

# Engineering Thermodynamics I

## Lecture 11

### Gas Power Cycles

**Lecturer:** Dr. Melaku Desta

# ***Lecture learning outcomes:***

At the end of this lecture, you will be able to:

- i. Understand air standard assumptions to recognize the simplifications made in the analysis of thermodynamic cycles
- ii. Analyze internal combustion cycles and compare and contrast the air-standard Otto and Diesel cycles, focusing on efficiency, compression ratios, and thermodynamic processes.
- iii. Examine gas-turbine power cycles and understand the Brayton cycle as the fundamental thermodynamic model for gas turbines, and assess modifications such as the gas turbine cycle with regeneration.
- iv. Apply thermodynamic concepts to practical systems to evaluate performance enhancements in power cycles, such as regeneration.

# Content

1. Fundamental Aspects of Power Cycle Analysis
2. The Carnot Cycle and its Value in Engineering
3. Air Standard Assumptions
4. Air-Standard Otto Cycle
5. Air-Standard Diesel Cycle
6. Brayton Cycle: The Ideal Cycle for Gas-Turbine Engines
7. Gas-Turbine Cycle with Regenerator

Summary

References

# 1. Fundamental Aspects of Power Cycle Analysis

- Thermodynamic Cycles can be grouped into:
  - Power cycles
  - Refrigeration cycles
- **Engines** - devices or systems used to produce a net power output – the thermodynamic cycles they operate on are called **Power Cycles**.
- **Refrigerators/Air Conditioners/Heat Pumps**- devices or systems to produce a refrigeration effect- the thermodynamic cycles they operate on are called **Refrigeration Cycles**.

- **Thermodynamic Cycles**

- **Closed cycles** - the working fluid is returned to the initial state at the end of the cycle and is recirculated.
- **Open cycles** - the working fluid is renewed at the end of each cycle instead of being recirculated.

- **Heat Engines**

- Internal Combustion Engines
- External Combustion Engine

# 1. Fundamental Aspects of Power Cycle Analysis

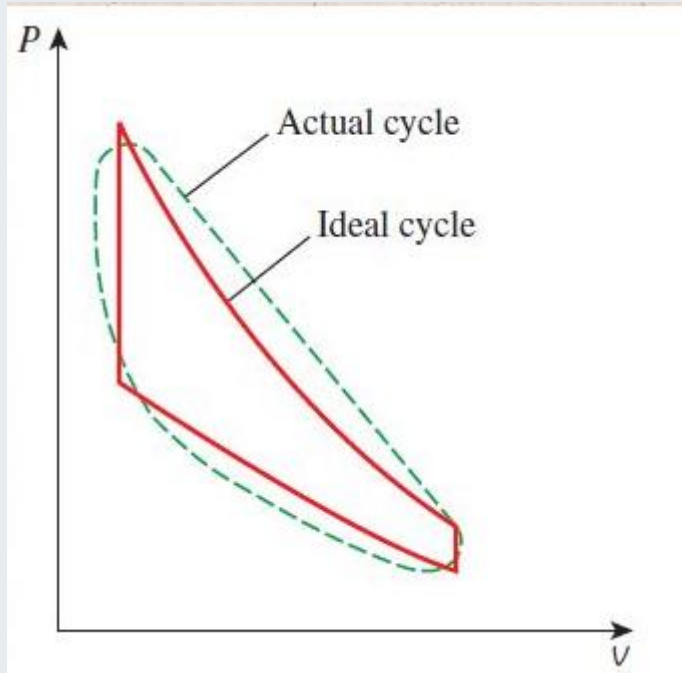
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- In **actual devices**, thermodynamic cycles (such as those in engines, refrigerators, or power plants) deviate significantly from **idealized cycles** due to real-world complications.
- Two major factors that make these cycles difficult to analyze are:
  - i. Friction and other irreversibilities
  - ii. Lack of equilibrium conditions
    - Finite time processes
    - Dynamic effects
    - Chemical non-equilibrium

# 1. Fundamental Aspects of Power Cycle Analysis

Cont...

- These **irreversibilities** mean that real cycles cannot achieve the theoretical maximum efficiency predicted by idealized models (e.g., Carnot efficiency).



**Figure 1:** P-v diagrams of Actual and Ideal Cycles

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# 1. Fundamental Aspects of Power Cycle Analysis

Cont...

- **Heat engines** are designed for the purpose of converting other forms of energy (usually in the form of heat) to work, and the thermal efficiency is:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad \text{or} \quad \eta_{th} = \frac{w_{net}}{q_{in}}$$

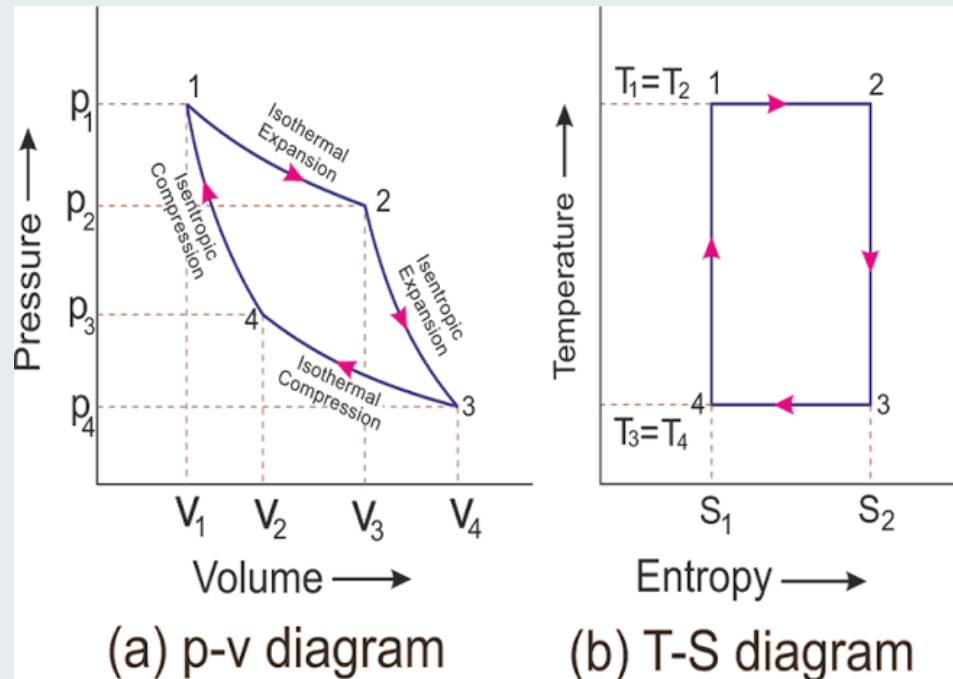
- No body can develop a cycle more efficient than the **Carnot cycle [1]**.
- Idealizations and simplifications – for analysis of power cycles
  1. Cycle does not involve any friction
  2. Expansion and compression processes –quasi-equilibrium
  3. Pipes are well-insulated
  4. Changes in kinetic and potential energy could be neglected

## 2. The Carnot Cycle and its Value in Engineering

- The Carnot cycle provides a fundamental guideline for energy efficiency.
- Though impractical, it inspires modern engineering innovations.
- Engineers strive to approach Carnot efficiency in practical designs.
- The Carnot cycle consists of four reversible processes:
  1. **Isothermal Expansion:** Heat absorption at constant temperature  $T_H$
  2. **Adiabatic Expansion:** Cooling without heat exchange.
  3. **Isothermal Compression:** Heat rejection at constant temperature  $T_L$
  4. **Adiabatic Compression:** Heating without heat exchange.

