Thermodynamics: An Engineering Approach, 6th Edition
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Chapter 9
GAS POWER CYCLES

Objectives

- Evaluate the performance of gas power cycles for which the working fluid remains a gas throughout the entire cycle.

- Develop simplifying assumptions applicable to gas power cycles.

- Review the operation of reciprocating engines.

- Analyze both closed and open gas power cycles.

- Solve problems based on the Otto, Diesel, Stirling, and Ericsson cycles.

- Solve problems based on the Brayton cycle; the Brayton cycle with regeneration; and the Brayton cycle with intercooling, reheating, and regeneration.

- Analyze jet-propulsion cycles.

- Identify simplifying assumptions for second-law analysis of gas power cycles.

- Perform second-law analysis of gas power cycles.

BASIC CONSIDERATIONS IN THE ANALYSIS OF POWER CYCLES

Thermal efficiency of heat engines

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

Most power-producing devices operate on cycles.

Ideal cycle: A cycle that resembles the actual cycle closely but is made up totally of internally reversible processes is called an ideal cycle.

Reversible cycles such as **Carnot cycle** have the highest thermal efficiency of all heat engines operating between the same temperature levels. Unlike ideal cycles, they are totally reversible, and unsuitable as a realistic model.

OVEN
Potato ← ACTUAL
175°C
WATER ← IDEAL
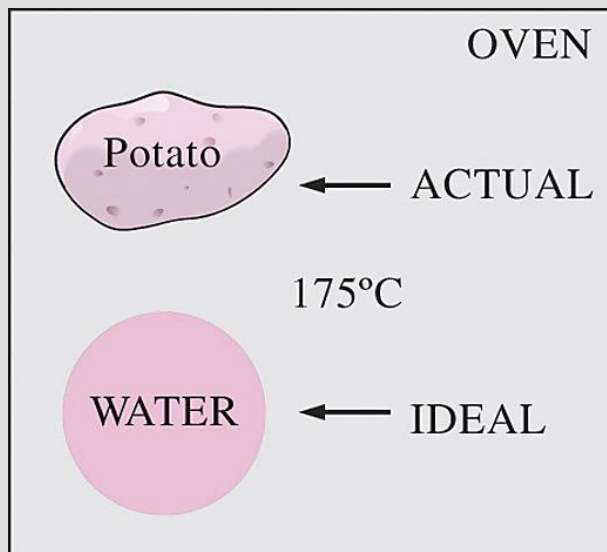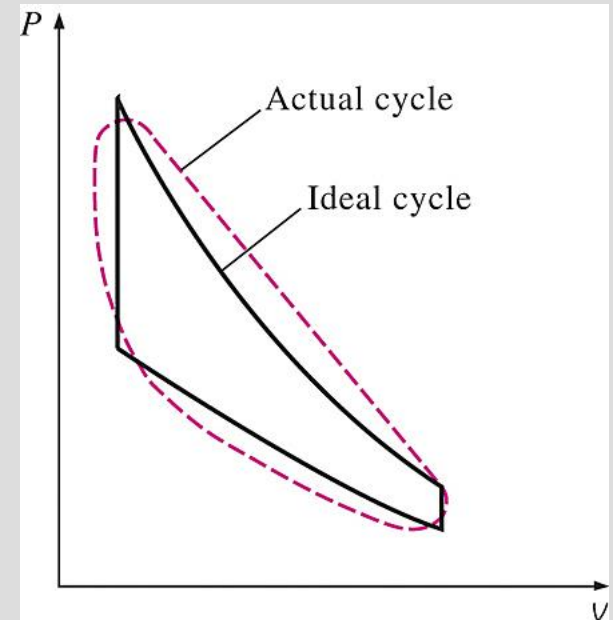
Modeling is a powerful engineering tool that provides great insight and simplicity at the expense of some loss in accuracy.

The analysis of many complex processes can be reduced to a manageable level by utilizing some idealizations.

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On a *T-s* diagram, the ratio of the area enclosed by the cyclic curve to the area under the heat-addition process curve represents the thermal efficiency of the cycle. Any modification that increases the ratio of these two areas will also increase the thermal efficiency of the cycle.

The idealizations and simplifications in the analysis of 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.
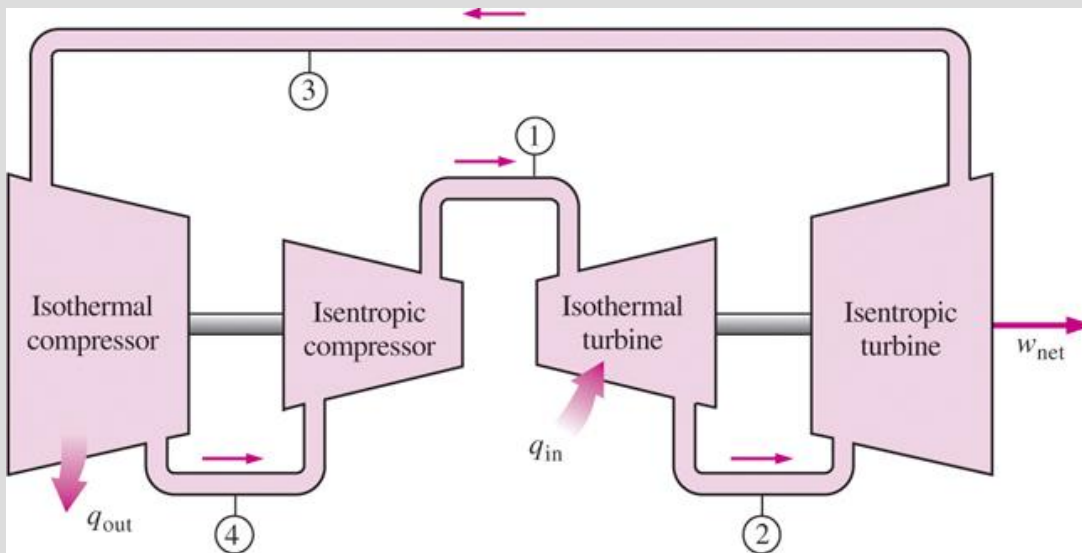
Care should be exercised in the interpretation of the results from ideal cycles.
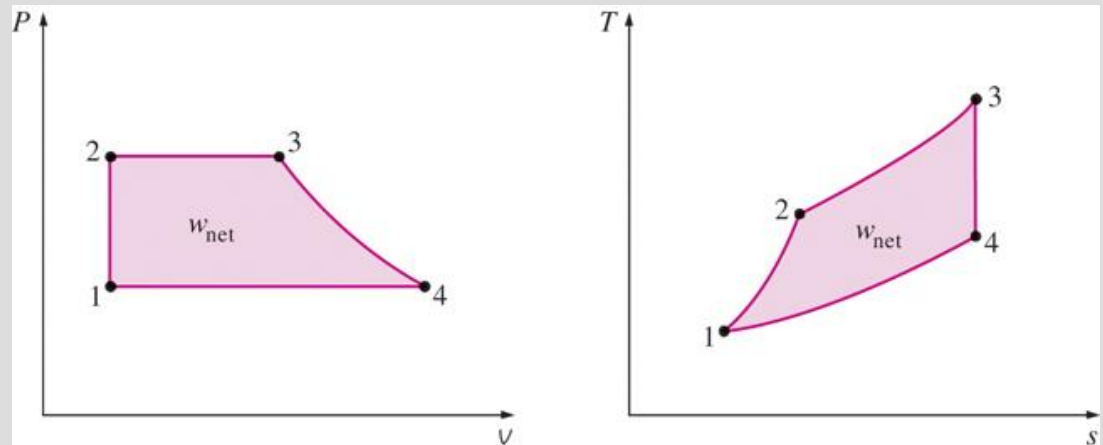
On both *P-v* and *T-s* diagrams, the area enclosed by the process curve represents the net work of the cycle.
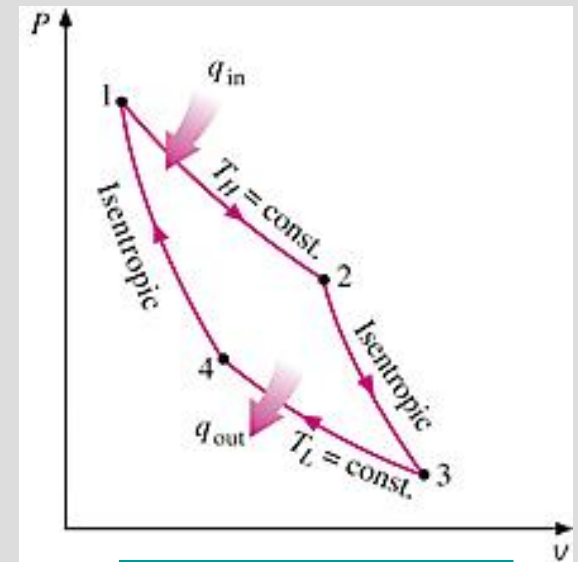
THE CARNOT CYCLE AND ITS VALUE IN ENGINEERING

