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THERMODYNAMIC I

FIRST STAGE

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8. Gas Power Cycles

Most power producing devices operate on cycles, and the study of power cycles is an exciting and important part of thermodynamics. 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 for establishment of the equilibrium conditions during the cycle. To make an analytical study of a cycle feasible, we have to keep the complexities at a manageable level and utilize some idealizations. When the actual cycle is stripped of all the internal irreversibilities and complexities, we end up with a cycle that resembles the actual cycle closely but is made up totally of internally reversible processes. Such a cycle is called an **ideal cycle**.

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.

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). 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**.

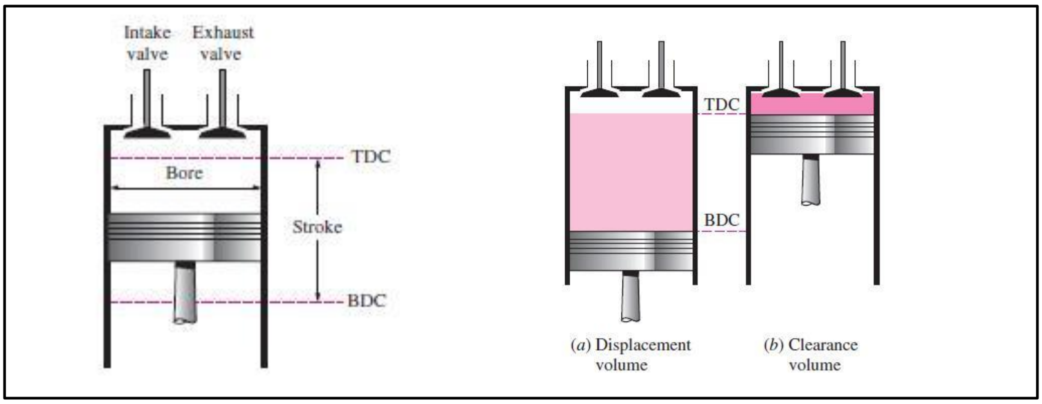
An Overview of Reciprocating Engines

Despite its simplicity, the reciprocating engine (basically a piston-cylinder device) is one of the rare inventions that have 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 aircrafts, ships and electric power generators, as well as many other devices.

The basic components of a reciprocating engine are shown in figure below. 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**.

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**. Figure below shoes both the clearance and displacement volumes**.** The ratio of the maximum volume formed in the cylinder to the minimum (clearance) volume is called the **compression ratio** r of the engine:

$$r = \frac{V_{max}}{V_{min}} = \frac{V_{BDC}}{V_{TDC}} \qquad \dots\dots\dots\dots\dots\dots\dots (8.1)$$

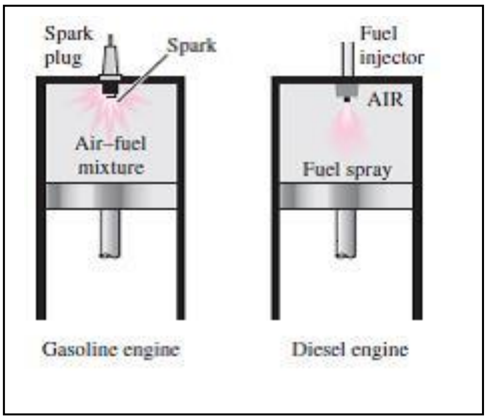


Another term frequently used in conjunction with reciprocating engines is the **mean effective pressure** (MEP). It is a fictitious pressure that, if it acted on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle:

$$MEP = \frac{W_{net}}{V_{max} - V_{min}} \qquad \dots\dots\dots\dots\dots\dots\dots (8.2)$$

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.

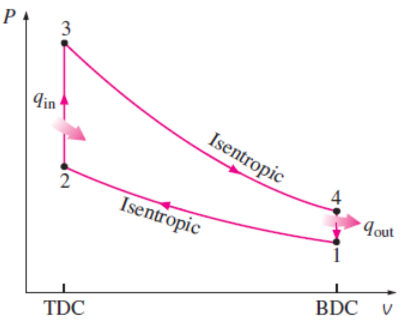
Reciprocating engines are classified as **spark-ignition (SI) engines** or **compression-ignition (CI) engines**, depending on how the combustion process in the cylinder is initiated. In SI engines, the combustion of the air-fuel mixture is initiated by a spark plug. In CI engines, the air-fuel mixture is self-ignited as a result of compressing the mixture above its self-ignition temperature. **Otto cycle** and **Diesel cycle** are the ideal cycles for the SI and CI reciprocating engines, respectively.