## Limitations of the Carnot Cycle

- Idealized assumptions make it impractical for real-world use.
- Requires perfectly reversible processes, which are impossible to achieve.
- Only applicable between two temperature reservoirs.



**Figure 2:** P-v and T-s diagrams of a Carnot Cycle  
[url: https://www.mechanicaltutorial.com/pictures/content\\_picture/carnot\\_cycle/carnot\\_cycle\\_graph.png](https://www.mechanicaltutorial.com/pictures/content_picture/carnot_cycle/carnot_cycle_graph.png)

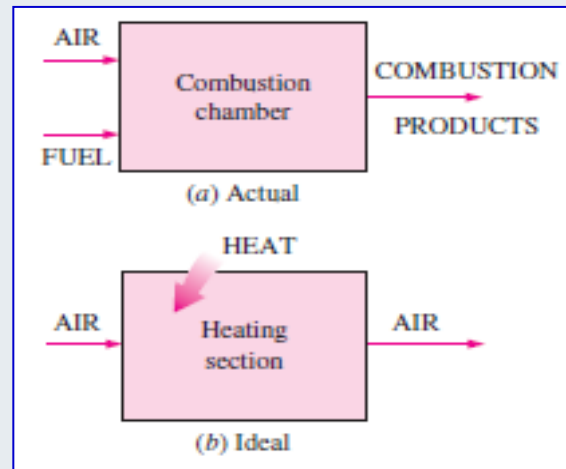
# 3. Air Standard Assumptions

- In **gas power cycles** working fluid remains a gas throughout the entire cycle.
- Examples of devices operating on gas power cycles
  - Spark-ignition automobile engines.
  - Diesel engines
  - Conventional gas turbines
- Because of the combustion process, the composition of the working fluid changes from **air** and **fuel** to combustion products during the course of the cycle.
- The actual gas power cycles are rather complex.
- To reduce the analysis to a manageable level, we utilize the **air-standard assumptions.**

# 3. Air Standard Assumptions

Cont...

- **Air standard assumptions** are simplifications used in thermodynamic analysis to make the study of internal combustion engines and gas power cycles more manageable **without** dealing with the **complexities of real-world combustion** and **fluid behavior** [2].
- The following are Air Standard Assumptions:
  - **The working fluid is air**
  - **Constant specific heats**
  - **Internally reversible processes**
  - **Heat addition and rejection**
  - **No chemical reactions**
  - **No exhaust losses**



**Figure 3:** Air Standard Assumptions

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# 4. Air Standard Otto Cycle

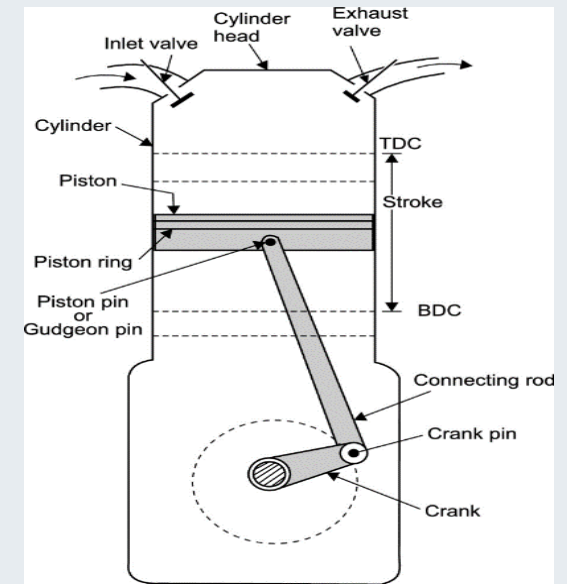
## An overview of reciprocating Engines

- A **reciprocating engine** is a type of internal combustion engine that converts chemical energy from fuel into mechanical work using reciprocating (back-and-forth) motion [3].
- These engines are widely used in transportation, power generation, and industrial applications.
- The reciprocating engine is the powerhouse of:
  - The vast majority of automobiles
  - Trucks,
  - Light aircraft
  - Ships, and
  - Electric power generators

# 4. Air Standard Otto Cycle

- **Top Dead Center (TDC)**- the position of the piston when it forms the smallest volume in the cylinder.
- **Bottom Dead Center (BDC)**-The position of the piston when it forms the largest volume in the cylinder
- **Stroke of the engine**- the distance between **TDC** and **BDC**- the largest distance that the piston can travel in one direction.
- **Bore** –the diameter of the piston
- **Intake Valve**- The air or air-fuel mixture is drawn into the cylinder through.
- **Exhaust Valve**- The combustion products are expelled from the cylinder through.

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**Figure 4:** Components of a reciprocating engine

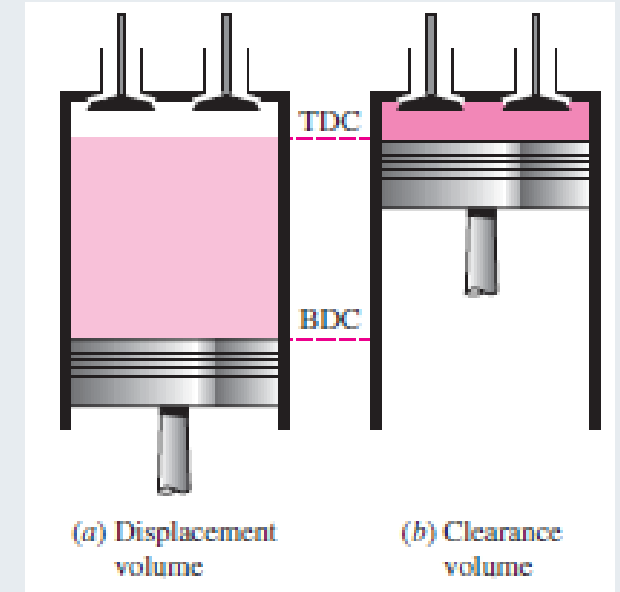
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# 4. Air Standard Otto Cycle

- 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:

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

Cont...



**Figure 5:** Displacement and Clearance Volume  
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# 4. Air Standard Otto Cycle

Cont...

- 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.
- The **Mean Effective Pressure** can be used as a parameter to compare the **performance of reciprocating engines of equal size**.
- The engine with a larger value of **MEP** will deliver more net work per cycle and thus will perform better.

