Gas Power Cycles

Thermodynamic cycles:

- Power cycles
- Refrigeration cycles

- The devices or systems used to produce a net power output are often called **engines**, and the thermodynamic cycles they operate on are called **power cycles**
- The devices or systems used to produce a refrigeration effect are called **refrigerators, air conditioners, or heat pumps,** and the cycles they operate on are called **refrigeration cycles**.

Thermodynamic cycles (phase of the working fluid)

- **Gas cycles**, the working fluid remains in the gaseous phase throughout the entire cycle
- **Vapor cycles** the working fluid exists in the vapor phase during one part of the cycle and in the liquid phase during another part

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. In automobile engines, the combustion gases are exhausted and replaced by fresh air–fuel mixture at the end of each cycle. The engine operates on a mechanical cycle, but the working fluid does not go through a complete thermodynamic cycle.

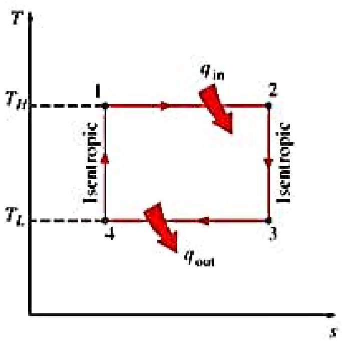
Heat engines:

- **External combustion engines** (such as steam power plants), heat is supplied to the working fluid from an external source such as a furnace, a geothermal well, a nuclear reactor, or even the sun.
- **Internal combustion engines** (such as automobile engines), this is done by burning the fuel within the system boundaries.

Gas Power Cycles

Idealizations and simplifications for power cycles:

1. The cycle does not involve any friction. Therefore, the working fluid does not experience any pressure drop as it flows in pipes or devices such as heat exchangers.
2. All expansion and compression processes take place in a quasi-equilibrium manner.
3. The pipes connecting the various components of a system are well insulated, and heat transfer through them is negligible.



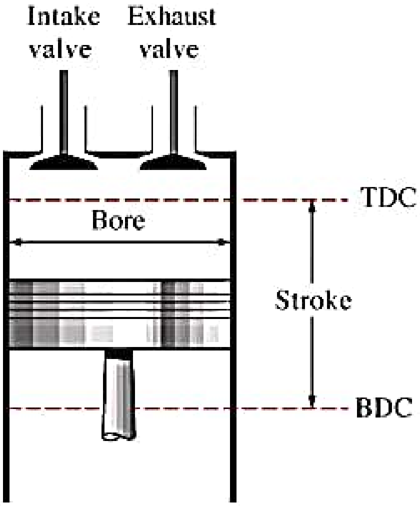
Air-standard Assumptions

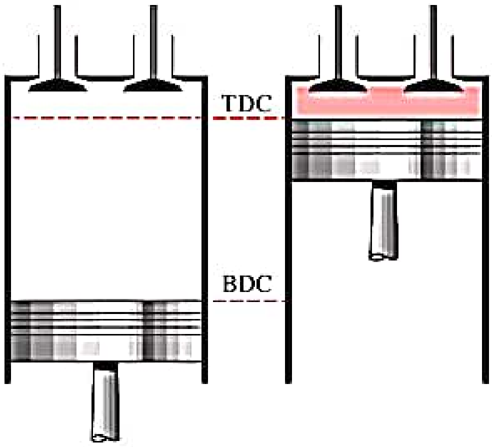
1. The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
2. All the processes that make up the cycle are internally reversible.
3. The combustion process is replaced by a heat-addition process from an external source.
4. The exhaust process is replaced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

Reciprocating Engines





(*a*) Displacement volume

(*b*) Clearance volume

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

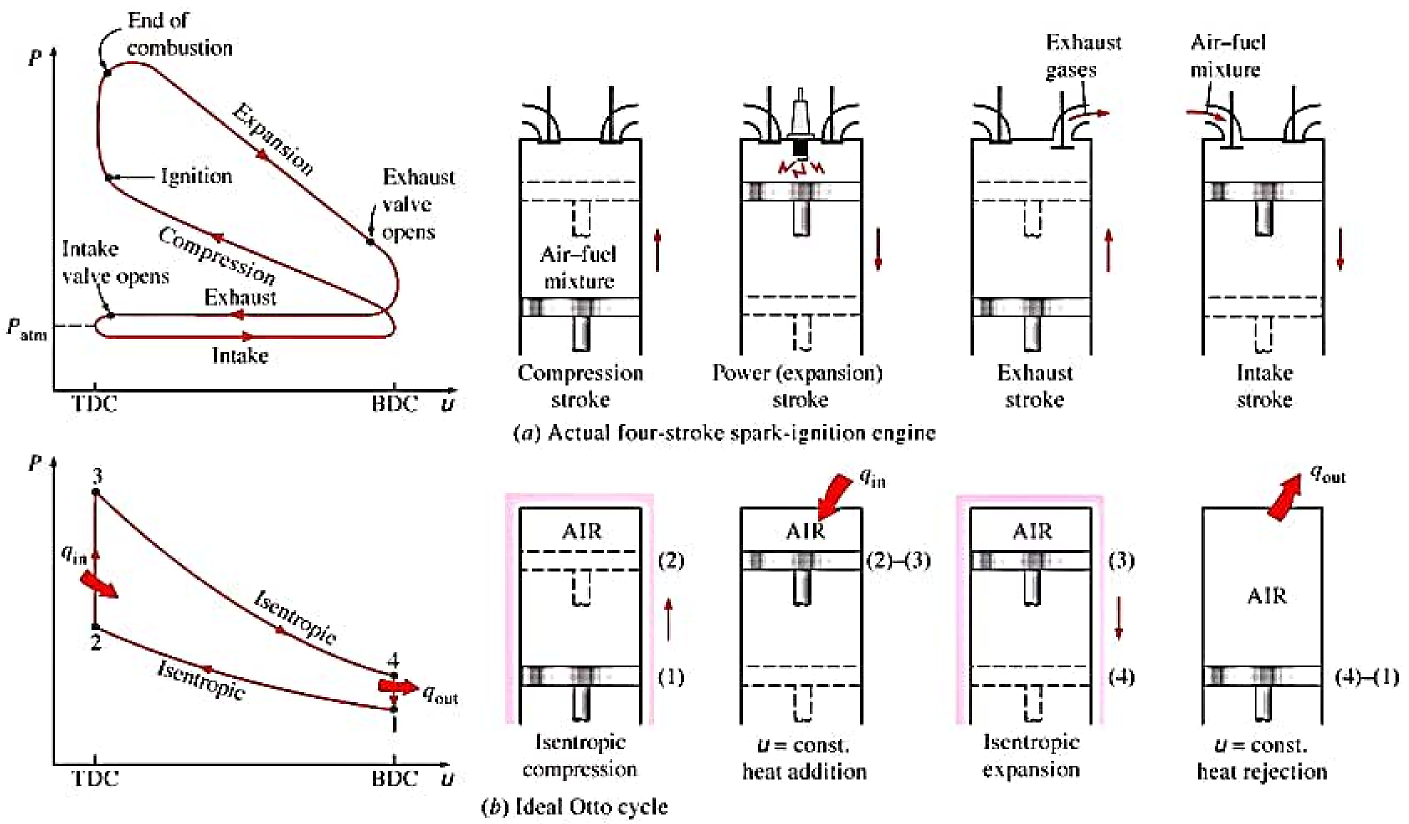
Mean effective pressure (MEP): It is a fictitious pressure that, if it acted on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle

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

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

Otto Cycle: Ideal Cycles in Spark-Ignition 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. These engines are called **four-stroke internal combustion engines.**



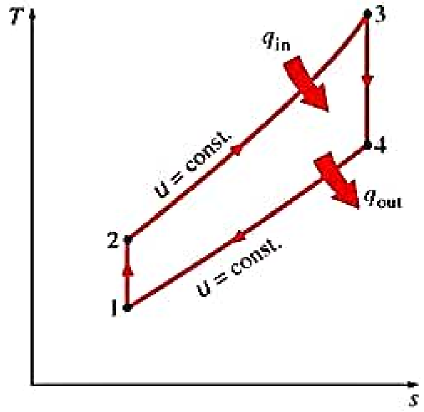
(a) Actual four-stroke spark-ignition engine

(b) Ideal Otto cycle

Otto Cycle: Ideal Cycles in Spark-Ignition Engines

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



Energy balance on a unit-mass basis

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta u \qquad (\text{kJ/kg})$$

