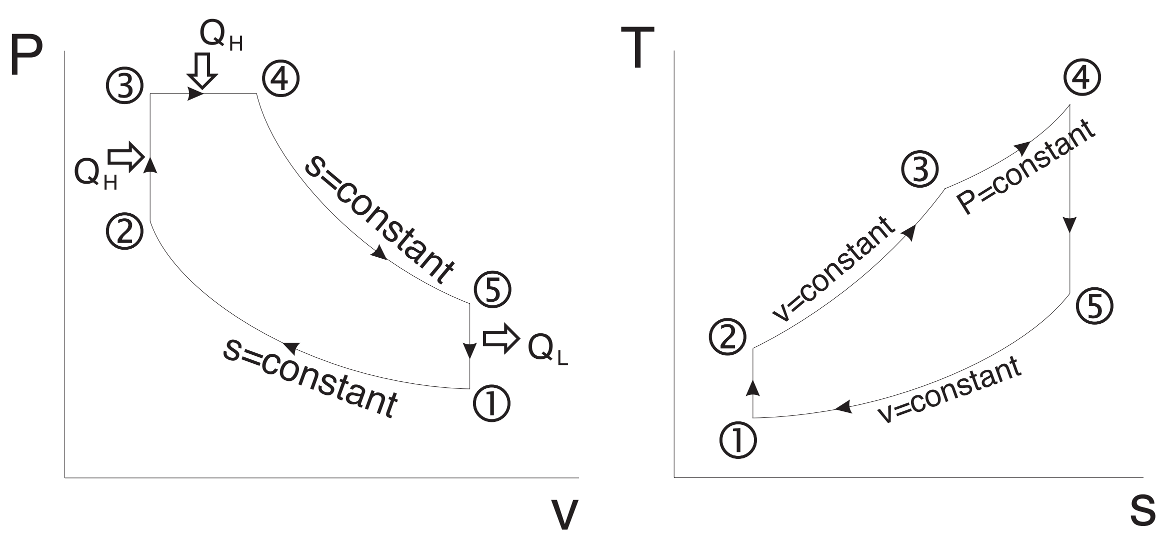
$$\eta_{Diesel} = 1 - \frac{1}{r^{k-1}} \underbrace{\left(\frac{1}{k}\right)\left(\frac{r_v^k - 1}{r_v - 1}\right)}_{=1 \text{ in the Otto Cycle}}$$

Comparison of the Otto and the Diesel Cycle

- $\eta_{Otto} > \eta_{Diesel}$ for the same compression ratio
- but a diesel engine can tolerate a higher ratio since only air is compressed in a diesel cycle and spark knock is not an issue
- direct comparisons are difficult

Dual Cycle (Limited Pressure Cycle)

- this is a better representation of the combustion process in both the gasoline and the diesel engines
- in a compression ignition engine, combustion occurs at TDC while the piston moves down to maintain a constant pressure



Dual Cycle Efficiency

Given

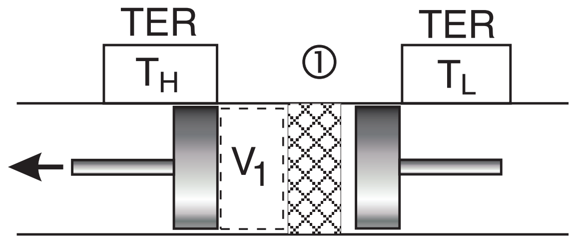
$$
\begin{aligned}
r &= \frac{V_1}{V_2} = compression\, ratio \\
r_v &= \frac{V_4}{V_3} = cutoff\, ratio \\
r_p &= \frac{P_3}{P_2} = pressure\, ratio
\end{aligned}
$$

$$
\boxed{\eta_{Dual} = 1 - \frac{r_p r_v^k - 1}{\left[(r_p - 1) + k r_p (r_v - 1)\right] r^{k-1}}}
$$

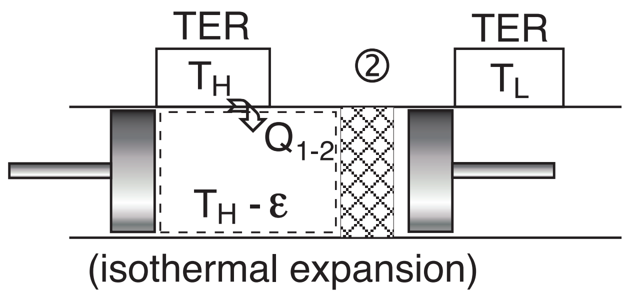
Note: if $r_p = 1$ we get the diesel efficiency.

Stirling Cycle

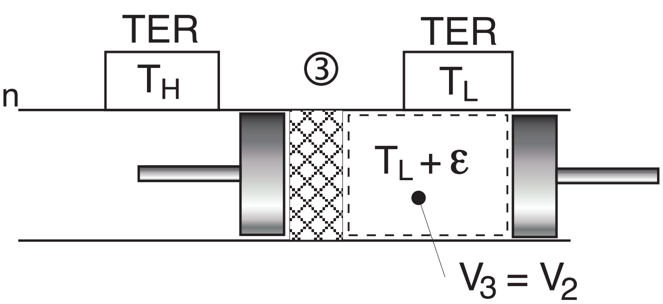
① → ②
isothermal expansion
at high temperature
- heat is added,
volume expands



