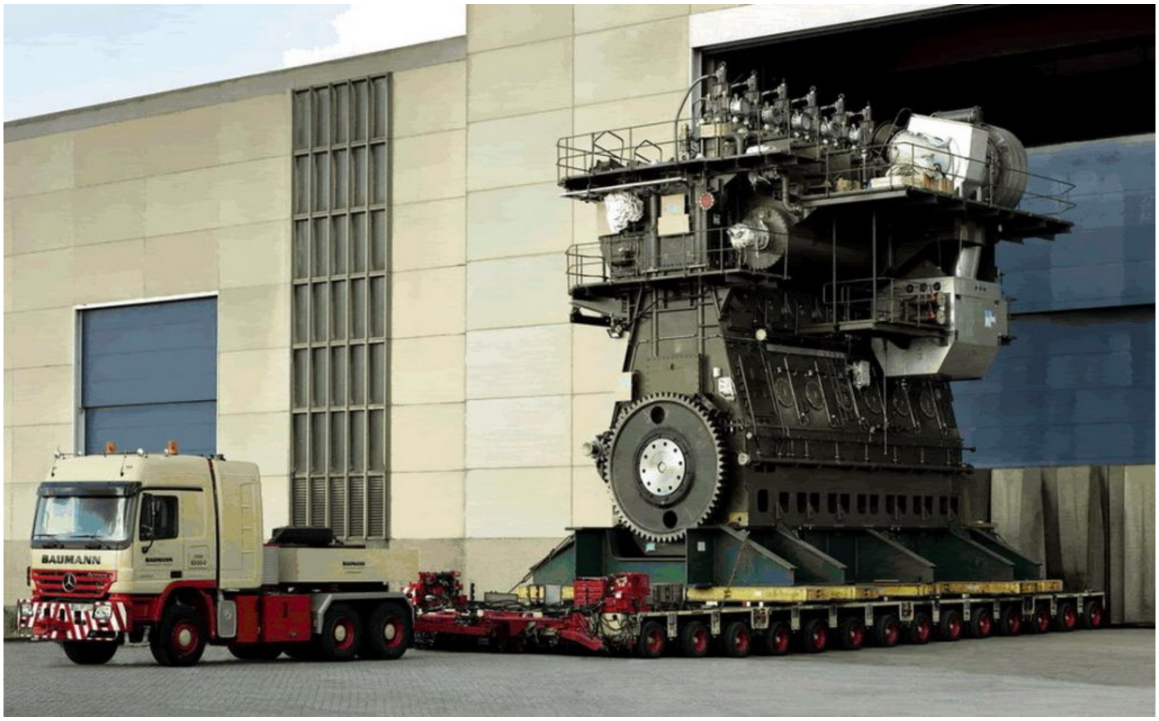


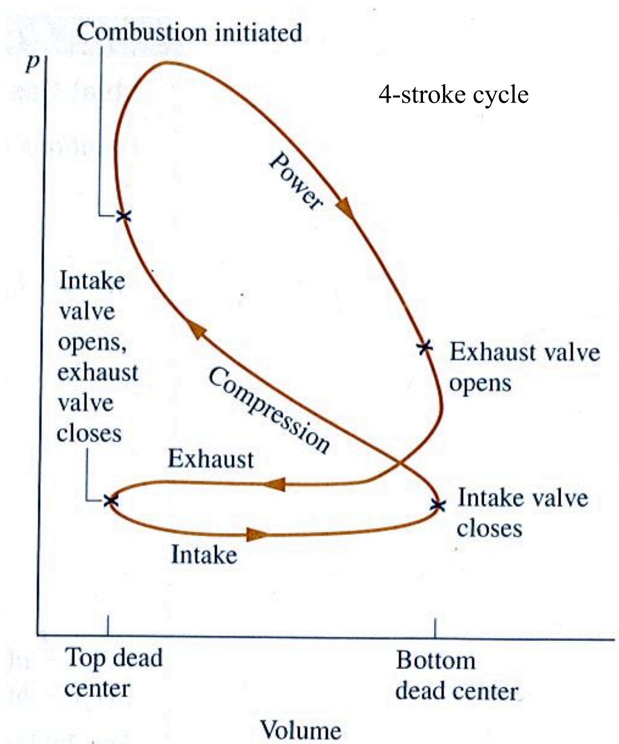
Wärtsilä RT-flex96C 109,000 hp engine

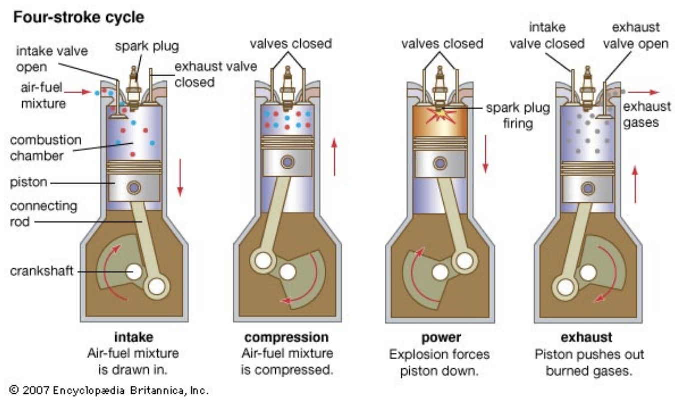
https://www.youtube.com/watch?v=xflY5uS-nnw
(high speed video of engine combustion)

ME 200 (Thermodynamics I)

Otto, Diesel, and Dual Power Cycles

4-stroke cycle





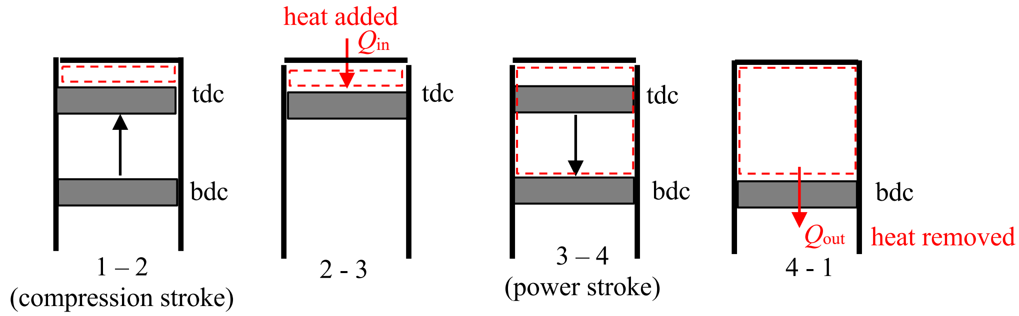
(Image from Moran et al., 7th ed.)

Air-Standard Otto Cycle

In a spark ignition engine, the fuel-air mixture ignites due to a spark generated near the end of the compression stroke.

1. The working fluid is air, which is treated as an ideal gas. The typical mass ratio of fuel to air is ~ 1/15.