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

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

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

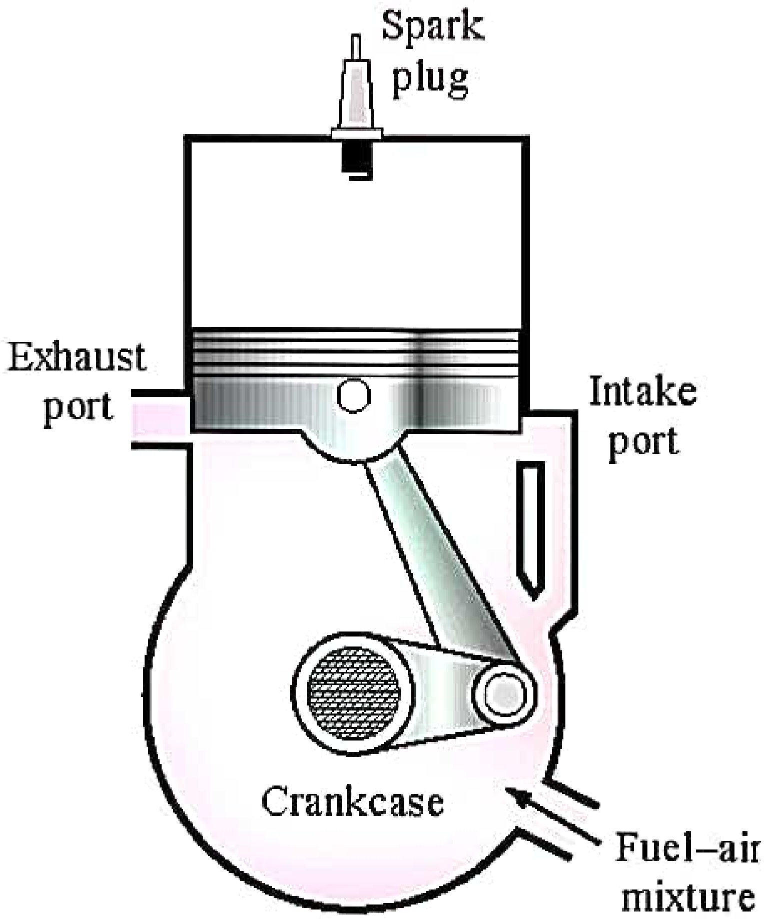
Processes 1-2 and 3-4 are isentropic, and $v_2 = v_3$ and $v_4 = v_1$. Thus,

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

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

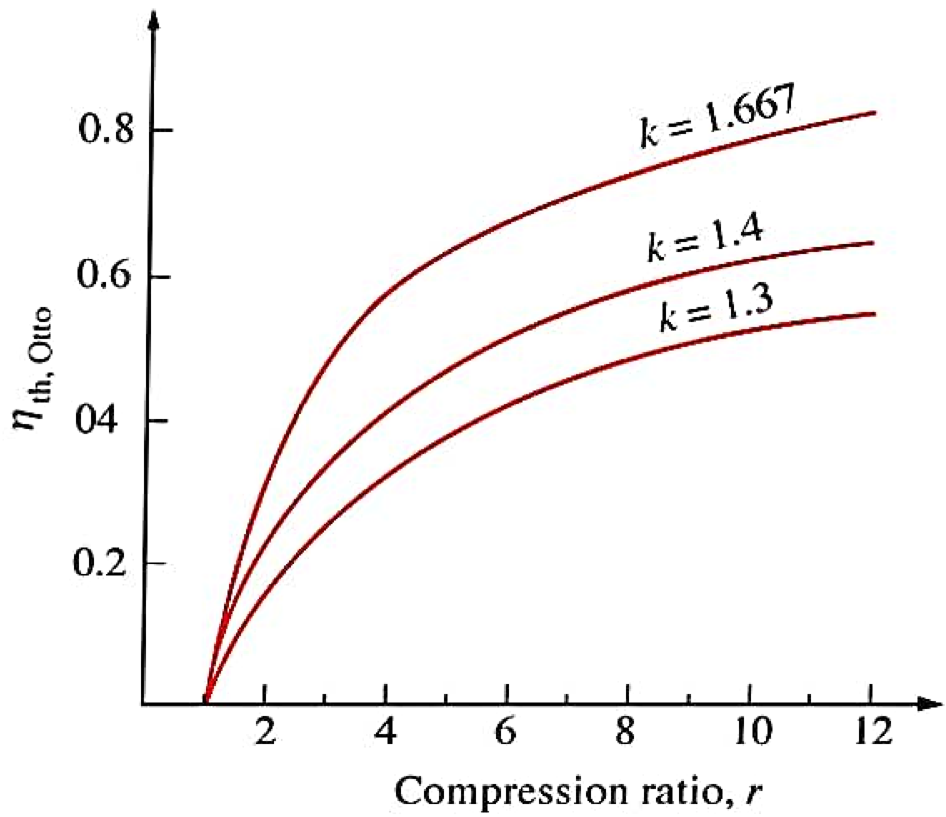
$$r = \frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2}$$

Schematic of a Two-Stroke Reciprocating Engine



The Thermal Efficiency of the Otto Cycle

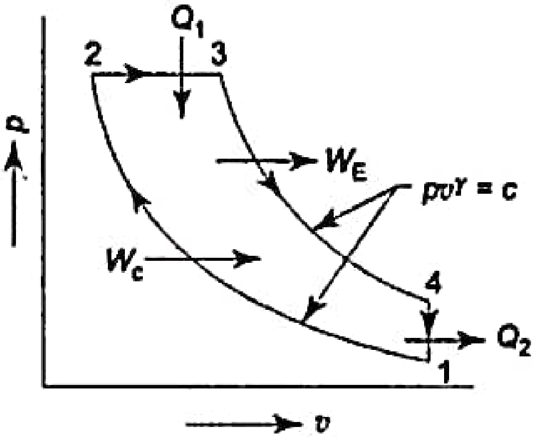
The thermal efficiency of the Otto Cycle increases with the specific heat ratio *k* of the working fluid



Ideal Diesel Cycle

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_4 - T_1)}{mc_p(T_3 - T_2)}$$

$$\eta = 1 - \frac{T_4 - T_1}{\gamma(T_3 - T_2)}$$



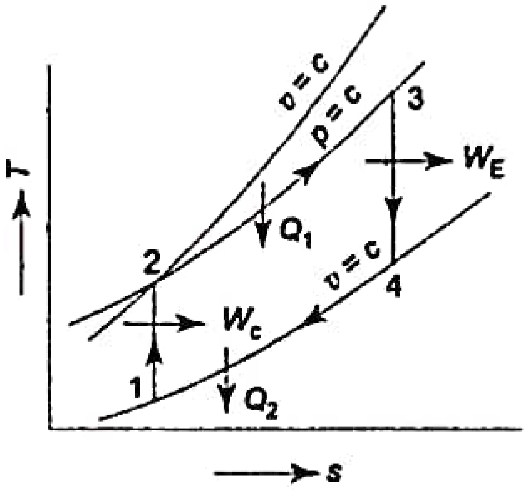
Compression ratio, $r_k = \frac{V_1}{V_2} = \frac{v_1}{v_2}$

Expansion ratio, $r_e = \frac{V_4}{V_3} = \frac{v_4}{v_3}$

Cut-off ratio, $r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2}$

It is seen that

$$r_k = r_e \cdot r_c$$



Process 3–4

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \frac{1}{r_e^{\gamma-1}}$$

$$T_4 = T_3 \frac{r_c^{\gamma-1}}{r_k^{\gamma-1}}$$

Ideal Diesel Cycle

Process 2–3

$$\frac{T_2}{T_3} = \frac{p_2 v_2}{p_3 v_3} = \frac{v_2}{v_3} = \frac{1}{r_c}$$

$$\therefore \quad T_2 = T_3 \cdot \frac{1}{r_c}$$

Process 1–2

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \frac{1}{r_k^{\gamma-1}}$$

$$\therefore \quad T_1 = T_2 \cdot \frac{1}{r_k^{\gamma-1}} = \frac{T_3}{r_c} \cdot \frac{1}{r_k^{\gamma-1}}$$

