Thermodynamics: An Engineering Approach
8th Edition
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Topic 20

Reciprocating Engine Cycles

Objectives

- Review the operation of reciprocating engines.
- Analyze both closed and open gas power cycles.
- Solve problems based on the Otto cycles.
- Solve problems based on the Diesel cycles.

AN OVERVIEW OF RECIPROCATING ENGINES

Compression ratio

$$r = \frac{V_{\max}}{V_{\min}} = \frac{V_{BDC}}{V_{TDC}}$$

- **Spark-ignition (SI) engines**
- **Compression-ignition (CI) engines**

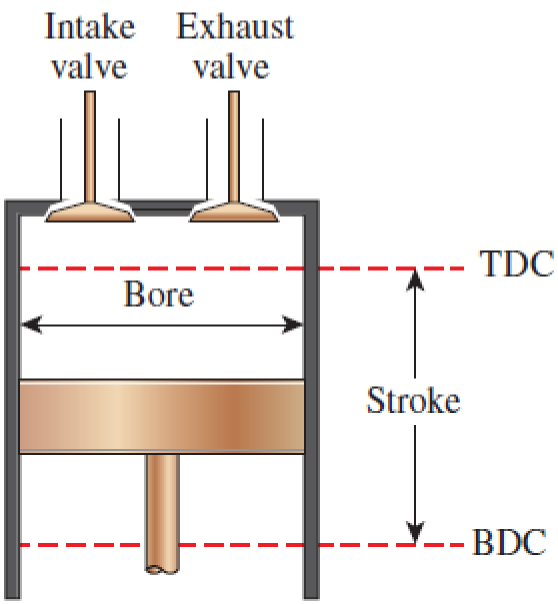


FIGURE 9–9
Nomenclature for reciprocating engines.

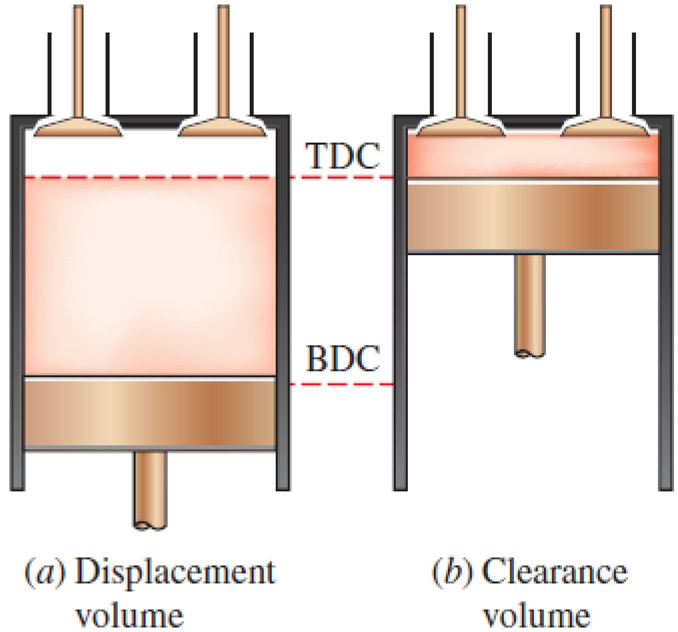


FIGURE 9–10
Displacement and clearance volumes of a reciprocating engine.

$$W_{net} = \text{MEP} \times \text{Piston area} \times \text{Stroke} = \text{MEP} \times \text{Displacement volume}$$

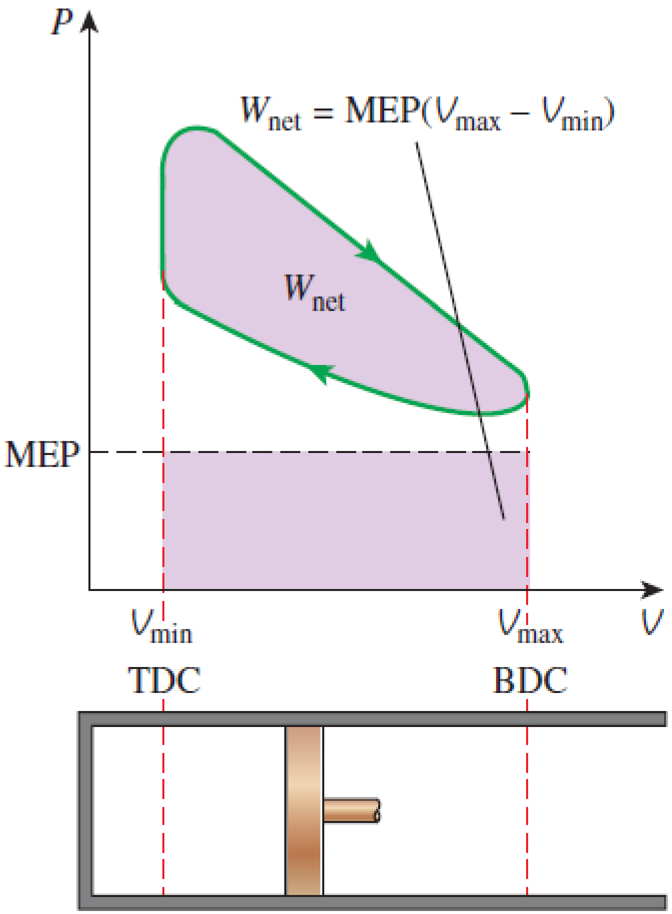


FIGURE 9–11
The net work output of a cycle is equivalent to the product of the mean effective pressure and the displacement volume.