2. There are no exhaust or intake processes. The air in the cylinder is a closed system.
3. The combustion process is modeled as constant <u>volume</u> heat addition to the working fluid. The combustion process and the changes to the working fluid properties are ignored.
4. *Cold air-standard analysis*: The working fluid is treated as a perfect gas, i.e., constant specific heats.

Ideal Air-Standard Otto Cycle

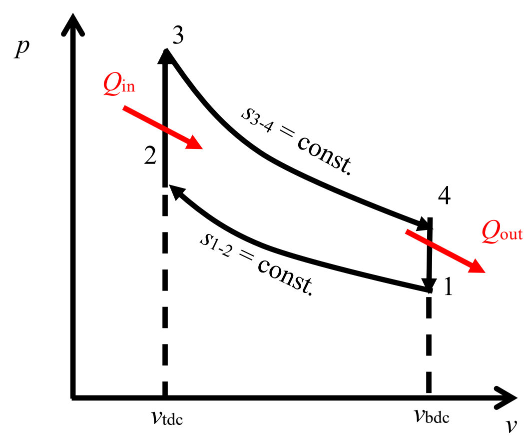


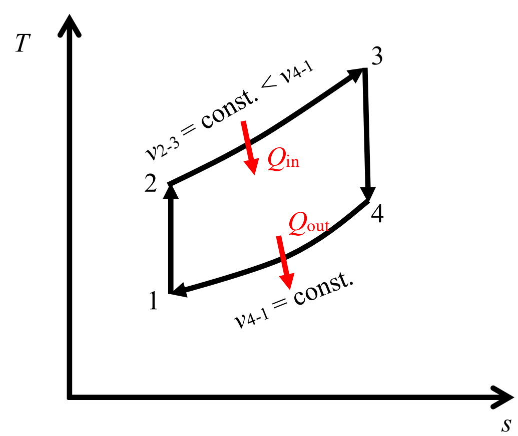
Process 1 – 2: <u>isentropic compression</u> of the working fluid as the piston moves from bottom dead center to top dead center