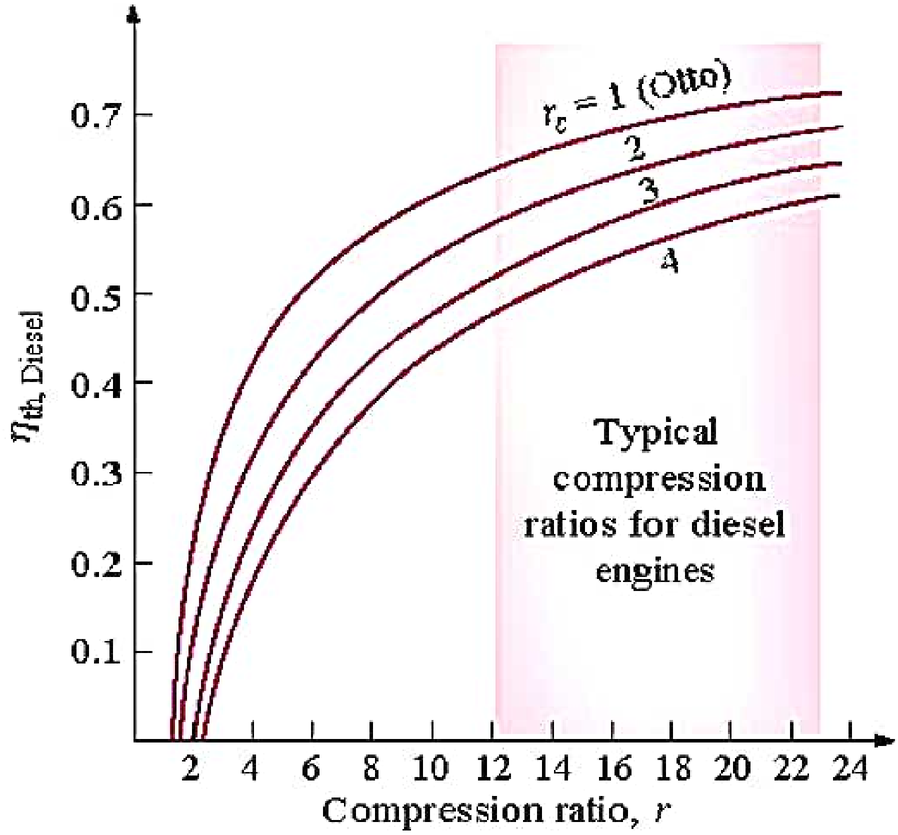
$$\eta = 1 - \frac{T_3 \cdot \frac{r_c^{\gamma-1}}{r_k^{\gamma-1}} - \frac{T_3}{r_c} \frac{1}{r_k^{\gamma-1}}}{\gamma\left(T_3 - T_3 \cdot \frac{1}{r_c}\right)}$$

$$\eta_{\text{Diesel}} = 1 - \frac{1}{\gamma} \cdot \frac{1}{r_k^{\gamma-1}} \cdot \frac{r_c^{\gamma} - 1}{r_c - 1}$$

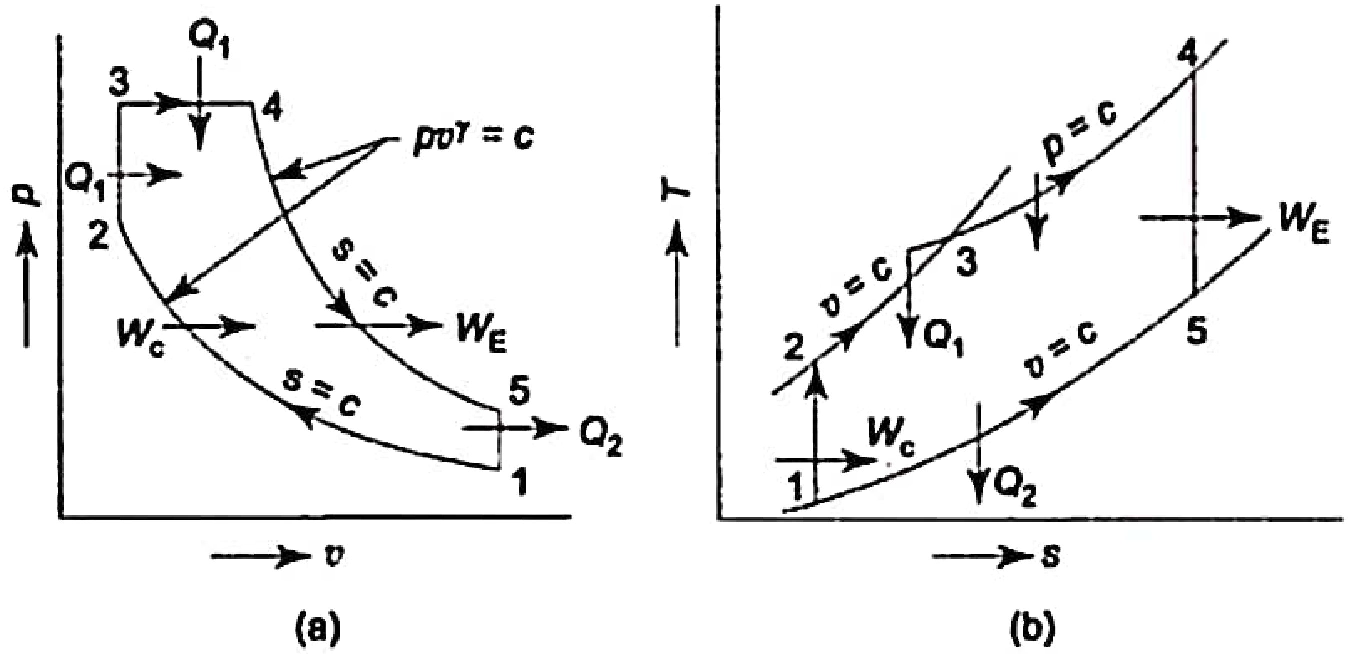
As $r_c > 1$, $\frac{1}{\gamma}\left(\frac{r_c^{\gamma} - 1}{r_c - 1}\right)$ is also greater than unity. Therefore, the efficiency of the Diesel cycle is less than that of the Otto cycle for the same compression ratio.

Thermal Efficiency of the Ideal Diesel Cycle

The thermal efficiency of the ideal Diesel cycle as a function of compression and cutoff rates (k=1.4)



Ideal Dual Cycle



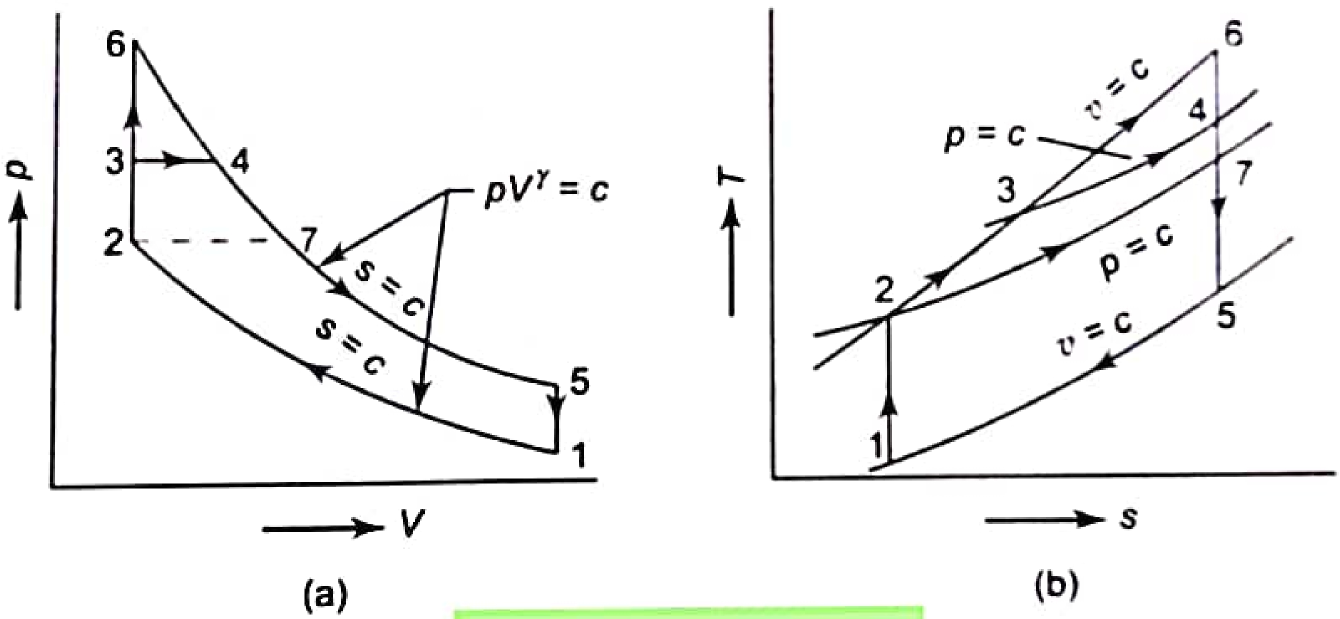
Comparison of Otto, Diesel & Dual Cycles