$$\text{MEP} = \frac{W_{net}}{V_{max} - V_{min}} = \frac{w_{net}}{v_{max} - v_{min}} \quad \text{(kPa)}$$

Mean effective pressure

The mean effective pressure can be used as a parameter to compare the performances of reciprocating engines of equal size.

The engine with a larger value of MEP delivers more net work per cycle and thus performs better.

OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES

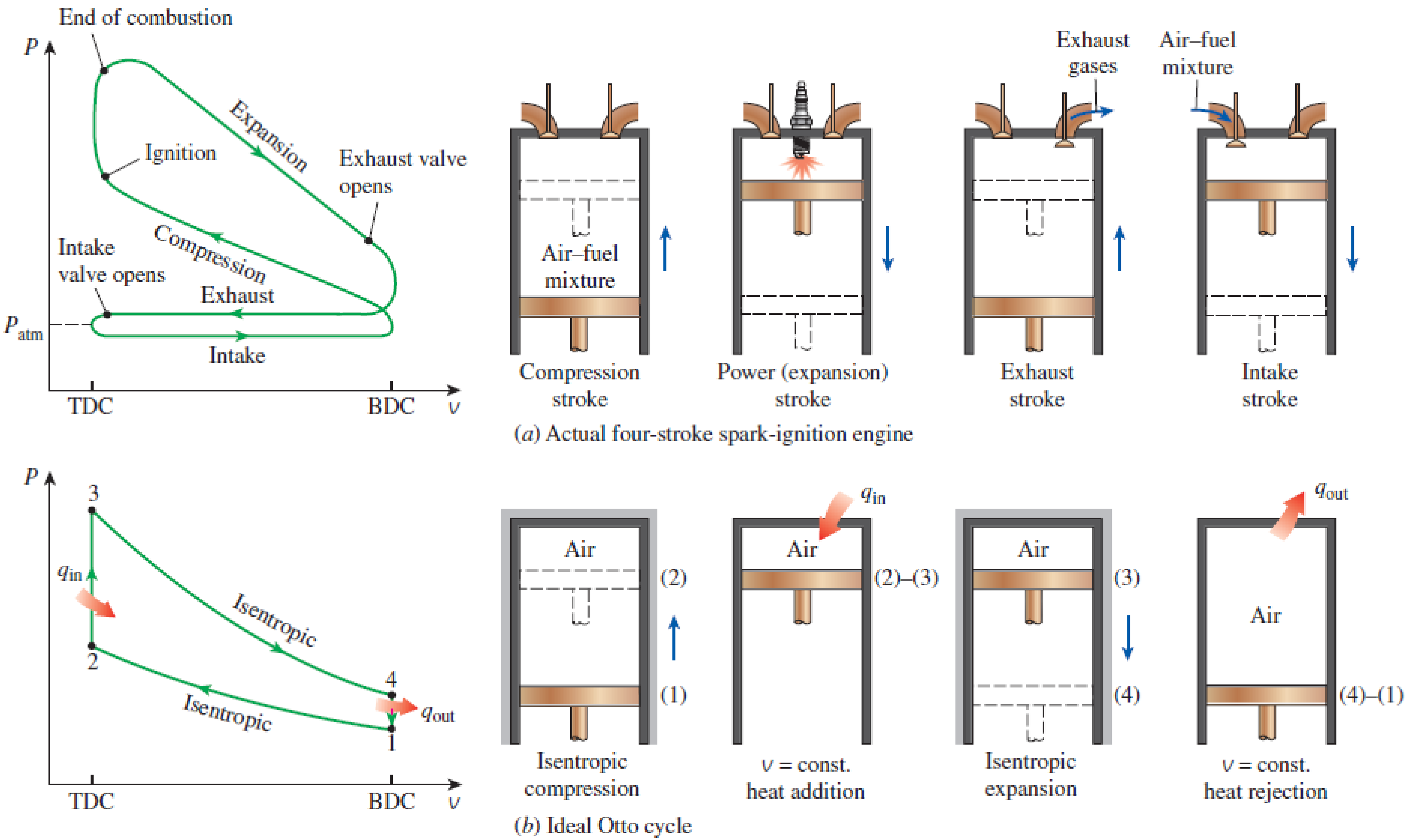


FIGURE 9–12

Actual and ideal cycles in spark-ignition engines and their *P*-*v* diagrams.