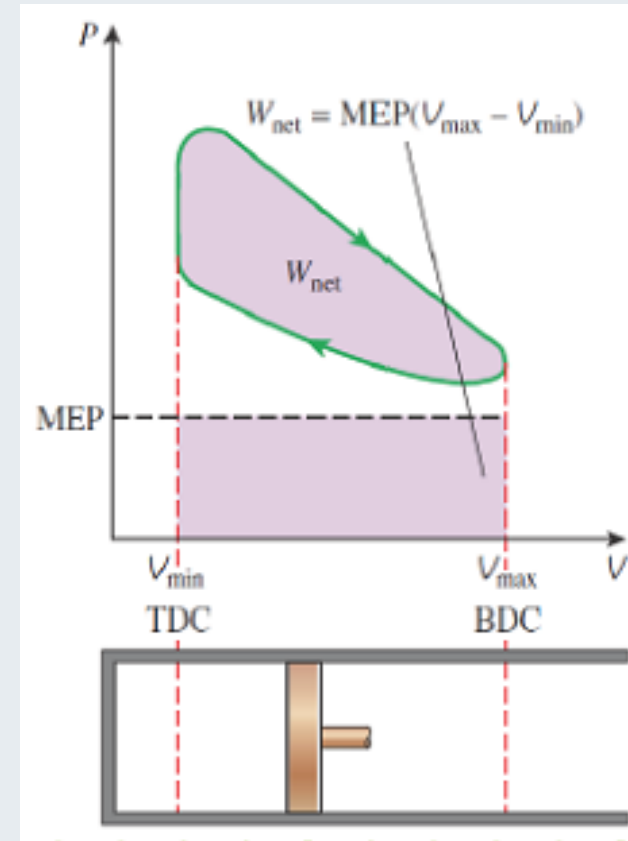
# 4. Air Standard Otto Cycle

Cont...

$$W_{net} = MEP \times \text{Piston Area} \times \text{Stroke}$$

$$W_{net} = MEP \times \text{Displacement Volume}$$

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



**Figure 6:** Mean Effective Pressure

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# 4. Air Standard Otto Cycle

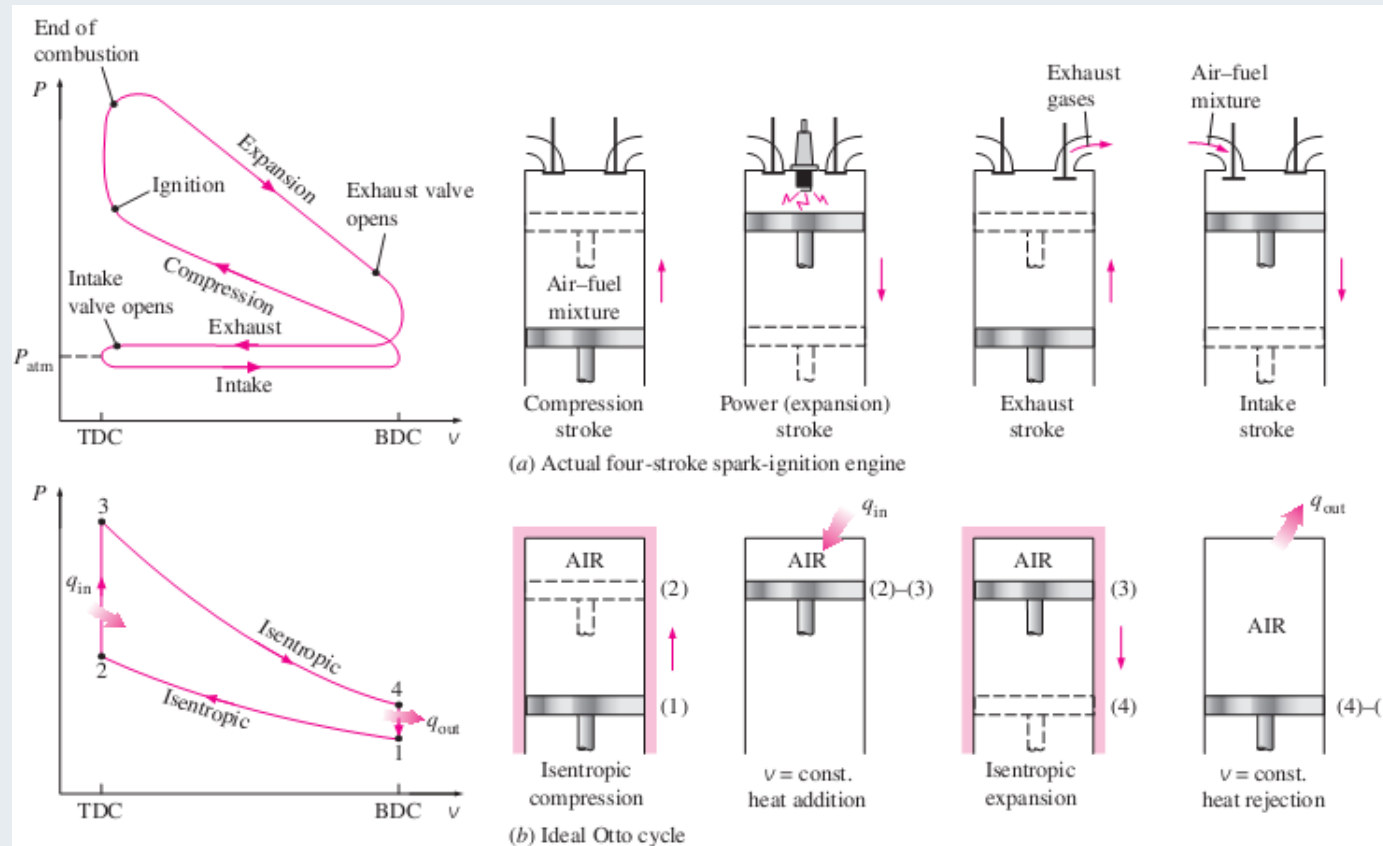
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- The **Air Standard Otto Cycle** is a theoretical model that approximates the behavior of a **spark-ignition internal combustion engine**, commonly found in gasoline-powered vehicles [3].
- The **Otto cycle** is the ideal cycle for **spark-ignition** reciprocating engines.
- 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.
- It consists of **four distinct processes** that occur in a **closed system**, assuming air as the working fluid and neglecting any real-world complexities like friction or heat losses.
- These engines are called **four-stroke internal combustion engines**.

# 4. Air Standard Otto Cycle

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The working Principle of Air Standard Otto Cycle



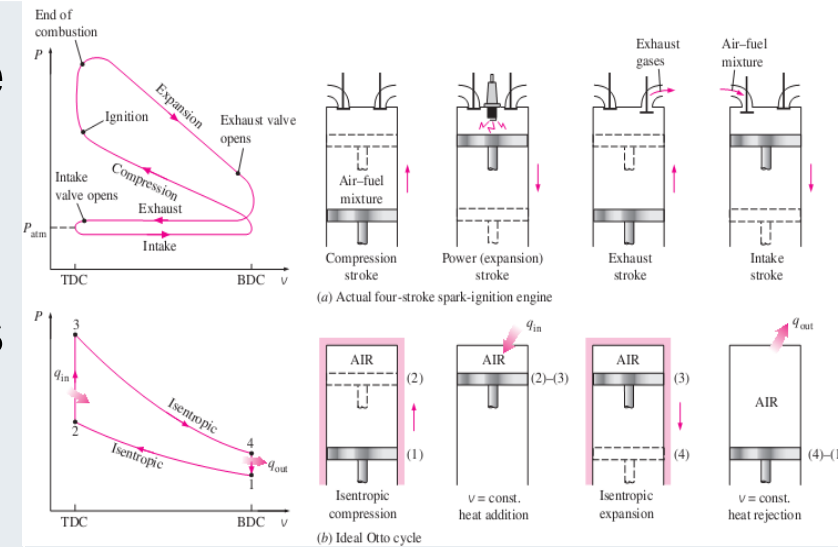
**Figure 7:** Working principle of Air Standard Otto Cycle