For same compression ratio and heat rejection

1–2–6–5 —Otto cycle

1–2–7–5 —Diesel cycle

1–2–3–4–5 —Dual cycle

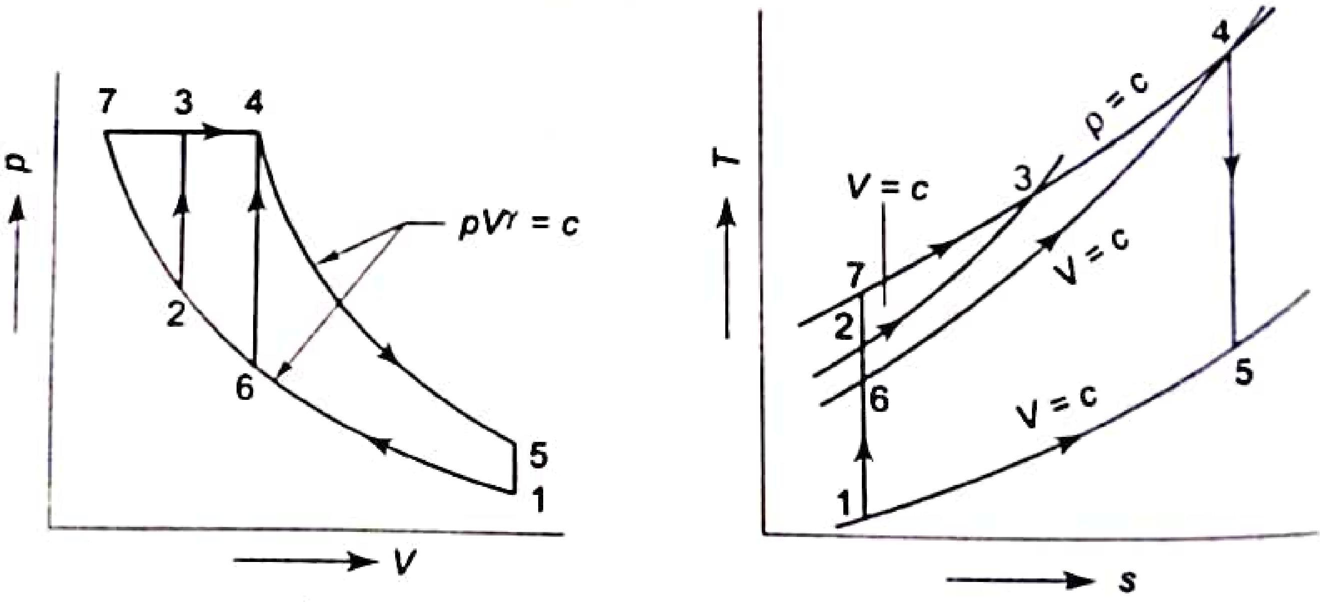


$$\eta_{\text{otto}} > \eta_{\text{Dual}} > \eta_{\text{Diesel}}$$

Comparison of Otto, Diesel & Dual Cycles

For same maximum pressure & temperature and heat rejection

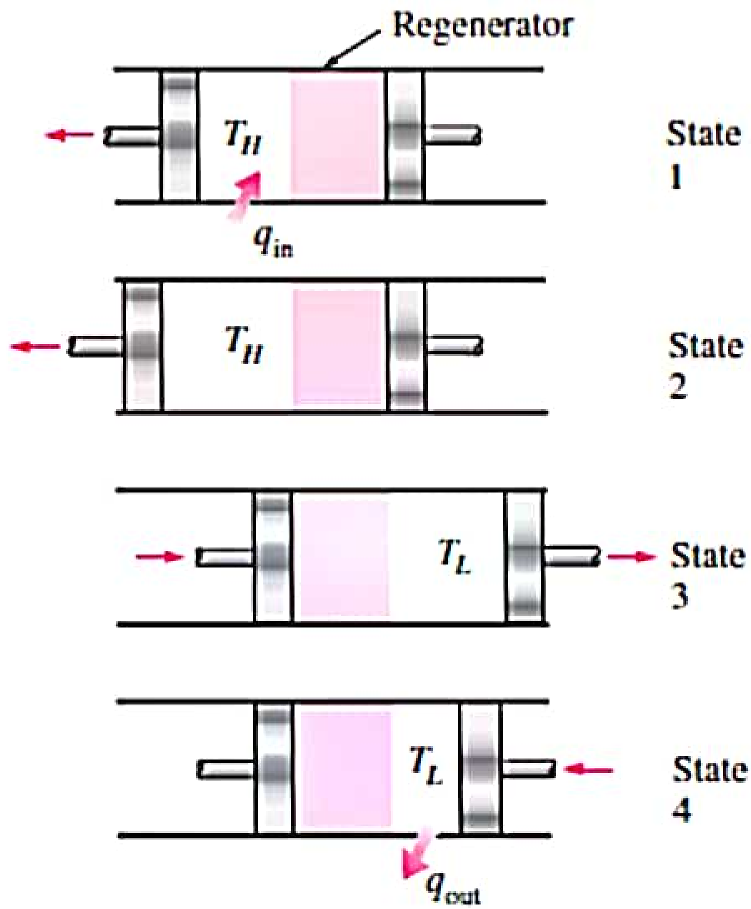
1–6–4–5 —Otto cycle
1–7–4–5 —Diesel cycle
1–2–3–4–5 —Dual cycle



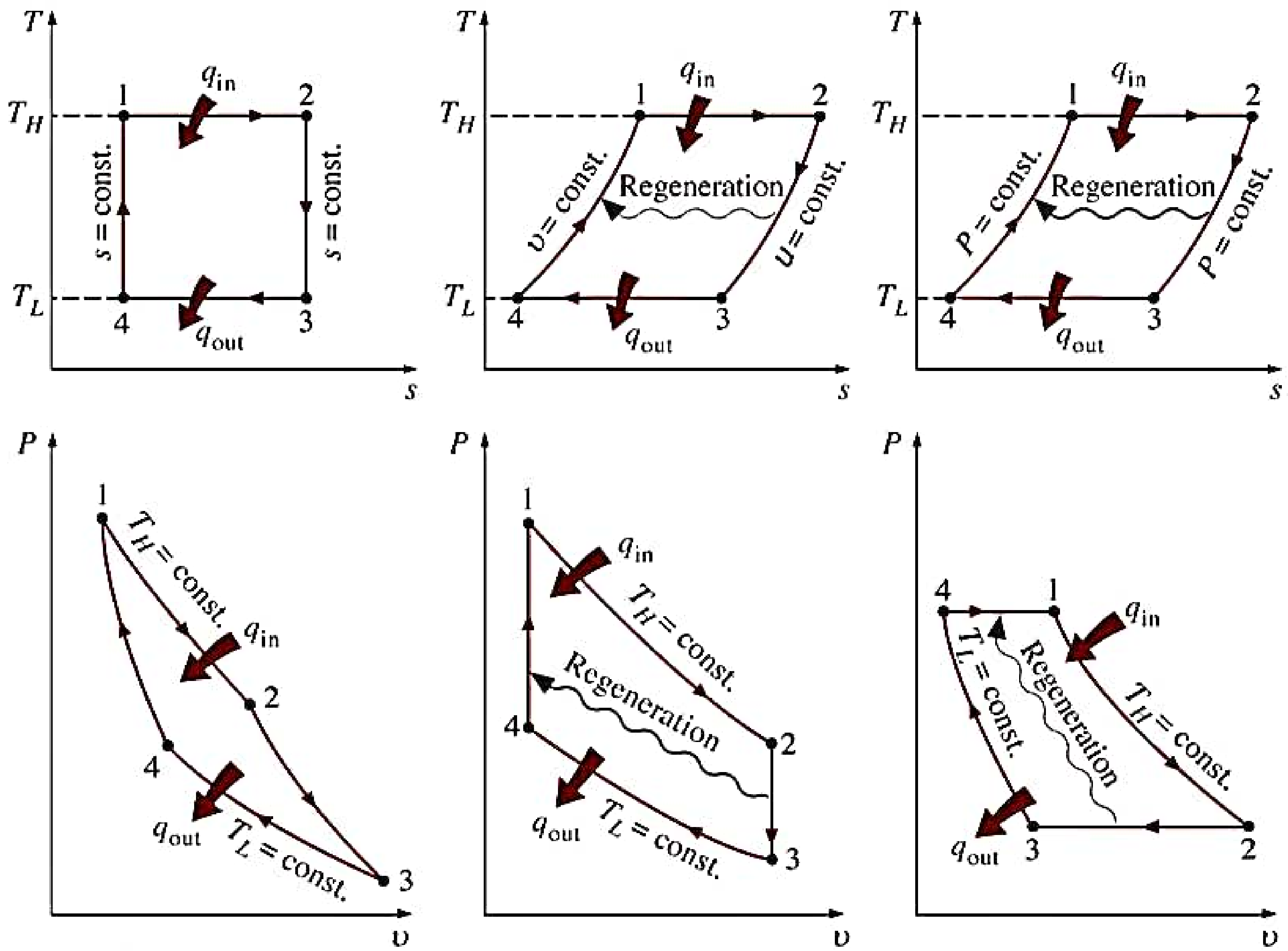
(a) (b)