Spark Ignition Engines and Otto Cycle

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. In **two-stroke engines**, all four functions described above are executed in just two strokes: the power stroke and the compression stroke. The thermodynamic analysis of the actual four-stroke or two-stroke cycles 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 as shown on the (*P*-*V*) diagram:

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



The Otto cycle is executed in a closed system, and disregarding the changes in kinetic and potential energies, the energy balance for any of the processes is expressed, on a unit mass basis, as:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta u \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.3)$$

No work is involved during the two heat transfer processes since both take place at constant volume. Therefore, heat transfer to and from the working fluid can be expressed as:

$$q_{in} = u_3 - u_2 = C_v(T_3 - T_2) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.4)$$

$$q_{out} = u_4 - u_1 = C_v(T_4 - T_1) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.5)$$

The net work of the cycle is:

$$w_{net} = w_{out} - w_{in} = q_{in} - q_{out} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.6)$$

Then the thermal efficiency of the ideal Otto cycle under cold-air-standard assumptions is expressed as:

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.7)$$

For constant specific heats:

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

Processes 1-2 and 3-4 are isentropic, and $v_2 = v_3$ and $v_4 = v_1$, thus:

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

Substituting these equations into the thermal efficiency relation and simplifying gives:

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.8)$$

where r is the **compression ratio** and equals:

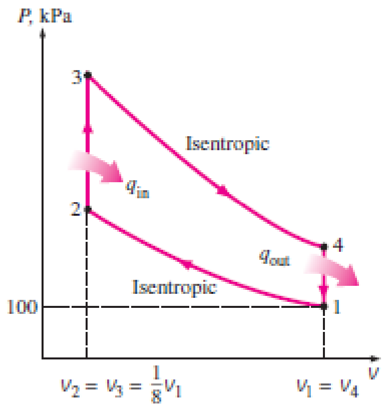
$$r = \frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.9)$$

Example (8.1): The compression ratio in an air-standard Otto cycle is 8. At the beginning of the compression stroke, the pressure is 0.1 MPa and the temperature is 15°C. The heat transferred to the air per cycle is 1800 kJ/kg. Draw the (*P*-*V*) diagram of the cycle and determine:

1) The pressure and temperature at the end of each process of the cycle.
2) The thermal efficiency of the cycle.
3) The mean effective pressure.

Solution:

1) The compression ratio $r = \frac{v_1}{v_2} = \frac{v_4}{v_3} = 8$



Process 1-2 (isentropic compression):

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = r^{\gamma-1} \rightarrow T_2 = (15 + 273) \times (8)^{1.4-1}$$

$\boldsymbol{T_2 = 662}$ **K** **Ans.**

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = r^{\gamma} \rightarrow P_2 = 0.1 \times 10^3 \times (8)^{1.4}$$

$\boldsymbol{P_2 = 1837.9}$ **kPa** **Ans.**

Process 2-3 (constant-volume heat addition):

$$q_{in} = C_v(T_3 - T_2) \rightarrow 1800 = 0.718 \times (T_3 - 662)$$

$\boldsymbol{T_3 = 3169}$ **K** **Ans.**

$$\frac{P_3}{P_2} = \frac{T_3}{T_2} \rightarrow P_3 = 1837.9 \times \frac{3169}{662}$$

$\boldsymbol{P_3 = 8798}$ **kPa** **Ans.**

Process 3-4 (isentropic expansion):

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = r^{\gamma-1} \rightarrow T_4 = \frac{3169}{(8)^{1.4-1}}$$

$\boldsymbol{T_4} = \mathbf{1380}$ **K** **Ans.**

$$\frac{P_3}{P_4} = \left(\frac{V_4}{V_3}\right)^{\gamma} = r^{\gamma} \rightarrow P_4 = \frac{8798}{(8)^{1.4}}$$

$\boldsymbol{P_4} = \mathbf{479}$ **kPa** **Ans.**

2) The thermal efficiency of the cycle:

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{(8)^{1.4-1}}$$

$\boldsymbol{\eta_{th}} = \mathbf{56.5}\%$ **Ans.**

3) From the equation of state:

$$P_1 v_1 = RT_1 \rightarrow v_1 = \frac{RT_1}{P_1} = \frac{0.287 \times 288}{0.1 \times 10^3} = 0.827 \text{ m}^3/\text{kg}$$

$$r = \frac{v_1}{v_2} \rightarrow v_2 = \frac{0.827}{8} = 0.1034 \text{ m}^3/\text{kg}$$

$$q_{out} = C_v(T_4 - T_1) = 0.718 \times (1380 - 288) = 784 \text{ kJ/kg}$$

$$w_{net} = q_{in} - q_{out} = 1800 - 784 = 1016 \text{ kJ/kg}$$

The mean effective pressure:

$$MEP = \frac{w_{net}}{v_1 - v_2} = \frac{1016}{0.827 - 0.1034}$$

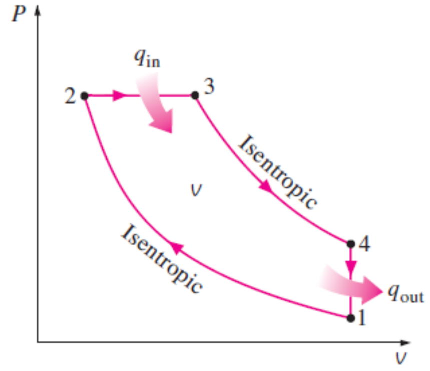
$\boldsymbol{MEP} = \mathbf{1404}$ **kPa** **Ans.**

Compression Ignition Engines and Diesel Cycle

The Diesel cycle is the ideal cycle for CI reciprocating engines. The CI engine is very similar to the SI engine, differing mainly in the method of initiating combustion. In spark-ignition engines (also known as gasoline engines), the air–fuel mixture is compressed to a temperature that is below the auto-ignition 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 auto-ignition temperature of the fuel, and combustion starts on contact as the fuel is injected into this hot air. Therefore, the spark plug and carburetor are replaced by a fuel injector in diesel engines.

The fuel injection process in diesel engines starts when the piston approaches TDC and continues during the first part of the power stroke. Therefore, the combustion process in these engines takes place over a longer interval. 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. The four processes comprising the cycle are shown on the (*P*-*V*) diagram:

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



Noting that the Diesel cycle is executed in a piston-cylinder device, which forms a closed system, the amount of heat transferred to the working fluid at constant pressure and rejected from it at constant volume can be expressed as:

$$q_{in} = h_3 - h_2 = C_p(T_3 - T_2) \quad \dots\dots\dots\dots\dots\dots\dots (8.10)$$

$$q_{out} = u_4 - u_1 = C_v(T_4 - T_1) \quad \dots\dots\dots\dots\dots\dots\dots (8.11)$$

Then the thermal efficiency of the ideal Diesel cycle under the cold-air-standard assumptions is expressed as:

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

We now define a new quantity, the **cutoff ratio** r_c as the ratio of the cylinder volumes after and before the combustion process:

$$r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2} \quad \dots\dots\dots\dots\dots\dots\dots (8.12)$$

Utilizing this definition and the isentropic ideal-gas relations for processes 1-2 and 3-4, we see that the thermal efficiency relation reduces to:

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}\right] \quad \dots\dots\dots\dots\dots\dots\dots (8.13)$$

where *r* is the compression ratio defined by equation (8.9). Looking at equation (8.13) carefully, one would notice that under the cold-air-standard assumptions, the efficiency of a Diesel cycle differs from the efficiency of an Otto cycle by the quantity in the brackets. This quantity is always greater than 1. Therefore:

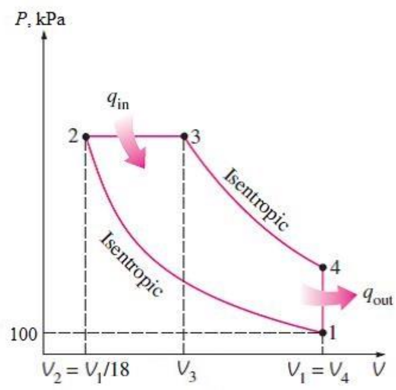
$$\eta_{th.Otto} > \eta_{th,Diesel} \quad \dots\dots\dots\dots\dots\dots\dots (8.14)$$

Example (8.2): An air-standard Diesel cycle has a compression ratio of 18, and the heat transferred to the working fluid per cycle is 1800 kJ/kg. At the beginning of the compression process, the pressure is 0.1 MPa and the temperature is 15°C. Draw the (*P*-*V*) diagram of the cycle and determine:

1) The pressure and temperature at the end of each process of the cycle.
2) The thermal efficiency of the cycle.
3) The mean effective pressure.