Process 2 – 3: <u>constant volume heat transfer</u> to the working fluid while the piston is at top dead center (ignition of the fuel-air mixture)

Process 3 – 4: <u>isentropic expansion</u> (power stroke)

Process 4 – 1: <u>constant volume heat transfer</u> from the working fluid while the piston is at bottom dead center (mimicking the removal and replenishing of the air in the cylinder)





Apply the 1st Law to the air in the cylinder:

$$\Delta E_{sys} = \Delta U_{sys} + \Delta KE_{sys} + \Delta PE_{sys} \approx \Delta U_{sys} = Q_{into\ sys} - W_{by\ sys}$$

From State 1 to State 2 (isentropic compression, compression stroke)

$$m(u_2 - u_1) = -W_{out,12},$$

From State 2 to State 3 (constant volume heat addition)

$$m(u_3 - u_2) = Q_{in,23}$$

From State 3 to State 4 (isentropic expansion, power stroke)

$$m(u_4 - u_3) = -W_{out,34},$$

From State 4 to State 1 (constant volume heat removal)

$$m(u_1 - u_4) = Q_{in,41} = -Q_{out,41}$$

The thermal efficiency of the cycle,

$$\eta \equiv \frac{W_{out,net}}{Q_{in}} = \frac{W_{out,12} + W_{out,34}}{Q_{in,23}} = \frac{m(u_1 - u_2) + m(u_3 - u_4)}{m(u_3 - u_2)} = \frac{(u_3 - u_2) - (u_4 - u_1)}{(u_3 - u_2)}$$

$$\eta = 1 - \frac{(u_4 - u_1)}{(u_3 - u_2)} = 1 - \frac{Q_{out,41}}{Q_{in,23}}$$

Mean Effective Pressure (MEP):

$$MEP \equiv \frac{W_{out,net}}{V_{bdc} - V_{tdc}}$$

Compression ratio, $r \equiv \frac{v_1}{v_2} = \frac{v_4}{v_3} = \frac{v_{bdc}}{v_{tdc}}$

Note that for isentropic compression (and expansion),

$r \equiv \frac{v_1}{v_2} = \frac{v_r(T_1)}{v_r(T_2)}$ and $r \equiv \frac{v_4}{v_3} = \frac{v_r(T_4)}{v_r(T_3)}$

For a perfect gas undergoing an isentropic process:

State 1 – State 2 (isentropic compression): $\frac{T_2}{T_1} = \left(\frac{V_2}{V_1}\right)^{1-k} = \left(\frac{1}{r}\right)^{1-k} = r^{k-1}$

State 3 – State 4 (isentropic expansion): $\frac{T_4}{T_3} = \left(\frac{V_4}{V_3}\right)^{1-k} = r^{1-k}$

Note: $r^{k-1} = \frac{T_2}{T_1} = \frac{T_3}{T_4}$ => $\frac{T_4}{T_1} = \frac{T_3}{T_2}$

Otto cycle thermal efficiency for a perfect gas:

$$\eta_{Otto} = 1 - \frac{(u_4 - u_1)}{(u_3 - u_2)} = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r^{k-1}}$$

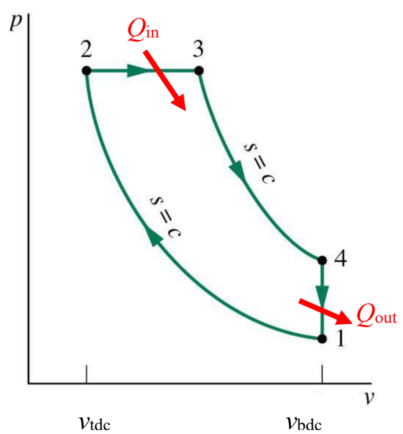
Notes:

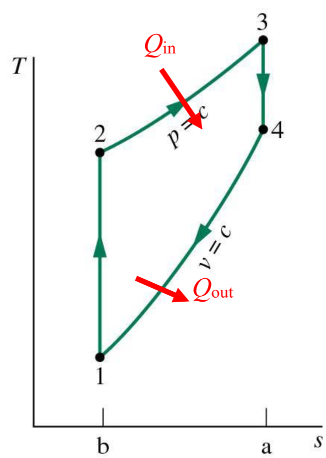
1. Typical: r = 8 to 10 and η = 30 to 35%.
2. As $r\uparrow$, $\eta\uparrow$. Practically, r is limited by auto-ignition causing engine knock. Higher octane fuels can go to higher compression ratios before knocking occurs.
3. As $k\uparrow$, $\eta\uparrow$. The specific heat ratio is determined by the type of fuel used.
4. As $T\downarrow$, $k\downarrow$ and $\eta\downarrow$.

Ideal Air-Standard Diesel Cycle
In a compression ignition engine, the fuel-air mixture ignites when fuel is added to the high temperature air generated during the compression process.

1. The working fluid is air, which is treated as an ideal gas.
2. There are no exhaust or intake processes. The air in the cylinder is a closed system.
3. The combustion process is modeled as constant pressure heat addition to the working fluid. The combustion process and the changes to the working fluid properties are ignored.
4. *Cold air-standard analysis*: The working fluid is treated as a perfect gas, i.e., constant specific heats.

Process 1 – 2:	isentropic compression of the working fluid as the piston moves from bottom dead center to top dead center
Process 2 – 3:	constant pressure heat transfer to the working fluid while the piston is at top dead center (ignition of the fuel-air mixture; start of the power stroke)
Process 3 – 4:	isentropic expansion (power stroke)
Process 4 – 1:	constant volume heat transfer from the working fluid while the piston is at bottom dead center





Apply the 1st Law to the air in the cylinder:

$$\Delta E_{sys} = \Delta U_{sys} + \Delta KE_{sys} + \Delta PE_{sys} \approx \Delta U_{sys} = Q_{into\ sys} - W_{by\ sys}$$

From State 1 to State 2 (isentropic compression, compression stroke)

$$m(u_2 - u_1) = -W_{out,12},$$

From State 2 to State 3 (constant pressure heat addition)

$$m(u_3 - u_2) = Q_{in,23} - p_{23}(V_3 - V_2) \;\Rightarrow\; Q_{in,23} = m[(u_3 - u_2) + p_{23}(v_3 - v_2)]$$

$$Q_{in,23} = m(h_3 - h_2)$$

From State 3 to State 4 (isentropic expansion, power stroke)

$$m(u_4 - u_3) = -W_{out,34},$$

From State 4 to State 1 (constant volume heat removal)

$$m(u_1 - u_4) = Q_{in,41}$$

The thermal efficiency of the cycle,

$$\eta \equiv \frac{W_{out,net}}{Q_{in}} = 1 - \frac{Q_{out,41}}{Q_{in,23}} = 1 - \frac{u_4 - u_1}{h_3 - h_2}$$

Cut-off ratio, $r_c \equiv \frac{v_3}{v_2} = \frac{T_3}{T_2}$

After some manipulation,

$$\eta_{Diesel} = 1 - \frac{r_c^k - 1}{kr^{k-1}(r_c - 1)}$$

Notes:

1. Typical: $r = 12$ to 25 and $\eta = 40$ to 45%.
2. Larger r means larger η. Diesel engines are not limited by engine knock.
3. Since they rely on compression ignition, Diesel cycle engines are built for larger pressures. They tend to last longer than spark ignition, Otto cycle engines.

Ideal Air-Standard Dual Cycle

A better approximation to the real cycle than the Otto or Diesel cycles.

Process 1 – 2:	<u>isentropic compression</u> of the working fluid as the piston moves from bottom dead center to top dead center
Process 2 – 3:	<u>constant volume heat transfer</u> to the working fluid while the piston is at top dead center
Process 3 – 4:	<u>constant pressure heat transfer</u> to the working fluid (start of the power stroke)
Process 4 – 5:	<u>isentropic expansion</u> (remainder of the power stroke)
Process 5 – 1:	<u>constant volume heat transfer</u> from the working fluid while the piston is at bottom dead center (mimicking the removal and replenishing of the air in the cylinder)