$$\eta_{Diesel} > \eta_{dual} > \eta_{otto}$$

Carnot, Stirling, and Ericsson Cycles

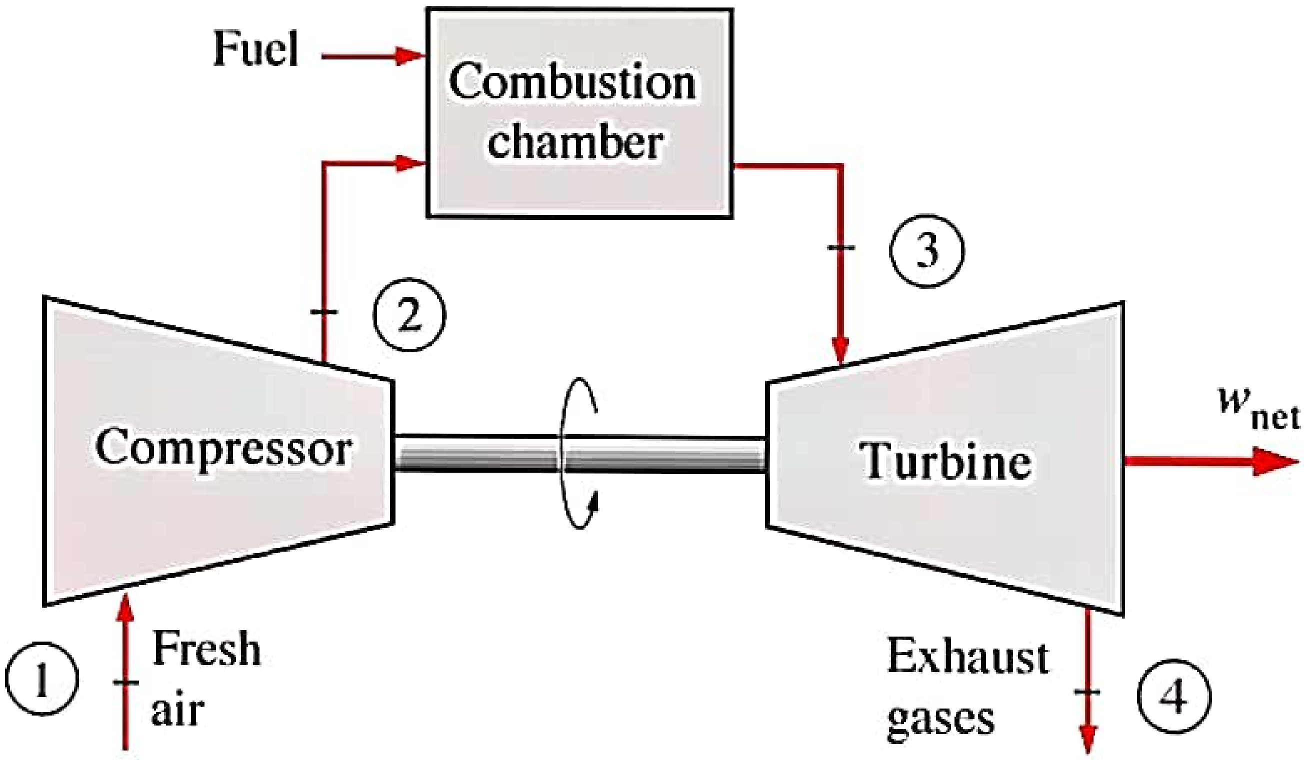


Carnot, Stirling, and Ericsson Cycles

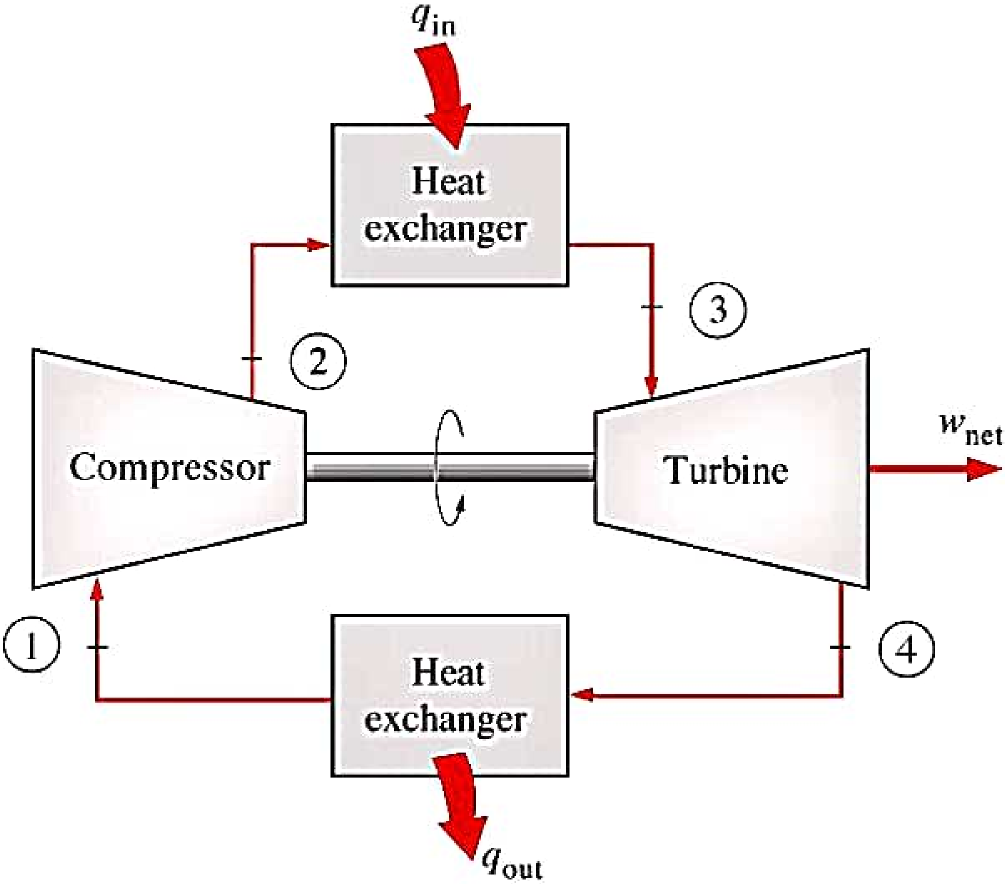


(*a*) Carnot cycle (*b*) Stirling cycle (*c*) Ericsson cycle

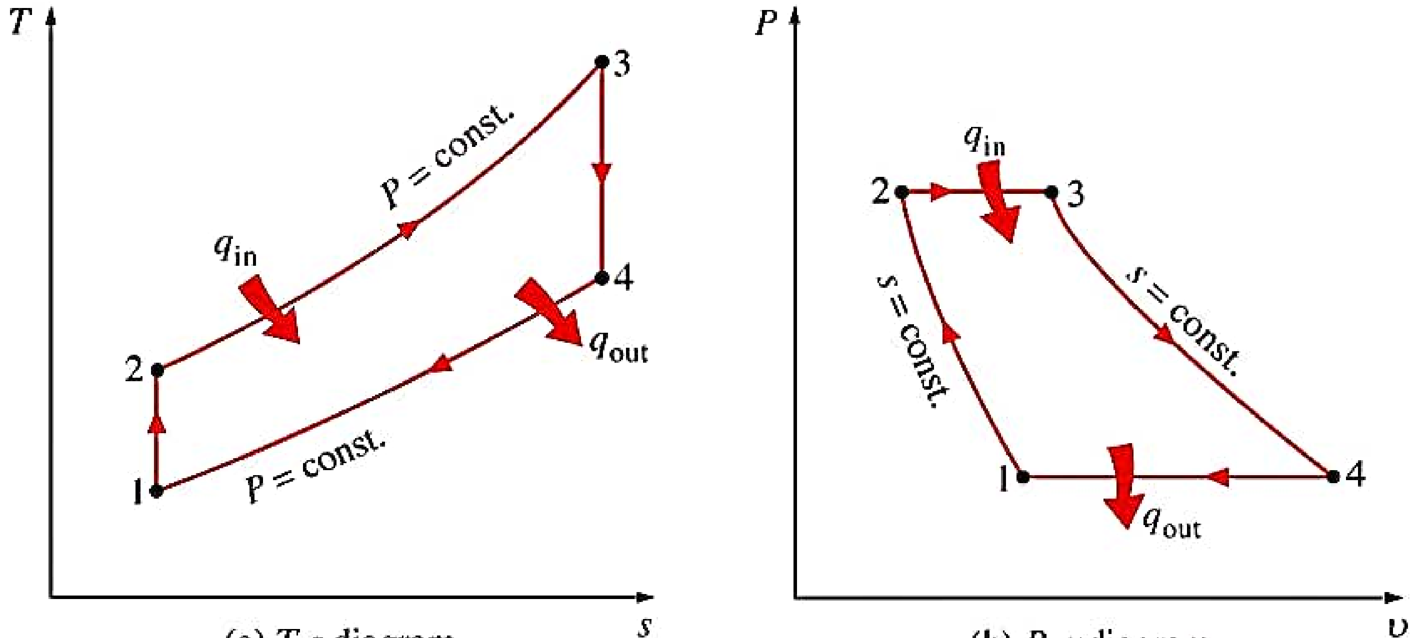
An Open-Cycle Gas-Turbine Engine