The Carnot cycle is composed of four totally reversible processes: isothermal heat addition, isentropic expansion, isothermal heat rejection, and isentropic compression.
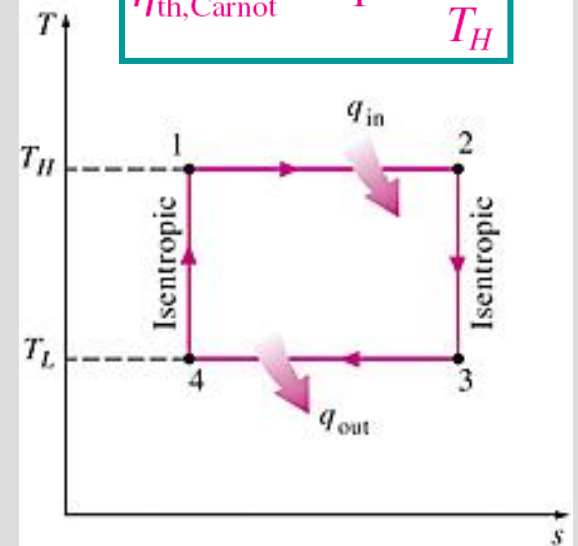
For both ideal and actual cycles: Thermal efficiency increases with an increase in the average temperature at which heat is supplied to the system or with a decrease in the average temperature at which heat is rejected from the system.
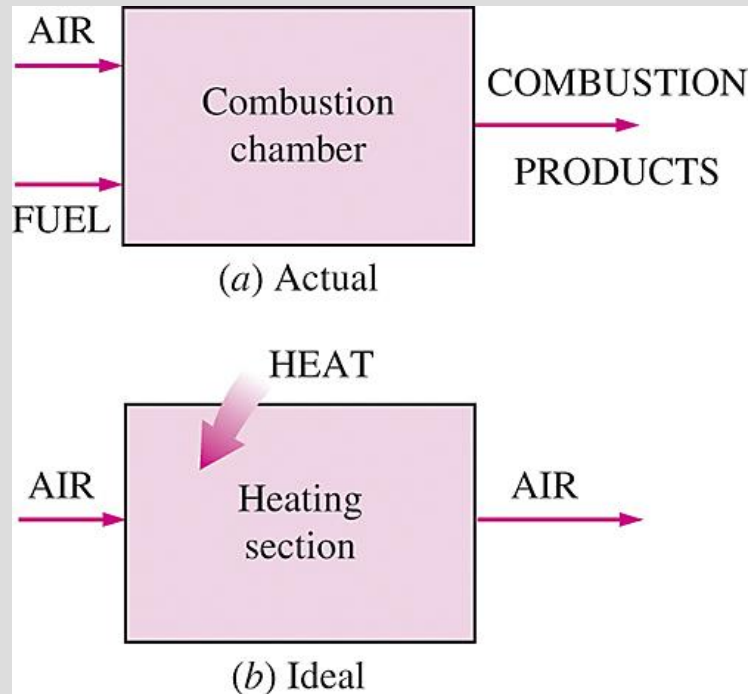

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$$

P-v and *T-s* diagrams of a Carnot cycle.

A steady-flow Carnot engine.

AIR-STANDARD ASSUMPTIONS

(a) Actual

(b) Ideal

The combustion process is replaced by a heat-addition process in ideal cycles.

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.

Cold-air-standard assumptions: When the working fluid is considered to be air with constant specific heats at room temperature (25°C).

Air-standard cycle: A cycle for which the air-standard assumptions are applicable.
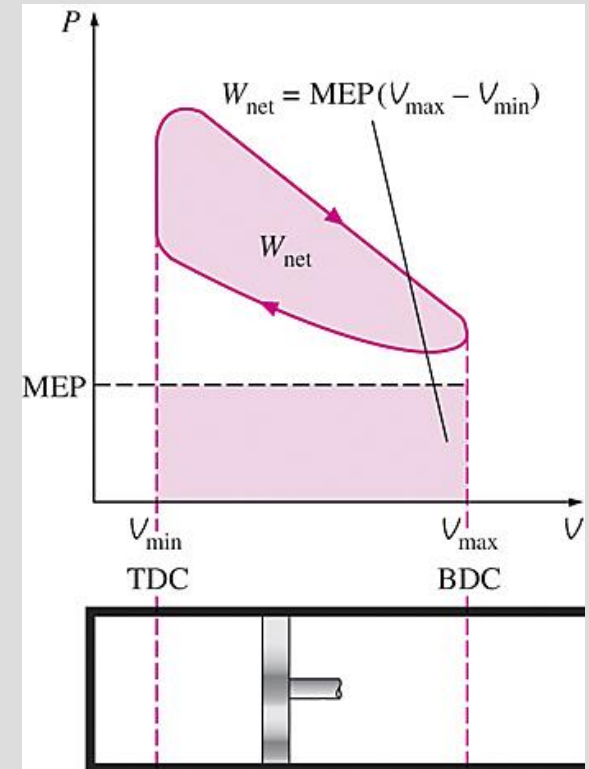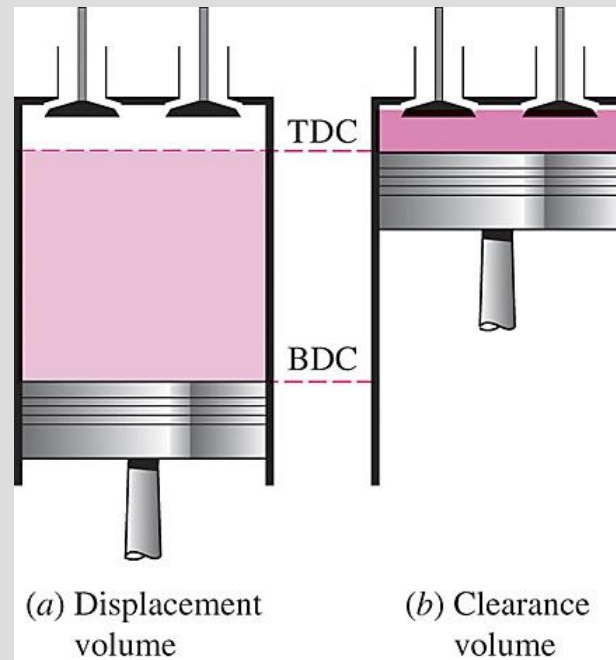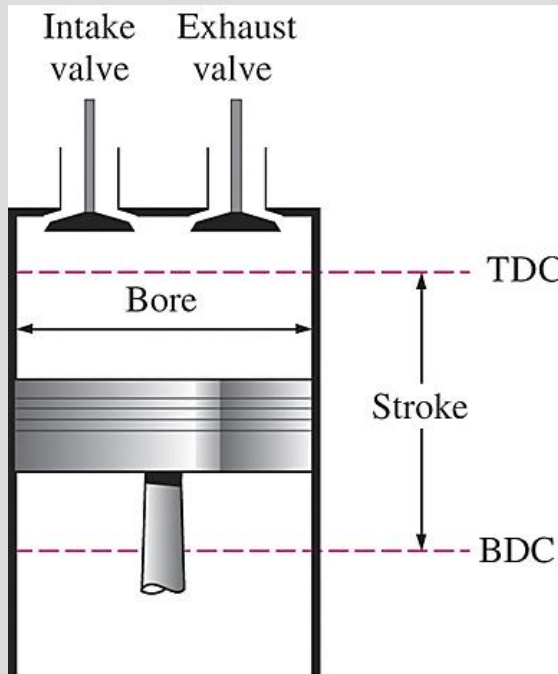
AN OVERVIEW OF RECIPROCATING ENGINES

