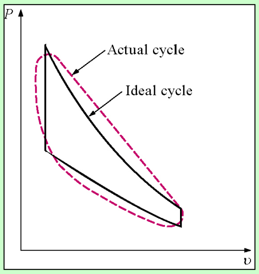
Chapter 8:

Gas Power Cycles

BASIC CONSIDERATIONS IN THE NALYSIS OF POWER CYCLES

- The cycles encountered in actual devices are difficult to analyze because of the presence of complicating effects, such as:
  - friction, and
  - the absence of sufficient time to establish equilibrium conditions.
  - neglecting heat transfer through connecting pipes.
- To make an analytical study of a cycle feasible, we have to keep the complexities at a manageable level and utilize some idealizations.
- Such a cycle is called an **ideal cycle.**
- The simplified analysis for various power cycles of practical interest serve as the starting point for a more in-depth study.



BASIC CONSIDERATIONS IN THE NALYSIS OF POWER CYCLES

- Recall that nobody can develop a cycle more efficient than the *Carnot cycle.*
- Then the following question arises naturally: If the Carnot cycle is the best possible cycle, why do we not use it as the model cycle for all the heat engines instead of bothering with several so-called *ideal* cycles?
- The answer to this question is hardware related.
- Most cycles encountered in practice differ significantly from the Carnot cycle, which makes it unsuitable as a realistic model.
- Each ideal cycle discussed in this chapter is related to a specific work-producing device and is an *idealized* version of the actual cycle.

BASIC CONSIDERATIONS IN THE NALYSIS OF POWER CYCLES

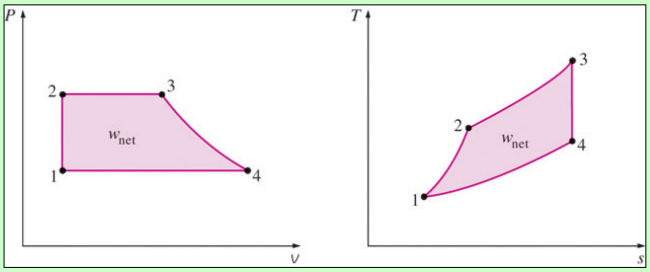
- The ideal cycles are *internally reversible*, but, unlike the Carnot cycle, they are not necessarily externally reversible.
- That is, they may involve irreversibilities external to the system such as heat transfer through a finite temperature difference.
- Therefore, the thermal efficiency of an ideal cycle, in general, is less than that of a totally reversible cycle operating between the same temperature limits.
- However, it is still considerably higher than the thermal efficiency of an actual cycle because of the idealizations utilized.

BASIC CONSIDERATIONS IN THE NALYSIS OF POWER CYCLES

- On both the *P-v* and *T-s* diagrams, the area enclosed by the process curves of a cycle represents the net work produced during the cycle.

- It is also equivalent to the net heat transfer for that cycle.

- *Any modification that increases the ratio of these two areas will also increase the thermal efficiency of the cycle.*



AIR-STANDARD ASSUMPTIONS

- In gas power cycles, the working fluid remains a gas throughout the entire cycle.

- Spark-ignition engines, diesel engines, and conventional gas turbines are familiar examples of devices that operate on gas cycles.

- In all these engines, energy is provided by burning a fuel within the system boundaries.

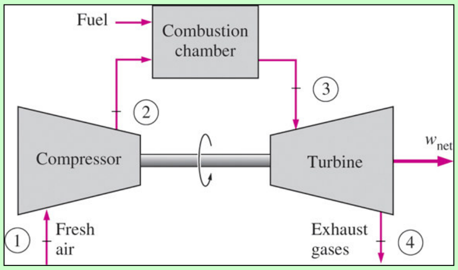
- That is, they are *internal combustion engines*.

- Because of this combustion process, the composition of the working fluid changes from air and fuel to combustion products during the course of the cycle.

- However, considering that air is predominantly nitrogen that undergoes hardly any chemical reactions in the combustion chamber, the working fluid closely resembles air at all times.

AIR-STANDARD ASSUMPTIONS

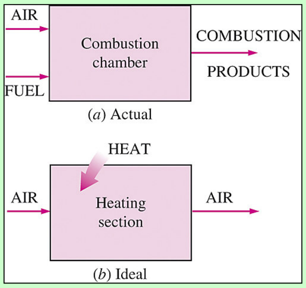
- Even though internal combustion engines operate on a mechanical cycle (the piston returns to its starting position at the end of each revolution), the working fluid does not undergo a complete thermodynamic cycle.
- It is thrown out of the engine at some point in the cycle (as exhaust gases) instead of being returned to the initial state.
- Working on an open cycle is the characteristic of all internal combustion engines.