A Closed-Cycle Gas-Turbine Engine



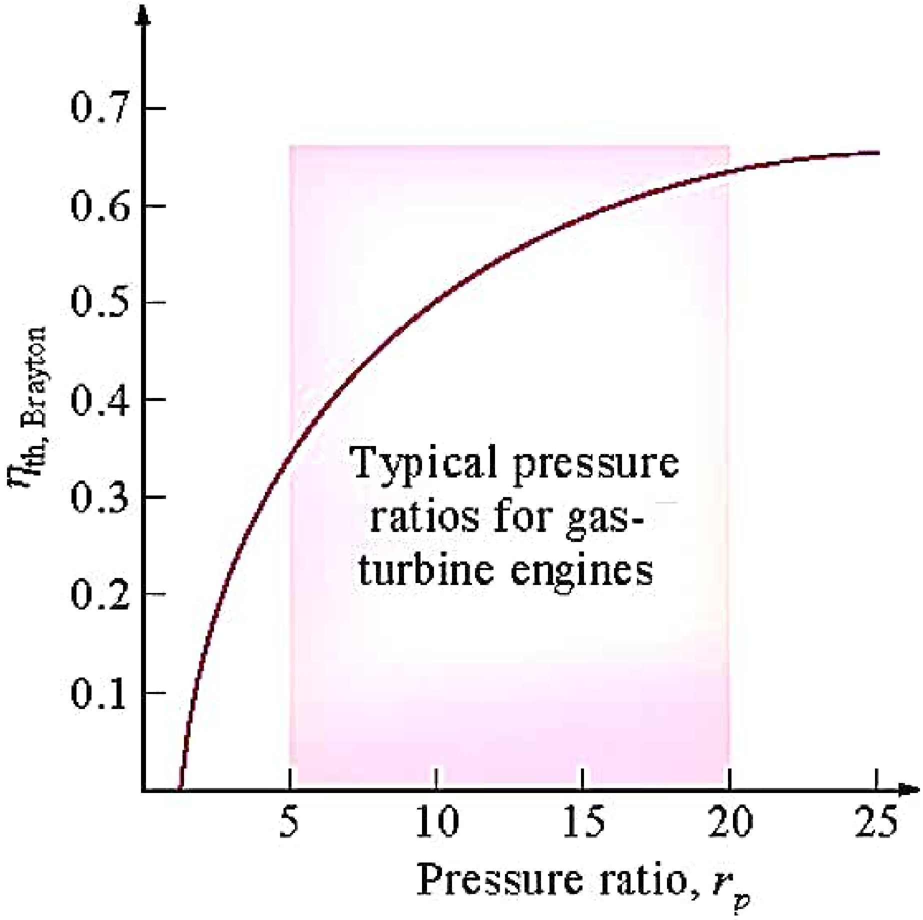
T-s and P-v Diagrams for the Ideal Brayton Cycle



(a) T-s diagram (b) P- υdiagram

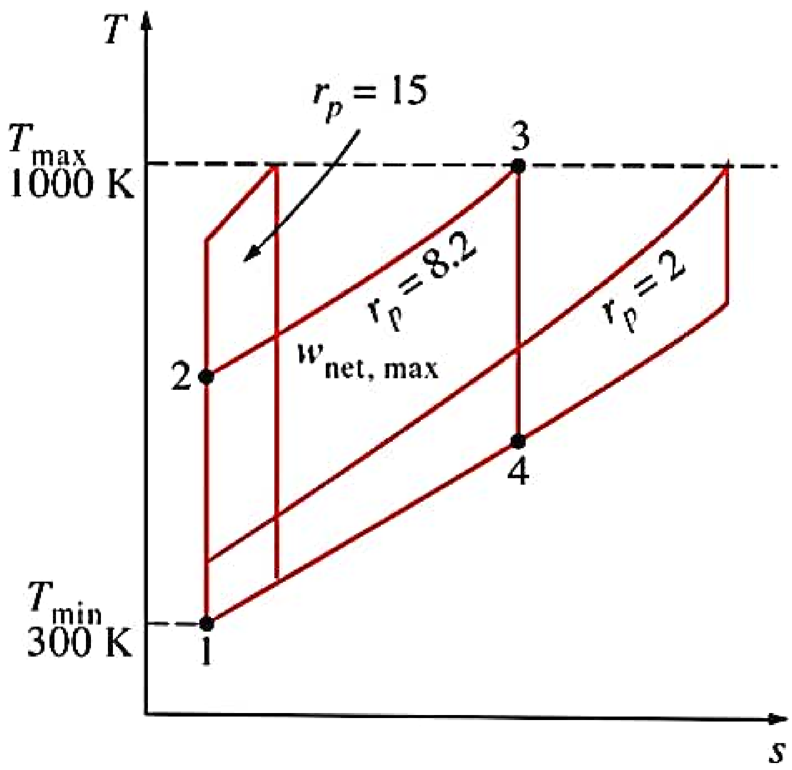
$$\eta_{th,\,Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

Thermal Efficiency of the Ideal Brayton Cycle as a Function of the Pressure Ratio