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# 4. Air Standard Otto Cycle

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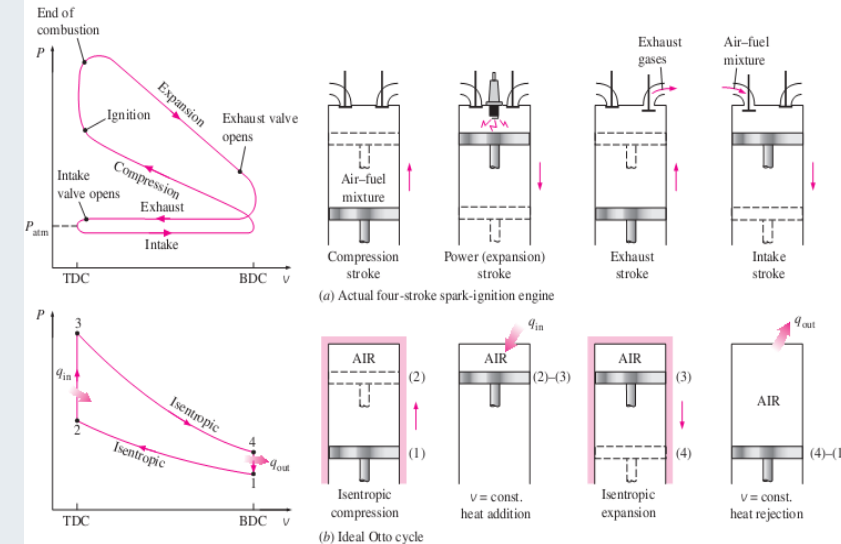
- Initially, both the intake and the exhaust valves are closed, and the piston is at its lowest position (**BDC**).
- During the **compression stroke**, the piston reaches its highest position (**TDC**).
- The spark plug fires and the mixture ignites, increasing the pressure and temperature of the system.
- 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**.



# 4. Air Standard Otto Cycle

Cont...

- 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 below during the intake stroke.



# 4. Air Standard Otto Cycle

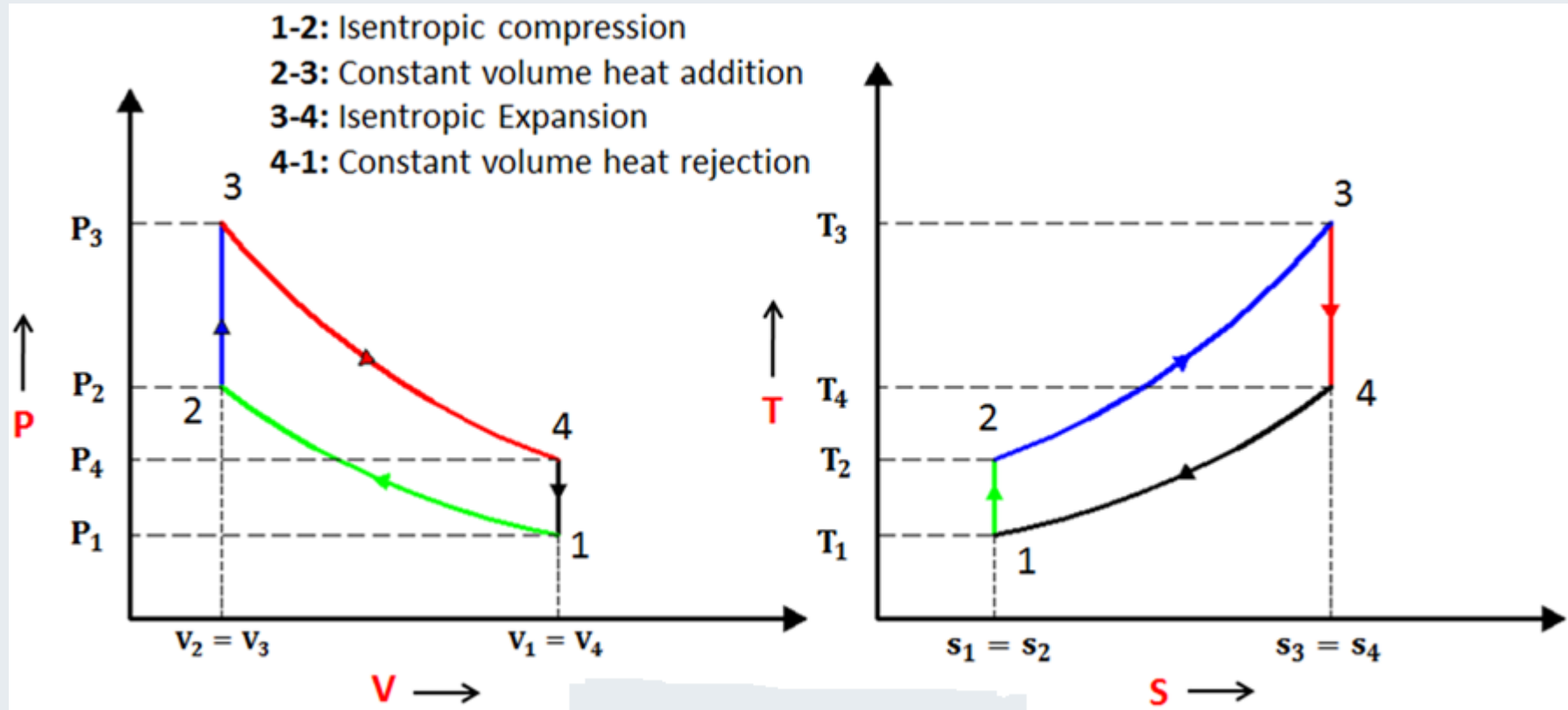
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- The thermodynamic analysis of the actual four-stroke or two-stroke cycles can be simplified significantly if the **air-standard assumptions** are utilized.
- The resulting cycle, which closely resembles the actual operating conditions, is the ideal **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**

# 4. Air Standard Otto Cycle

Cont...

## The P-v and T-s diagram of an Otto Cycle



**Figure 8:** P-v and T-s diagram of an Otto Cycle

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# 4. Air Standard Otto Cycle

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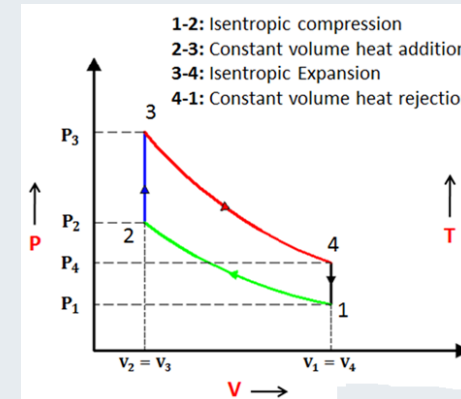
- The **Otto cycle** is executed in a **closed system**, and disregarding the changes in kinetic and potential energies, the **1<sup>st</sup> law relation** for any of the processes is expressed, on a unit-mass basis, as

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

- No work is involved during the two heat transfer processes since both take place at constant volume.