Four-stroke cycle
1 cycle = 4 stroke = 2 revolution
Two-stroke cycle
1 cycle = 2 stroke = 1 revolution

1-2 Isentropic compression
2-3 Constant-volume heat addition
3-4 Isentropic expansion
4-1 Constant-volume heat rejection

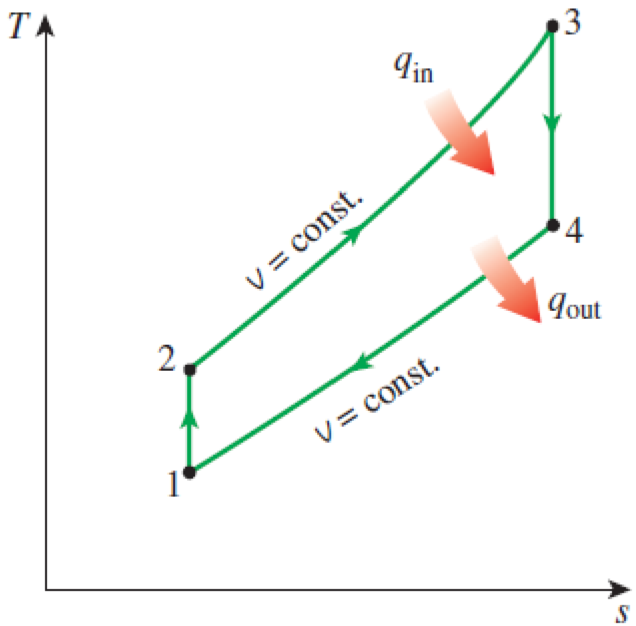
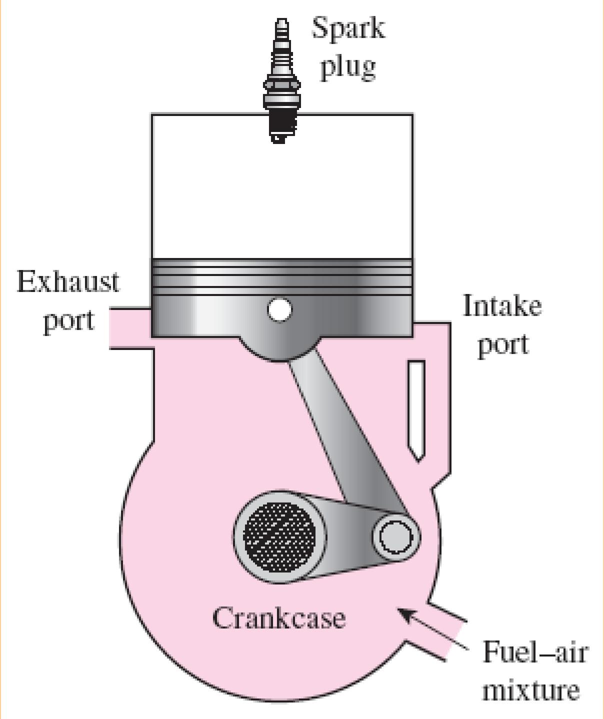


FIGURE 9–15
T-s diagram of the ideal Otto cycle.

The two-stroke engines are generally less efficient than their four-stroke counterparts but they are relatively simple and inexpensive, and they have high power-to-weight and power-to-volume ratios.



Schematic of a two-stroke reciprocating engine.