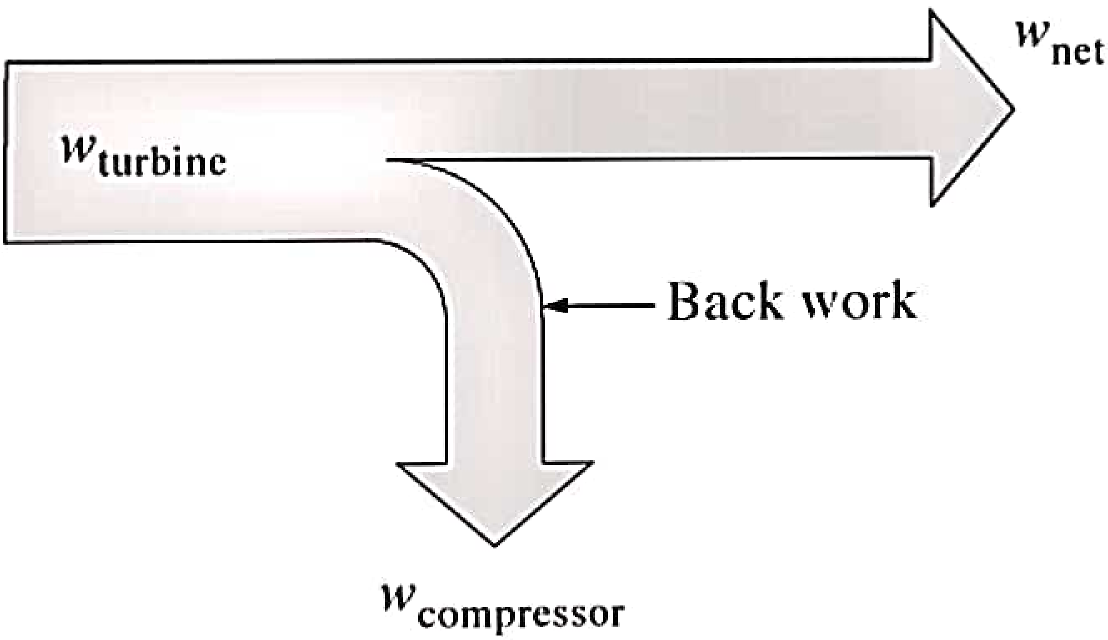


The Net Work of the Brayton Cycle

For fixed values of T_{min} and T_{max}, the net work of the Brayton cycle first increases with the pressure ratio, then reaches a maximum at $r_p=(T_{max}/T_{min})^{k/[2(k-1)]}$, and finally decreases



The Back-Work Ratio is the Fraction of Turbine Work Used to Drive the Compressor



Development of Gas Turbines

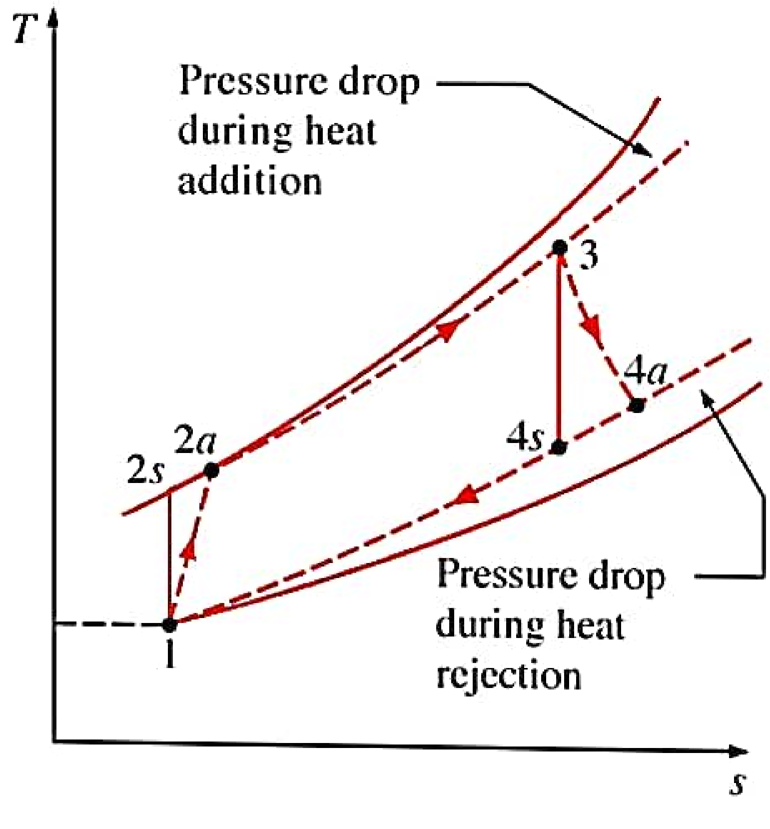
1. Increasing the turbine inlet (or firing) temperatures

2. Increasing the efficiencies of turbomachinery components

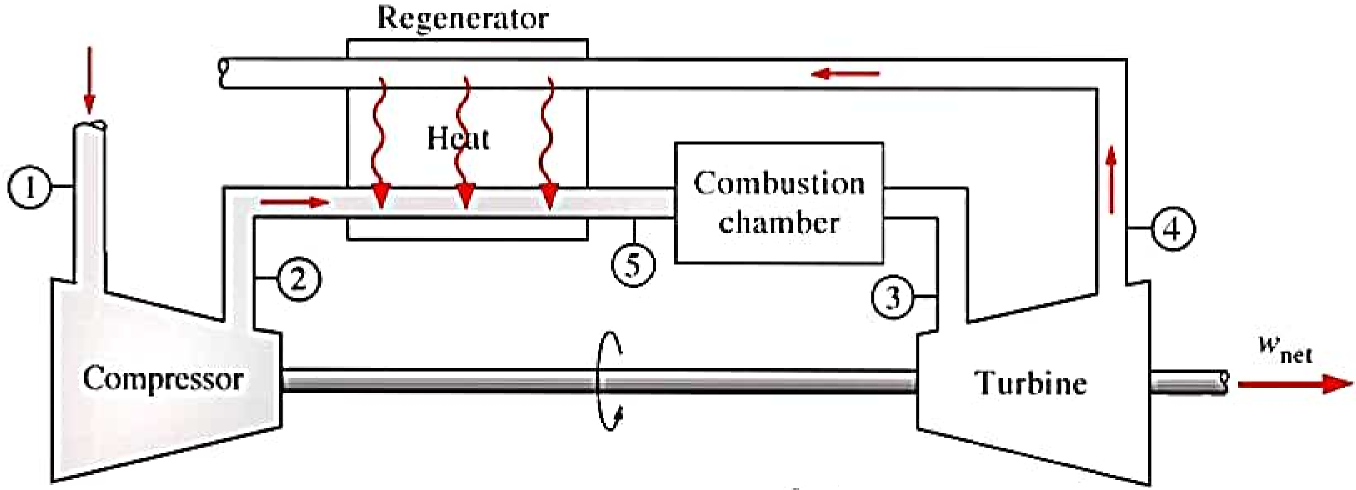
3. Adding modifications to the basic cycle

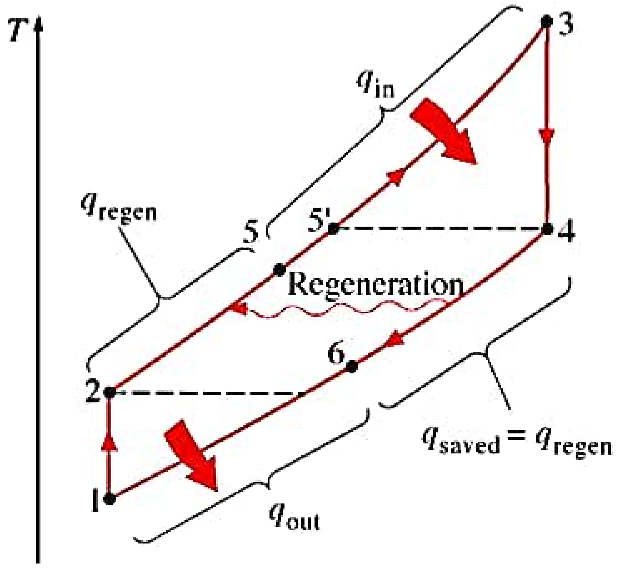
Deviation of Actual Gas-Turbine Cycle From Brayton cycle

The deviation of an actual gas-turbine cycle from the ideal Brayton cycle as a result of irreversibilities