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

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



# 4. Air Standard Otto Cycle

Cont...

Then, the thermal efficiency of the ideal Otto cycle under the cold air standard assumptions becomes:

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

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

$$\frac{T_1}{T_2} = \left( \frac{v_2}{v_1} \right)^{k-1} = \left( \frac{v_3}{v_4} \right)^{k-1} = \frac{T_4}{T_3}$$

$$\eta_{th} = 1 - \frac{1}{r^{k-1}} \quad r = \frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2}$$

# 4. Air Standard Otto Cycle

Cont...

## Example:

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<sup>3</sup>. The temperature at the end of the isentropic expansion process is 800 K. Using specific heat values at room temperature, determine:

- The highest temperature and pressure in the cycle,
- The amount of heat transferred in (in kJ),
- The thermal efficiency, and
- The mean effective pressure (MEP).

*Air:*

$$C_p = 1.005 \text{ kJ/kgK}$$

$$C_v = 0.718 \text{ kJ/kgK}$$

$$K = 1.4, R = 0.287 \text{ kJ/kgK}$$

# 4. Air Standard Otto Cycle

Cont...

**Solution:**

$$\text{Compression Ratio, } r = \frac{V_1}{V_2} = 9.5$$

State 1:

$$P_1 = 100 \text{ kPa}$$

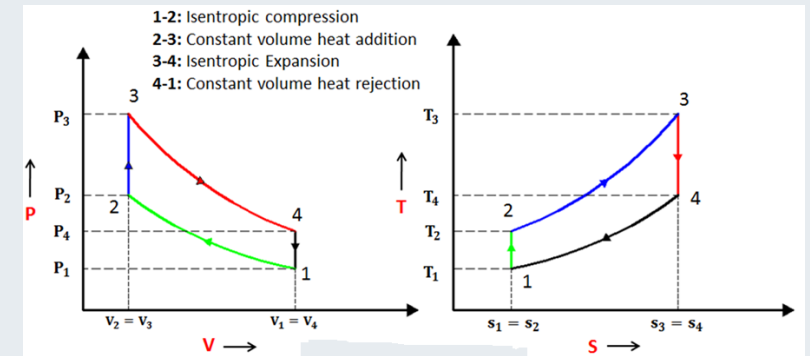
$$T_1 = 35 \text{ }^\circ\text{C} = 308 \text{ K}$$

$$V_1 = 0.0006 \text{ m}^3$$

State 4:

$$T_4 = 800 \text{ K}$$

$$K = \frac{C_P}{C_V} = 1.4$$



For the Isentropic Compression:

$$T_2 = T_1 \times r^{k-1} = 308 \times (9.5)^{1.4-1}$$

$$T_2 = 741.7 \text{ K}$$

$$P_2 = P_1 \times r^k = 100 \times (9.5)^{1.4}$$

and,

$$P_2 = 2260 \text{ kPa}$$

**The highest temperature** occurs at state 3:

Given  $T_4 = 800 \text{ K}$

$$T_3 = T_4 \times r^{k-1} = 800 \times (9.5)^{1.4-1}$$

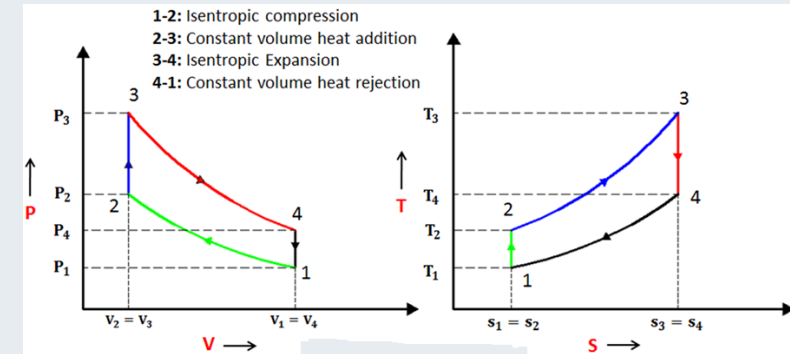
$$T_3 = 1926.4 \text{ K}$$

# 4. Air Standard Otto Cycle

Cont...

The highest pressure  $P_3$  is found using the ideal gas law:

$$\frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3}$$
$$P_3 = P_2 \times \frac{T_3}{T_2} = 2260 \times \frac{1926.4}{741.7}$$
$$P_3 = 5870 \text{ kPa}$$



Heat addition occurs during State 2 → State 3 process

The mass of air is determined:

$$m = \frac{P_1 V_1}{RT_1} = \frac{100 \times 0.0006}{0.287 \times 308} = 0.00068 \text{ kg}$$

Heat added:  $Q_{in} = m \times C_v \times (T_3 - T_2)$

$$Q_{in} = 0.00068 \times 0.718 \times (1926.4 - 741.7) = 0.578 \text{ kJ}$$

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# 4. Air Standard Otto Cycle

Cont...

The thermal efficiency:

It is dependent on the compression ratio:

$$\eta_{th} = 1 - \frac{1}{r^{k-1}} = 1 - \frac{1}{9.5^{0.4}} = 0.585$$

$$\eta_{th} = \mathbf{58.5\%}$$

Mean Effective Pressure (MEP) is defined as:  $MEP = \frac{W_{net}}{V_1 - V_2}$

And, the net work output:  $W_{net} = \eta \times Q_{in} = 0.585 \times 0.578 = 0.338 \text{ kJ}$

Displacement Volume:

$$V_1 - V_2 = V_1 \left(1 - \frac{1}{r}\right) = 0.0006 \left(1 - \frac{1}{9.5}\right) = 0.000537 \text{ m}^3$$

$$MEP = \frac{0.338}{0.000537} = \mathbf{629.4 \text{ kPa}}$$

# 4. Air Standard Diesel Cycle

Cont...

- The **Diesel cycle** is the ideal cycle for the compressed ignition (CI) reciprocating engines.
- 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, the combustion process is initiated by **firing a spark plug** [4].
- 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.

# 4. Air Standard Diesel Cycle

Cont...