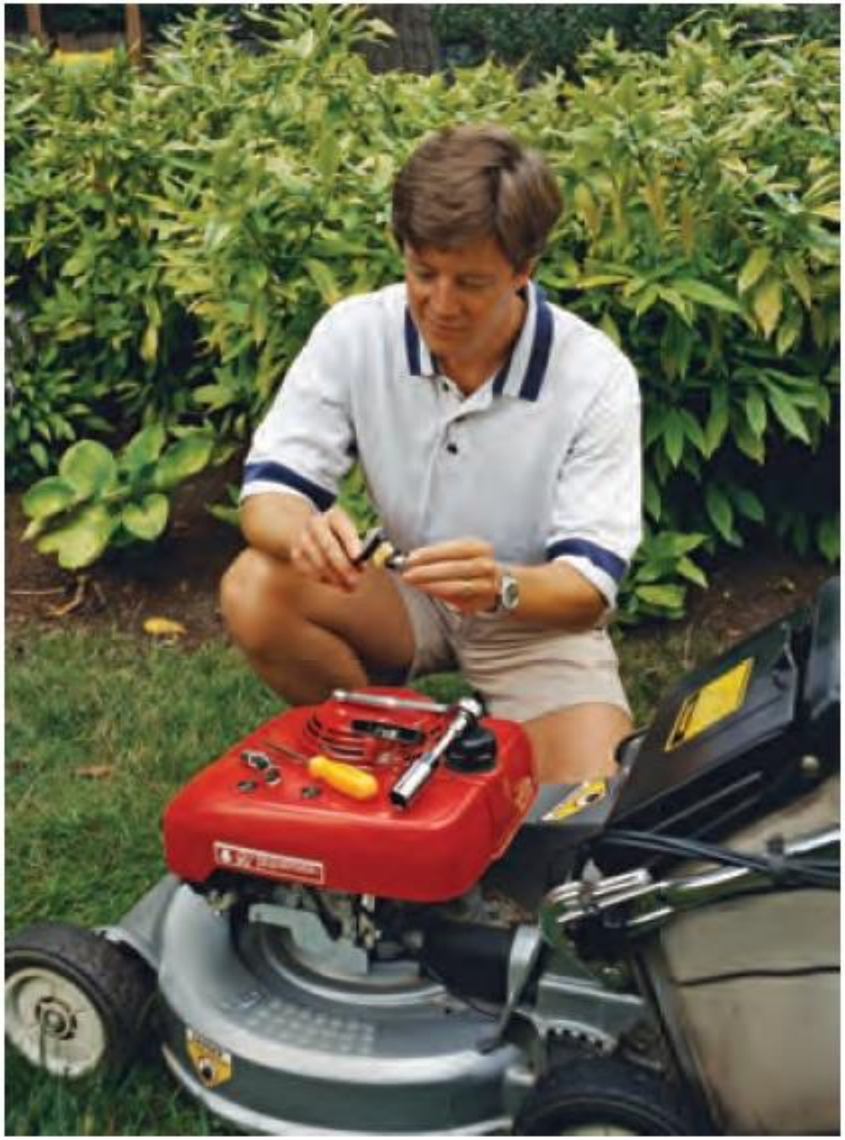


FIGURE 9–14
Two-stroke engines are commonly used in motorcycles and lawn mowers.

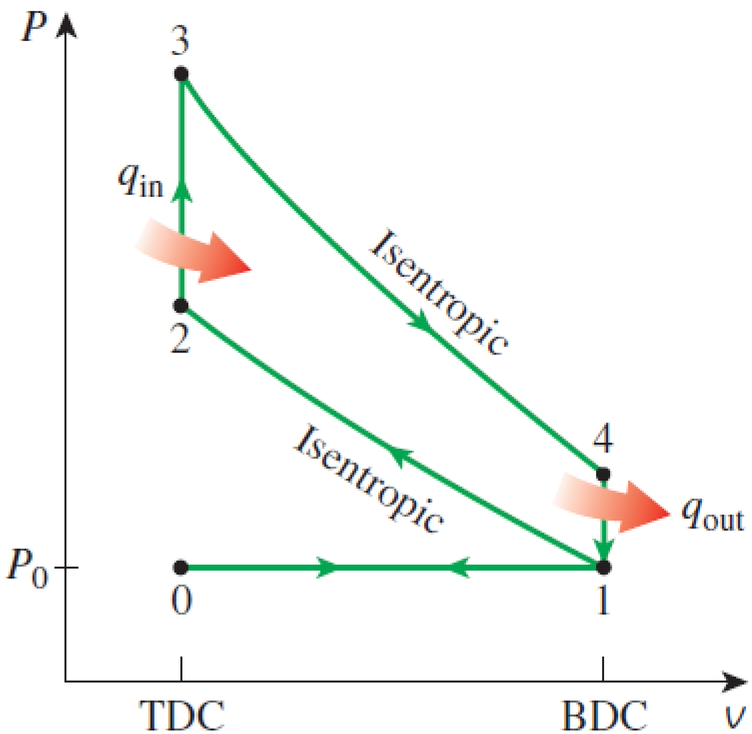


FIGURE 9–16

P-*v* diagram of the ideal Otto cycle that includes intake and exhaust strokes.

$$W_{out,0-1} = P_0(v_1 - v_0)$$

$$W_{in,1-0} = P_0(v_1 - v_0)$$

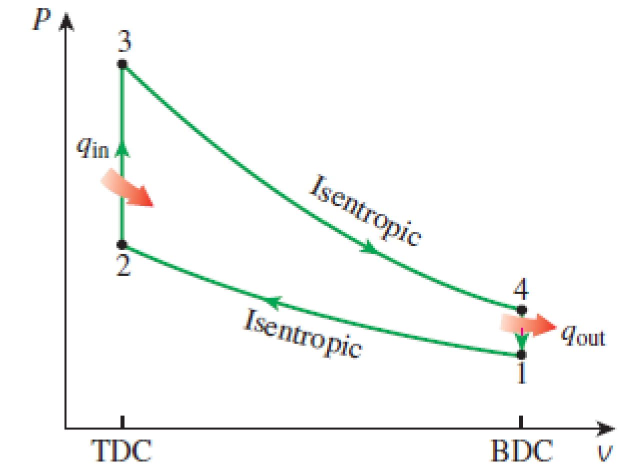
Air enters the cylinder through the open intake valve at atmospheric pressure P_0 during process 0-1 as the piston moves from TDC to BDC.

The intake valve is closed at state 1 and air is compressed isentropically to state 2. Heat is transferred at constant volume (process 2-3); it is expanded isentropically to state 4; and heat is rejected at constant volume (process 4-1).

