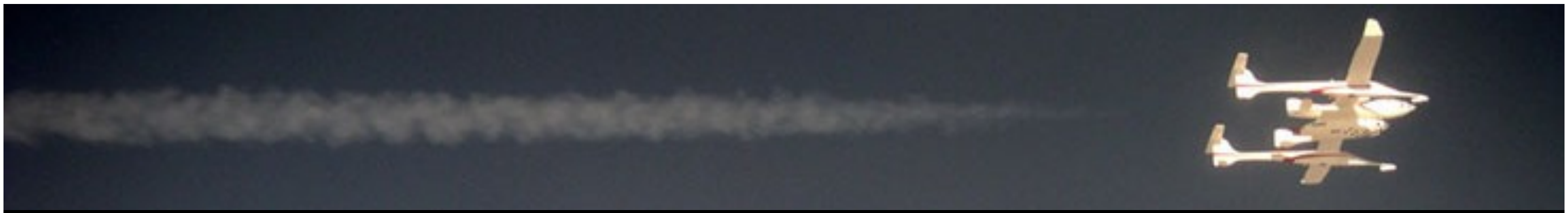

Subsections

3.5 The Internal combustion engine (Otto Cycle)

[VW, S & B: 9.13]

The Otto cycle is a set of processes used by spark ignition internal combustion engines (2-stroke or 4-stroke cycles). These engines a) ingest a mixture of fuel and air, b) compress it, c) cause it to react, thus effectively adding heat through converting chemical energy into thermal energy, d) expand the combustion products, and then e) eject the combustion products and replace them with a new charge of fuel and air. The different processes are shown in Figure 3.8:

1. Intake stroke, gasoline vapor and air drawn into engine ($5 \rightarrow 1$).
2. Compression stroke, p , T increase ($1 \rightarrow 2$).
3. Combustion (spark), short time, essentially constant volume ($2 \rightarrow 3$). Model: heat absorbed from a series of reservoirs at temperatures T_2 to T_3 .
4. Power stroke: expansion ($3 \rightarrow 4$).
5. Valve exhaust: valve opens, gas escapes.
6. ($4 \rightarrow 1$) Model: rejection of heat to series of reservoirs at temperatures T_4 to T_1 .
7. Exhaust stroke, piston pushes remaining combustion products out of chamber ($1 \rightarrow 5$).

We model the processes as all acting on a fixed mass of air contained in a piston-cylinder arrangement, as shown in Figure 3.10.

