**Internal Combustion Engines**

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**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**

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- **Compression Stroke**: The piston moves downward, compressing the air and fuel mixture in the cylinder.
- **Power Stroke**: The piston moves upward, igniting the compressed mixture and pushing the crankshaft, generating power.
- **Exhaust Stroke**: The piston moves downward, allowing the burned gases to be expelled from the cylinder.
- **Intake Stroke**: The piston moves upward, drawing a fresh mixture of air and fuel into the cylinder.

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4-stroke 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.

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

The mean effective pressure is an index that relates the work output of the engine to its 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

\[ r = \frac{V_1}{V_2} = \frac{V_4}{V_3} = \text{compression ratio} \]

Then

\[ \eta_{\text{Otto}} = 1 - r^{1-k} \]

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

\[ r = \frac{V_1}{V_2} = \text{compression ratio} = \frac{V_4}{V_2} \]

\[ r_v = \frac{V_3}{V_2} = \text{cutoff ratio} \rightarrow \text{injection period} \]

then the diesel cycle efficiency is given as

\[ \eta_{\text{Diesel}} = 1 - \frac{1}{r^{k-1}} \left( \frac{1}{k} \right) \left( \frac{r_v^k - 1}{r_v - 1} \right) \]
Where we note

\[ \eta_{Diesel} = 1 - \frac{1}{r^{k-1}} \left( \frac{1}{k} \right) \left( \frac{r^k - 1}{r^v - 1} \right) = 1 \text{ in the Otto Cycle} \]

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

\[ r = \frac{V_1}{V_2} = \text{compression ratio} \]
\[ r_v = \frac{V_4}{V_3} = \text{cutoff ratio} \]
\[ r_p = \frac{P_3}{P_2} = \text{pressure ratio} \]

\[ \eta_{\text{Dual}} = 1 - \frac{r_p r_v^k - 1}{[(r_p - 1) + k r_p (r_v - 1)] r^{k-1}} \]

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

4 → 1
constant volume process

TER

\[ T_H \]

\[ T_L \]

\[ T_H - \varepsilon \]

\[ T_H - \varepsilon \]

\[ T_L + \varepsilon \]

\[ V_3 = V_2 \]

\[ V_4 = V_1 \]

TER

TER

TER

TER

\[ Q_{1-2} \]

\[ Q_{3-4} \]

heat the regenerator by pushing the hot gas through it

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 $T_L$

• $\eta_{\text{Stirling}} = 1 - T_L/T_H$ (Carnot efficiency)

With perfect regeneration

$$Q_H = T_H(s_2 - s_1)$$

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

From Gibb’s equation

\[
Tds = du + Pdv = c_vdT + Pdv
\]

if \( T = \text{constant} \) \( \Rightarrow Tds = Pdv \) \( \Rightarrow \) \( ds = \frac{Pdv}{T} = \frac{Rdv}{v} \)

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

\[
\eta = 1 - \frac{T_L}{T_H} \quad \Rightarrow \quad \text{Carnot efficiency}
\]