AIR-STANDARD ASSUMPTIONS

- The actual gas power cycles are rather complex.
- To reduce the analysis to a manageable level, we utilize the following approximations, commonly known as the **air-standard assumptions:**

1. The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
2. All the processes that make up the cycle are internally reversible.
3. The combustion process is replaced by a heat-addition process from an external source.
4. The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.

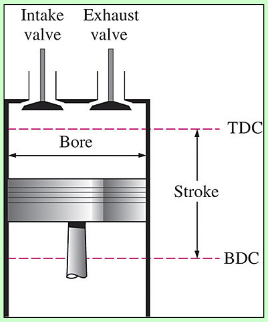


AIR-STANDARD ASSUMPTIONS

- Another assumption that is often utilized to simplify the analysis even more is that air has constant specific heats whose values are determined at *room temperature* (25°C, or 77°F).
- When this assumption is utilized, the air-standard assumptions are called the **cold-air-standard assumptions.**
- A cycle for which the air-standard assumptions are applicable is frequently referred to as an **air-standard cycle.**
- The air-standard assumptions previously stated provide considerable simplification in the analysis without significantly deviating from the actual cycles.
- This simplified model enables us to study qualitatively the influence of major parameters on the performance of the actual engines.

AN OVERVIEW OF RECIPROCATING ENGINES

- Despite its simplicity, the reciprocating engine (basically a piston–cylinder device) is one of the rare inventions that has proved to be very versatile and to have a wide range of applications.
- It is the powerhouse of the vast majority of automobiles, trucks, light aircraft, ships, and electric power generators, as well as many other devices.
- The piston reciprocates in the cylinder between two fixed positions called the **top dead center** (TDC)—the position of the piston when it forms the smallest volume in the cylinder—and the **bottom dead center** (BDC)—the position of the piston when it forms the largest volume in the cylinder.
- The distance between the TDC and the BDC is the largest distance that the piston can travel in one direction, and it is called the **stroke** of the engine. The diameter of the piston is called the **bore.**
- The air or air–fuel mixture is drawn into the cylinder through the **intake valve**, and the combustion products are expelled from the cylinder through the **exhaust valve.**

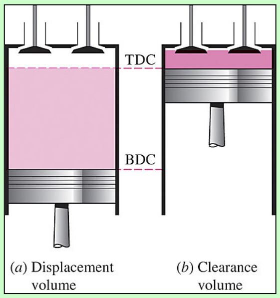


AN OVERVIEW OF RECIPROCATING ENGINES

- The minimum volume formed in the cylinder when the piston is at TDC is called the **clearance volume**.
- The volume displaced by the piston as it moves between TDC and BDC is called the **displacement volume**.
- The ratio of the maximum volume formed in the cylinder to the minimum (clearance) volume is called the **compression ratio** r of the engine:

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

- Notice that the compression ratio is a *volume ratio* and should not be confused with the pressure ratio.



(*a*) Displacement volume

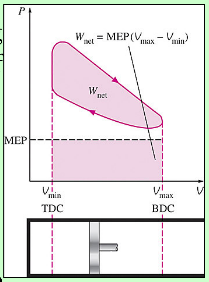
(*b*) Clearance volume

AN OVERVIEW OF RECIPROCATING ENGINES

- Another term frequently used in conjunction with reciprocating engines is the **mean effective pressure** (MEP).
- It is a fictitious pressure that, if it acted on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle. That is,
  - W_{net} = MEP X Piston area X Stroke = MEP X Displacement volume
- Or

$$MEP = \frac{W_{net}}{V_{\max} - V_{\min}} = \frac{w_{net}}{v_{\max} - v_{\min}}$$

- 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.



AN OVERVIEW OF RECIPROCATING ENGINES

- Reciprocating engines are classified as **spark-ignition** **(SI) engines** or **compression-ignition** **(CI) engines,** depending on how the combustion process in the cylinder is initiated.

- In SI engines, the combustion of the air–fuel mixture is initiated by a spark plug.

- In CI engines, the air–fuel mixture is self-ignited as a result of compressing the mixture above its self-ignition temperature.

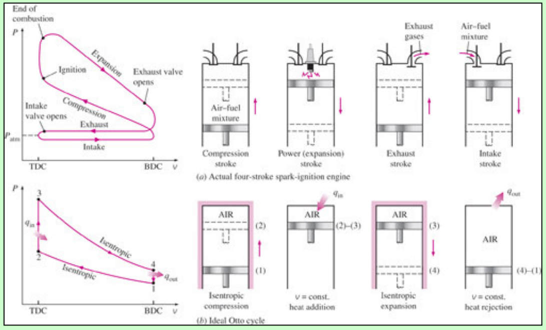
- In the next two sections, we discuss the *Otto* and *Diesel cycles*, which are the ideal cycles for the SI and CI reciprocating engines, respectively.

OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES

- It is named after Nikolaus A. Otto, who built a successful four-stroke engine in 1876 in Germany.

- In most spark-ignition engines, the piston executes four complete strokes (two mechanical cycles) within the cylinder, and the crankshaft completes two revolutions for each thermodynamic cycle.

- These engines are called **four-stroke** internal combustion engines.

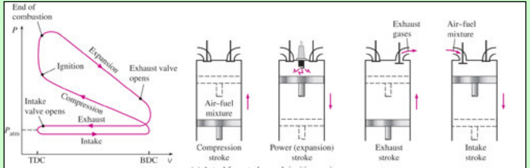


(a) Actual four-stroke spark-ignition engine

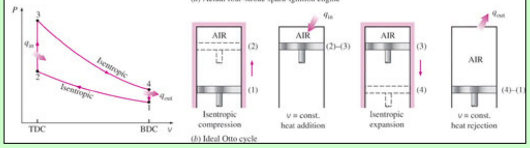
(b) Ideal Otto cycle

OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES

- Initially, both the intake and the exhaust valves are closed, and the piston is at its lowest position (BDC). During the *compression stroke*, the piston moves upward, compressing the air–fuel mixture. Shortly before the piston reaches its highest position (TDC), the spark plug fires and the mixture ignites, increasing the pressure and temperature of the system. The high-pressure gases force the piston down, which in turn forces the crankshaft to rotate, producing a useful work output during the *expansion* or *power stroke*. At the end of this stroke, the piston is at its lowest position (the completion of the first mechanical cycle), and the cylinder is filled with combustion products. Now the piston moves upward one more time, purging the exhaust gases through the exhaust valve (the *exhaust stroke*), and down a second time, drawing in fresh air–fuel mixture through the intake valve (the *intake stroke*).
- Notice that the pressure in the cylinder is slightly above the atmospheric value during the exhaust stroke and slightly below during the intake stroke.



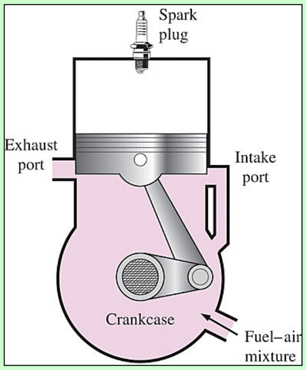
(a) Actual four-stroke spark-ignition engine



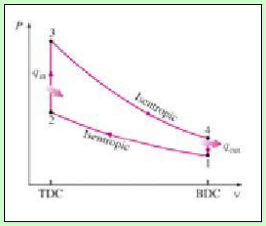
(b) Ideal Otto cycle

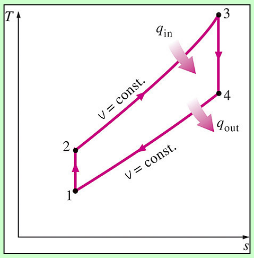
OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES

- In **two-stroke engines**, all four functions described above are executed in just two strokes: the power stroke and the compression stroke.
- The two-stroke engines are generally less efficient than their four-stroke counterparts because of the incomplete expulsion of the exhaust gases.
- However, they are relatively simple and inexpensive, and they have high power-to-weight and power-to-volume ratios, which make them suitable for applications requiring small size and weight such as for motorcycles, chain saws, and lawn mowers.
- Advances in several technologies, for a given weight and displacement, a well-designed two-stroke engine can provide significantly more power than its four-stroke counterpart because two-stroke engines produce power on every engine revolution instead of every other one.



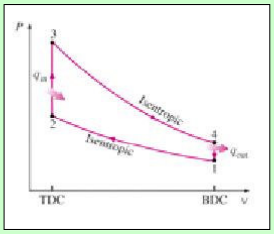
OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES

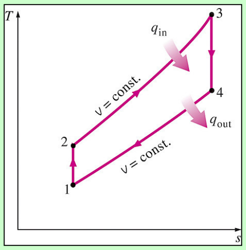




- The thermodynamic analysis of the actual four-stroke or two-stroke cycles described is not a simple task.
- However, the analysis can be simplified significantly if the air-standard assumptions are utilized.
- The resulting cycle, which closely resembles the actual operating conditions, is the ideal **Otto cycle.**
- It consists of four internally reversible processes:
  - 1-2 Isentropic compression
  - 2-3 Constant-volume heat addition
  - 3-4 Isentropic expansion
  - 4-1 Constant-volume heat rejection

OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES





Thermal Efficiency of the Otto cycle:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Now to find Q_{in} and Q_{out}.

