# Chapter 11: Internal Combustion Engines

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Introduction
There are two types of internal combustion (IC) engines. In a spark-ignition (SI) IC engine, a mixture of fuel and air is ignited by a spark plug. SI engines use gasoline as fuel. In a compression-ignition (CI) IC engine, air is compressed to a high temperature and pressure. Combustion occurs spontaneously when fuel is added. CI engines use diesel as fuel.

Engine Terminology
In an IC engine, the piston moves up and down inside a cylinder, causing the crankshaft to rotate. The piston and crankshaft are connected by a connecting rod.

- The bore is the cylinder diameter.
- Top dead center (TDC) is the piston position when the cylinder volume is a minimum.
- Bottom dead center (BDC) is the piston position when the cylinder volume is a maximum.
- The stroke is the distance traveled by the piston from TDC to BDC, or vice versa.
- The displacement volume is the volume change between TDC and BDC. The displacement volume for a single cylinder is can be calculated in terms of the bore and the stroke:

\[
\text{displacement volume} = \text{stroke} \cdot \frac{\pi}{4} \cdot \text{bore}^2
\]

- The compression ratio compares the volume at BDC and the volume at TDC. Compression ratios for diesel engines (14:1 to 25:1) are much higher than for gasoline engines (8:1 to 12:1).

\[
r = \frac{\text{volume at BDC}}{\text{volume at TDC}}
\]

Four Stroke IC Engine
A four-stroke IC engine utilizes four distinct piston strokes (intake, compression, power, and exhaust) to complete one operating cycle. The piston makes two complete passes in the cylinder, requiring two revolutions (720°) of the crankshaft.

1. During the intake stroke, the intake valve opens and fresh charge is drawn into the cylinder. The piston moves from TDC to BDC.
2. During the compression stroke, the piston moves from BDC to TDC, increasing the temperature and pressure of the cylinder contents. Combustion occurs near the end of the compression stroke.
3. During the power stroke, the cylinder contents rapidly expand and the piston returns to BDC.
4. **During the exhaust stroke**, the exhaust valve opens and burned gas is purged from the cylinder. The piston moves from BDC to TDC.

**Air-Standard Cycles**

IC engines are complex. To simply analysis of IC engines, we make the following assumptions:

- The working fluid is a fixed amount of air
- Air is modeled as an ideal gas
- Combustion is replaced with a single heat transfer
- All processes are reversible

**Otto Cycles**

An **Otto cycle** is an idealized thermodynamic cycle that describes a typical SI engine. The four processes of an Otto cycle are:

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1→2</td>
<td>Isentropic compression from BDC to TDC</td>
</tr>
<tr>
<td>2→3</td>
<td>Constant volume heat addition at TDC</td>
</tr>
<tr>
<td>3→4</td>
<td>Isentropic expansion from TDC to BDC</td>
</tr>
<tr>
<td>4→1</td>
<td>Constant volume heat rejection at BDC</td>
</tr>
</tbody>
</table>

**Analyzing Otto Cycles**

We will analyze Otto cycles by applying the 1st Law to each process. For all processes we will employ air standard analysis (a fixed amount of air, air behaves as an ideal gas, combustion is replaced by a single heat transfer, and all processes are reversible). We will also neglect any changes in kinetic and potential energy.
\[ \frac{dE_{\text{system}}}{dt} = \dot{Q} - \dot{W} + \sum_{\text{in}} \dot{m}_{\text{in}} \left( h + \frac{V^2}{2} + gz \right)_{\text{in}} - \sum_{\text{out}} \dot{m}_{\text{out}} \left( h + \frac{V^2}{2} + gz \right)_{\text{out}} \]

\[ Q - W = \Delta E = \Delta KE + \Delta PE + \Delta U \]

The isentropic processes of the Otto cycle (1\(\rightarrow\)2 and 3\(\rightarrow\)4) will be adiabatic by the entropy balance:

\[ \frac{dS_{\text{system}}}{dt} = \sum_{j} \frac{Q_j}{T_j} + \sum_{\text{in}} \dot{m}_{\text{in}} s_{\text{in}} - \sum_{\text{out}} \dot{m}_{\text{out}} s_{\text{out}} + \sigma_{\text{system}} \]

\[ \Delta S_{\text{system}} = \sum_{j} \frac{Q_j}{T_j} + \sigma_{\text{system}} \]