Compression ratio

$$W_{net} = MEP \times \text{Piston area} \times \text{Stroke} = MEP \times \text{Displacement volume}$$
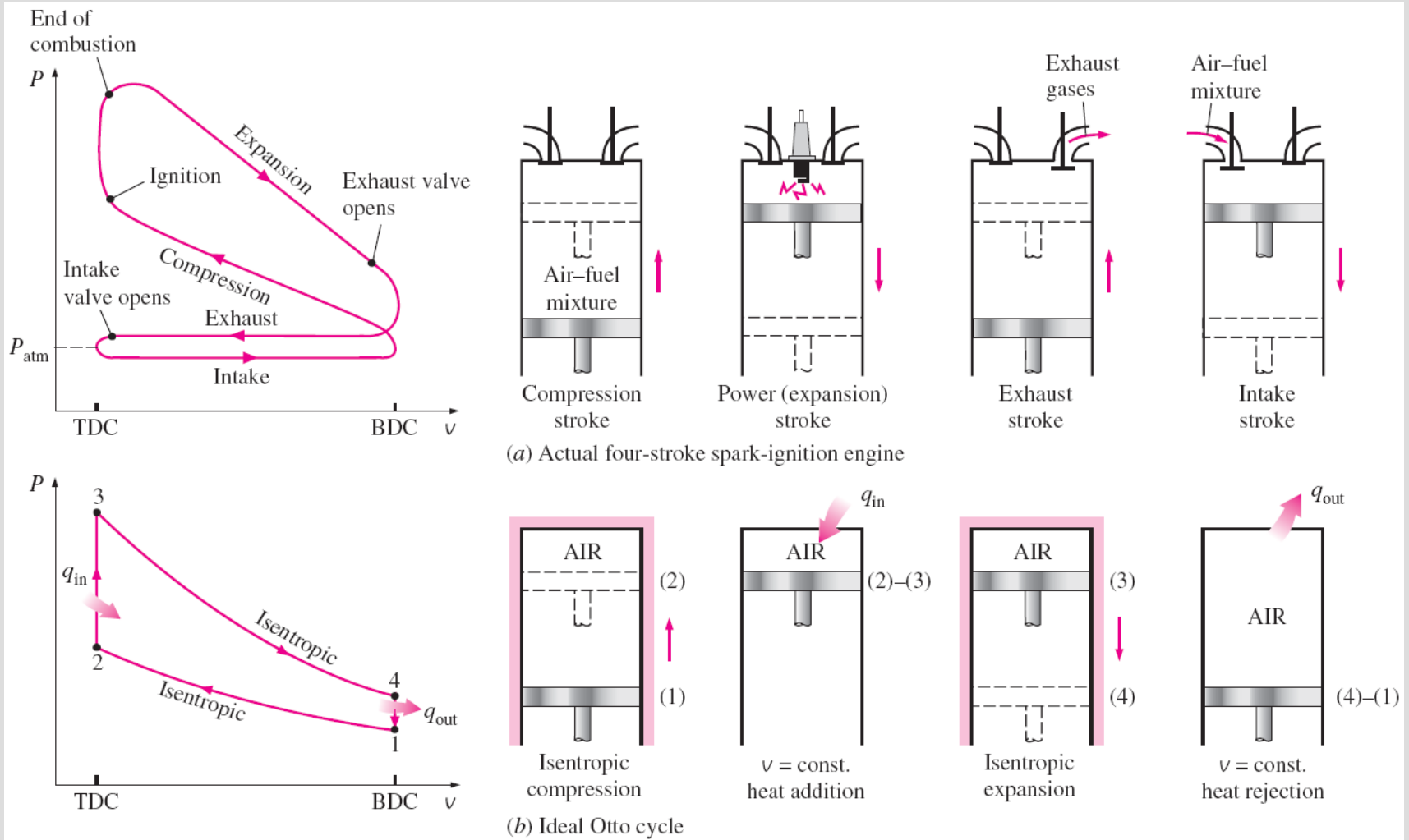
$$r = \frac{V_{max}}{V_{min}} = \frac{V_{BDC}}{V_{TDC}}$$

Mean effective pressure

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

- **Spark-ignition (SI) engines**
- **Compression-ignition (CI) engines**

Nomenclature for reciprocating engines.

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OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES

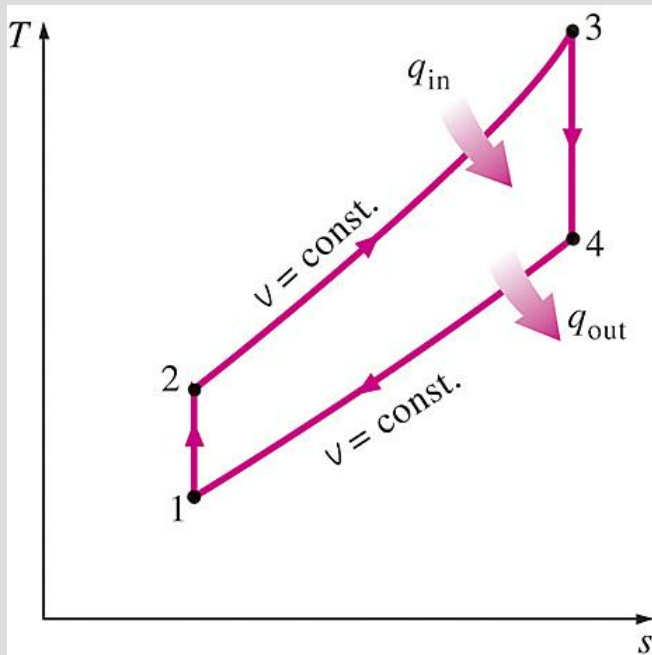Actual and ideal cycles in spark-ignition engines and their *P-v* diagrams.

Four-stroke cycle
1 cycle = 4 stroke = 2 revolution
Two-stroke cycle
1 cycle = 2 stroke = 1 revolution

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

The two-stroke engines are generally less efficient than their four-stroke counterparts but they are relatively simple and inexpensive, and they have high power-to-weight and power-to-volume ratios.

T-s diagram of the ideal Otto cycle.
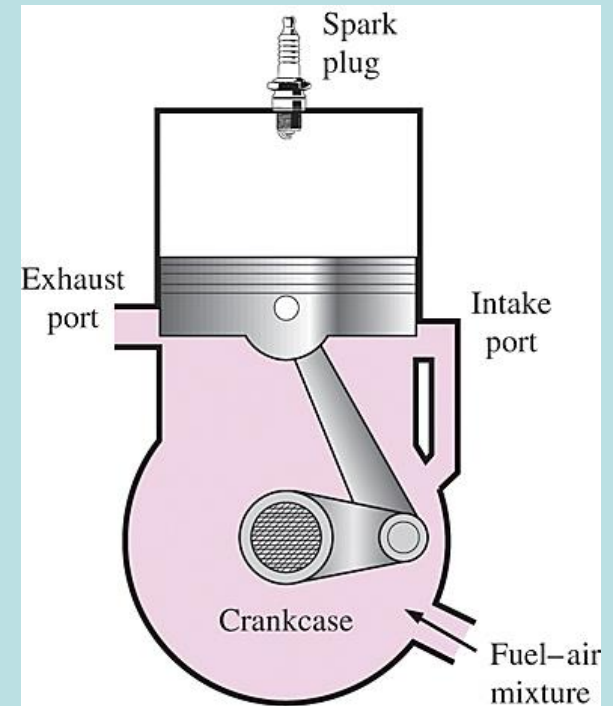
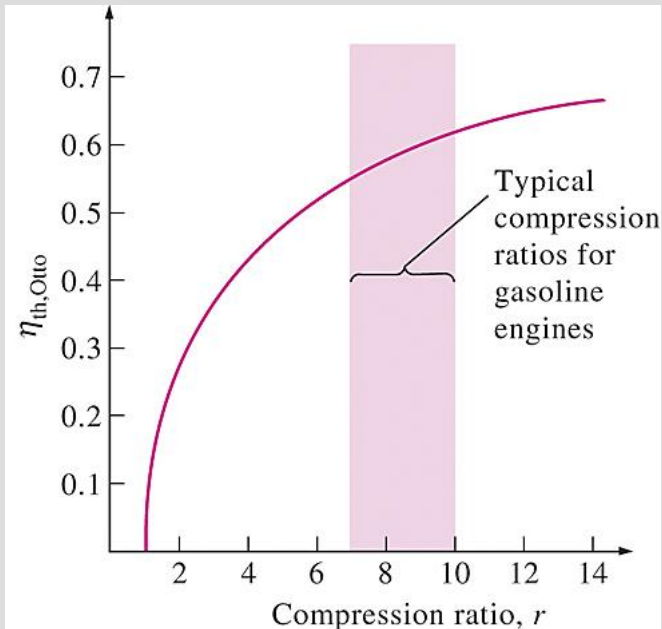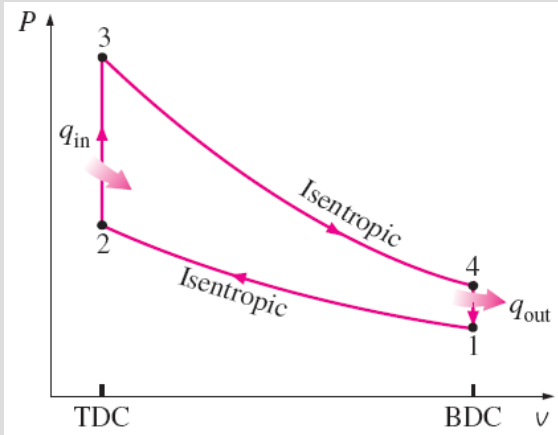Schematic of a two-stroke reciprocating engine.