Air is expelled through the open exhaust valve (process 1-0).

Work interactions during intake and exhaust cancel each other, and thus inclusion of the intake and exhaust processes has no effect on the net work output from the cycle.

However, when calculating power output from the cycle during an ideal Otto cycle analysis, we must consider the fact that the ideal Otto cycle has four strokes just like actual four-stroke spark-ignition engine.



$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet}$$

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

$$\eta_{th,Otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{k-1} = \left(\frac{v_3}{v_4}\right)^{k-1} = \frac{T_4}{T_3} \qquad r = \frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2}$$

$$\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}}$$

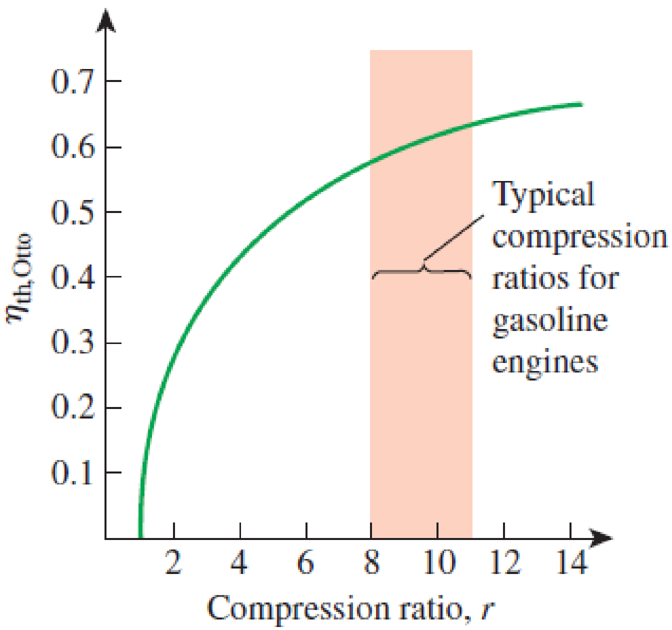


FIGURE 9–17
Thermal efficiency of the ideal Otto cycle as a function of compression ratio ($k = 1.4$).

In SI engines, the compression ratio is limited by **autoignition** or **engine knock**.

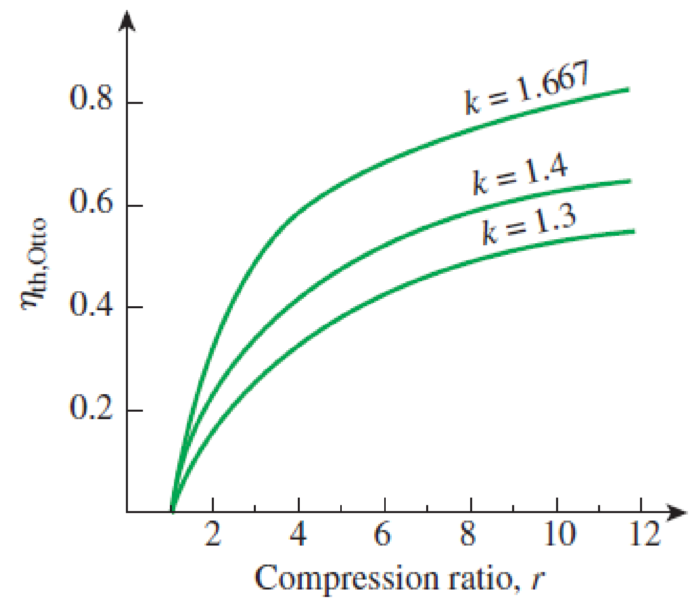
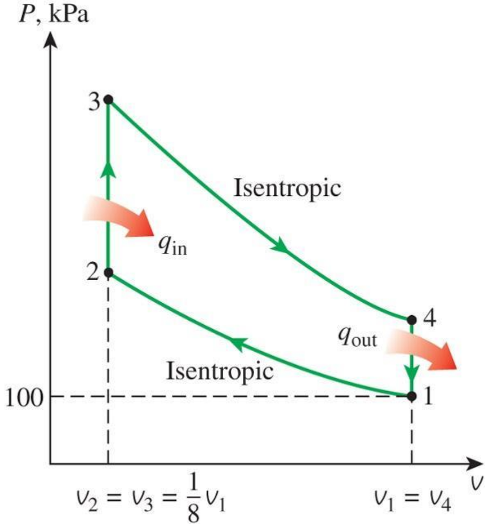


FIGURE 9–18
The thermal efficiency of the Otto cycle increases with the specific heat ratio k of the working fluid.

The Ideal Otto Cycle

An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, air is at 100 kPa and 17°C, and 800 kJ/kg of heat is transferred to the air during the constant volume heat addition process. Accounting for the variation of specific heats of air with temperature, determine (a) the maximum temperature and pressure that occur during the cycle, (b) the net work output, (c) the thermal efficiency, and (d) the mean effective pressure for the cycle. Also, (e) determine the power output from the cycle, in kW, for an engine speed of 4000 rpm (rev/min). Assume this cycle is operated on an engine that has four cylinders with a total displacement volume of 1.6 L.