② → ③
constant volume
process

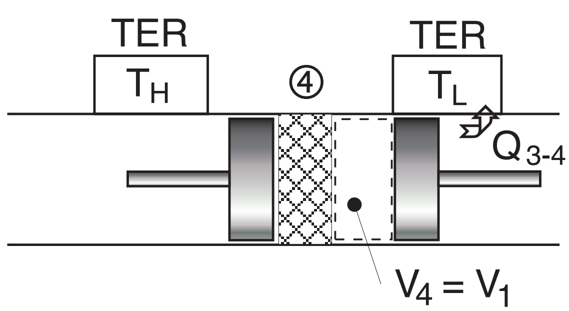


③ → ④
isothermal compression
at low temperature

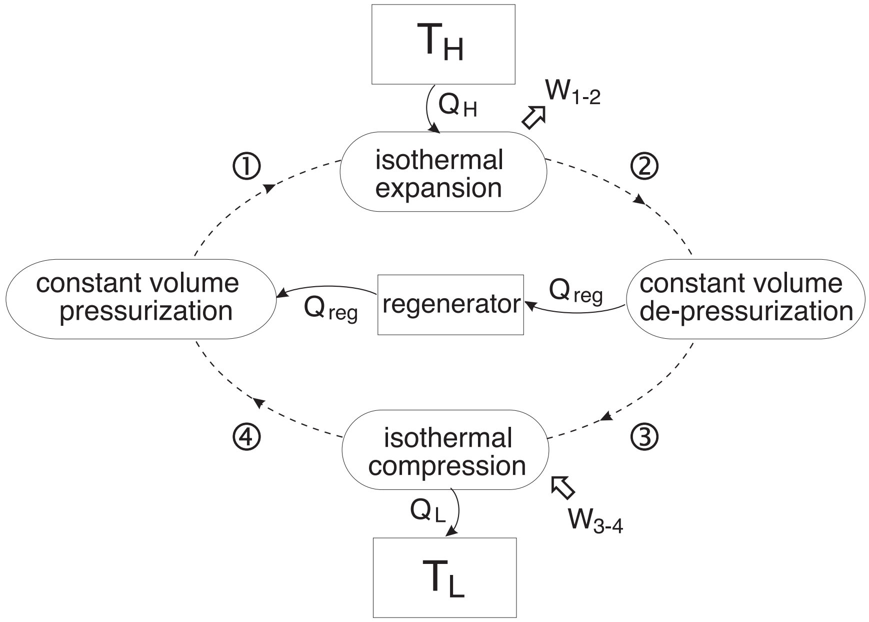


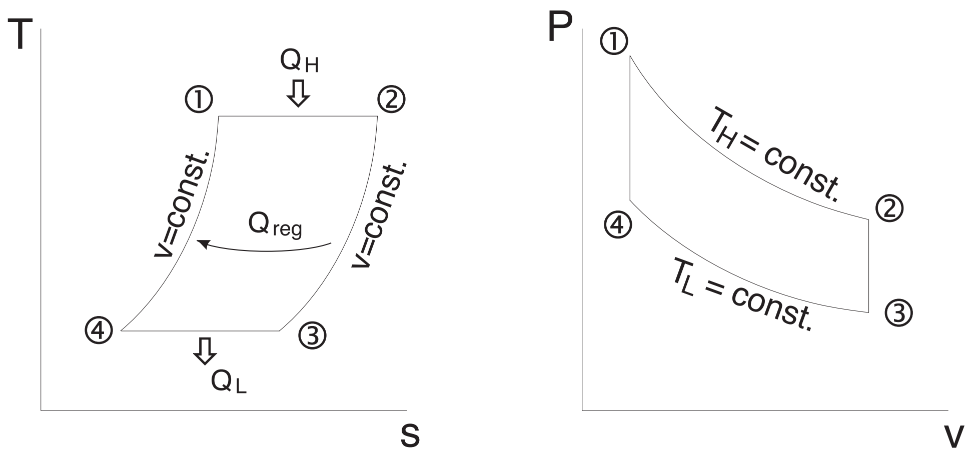
heat the regenerator
by pushing the hot
gas through it

④ → ①
constant volume
process



move both pistons
to the left to get back
to state 1.
During this process the
regenerator cools down
by giving off energy to
the gas





- reversible regenerator used as an energy storage device
- possible to recover all heat given up by the working fluid in the constant volume cooling process
- all the heat received by the cycle is at T_H and all heat rejected at T_L
- $\eta_{Stirling} = 1 - T_L/T_H$ (Carnot efficiency)

With perfect regeneration

$$Q_H = T_H(s_2 - s_1)$$
$$Q_L = T_L(s_3 - s_4)$$

$$\eta = \frac{W_{net}}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L(s_3 - s_4)}{T_H(s_2 - s_1)} \qquad (1)$$

From Gibb's equation

$$Tds = du + Pdv = c_v dT + Pdv$$

if $T = constant \ \Rightarrow Tds = Pdv \quad \Rightarrow \quad ds = \frac{Pdv}{T} = \frac{Rdv}{v}$

Integrating gives

$$s_3 - s_4 = R\ln\left(\frac{v_3}{v_4}\right) = R\ln\left(\frac{v_2}{v_1}\right) = s_2 - s_1$$

Therefore $s_3 - s_4 = s_2 - s_1$, and Eq. 1 gives

$$\eta = 1 - \frac{T_L}{T_H} \quad \Rightarrow \quad Carnot\, efficiency$$