Apply first law closed system to process 2-3, V = constant.
and, for constant specific heats,

$$Q_{net,\,23} = \Delta U_{23}$$

$$Q_{in} = mC_v\,(T_3 - T_2)$$

Apply first law closed system to process 4-1, V = constant.
and, for constant specific heats,

$$Q_{net,\,41} = \Delta U_{41}$$

$$Q_{net,\,41} = -Q_{out} = mC_v\,(T_1 - T_4)$$

$$Q_{out} = -mC_v\,(T_1 - T_4) = mC_v\,(T_4 - T_1)$$

OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES

Thermal Efficiency of the Otto cycle becomes:

$$\eta_{th,\,Otto} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$= 1 - \frac{mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

Recall processes 1-2 and 3-4 are isentropic, so

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} \quad and \quad \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{k-1}$$

Since $V_3 = V_2$ and $V_4 = V_1$, we see that

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \qquad or \qquad \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES

The Otto cycle efficiency becomes

$$\eta_{th,\,Otto} = 1 - \frac{T_1}{T_2}$$

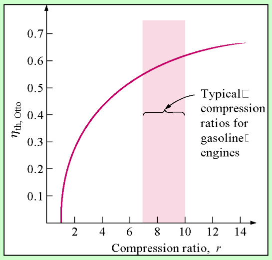
Since process 1-2 is isentropic,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$$

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{k-1} = \left(\frac{1}{r}\right)^{k-1}$$

where the compression ratio is $r = V_1/V_2$ and

$$\boxed{\eta_{th,\,Otto} = 1 - \frac{1}{r^{k-1}}} \qquad \eta_{th,act} = 25 - 30\%$$



We see that increasing the compression ratio increases the thermal efficiency.

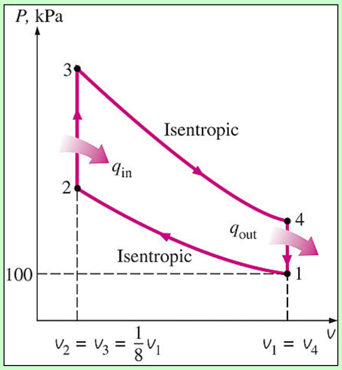
However, there is a limit on *r* depending upon the fuel.

Fuels under high temperature will prematurely ignite, causing engine damage.

EXAMPLE 8–2

The Idea 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 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.



DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES

The Diesel cycle is the ideal cycle for CI reciprocating engines.

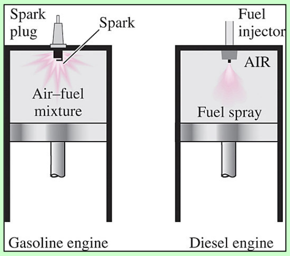
The CI engine, first proposed by Rudolph Diesel in the 1890s.

It is very similar to the SI engine, differing mainly in the method of initiating combustion.

In SI engines (also known as *gasoline engines*), the air–fuel mixture is compressed to a temperature that is below the autoignition temperature of the fuel, and the combustion process is initiated by firing a spark plug.

In CI engines (also known as *diesel engines*), the air is compressed to a temperature that is above the autoignition temperature of the fuel, and combustion starts on contact as the fuel is injected into this hot air.

DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES



Therefore, the spark plug and carburetor are replaced by a fuel injector in diesel engines.

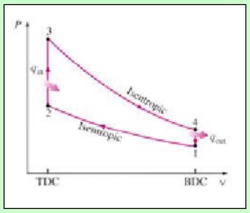
Carburetor is a device to produce an explosive mixture of vaporized fuel and air.

Therefore, diesel engines can be designed to operate at much higher compression ratios, typically between 12 and 24.

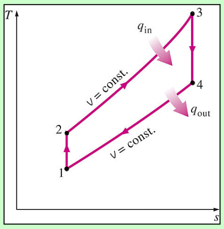
In gasoline engines, a mixture of air and fuel is compressed during the compression stroke.

In diesel engines, only air is compressed during the compression stroke. The fuel injection process starts when the piston approaches TDC and continues during the first part of the power stroke.

DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES



The Otto cycle

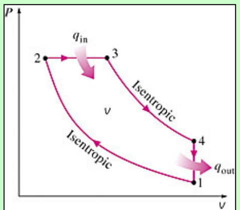


Because of this longer duration, the combustion process in the ideal Diesel cycle is approximated as a constant-pressure heat-addition process.