Example 1

DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES

In diesel engines, only air is compressed during the compression stroke, eliminating the possibility of autoignition (engine knock). Therefore, diesel engines can be designed to operate at much higher compression ratios than SI engines, typically between 12 and 24.

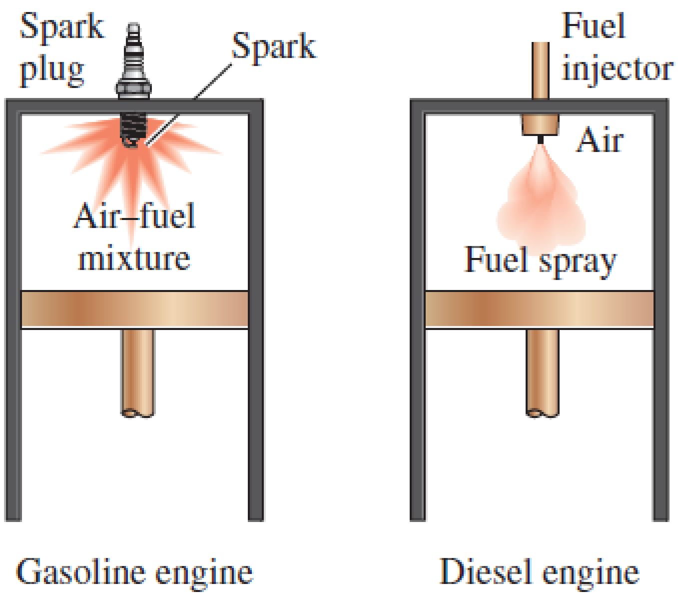


FIGURE 9–20
In diesel engines, the spark plug is replaced by a fuel injector, and only air is compressed during the compression process.

1-2 isentropic compression
2-3 constant-volume heat addition
3-4 isentropic expansion
4-1 constant-volume heat rejection.

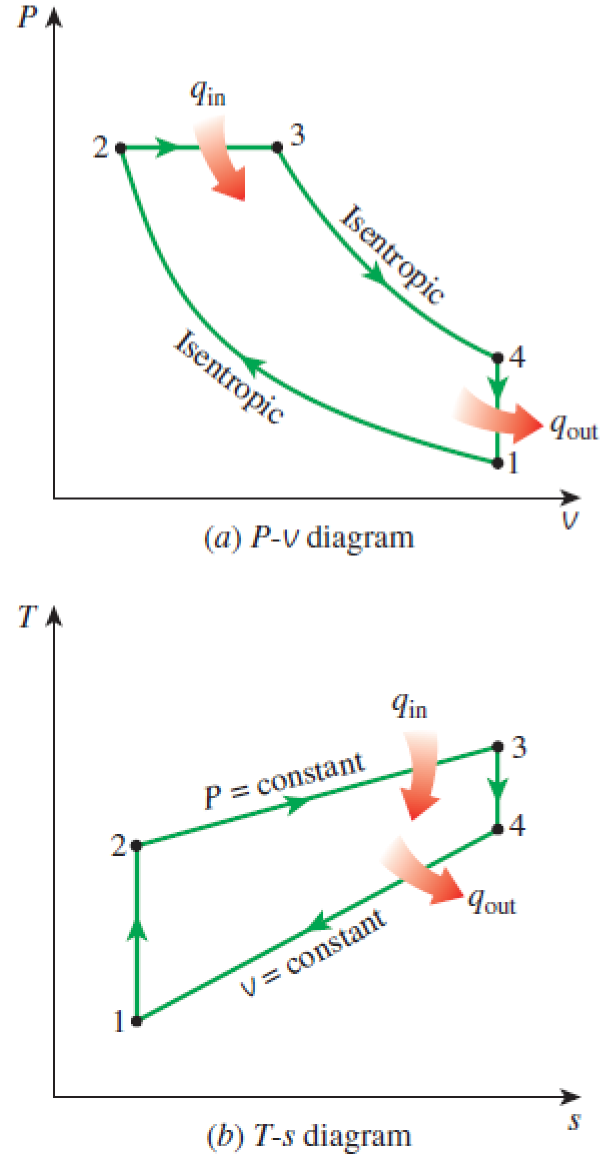
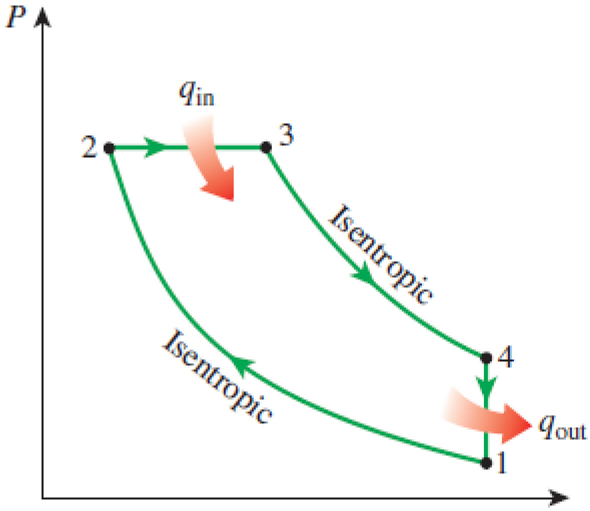
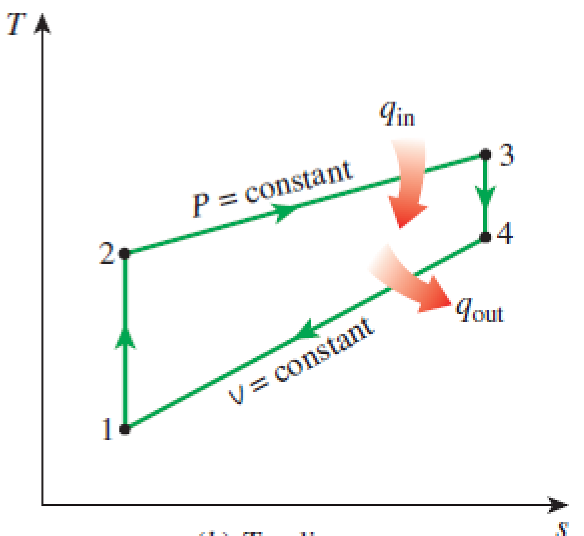