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

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$
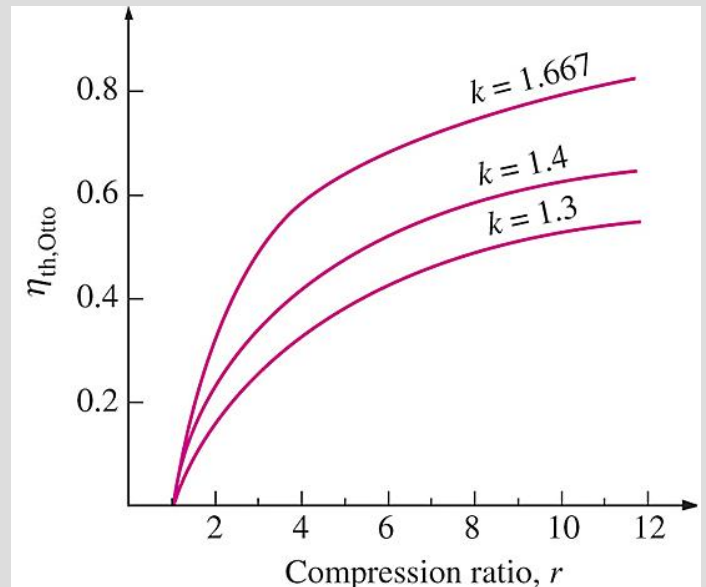
$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

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

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{k-1} = \left(\frac{v_3}{v_4}\right)^{k-1} = \frac{T_4}{T_3} \quad r = \frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2}$$

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

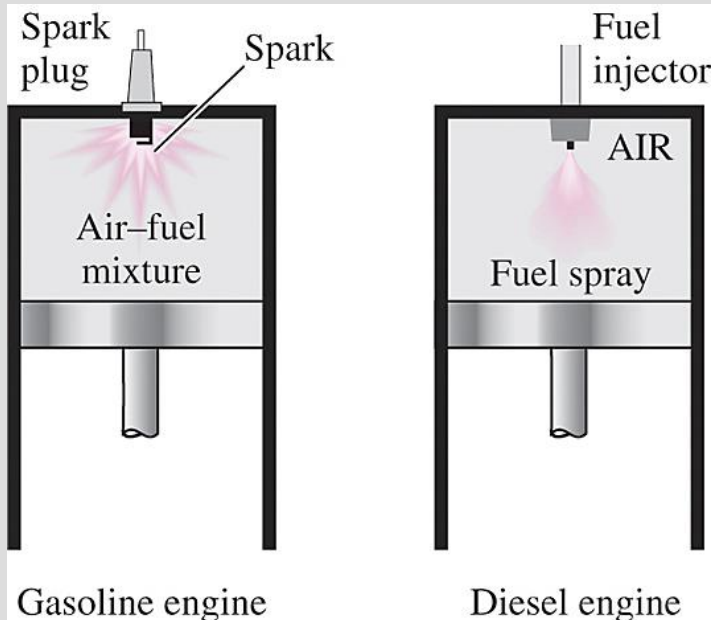In SI engines, the compression ratio is limited by autoignition or engine knock.

Typical compression ratios for gasoline engines

Thermal efficiency of the ideal Otto cycle as a function of compression ratio ($k = 1.4$).

The thermal efficiency of the Otto cycle increases with the specific heat ratio k of the working fluid.

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DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES

In diesel engines, only air is compressed during the compression stroke, eliminating the possibility of autoignition (engine knock). Therefore, diesel engines can be designed to operate at much higher compression ratios than SI engines, typically between 12 and 24.


Spark plug — Spark
Air–fuel mixture
Gasoline engine

Fuel injector
AIR
Fuel spray
Diesel engine

(a) P- v diagram

- **1-2** isentropic compression
- **2-3** constant-pressure heat addition
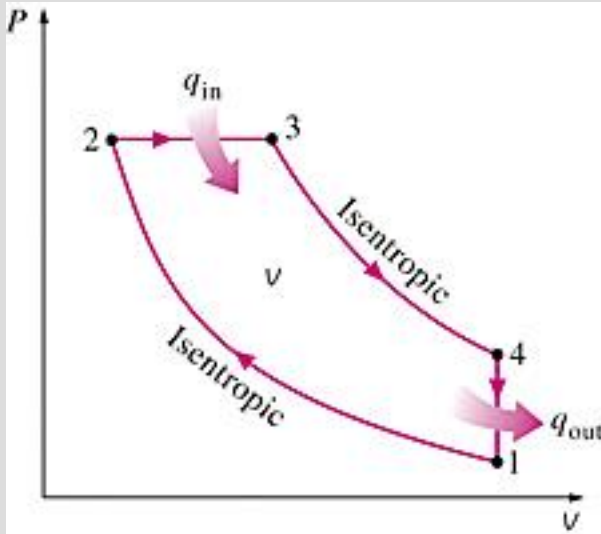- **3-4** isentropic expansion
- **4-1** constant-volume heat rejection.

(b) T-s diagram

In diesel engines, the spark plug is replaced by a fuel injector, and only air is compressed during the compression process.
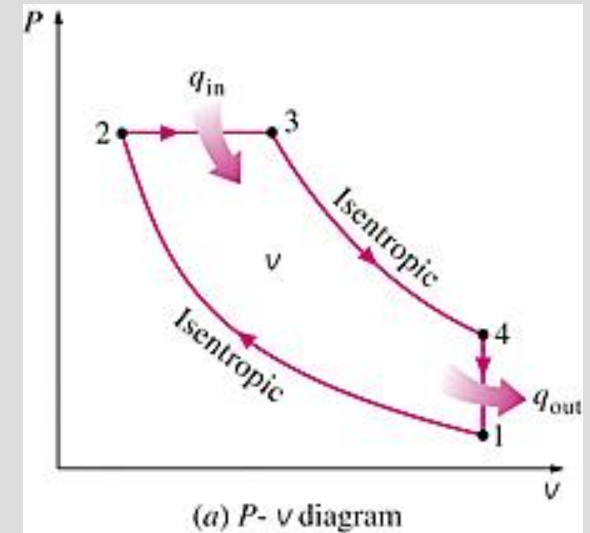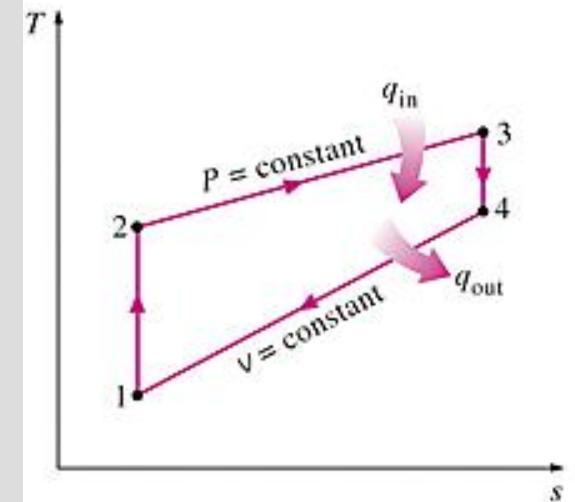
(a) P-v diagram

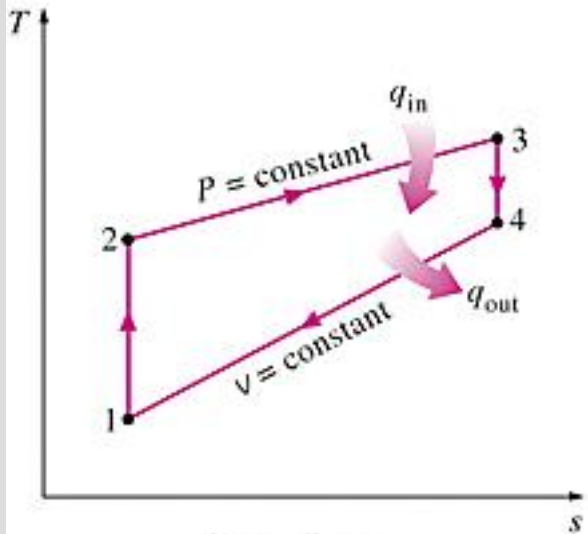$$q_{in} - w_{b,out} = u_3 - u_2 \rightarrow q_{in} = P_2(v_3 - v_2) + (u_3 - u_2)$$
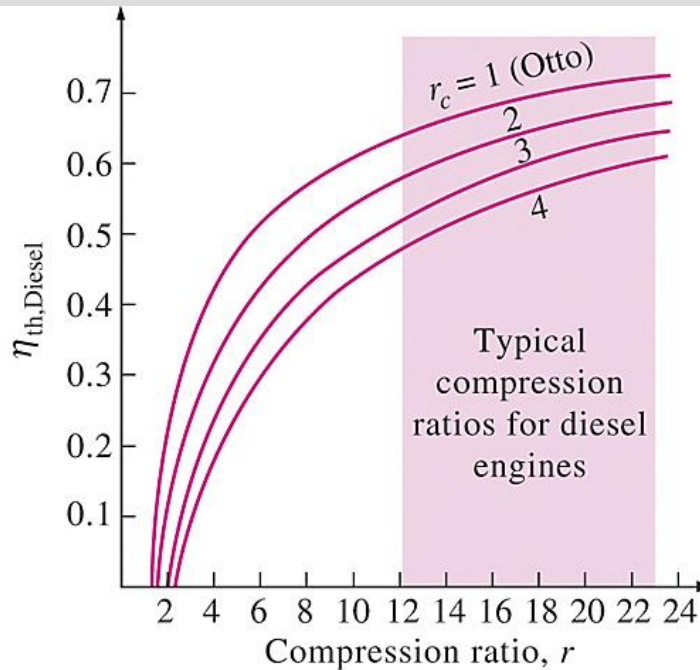$$= h_3 - h_2 = c_p(T_3 - T_2)$$