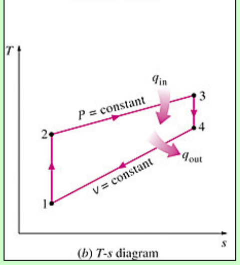
In fact, this is the only process where the Otto and the Diesel cycles differ.

The remaining three processes are the same for both ideal cycles. That is,

1-2 is isentropic compression,
3-4 is isentropic expansion, and
4-1 is constant-volume heat rejection.



(*a*) *P*- *v* diagram



(*b*) *T-s* diagram

DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES

Thermal efficiency of the Diesel cycle

$$\eta_{th,\ Diesel} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Now to find Q_{in} and Q_{out}.

Apply the first law closed system to process 2-3 (P = constant), and to process 4-1 (V = constant) (just as we did for the Otto cycle)
Thus, for constant specific heats

$$Q_{net,\,23} = \Delta U_{23} + W_{23}$$
$$Q_{net,\,23} = \Delta U_{23} + P_2(V_3 - V_2)$$
$$Q_{net,\,23} = \Delta H_{23}$$
$$Q_{in} = mC_p(T_3 - T_2)$$

$$Q_{net,\,41} = \Delta U_{41}$$
$$Q_{net,\,41} = mC_v(T_1 - T_4)$$
$$Q_{net,\,41} = -Q_{out}$$
$$Q_{out} = mC_v(T_4 - T_1)$$

DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES

The thermal efficiency becomes

$$\eta_{th,\,Diesel} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)} = 1 - \frac{1}{k}\frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

What is T_4/T_1 ?

$$\frac{P_4V_4}{T_4} = \frac{P_1V_1}{T_1} \quad \text{where } V_4 = V_1$$
$$\frac{T_4}{T_1} = \frac{P_4}{P_1}$$

What is T_3/T_2 ?

$$\frac{P_3V_3}{T_3} = \frac{P_2V_2}{T_2} \quad \text{where } P_3 = P_2$$
$$\frac{T_3}{T_2} = \frac{V_3}{V_2} = r_c$$

where r_c is called the cutoff ratio, defined as V_3/V_2, and is a measure of the duration of the heat addition at constant pressure.

DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES

Recall processes 1-2 and 3-4 are isentropic, so

$$P_1V_1^k = P_2V_2^k \quad \text{and} \quad P_4V_4^k = P_3V_3^k$$

Since $V_4 = V_1$ and $P_3 = P_2$, we divide the second equation by the first equation and obtain

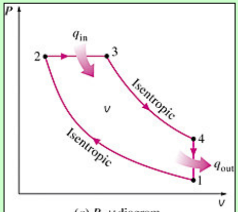
$$\frac{P_4}{P_1} = \left(\frac{V_3}{V_2}\right)^k = r_c^k$$

Therefore,

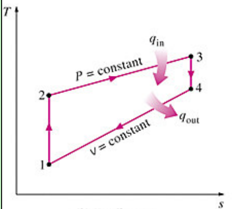
$$\eta_{th,\,Diesel} = 1 - \frac{1}{k}\frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)} = 1 - \frac{1}{k}\frac{T_1}{T_2}\frac{r_c^k - 1}{(r_c - 1)}$$

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

$$\eta_{th,act} = 35 - 40\%$$



(*a*) *P*- v diagram

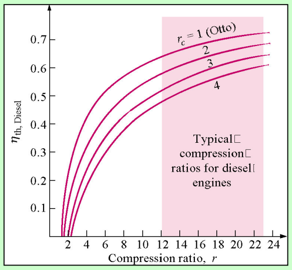


(*b*) *T-s* diagram

DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES

When $r_c > 1$ for a fixed r, $\quad \eta_{th,\,Diesel} < \eta_{th,\,Otto}$

But, since $\quad r_{Diesel} > r_{Otto} \qquad \eta_{th,\,Diesel} > \eta_{th,\,Otto}$



The higher efficiency and lower fuel costs of diesel engines make them attractive in applications requiring relatively large amounts of power, such as in locomotive engines, emergency power generation units, large ships, and heavy trucks.

As an example of how large a diesel engine can be, a 12- cylinder diesel engine built in 1964 by the Fiat Corporation of Italy had a normal power output of 25,200 hp (18.8 MW) at 122 rpm, a cylinder bore of 90 cm, and a stroke of 91 cm.

EXAMPLE 8–3

The Idea 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°F, and 117 in3. Utilizing the cold-airstandard assumptions, determine:
- (*a*) the temperature and pressure of air at the end of each process,
- (*b*) the net work output and the thermal efficiency, and
- (*c*) the mean effective pressure.