

Lecture 9 Gas Cycle Analysis: Otto, Diesel, and Brayton Applied to Heat Engines

Goal of the lecture: To study the thermodynamic principles, processes, and efficiency characteristics of the Otto, Diesel, and Brayton gas cycles as models for internal combustion and gas turbine engines.

Brief lecture notes: This lecture introduces the main thermodynamic gas cycles used to model the operation of real heat engines: the Otto, Diesel, and Brayton cycles. We will analyze the processes that constitute each cycle, derive their efficiency expressions, and compare their performance under varying compression ratios and temperature limits. The discussion will focus on energy transformation, heat addition and rejection modes, and how these cycles are applied in internal combustion engines and gas turbines. Special attention will be given to the assumptions of air-standard analysis, the influence of compression ratio on efficiency, and practical considerations in modern energy systems.

Main part

Gas power cycles describe idealized processes that convert heat energy into mechanical work through the cyclic operation of a working fluid, typically modeled as air. They provide a theoretical basis for understanding real engines such as automobile internal combustion engines and gas turbines.

The Otto Cycle

The Otto cycle represents the idealized model of a spark-ignition internal combustion engine. It consists of four processes:

1. Isentropic compression (1–2)
2. Constant-volume heat addition (2–3)
3. Isentropic expansion (3–4)
4. Constant-volume heat rejection (4–1)

The efficiency of the Otto cycle depends solely on the compression ratio (r) and the specific heat ratio γ of the working fluid:

$$\eta_{Otto} = 1 - \frac{1}{r^{(\gamma-1)}}$$

$$\text{where } r = \frac{V_1}{V_2}.$$

An increase in compression ratio leads to higher efficiency, but practical limits arise due to engine knocking and material strength. The Otto cycle is widely used in gasoline engines for automobiles and small generators.

The Diesel Cycle

The Diesel cycle models a compression-ignition engine where fuel is injected at high temperature and pressure near the end of the compression stroke. The four main processes are:

1. Isentropic compression (1–2)
2. Constant-pressure heat addition (2–3)
3. Isentropic expansion (3–4)
4. Constant-volume heat rejection (4–1)

The efficiency of the Diesel cycle is given by:

$$\eta_{Diesel} = 1 - \frac{1}{r^{(\gamma-1)}} \cdot \frac{(\rho^\gamma - 1)}{\gamma(\rho - 1)}$$

where ρ is the cutoff ratio, representing the ratio of volumes at the end and beginning of heat addition. Diesel engines operate at higher compression ratios (14–22) than Otto engines (8–12), giving them higher efficiency and better fuel economy, but they are heavier and more expensive. Diesel cycles are widely used in trucks, ships, and power plants.

The Brayton Cycle

The Brayton cycle (also called the gas turbine cycle) is used in jet engines and power generation turbines. The cycle involves:

1. Isentropic compression (1–2) in a compressor,
2. Constant-pressure heat addition (2–3) in a combustion chamber,
3. Isentropic expansion (3–4) in a turbine,
4. Constant-pressure heat rejection (4–1).

The thermal efficiency for an ideal Brayton cycle is:

$$\eta_{Brayton} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

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

Higher pressure ratios improve efficiency, but materials must withstand extreme turbine temperatures. Modern gas turbines often include intercooling, reheating, and regeneration to improve performance.

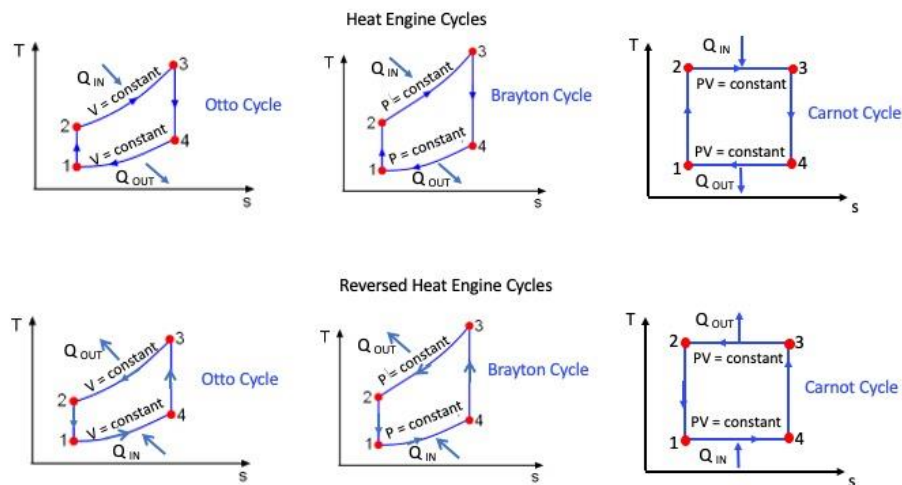


Figure 1 illustrates the P–V and T–s diagrams of the three cycles, showing distinct heat addition and rejection paths.

Comparative Analysis of Gas Cycles

Each of these cycles converts heat into work but differs in practical application and efficiency characteristics.

- The Otto cycle provides high power density and quick response, suitable for cars and motorcycles.
- The Diesel cycle achieves higher efficiency and torque, ideal for heavy vehicles and industrial engines.

- The Brayton cycle delivers continuous power and high efficiency at large scales, used in aircraft propulsion and power generation.

In terms of efficiency trends, at equal compression ratios, the Otto cycle is more efficient than Diesel because it adds heat at constant volume, while the Diesel adds it at constant pressure. However, Diesel cycles can achieve higher compression ratios in practice, partially compensating for this difference. The Brayton cycle operates with gases instead of reciprocating pistons, enabling continuous flow and higher speed operation.

Cycle Type	Heat Addition Mode	Typical Compression Ratio	Efficiency Trend	Common Applications
Otto	Constant volume	8–12	Moderate to high	Gasoline engines
Diesel	Constant pressure	14–22	Higher than Otto	Diesel engines
Brayton	Constant pressure	10–30 (pressure ratio)	High (turbine-based)	Jet engines, power plants

Questions for Self-Control

1. What are the four main processes of the Otto, Diesel, and Brayton cycles?
2. How does the compression ratio affect the efficiency of the Otto cycle?
3. What is the significance of the cutoff ratio in the Diesel cycle?
4. Why does the Brayton cycle use a pressure ratio instead of a compression ratio?
5. How are these theoretical cycles applied in real heat engines?

Literature

1. Çengel, Y. A., & Boles, M. A. Thermodynamics: An Engineering Approach. McGraw-Hill Education, 2020.
2. Moran, M. J., & Shapiro, H. N. Fundamentals of Engineering Thermodynamics. Wiley, 2018.
3. Eastop, T. D., & McConkey, A. Applied Thermodynamics for Engineering Technologists. Longman, 1993.
4. Nag, P. K. Engineering Thermodynamics. Tata McGraw-Hill, 2013.
5. Sonntag, R. E., & Borgnakke, C. Introduction to Thermodynamics: Classical and Statistical. Wiley, 2019.