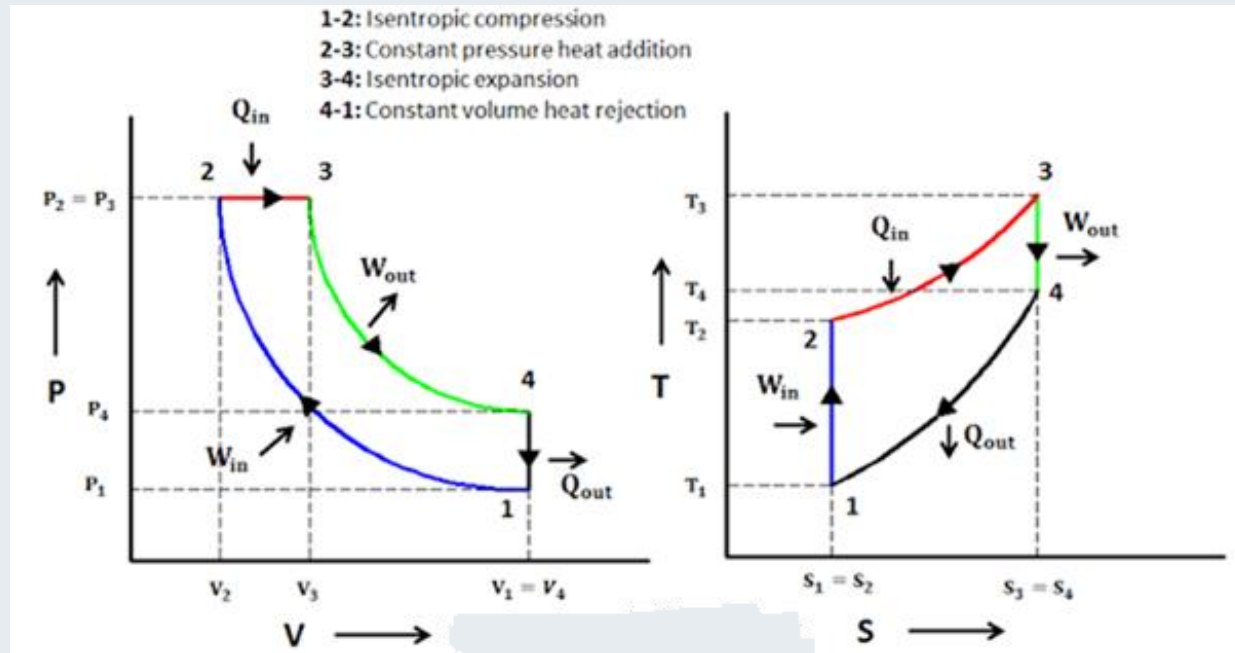
The working principle is:

- The fuel injection process in diesel engines starts when the piston approaches **TDC** and continues during the first part of the **power stroke**.
- Because of this longer duration, the combustion process in the ideal Diesel cycle is approximated as a **constant-pressure heat-addition process**.
- This is the only process where the Otto and the Diesel cycles differ.
- The remaining three processes are the same for both ideal cycles.
  - **Process 1-2 : Isentropic compression**
  - **Process 2-3 : Constant pressure heat addition**
  - **Process 3-4 : Isentropic expansion**
  - **Process 4-1 : Constant-volume heat rejection**

# 4. Air Standard Diesel Cycle

Cont...

- The **Diesel cycle** is the ideal cycle for the compressed ignition (CI) reciprocating engines.



**Figure 9:** P-v and T-s diagram of Diesel Cycle

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# 4. Air Standard Diesel Cycle

Cont...

- 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:

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

$$q_{in} = h_3 - h_2 = C_p(T_3 - T_2)$$

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

- The thermal efficiency of the ideal Diesel cycle under the cold-air-standard assumption becomes:

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

# 4. Air Standard Diesel Cycle

Cont...

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

$$\text{Cutoff Ratio, } r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2}$$

- 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:

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

# 4. Air Standard Diesel Cycle

Cont...

## Example:

An ideal Diesel engine has a compression ratio of 18 and uses air as the working fluid. The state of air at the beginning of the compression process is 100 kPa and 25°C. If the maximum temperature in the cycle is not to exceed 2100 K, determine:

- The thermal efficiency of the cycle.
- The mean effective pressure (MEP).

Assume constant specific heats for air at room temperature.

# 4. Air Standard Diesel Cycle

Cont...

**Solution:**

$$\text{Compression Ratio, } r = \frac{V_1}{V_2} = 18$$

State 1:

$$P_1 = 100 \text{ kPa}$$

$$T_1 = 25 \text{ }^\circ\text{C} = 298 \text{ K}$$

$$\text{Maximum } T, T_3 = 2100 \text{ K}$$

$$K = \frac{C_P}{C_V} = 1.4$$

Let's determine  $T_2$  and  $P_2$  for isentropic compression:

$$T_2 = T_1 \times r^{k-1} = 298 \times (18)^{1.4-1}$$

$$T_2 = 946.7 \text{ K}$$

$$P_2 = P_1 \times r^k = 100 \times (18)^{1.4}$$

$$P_2 = 5720 \text{ kPa}$$

For the constant pressure heat addition:

$$\frac{V_3}{V_2} = \frac{T_3}{T_2} = \frac{2100}{946.7} = 2.218, \text{ Cutoff ratio}$$

# 4. Air Standard Diesel Cycle

Cont...

Calculate Heat Input and Heat Rejected:

Heat Input ( $Q_{in}$ )

$$Q_{in} = C_p(T_3 - T_2) = 1.005 \times (2100 - 946.7) = 1159.6 \text{ kJ/kg}$$

Heat Rejected ( $Q_{out}$ )

$$Q_{out} = C_v(T_4 - T_1) = 0.718 \times (913.5 - 298) = 441.8 \text{ kJ/kg}$$

- Thermal efficiency

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{441.8}{1159.6} = \mathbf{0.619} = \mathbf{61.9\%}$$

Alternatively, using Diesel efficiency formula

$$\eta_{th,Diesel} = 1 - \frac{1}{r^k} \left[ \frac{r_c^k - 1}{k(r_c - 1)} \right] = 1 - \frac{1}{18^{0.4}} \left[ \frac{2.218^{1.8} - 1}{1.4(2.218 - 1)} \right] = \mathbf{0.619}$$

# 4. Air Standard Diesel Cycle

Cont...

- Mean Effective Pressure (MEP)

Net Work Output ( $W_{net}$ )

$$W_{net} = Q_{in} - Q_{out} = 1159.6 - 441.8 = 717.8 \text{ kJ/kg}$$

Displacement Volume ( $V_1 - V_2$ )

First, find specific volume at State 1:

$$v_1 = \frac{RT_1}{P_1} = \frac{0.287 \times 298}{100} = 0.855 \text{ m}^3/\text{kg}$$

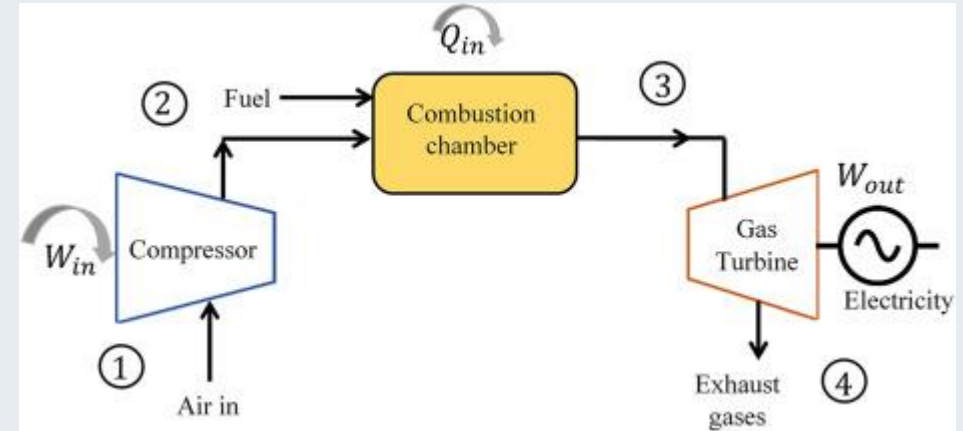
$$v_2 = \frac{v_1}{r} = \frac{0.855}{18} = 0.0475 \text{ m}^3/\text{kg}$$

$$v_1 - v_2 = 0.855 - 0.0475 = 0.8075 \text{ m}^3/\text{kg}$$

$$\text{Therefore, } MEP = \frac{W_{net}}{v_1 - v_2} = \frac{717.8}{0.8075} = \mathbf{888.9 \text{ kPa}}$$

## 6. Brayton Cycle

- **Brayton cycle** is used for **gas turbines only** where both the compression and expansion processes take place in rotating machinery.
- Gas turbines usually operate on an **open cycle**.
- Fresh air at ambient conditions is drawn into the compressor, where its temperature and pressure are raised.
- The high-pressure air proceeds into the combustion chamber, where the fuel is burned at constant pressure.