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

$$\eta_{th,Diesel} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{kT_2(T_3/T_2 - 1)}$$
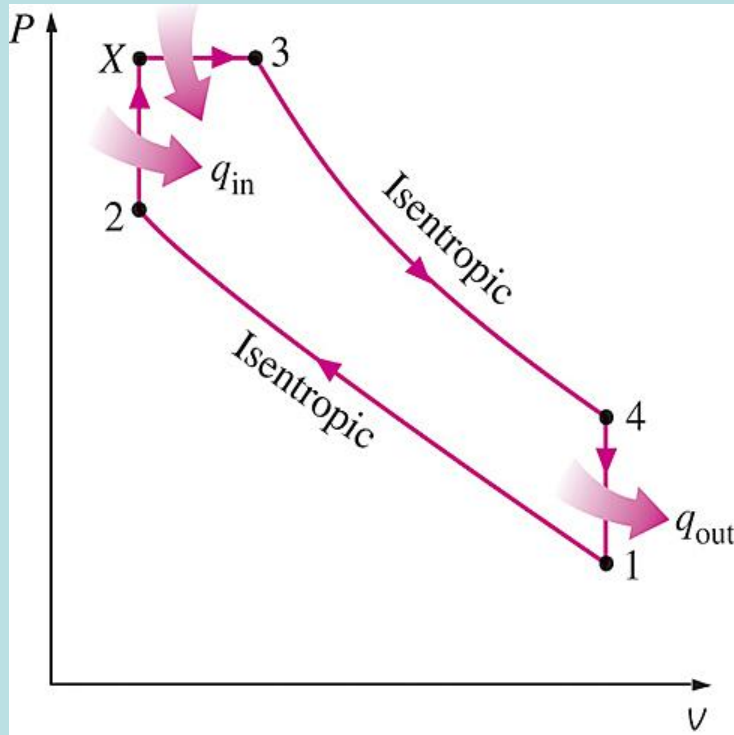
$$r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2}$$ Cutoff ratio

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

$$\eta_{th,Otto} > \eta_{th,Diesel}$$ for the same compression ratio

(b) T-s diagram

Thermal efficiency of the ideal Diesel cycle as a function of compression and cutoff ratios (*k*=1.4).

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Dual cycle: A more realistic ideal cycle model for modern, high-speed compression ignition engine.

P-v diagram of an ideal dual cycle.

QUESTIONS

Diesel engines operate at higher air-fuel ratios than gasoline engines. Why?

Despite higher power to weight ratios, two-stroke engines are not used in automobiles. Why?

The stationary diesel engines are among the most efficient power producing devices (about 50%). Why?

What is a turbocharger? Why are they mostly used in diesel engines compared to gasoline engines.
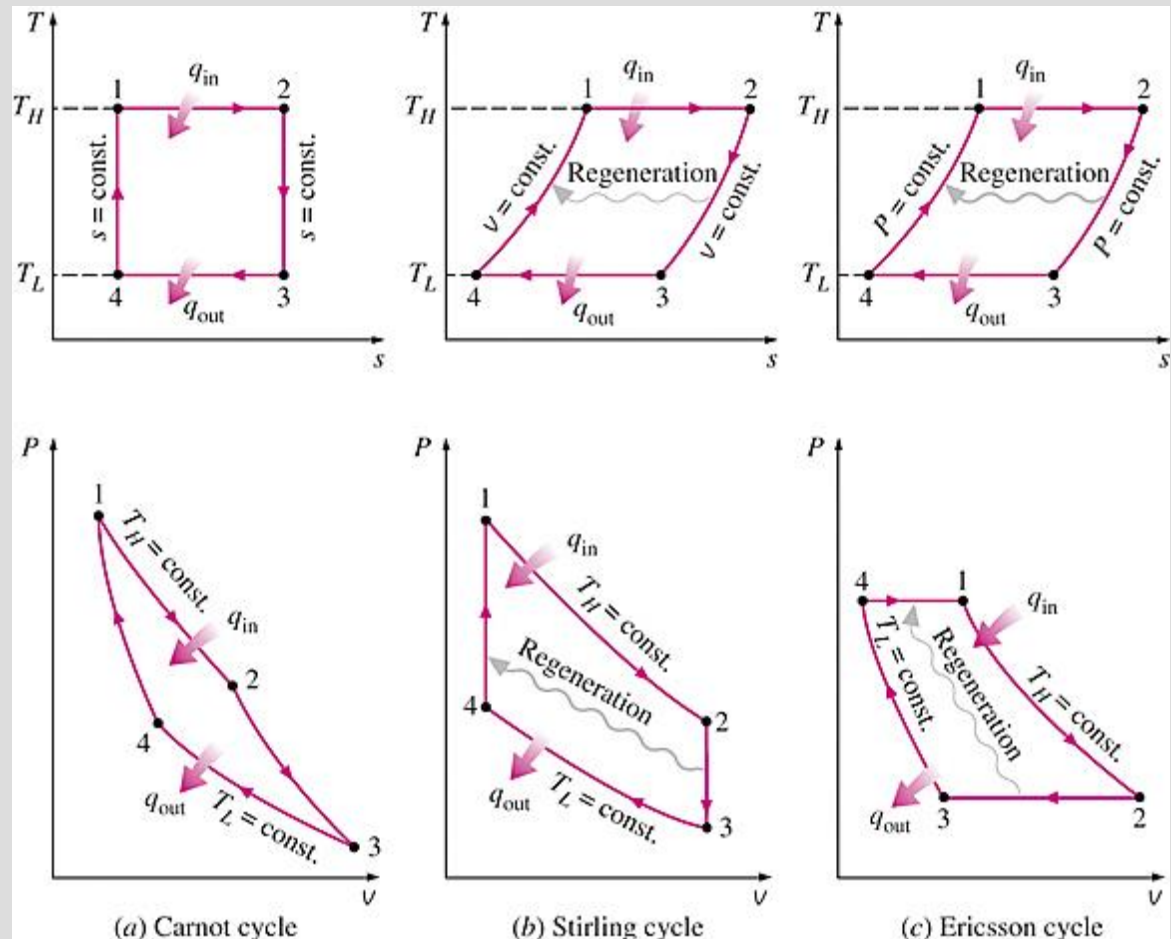
STIRLING AND ERICSSON CYCLES

Stirling cycle

- **1-2** $T = constant$ expansion (heat addition from the external source)
- **2-3** $v = constant$ regeneration (internal heat transfer from the working fluid to the regenerator)
- **3-4** $T = constant$ compression (heat rejection to the external sink)
- **4-1** $v = constant$ regeneration (internal heat transfer from the regenerator back to the working fluid)
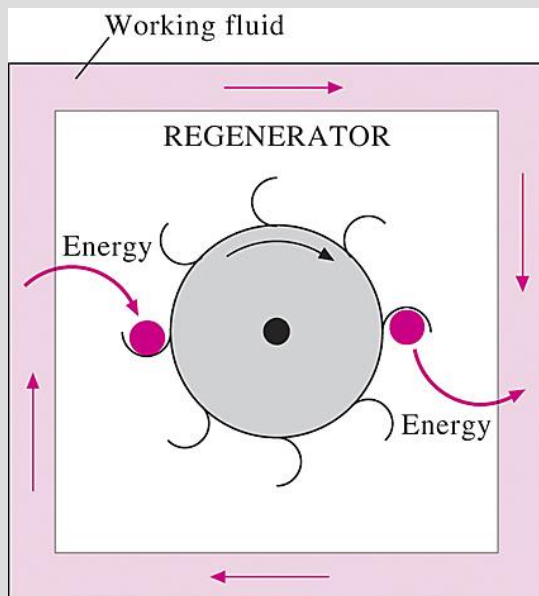
A regenerator is a device that borrows energy from the working fluid during one part of the cycle and pays it back (without interest) during another part.