Solution:

1) The compression ratio $r = \frac{v_1}{v_2} = 18$



$$P_1 v_1 = RT_1 \rightarrow v_1 = \frac{RT_1}{P_1} = \frac{0.287 \times 288}{0.1 \times 10^3} = 0.827 \text{ m}^3/\text{kg}$$

$$v_4 = v_1 = 0.827 \text{ m}^3/\text{kg}$$

$$r = \frac{v_1}{v_2} \rightarrow v_2 = \frac{0.827}{18} = 0.0459 \text{ m}^3/\text{kg}$$

Process 1-2 (isentropic compression):

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = r^{\gamma-1} \rightarrow T_2 = (15 + 273) \times (18)^{1.4-1}$$

$\boldsymbol{T_2 = 915}$ **K** **Ans.**

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = r^{\gamma} \rightarrow P_2 = 0.1 \times 10^3 \times (18)^{1.4}$$

$\boldsymbol{P_2 = 5720}$ **kPa** **Ans.**

Process 2-3 (constant-pressure heat addition):

$\boldsymbol{P_3 = P_2 = 5720}$ **kPa** **Ans.**

$$q_{in} = C_p(T_3 - T_2) \rightarrow 1800 = 1.005 \times (T_3 - 915)$$

$\boldsymbol{T_3 = 2706}$ **K** **Ans.**

$$\frac{v_3}{v_2} = \frac{T_3}{T_2} \rightarrow v_3 = 0.0459 \times \frac{2706}{915} = 0.1357 \text{ m}^3/\text{kg}$$

Process 3-4 (isentropic expansion):

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} \rightarrow T_4 = \frac{2706}{(0.827/0.1357)^{1.4-1}}$$

$\boldsymbol{T_4 = 1313}$ **K** **Ans.**

$$\frac{P_3}{P_4} = \left(\frac{V_4}{V_3}\right)^{\gamma} \rightarrow P_4 = \frac{5720}{(0.827/0.1357)^{1.4}}$$

$\boldsymbol{P_4 = 456\ \text{kPa}}$ **Ans.**

2) $q_{out} = C_v(T_4 - T_1) = 0.718 \times (1313 - 288) = 736\ \text{kJ/kg}$

$w_{net} = q_{in} - q_{out} = 1800 - 736 = 1064\ \text{kJ/kg}$

The thermal efficiency of the cycle:

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{1064}{1800}$$

$\boldsymbol{\eta_{th} = 59\%}$ **Ans.**

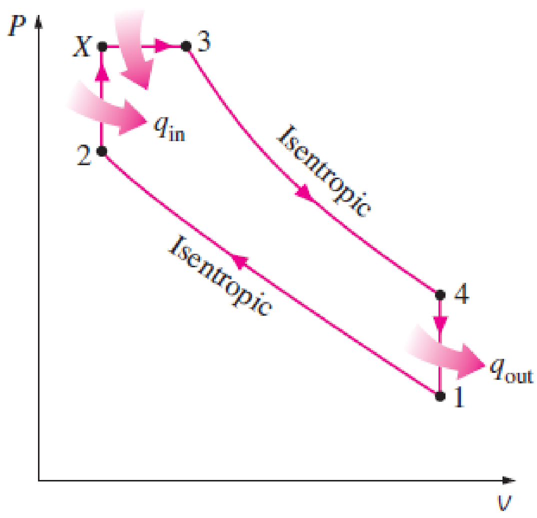
3) The mean effective pressure:

$$MEP = \frac{w_{net}}{v_1 - v_2} = \frac{1064}{0.827 - 0.0459}$$

$\boldsymbol{MEP = 1362\ \text{kPa}}$ **Ans.**

Dual Cycle

Approximating the combustion process in internal combustion engines as a constant-volume or a constant-pressure heat-addition process is overly simplistic and not quite realistic. Probably a better (but slightly more complex) approach would be to model the combustion process in both gasoline and diesel engines as a combination of two heat-transfer processes, one at constant volume and the other at constant pressure. The ideal cycle based on this concept is called the **dual cycle,** and a (*P*-*V*) diagram for it is shown below. The relative amounts of heat transferred during each process can be adjusted to approximate the actual cycle more closely. Note that both the Otto and the Diesel cycles can be obtained as special cases of the dual cycle.



Exercises

Problem (8.1): The compression ratio of an air-standard Otto cycle is 9.5. Prior to the isentropic compression process, the air is at 100 kPa, 35°C and 600 cm^3. The temperature at the end of the isentropic expansion process is 800 K. Determine (a) the highest temperature in the cycle (b) the highest pressure in the cycle (c) the amount of heat transferred in (d) the thermal efficiency (e) the mean effective pressure.

Ans. (1969 K, 6072 kPa, 0.59 kJ, 59.4%, 652 kPa)

Problem (8.2): An ideal diesel engine has a compression ratio of 20 and uses air as the working fluid. The state of air at the beginning of the compression process is 95 kPa and 20°C. If the maximum temperature in the cycle is not to exceed 2200 K, determine (a) the thermal efficiency (b) the mean effective pressure.

Ans. (63.5%, 933 kPa)