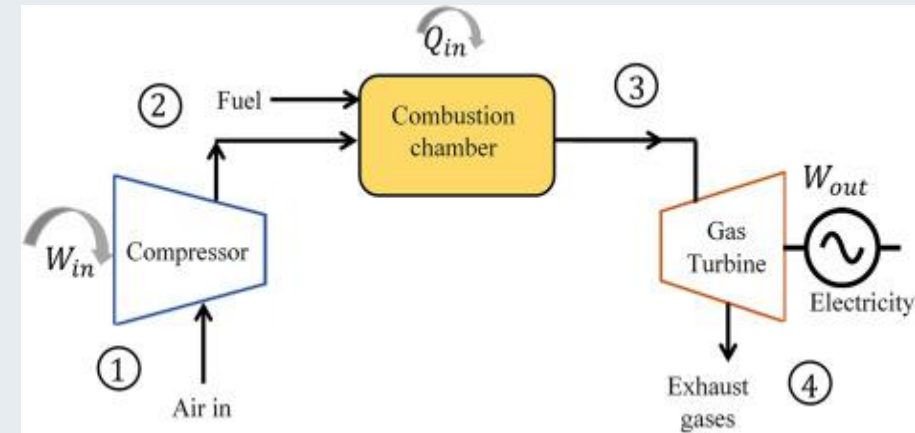
**Figure 10:** An Open Cycle Gas Turbine Cycle

[url: https://ars.els-cdn.com/content/image/3-s2.0-B9780323995603000065-f07-04-9780323995603.jpg](https://ars.els-cdn.com/content/image/3-s2.0-B9780323995603000065-f07-04-9780323995603.jpg)

# 6. Brayton Cycle

- The resulting high-temperature gases then enter the turbine, where they expand to the atmospheric pressure, producing power.
- The exhaust gases leaving the turbine are thrown out (not recirculated), causing the cycle to be classified as an open cycle.
- The open gas-turbine cycle can be modeled as a **closed cycle**, by utilizing the air-standard assumptions.

Cont...



# 6. Brayton Cycle

Cont...

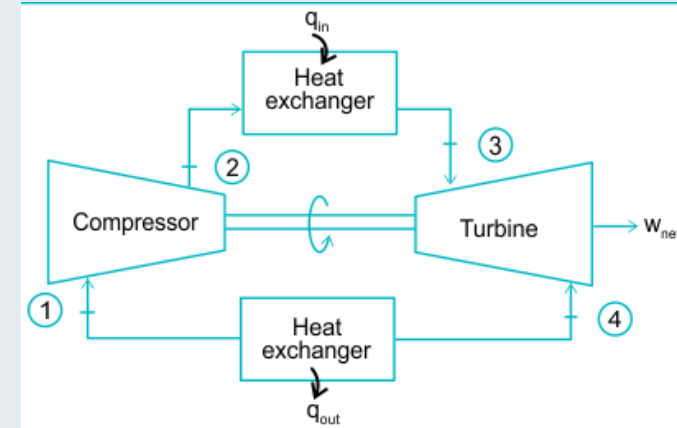
- **Brayton cycle**: the compression and expansion processes remain the same, but the combustion process is replaced by a **constant-pressure heat-addition** process from an external source, and the exhaust process is replaced by a **constant-pressure heat-rejection** process to the ambient air.
- The ideal cycle that the working fluid undergoes in this closed loop is the Brayton cycle, which is made up of four reversible processes:

1-2: Isentropic compression (in a compressor)

2-3: Constant pressure heat addition

3-4: Isentropic expansion (in a turbine)

4-1: Constant pressure heat rejection



**Figure 11:** A Closed Cycle Gas Turbine Cycle

[url: https://blogmedia.testbook.com/blog/wp-content/uploads/2023/09/closed-cycle-gas-turbine-1e9a752b.png](https://blogmedia.testbook.com/blog/wp-content/uploads/2023/09/closed-cycle-gas-turbine-1e9a752b.png)

# 6. Brayton Cycle

Cont...

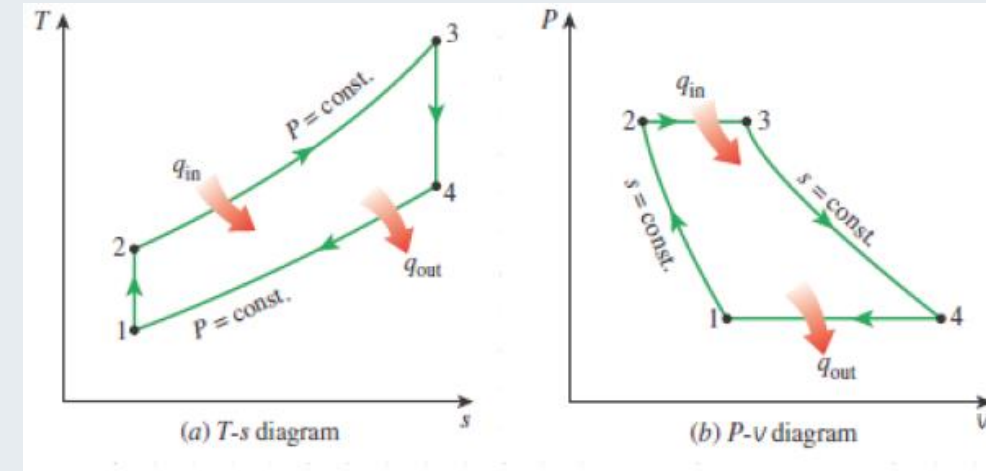
- All four processes of the **Brayton cycle** are executed in steady-flow devices; thus, they should be analyzed as steady-flow processes.
- When the changes in kinetic and potential energies are neglected, the **energy balance** for a steady-flow process can be expressed as:

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

- Heat transfers to and from the working fluid are:

$$q_{in} = h_3 - h_2 = C_P(T_3 - T_2)$$

$$q_{out} = h_4 - h_1 = C_P(T_4 - T_1)$$



**Figure 12:** T-s and P-v diagrams of a simple Brayton Cycle

[url: https://www.engineersedge.com/graphics/cha\\_p11-4.png](https://www.engineersedge.com/graphics/cha_p11-4.png)

# 6. Brayton Cycle

Cont...