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

The Stirling and Ericsson cycles give a message: *Regeneration can increase efficiency.*

Both the Stirling and Ericsson cycles are totally reversible, as is the Carnot cycle, and thus:

$$\eta_{th,Stirling} = \eta_{th,Ericsson} = \eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$$

The Ericsson cycle is very much like the Stirling cycle, except that the two constant-volume processes are replaced by two constant-pressure processes.
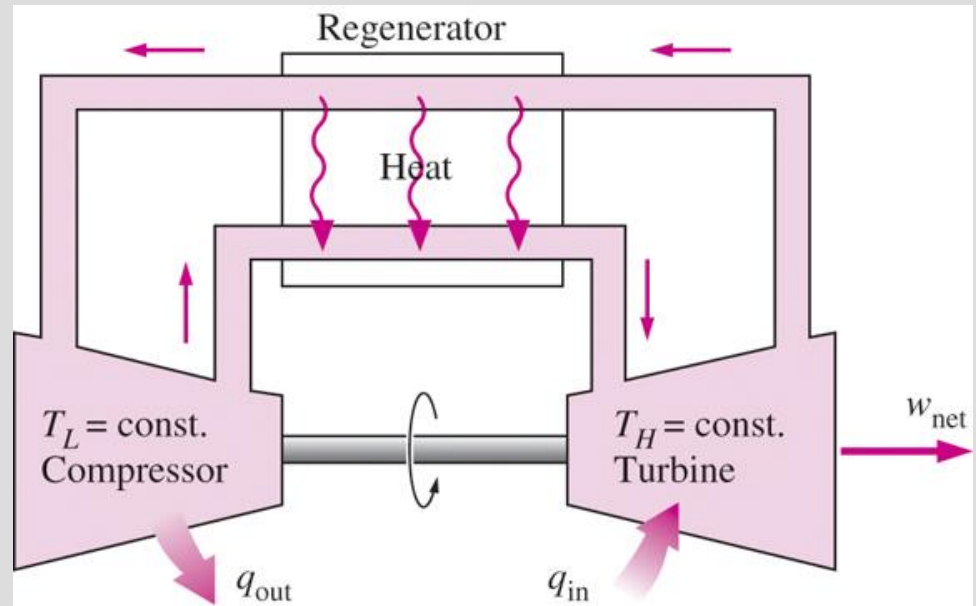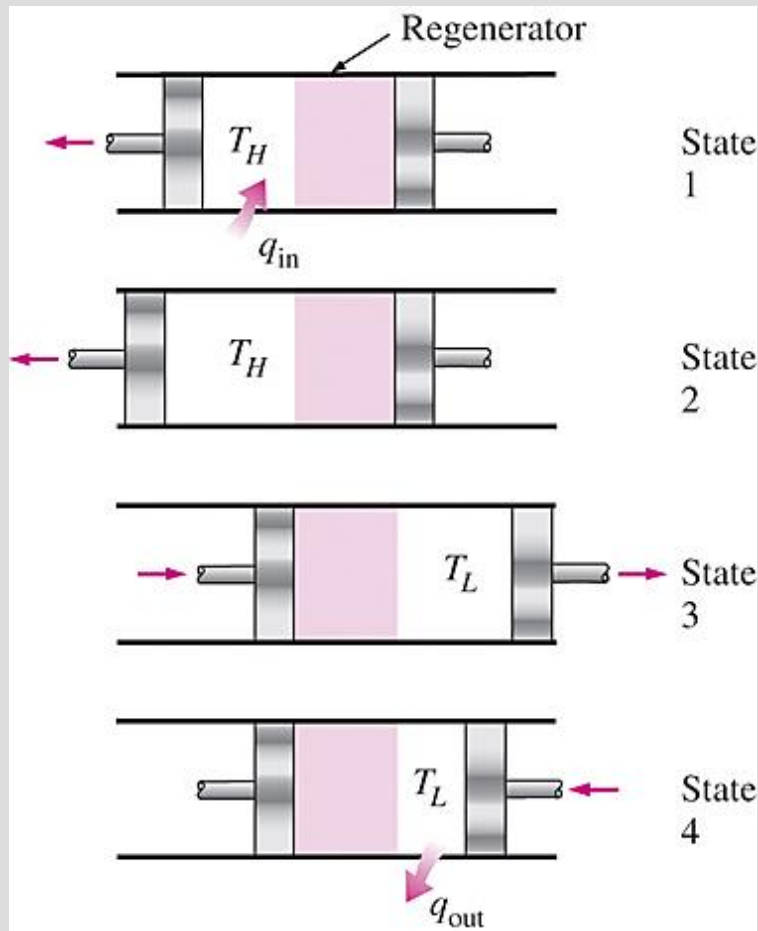
The execution of the Stirling cycle.

A steady-flow Ericsson engine.

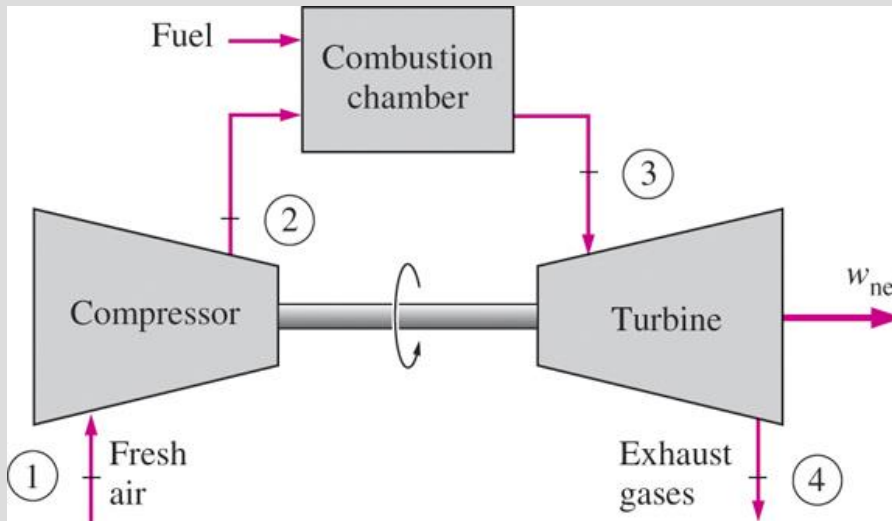# BRAYTON CYCLE: THE IDEAL CYCLE FOR GAS-TURBINE ENGINES

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.

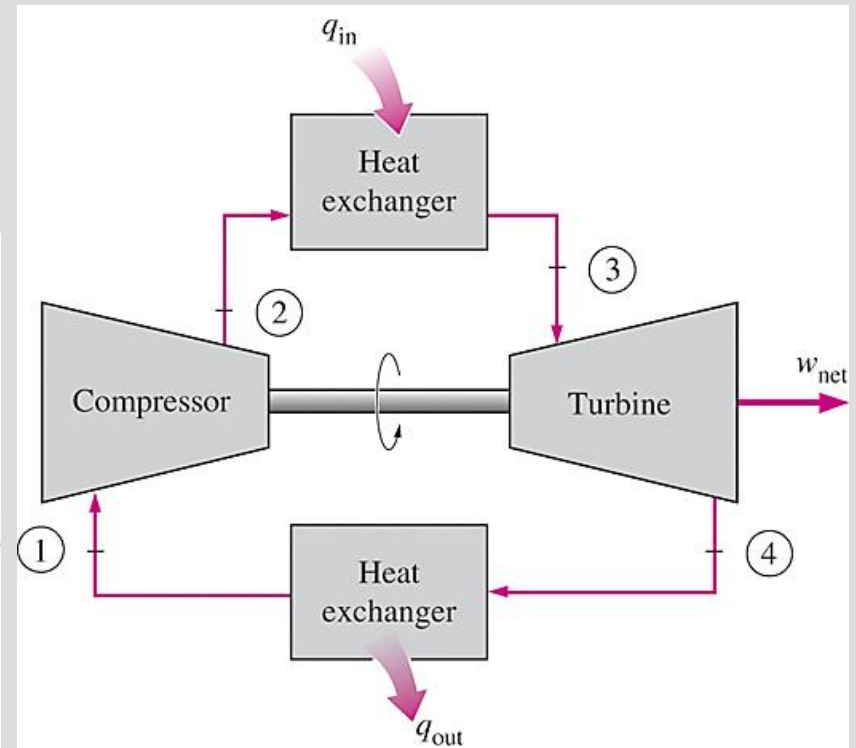1-2 Isentropic compression (in a compressor)
2-3 Constant-pressure heat addition
3-4 Isentropic expansion (in a turbine)
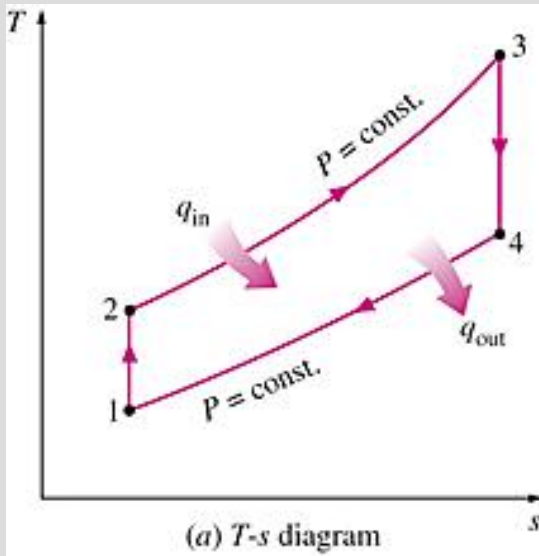4-1 Constant-pressure heat rejection

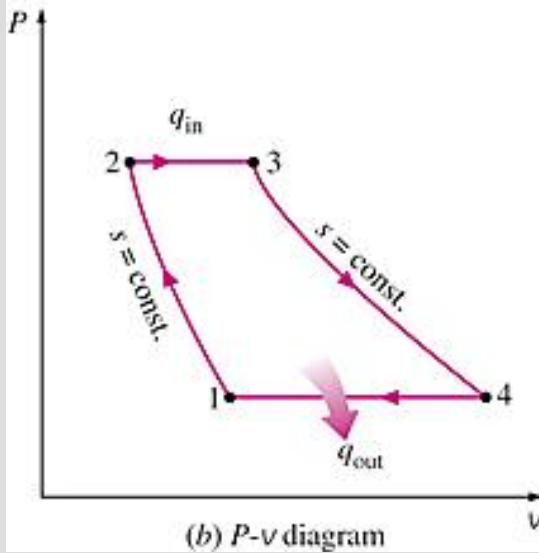An open-cycle gas-turbine engine.