FIGURE 9–21
T-s and *P-v* diagrams for the ideal Diesel cycle.



(a) P-v diagram



(b) T-s diagram

FIGURE 9–21

T-s and P-v diagrams for the ideal Diesel cycle.

$$q_{in} - w_{b,out} = u_3 - u_2 \rightarrow q_{in} = P_2(v_3 - v_2) + (u_3 - u_2)$$
$$= h_3 - h_2 = c_p(T_3 - T_2)$$

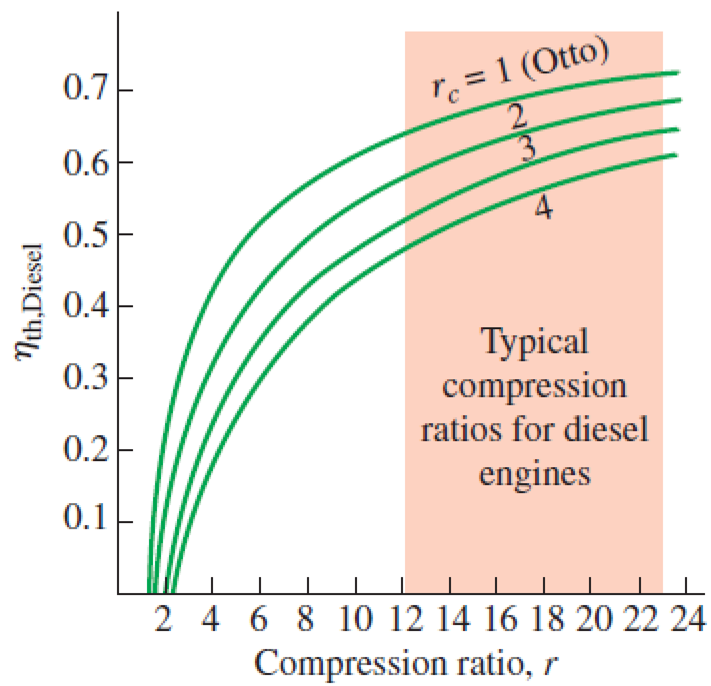
$$-q_{out} = u_1 - u_4 \rightarrow q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

$$\eta_{th,Diesel} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{kT_2(T_3/T_2 - 1)}$$