- The thermal efficiency of the ideal Brayton cycle under the cold air standard assumptions becomes:

$$\eta_{th,Brayton} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \quad \text{Or, } \eta_{th,Brayton} = 1 - \frac{C_P(T_4 - T_1)}{C_P(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$$

- Process 1-2 and 3-4 are isentropic and  $P_2 = P_3$  and  $P_4 = P_1$ , thus

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{k-1/k} = \left(\frac{P_3}{P_4}\right)^{k-1/k} = \frac{T_3}{T_4}$$

Substituting these equations into the thermal efficiency relation and simplifying:

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

Where,

$$r_p = \frac{P_2}{P_1} \text{ is the pressure ratio}$$

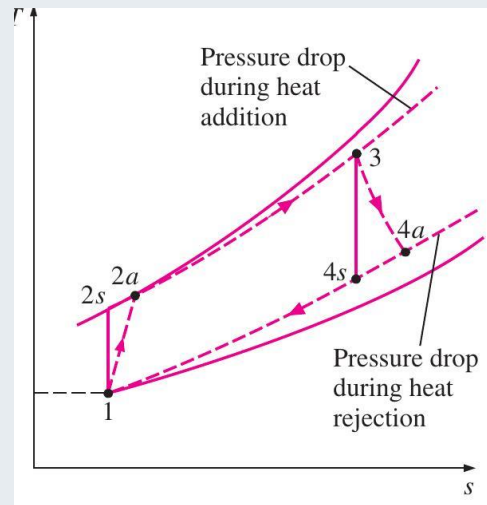
# 6. Brayton Cycle

Cont...

- Deviation of Actual Gas-Turbine Cycles from Idealized Ones is due to:
  - Pressure drop
  - Irreversibilities
- The deviation of actual compressor and turbine behavior from the idealized isentropic behavior can be accurately accounted for by utilizing the **adiabatic efficiencies** of the turbine and compressor, defined as:

$$\eta_C = \frac{w_s}{w_a} \cong \frac{h_1 - h_{2s}}{h_1 - h_{2a}}$$

$$\eta_T = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

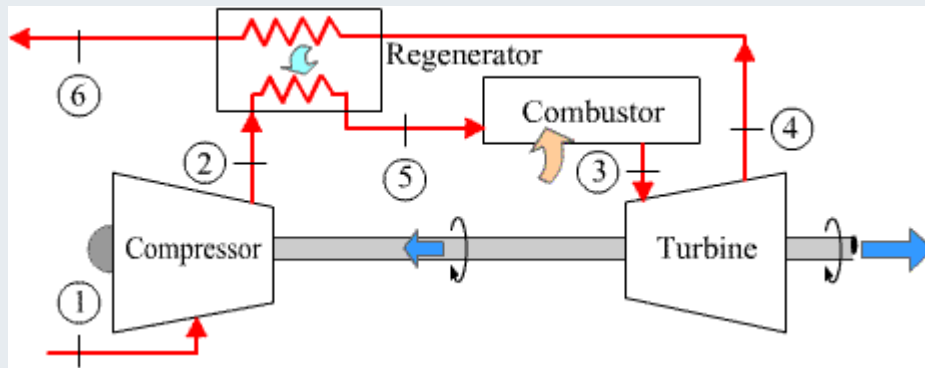


**Figure 13:** Deviation of Actual Gas Turbine with the Idealized ones

[url: https://figures.academia-assets.com/51221247/figure\\_001.jpg](https://figures.academia-assets.com/51221247/figure_001.jpg)

# 7. Gas-Turbine Cycle with Regenerator

- In **gas-turbine engines**, the temperature of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the compressor [5].
- The high-pressure air leaving the compressor can be heated by transferring heat to it from the hot exhaust gases in a counter-flow heat exchanger, which is also known as a **regenerator**.



**Figure 14:** Gas Turbine Cycle with Regenerator

[url: https://energy.sdsu.edu/testhome/introModule/introimages/TESTcalcrias/gasturbine4.gif](https://energy.sdsu.edu/testhome/introModule/introimages/TESTcalcrias/gasturbine4.gif)

# 7. Gas-Turbine Cycle with Regenerator

Cont...

- Assuming the regenerator to be **well insulated** and any changes in kinetic and potential energies to be negligible,

- the actual and maximum heat transfers from the exhaust gases to the air can be expressed as:

$$q_{regen,act} = h_5 - h_2$$

$$q_{regen,max} = h_{5'} - h_2 = h_4 - h_2$$

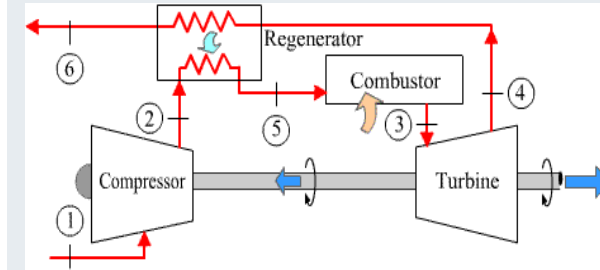
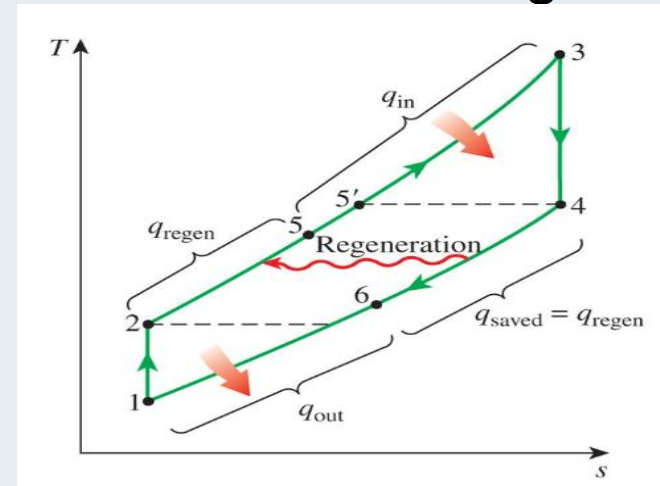
- For ideal regeneration,

$$T_5 = T_4 \text{ and } T_2 = T_6$$

$$W_t = h_3 - h_4 \text{ and } W_c = h_2 - h_1$$

$$Q_{in} = h_3 - h_5 = h_3 - h_4 = W_t$$

$$\eta_{th} = 1 - \frac{W_c}{W_t}$$



**Figure 15: T-s diagram of Gas Turbine Cycle with Regenerator**

url: <https://media.cheggcdn.com/media/04f/04fdf153-51c2-4070-a2e3-e571da50da45/phpC5REzG>

# Summary

- Power cycles convert heat energy into mechanical work, forming the basis of engines and turbines.
- The Carnot cycle represents the idealized thermodynamic cycle with maximum efficiency, serving as a benchmark for real-world power systems.
- Air Standard Assumptions simplify thermodynamic analysis by treating the working fluid as air with ideal gas properties, neglecting combustion and heat losses.
- Air-Standard Otto Cycle models gasoline engines, consisting of two isentropic and two constant-volume processes.
- Air-Standard Diesel Cycle is used for diesel engines, this cycle differs from the Otto cycle by having constant-pressure heat addition, improving efficiency at higher compression ratios.
- The Brayton cycle describes gas-turbine engines, vital in aviation and power generation. Regenerators enhance thermal efficiency by recycling exhaust heat.

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- [5]. Gas Turbine Combustion: Alternative Fuels and Emissions, A. H. Lefebvre and D. R. Ballal, 3rd ed. Boca Raton, FL, USA: CRC Press, 2010.

**Thank you !**