A closed-cycle gas-turbine engine.

(a) T-s diagram

(b) P-v diagram

T-s and *P-v* diagrams for the ideal Brayton cycle.

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

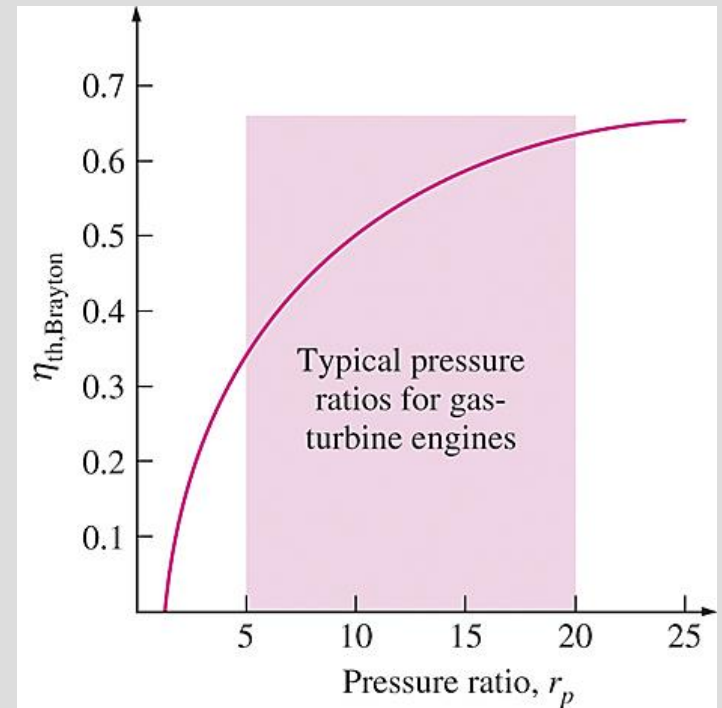$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$$

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

$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$
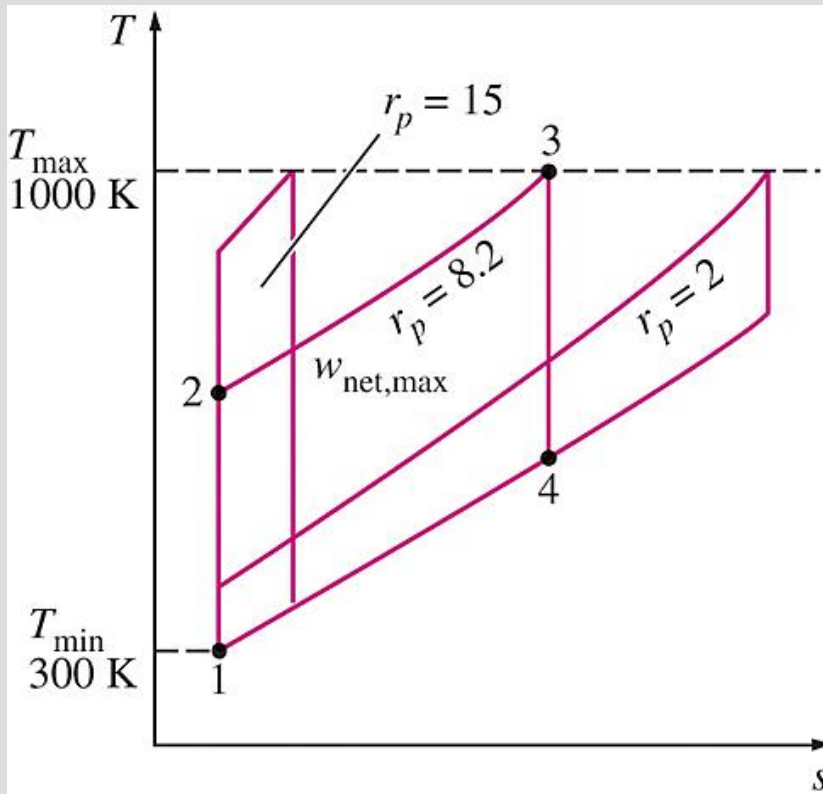
$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4} \qquad r_p = \frac{P_2}{P_1}$$ Pressure ratio

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

Thermal efficiency of the ideal Brayton cycle as a function of the pressure ratio.

Typical pressure ratios for gas-turbine engines

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The two major application areas of gas-turbine engines are *aircraft propulsion* and *electric power generation.*

The highest temperature in the cycle is limited by the maximum temperature that the turbine blades can withstand. This also limits the pressure ratios that can be used in the cycle.

The air in gas turbines supplies the necessary oxidant for the combustion of the fuel, and it serves as a coolant to keep the temperature of various components within safe limits. An air–fuel ratio of 50 or above is not uncommon.

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.
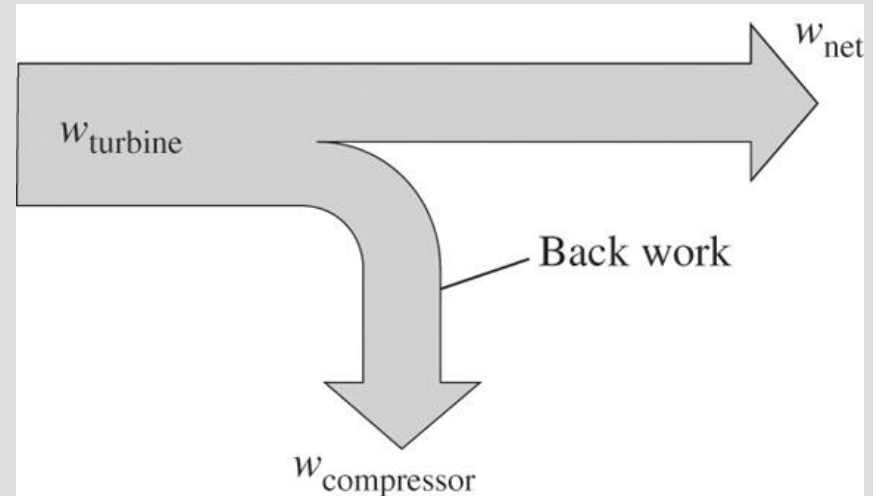
The fraction of the turbine work used to drive the compressor is called the back work ratio.

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Development of Gas Turbines

1. Increasing the turbine inlet (or firing) temperatures
2. Increasing the efficiencies of turbomachinery components (turbines, compressors):
3. Adding modifications to the basic cycle (intercooling, regeneration or recuperation, and reheating).

Deviation of Actual Gas-Turbine Cycles from Idealized Ones

Reasons: Irreversibilities in turbine and compressors, pressure drops, heat losses

Isentropic efficiencies of the compressor and turbine

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

$$\eta_T = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$
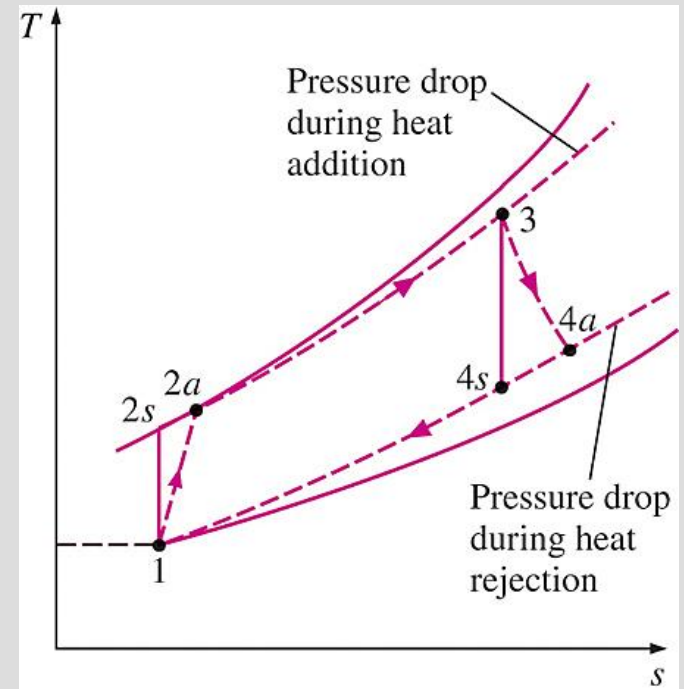
The deviation of an actual gas-turbine cycle from the ideal Brayton cycle as a result of irreversibilities.

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THE BRAYTON CYCLE WITH REGENERATION

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.