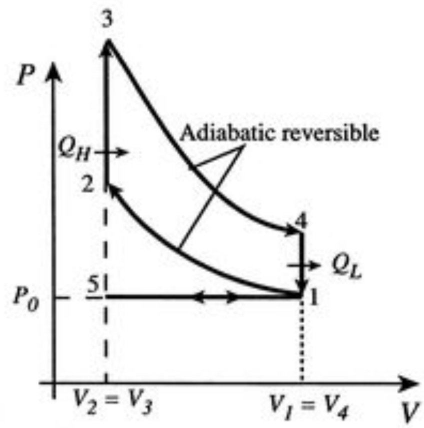

Figure 3.8: The ideal Otto cycle

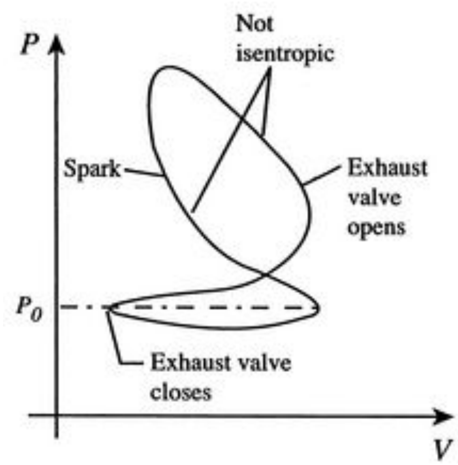

Figure 3.9: Sketch of an actual Otto cycle

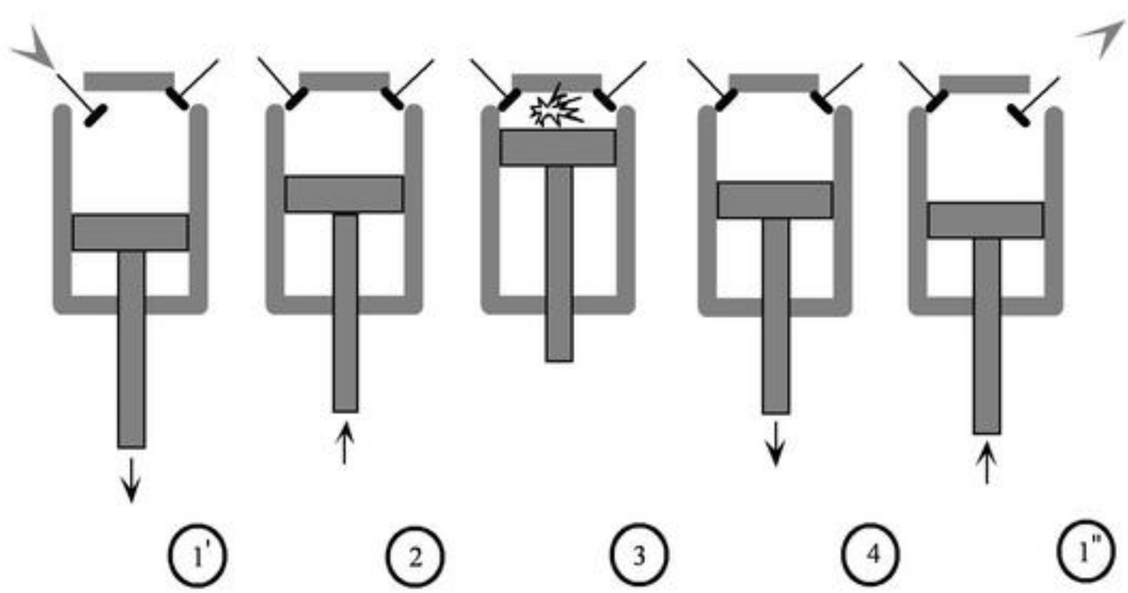

Figure 3.10: Piston and valves in a four-stroke internal combustion engine

The actual cycle does not have the sharp transitions between the different processes that the ideal cycle has, and might be as sketched in Figure 3.9.

3.5.1 Efficiency of an ideal Otto cycle

The starting point is the general expression for the thermal efficiency of a cycle:

$$\eta = \frac{\text{work}}{\text{heat input}} = \frac{Q_H + Q_L}{Q_H} = 1 + \frac{Q_L}{Q_H}.$$

The convention, as previously, is that heat exchange is positive if heat is flowing into the system or engine, so Q_L is negative. The heat absorbed occurs during combustion when the spark occurs, roughly at constant volume. The heat absorbed can be related to the temperature change from state 2 to state 3 as:

$$\begin{aligned} Q_H &= Q_{23} = \Delta U_{23} \qquad (W_{23} = 0) \\ &= \int_{T_2}^{T_3} C_v dT = C_v(T_3 - T_2). \end{aligned}$$

The heat rejected is given by (for a perfect gas with constant specific heats)

$$Q_L = Q_{41} = \Delta U_{41} = C_v(T_1 - T_4).$$

Substituting the expressions for the heat absorbed and rejected in the expression for thermal efficiency yields

$$\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2}.$$

We can simplify the above expression using the fact that the processes from 1 to 2 and from 3 to 4 are isentropic:

$$T_4 V_1^{\gamma-1} = T_3 V_2^{\gamma-1}, \qquad T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$$

$$(T_4 - T_1) V_1^{\gamma-1} = (T_3 - T_2) V_2^{\gamma-1}$$

$$\frac{T_4 - T_1}{T_3 - T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma - 1}.$$

The quantity $V_1/V_2 = r$ is called the compression ratio. In terms of compression ratio, the efficiency of an ideal Otto cycle is:

$$\eta_{\text{Otto}} = 1 - \frac{1}{(V_1/V_2)^{\gamma-1}} = 1 - \frac{1}{r^{\gamma-1}}.$$

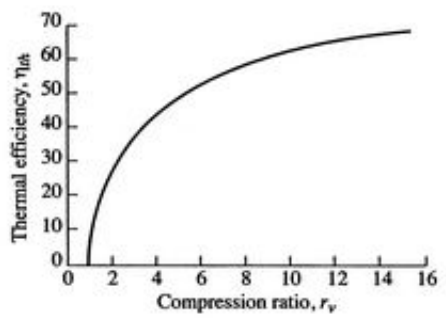

Figure 3.11: Ideal Otto cycle thermal efficiency

The ideal Otto cycle efficiency is shown as a function of the compression ratio in Figure 3.11. As the compression ratio, r , increases, η_{Otto} increases, but so does T_2 . If T_2 is too high, the mixture will ignite without a spark (at the wrong location in the cycle).

3.5.2 Engine work, rate of work per unit enthalpy flux

The non-dimensional ratio of work done (the power) to the enthalpy flux through the engine is given by

$$\frac{\text{Power}}{\text{Enthalpy flux}} = \frac{\dot{W}}{\dot{m} c_p T_1} = \frac{\dot{Q}_{23}\eta_{\text{Otto}}}{\dot{m} c_p T_1}.$$

There is often a desire to increase this quantity, because it means a smaller engine for the same power. The heat input is given by

$$\dot{Q}_{23} = \dot{m}_{\text{fuel}} \Delta h_{\text{fuel}},$$

where

- Δh_{fuel} is the heat of reaction, i.e. the chemical energy liberated per unit mass of fuel,
- $\dot{m}_{\text{fuel}}$ is the fuel mass flow rate.

The non-dimensional power is

$$\frac{\dot{W}}{\dot{m} c_p T_1} = \frac{\dot{m}_{\text{fuel}}}{\dot{m}} \frac{\Delta h_{\text{fuel}}}{c_p T_1} \left[1 - \frac{1}{r^{\gamma-1}} \right].$$

The quantities in this equation, evaluated at stoichiometric conditions are:

$$\begin{aligned} \frac{\dot{m}_{\text{fuel}}}{\dot{m}} &\approx \frac{1}{15} \\ \frac{\Delta h_{\text{fuel}}}{c_p T_1} &\approx \frac{4 \times 10^7}{10^3 \times 288}, \end{aligned}$$

so

$$\frac{\dot{W}}{\dot{m} c_p T_1} \approx 9 \left[1 - \frac{1}{r^{\gamma-1}} \right].$$

Muddy Points

How is Δh_{fuel} calculated? (MP 3.6)

What are ``stoichiometric conditions?'' (MP 3.7)