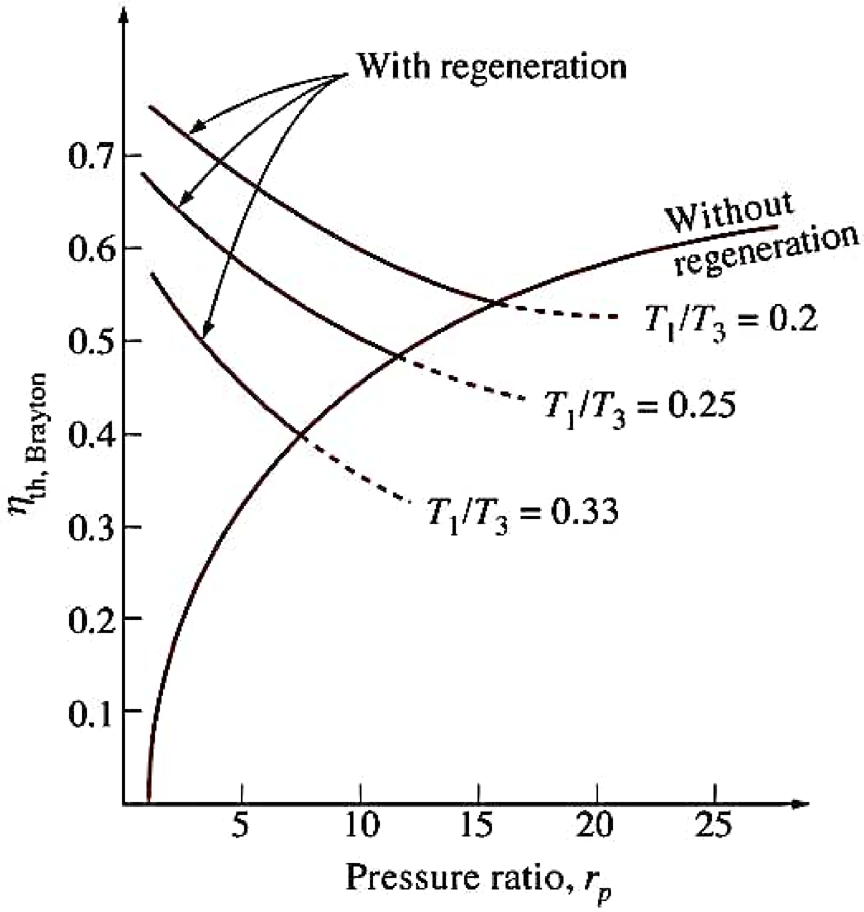


A Gas-Turbine Engine With Regenerator



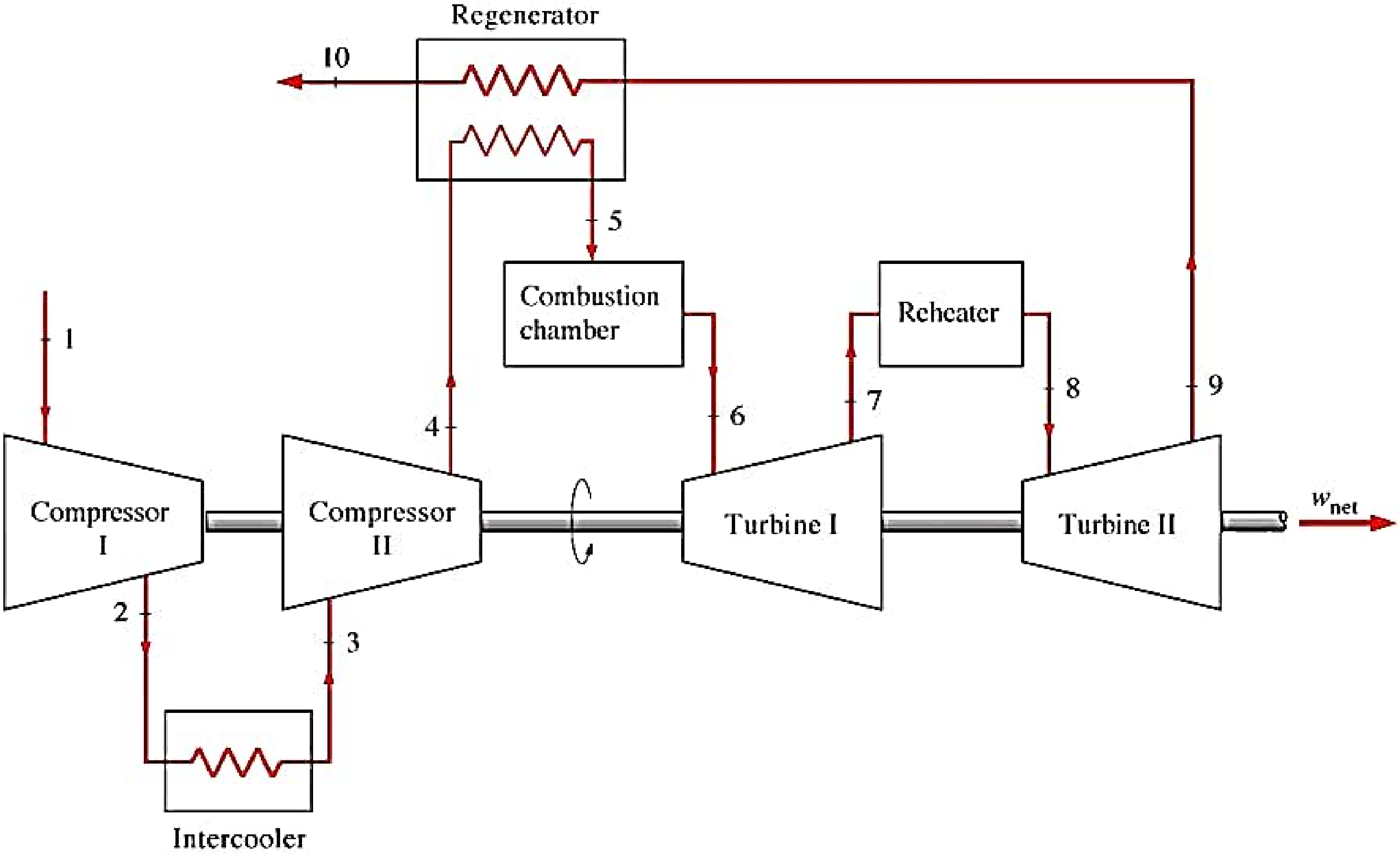


Thermal Efficiency of the ideal Brayton cycle with and without regeneration

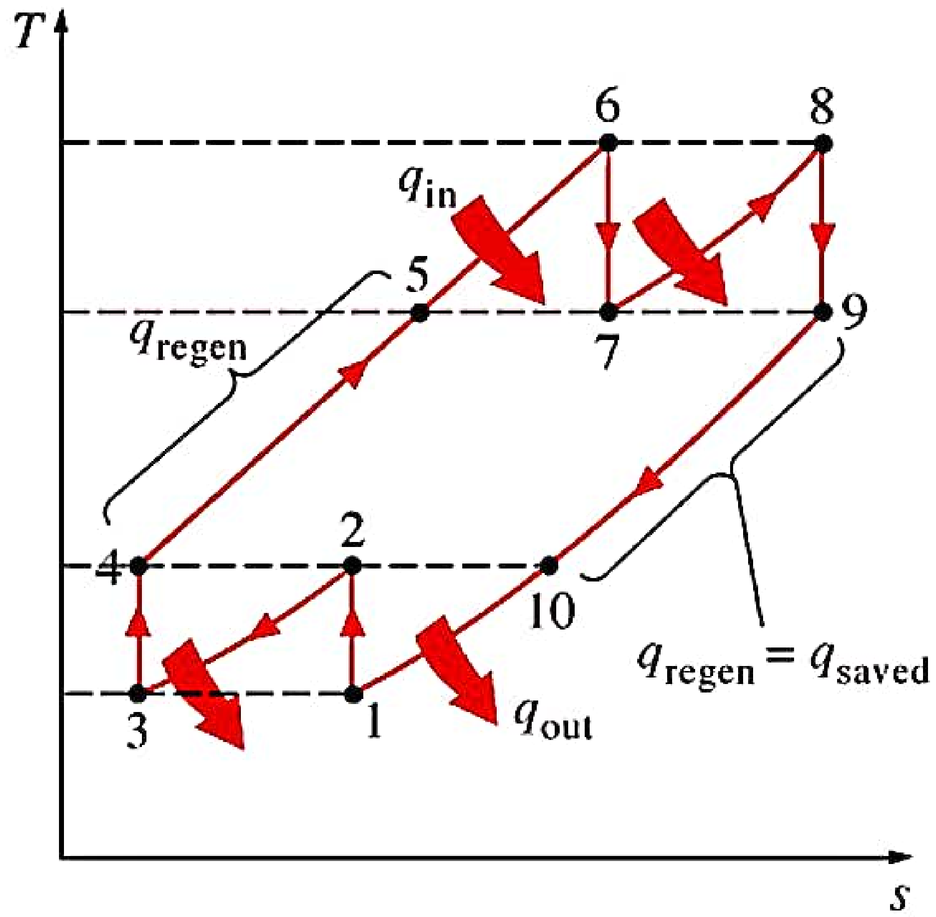


A Gas-Turbine Engine

A gas-turbine engine with two-stage compression with intercooling, two-stage expansion with reheating, and regeneration



T-s Diagram of Ideal Gas-Turbine Cycle with Intercooling, Reheating, and Regeneration



H/W: Example 9.1 – 9.8