No work will be done during the constant volume processes of the Otto cycle (2\(\rightarrow\)3 and 4\(\rightarrow\)1) due to the expression for boundary work:

\[ w_{\text{boundary}} = \int p\,dv \]

The work during isentropic compression from BDC to TDC is:

\[ W_{12} = m(u_1 - u_2) \]

The heat transfer during constant volume heat addition at TDC is:

\[ Q_{23} = m(u_3 - u_2) = Q_H \]

The work during isentropic expansion from TDC to BDC is:

\[ W_{34} = m(u_3 - u_4) \]

The heat transfer during constant volume heat rejection at BDC is:

\[ Q_{41} = m(u_1 - u_4) = -Q_C \]

**Performance Parameters**

The thermal efficiency of an Otto cycle is calculated by:

\[ \eta = \frac{W_{\text{cycle}}}{Q_H} \]
Example
At the beginning of the compression process of an air-standard Otto cycle, the pressure is 1 bar, the temperature is 290 K, and the cylinder volume is 400 cm$^3$. The maximum temperature of the cycle is 2200 K. The compression ratio is 8. Find the heat addition in kJ, the net work in kJ, and the thermal efficiency of the cycle.
Diesel Cycle
A diesel cycle is an idealized thermodynamic cycle that describes a typical CI engine. The four processes of a diesel cycle are:

<table>
<thead>
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<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1→2</td>
<td>Isentropic compression from BDC to TDC</td>
</tr>
<tr>
<td>2→3</td>
<td>Constant pressure heat addition</td>
</tr>
<tr>
<td>3→4</td>
<td>Isentropic expansion</td>
</tr>
<tr>
<td>4→1</td>
<td>Constant volume heat rejection at BDC</td>
</tr>
</tbody>
</table>

The cutoff ratio specifies the relationship between volumes at states 2 and 3:

\[ r_c = \frac{V_3}{V_2} = \frac{mRT_3p_2}{mRT_2p_3} = \frac{T_3}{T_2} \]

Analyzing Diesel Cycles
We will analyze diesel cycles by applying the 1st Law to each process. For all processes we will employ air standard analysis. We will also neglect any changes in kinetic and potential energy.

The isentropic processes of the diesel cycle (1→2 and 3→4) will be adiabatic by the entropy balance. No work will be done during the constant volume process of the Diesel cycle (4→1) due to the expression for boundary work.

The work during isentropic compression from BDC to TDC is:

\[ W_{12} = m(u_1 - u_2) \]

The work during the constant pressure process is:

\[ W_{23} = m \int_{v_2}^{v_3} pdv = mp_2(v_3 - v_2) = m(p_3v_3 - p_2v_2) \]
The heat transfer during the constant pressure process is:

\[ Q_{23} = W_{23} + m(u_3 - u_2) = m(p_3v_3 - p_2v_2) + m(u_3 - u_2) = m(h_3 - h_2) = Q_H \]

The work during the isentropic expansion process is:

\[ W_{34} = m(u_3 - u_4) \]

The heat transfer during constant volume heat rejection at BDC is:

\[ Q_{41} = m(u_1 - u_4) = -Q_C \]

Performance Parameters
The thermal efficiency of a diesel cycle is calculated by:

\[ \eta = \frac{W_{\text{cycle}}}{Q_H} \]
Example
At the beginning of the compression process of an air-standard diesel cycle, the pressure is 95 kPa and the temperature is 300 K. At the end of heat addition, the pressure is 7.2 MPa and the temperature is 2150 K. Find the compression ratio, the cutoff ratio, and the thermal efficiency of the cycle.
Numerical Answers to Examples

<table>
<thead>
<tr>
<th>Page</th>
<th>Answer(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.672 kJ, 0.34 kJ, 51%</td>
</tr>
<tr>
<td>8</td>
<td>23.2, 2.2, 59.7%</td>
</tr>
</tbody>
</table>