$$r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2}$$ Cutoff ratio

$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$$

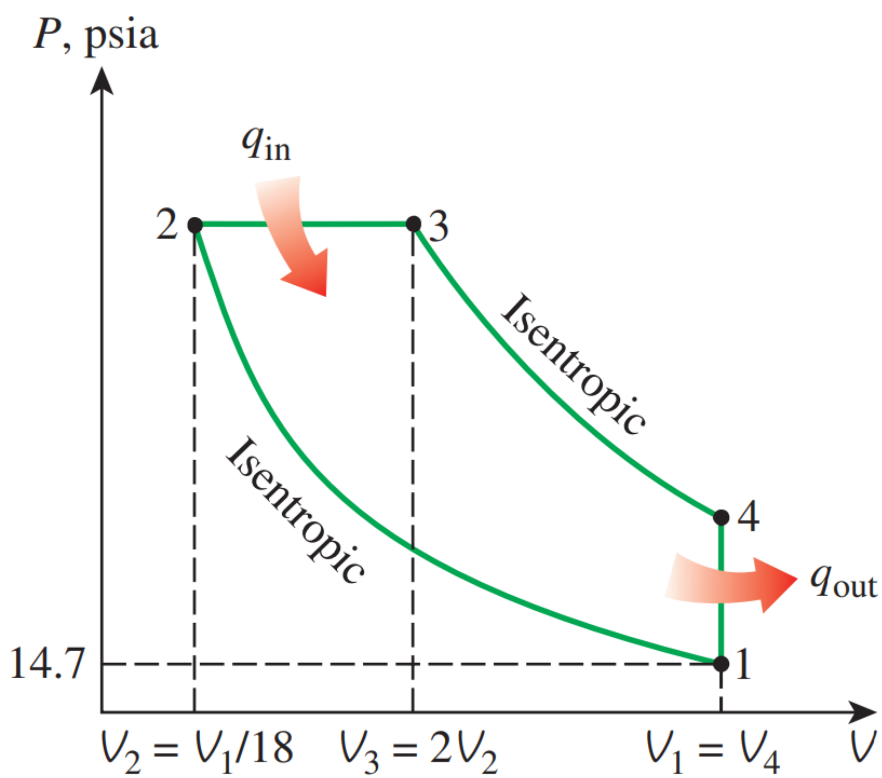
$\eta_{th,Otto} > \eta_{th,Diesel}$ for the same compression ratio



Thermal efficiency of the ideal Diesel cycle as a function of compression and cutoff ratios (k=1.4).

The Ideal Diesel Cycle

An ideal Diesel cycle with air as the working fluid has a compression ratio of 18 and a cutoff ratio of 2. At the beginning of the compression process, the working fluid is at $14.7\ psia$, $80°\text{F}$, and $117 in^3$. Utilizing the cold-air-standard assumptions, determine the temperature and pressure of air at the end of each process, the net work output and the thermal efficiency, and the mean effective pressure.



Example 2

Dual cycle: A more realistic ideal cycle model for modern, high-speed compression ignition engine.

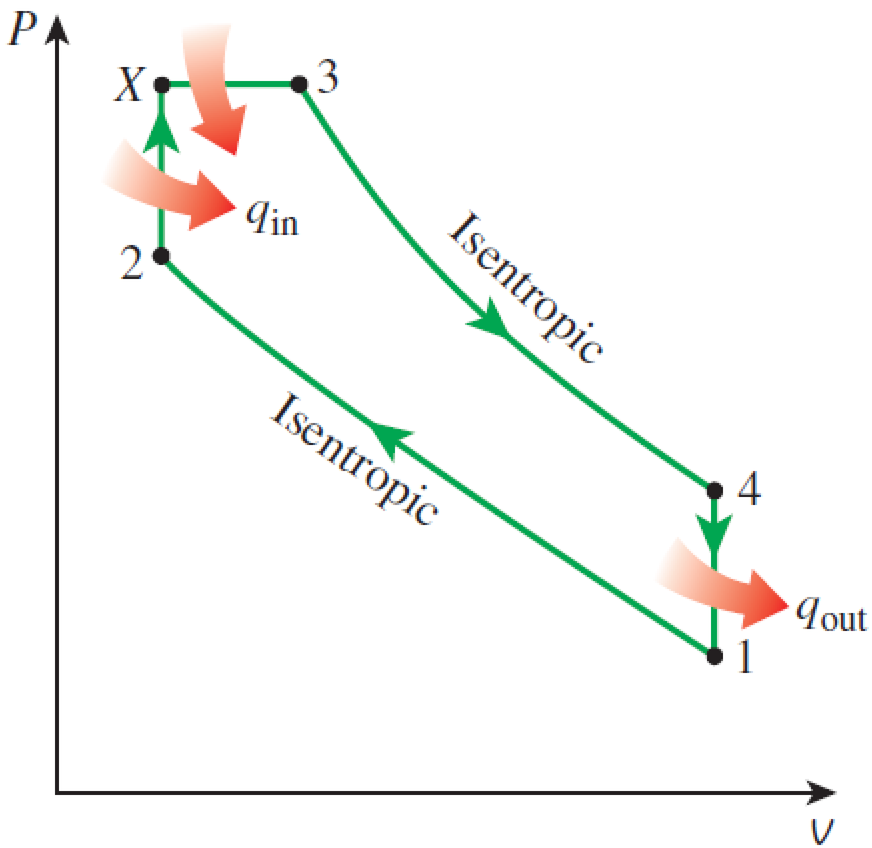


FIGURE 9–23

P-*v* diagram of an ideal dual cycle.

In modern high-speed compression ignition engines, fuel is injected into the combustion chamber much sooner compared to the early diesel engines.

Fuel starts to ignite late in the compression stroke, and consequently part of the combustion occurs almost at constant volume.

Fuel injection continues until the piston reaches the top dead center, and combustion of the fuel keeps the pressure high well into the expansion stroke.

Thus, the entire combustion process can better be modeled as the combination of constant-volume and constant-pressure processes.

Summary

- An overview of reciprocating engines
- Otto cycle: The ideal cycle for spark-ignition engines
- Diesel cycle: The ideal cycle for compression-ignition engines