Therefore, the high-pressure air leaving the compressor can be heated by the hot exhaust gases in a counter-flow heat exchanger (a *regenerator* or a *recuperator*).
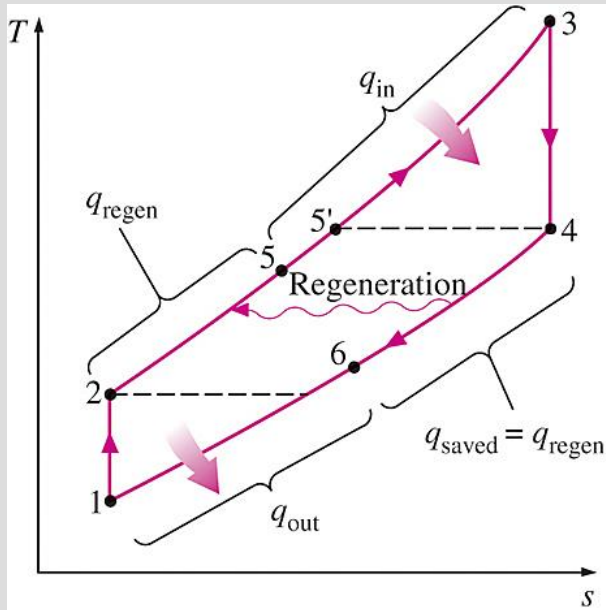
The thermal efficiency of the Brayton cycle increases as a result of regeneration since less fuel is used for the same work output.
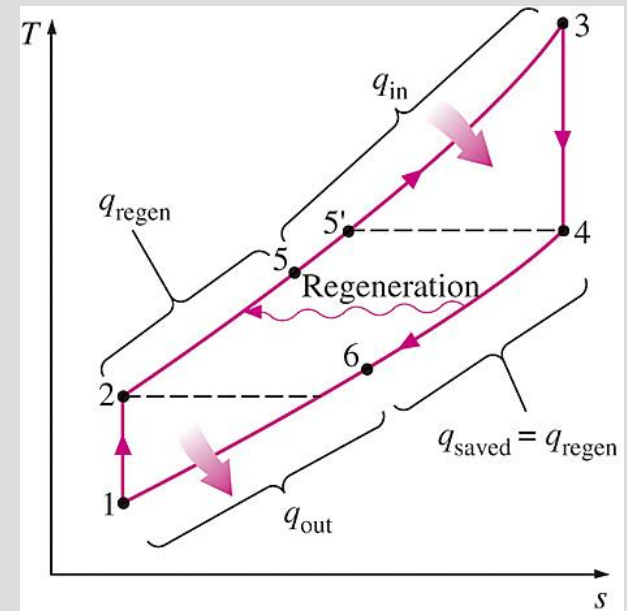
T-s diagram of a Brayton cycle with regeneration.
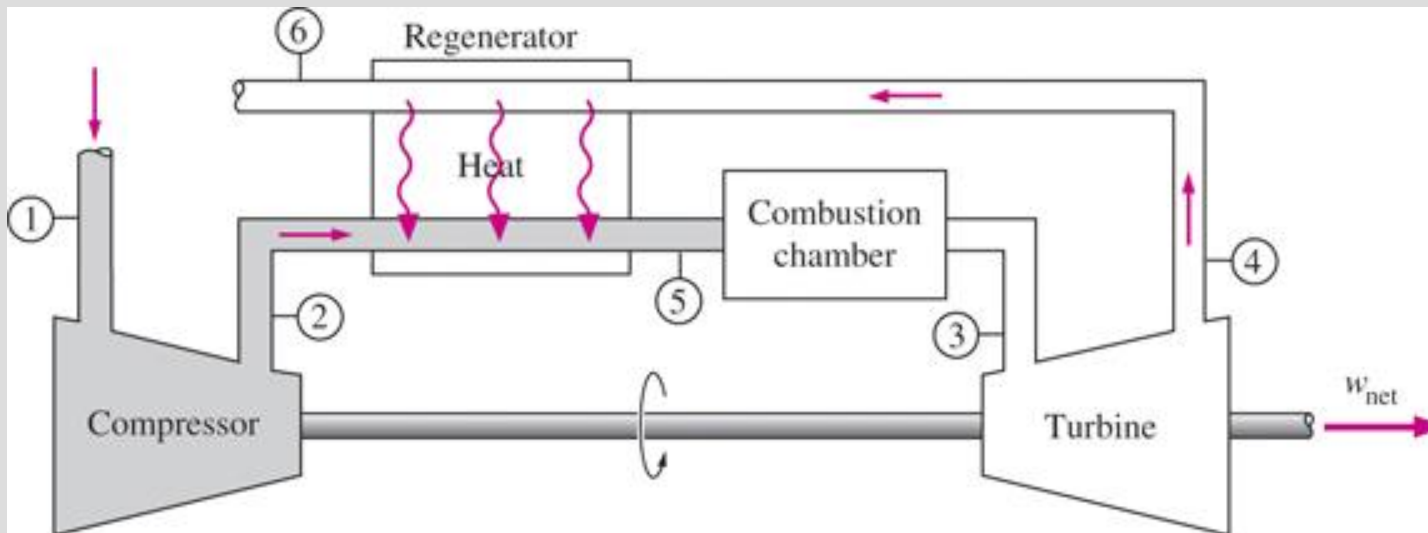
A gas-turbine engine with regenerator.

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

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

$$\epsilon = \frac{q_{regen,act}}{q_{regen,max}} = \frac{h_5 - h_2}{h_4 - h_2}$$ Effectiveness of regenerator

$$\epsilon \cong \frac{T_5 - T_2}{T_4 - T_2}$$ Effectiveness under cold-air standard assumptions

$$\eta_{th,regen} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(k-1)/k}$$ Under cold-air standard assumptions

T-s diagram of a Brayton cycle with regeneration.

Can regeneration be used at high pressure ratios?

The thermal efficiency depends on the ratio of the minimum to maximum temperatures as well as the pressure ratio.

Regeneration is most effective at lower pressure ratios and low minimum-to-maximum temperature ratios.
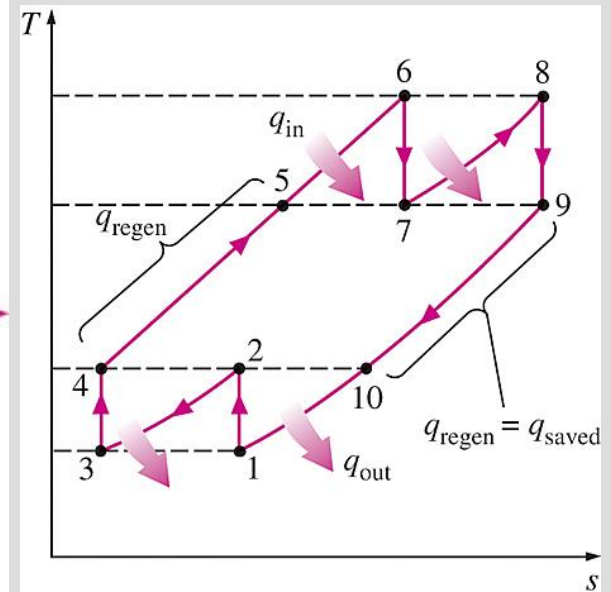
Thermal efficiency of the ideal Brayton cycle with and without regeneration.
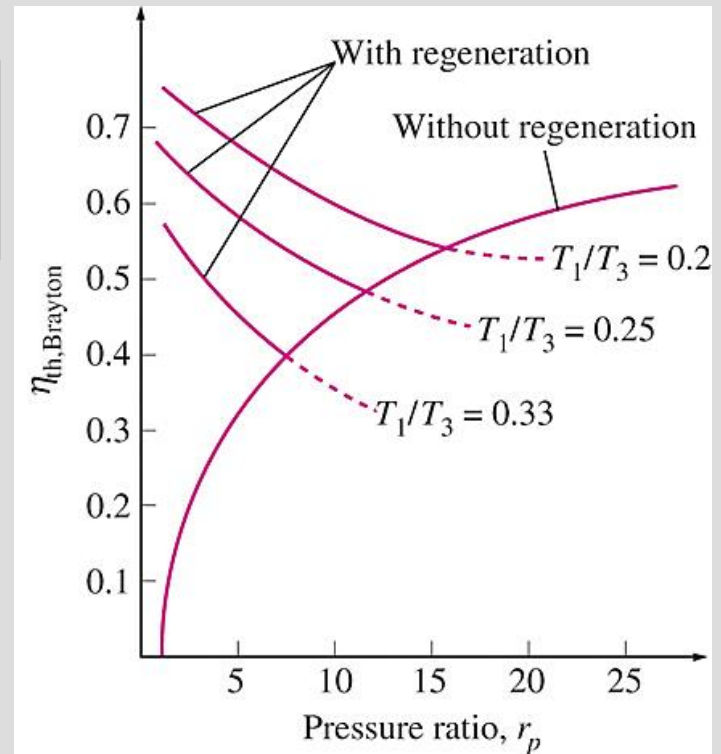
THE BRAYTON CYCLE WITH INTERCOOLING, REHEATING, AND REGENERATION

For minimizing work input to compressor and maximizing work output from turbine:

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} \quad \text{and} \quad \frac{P_6}{P_7} = \frac{P_8}{P_9}$$
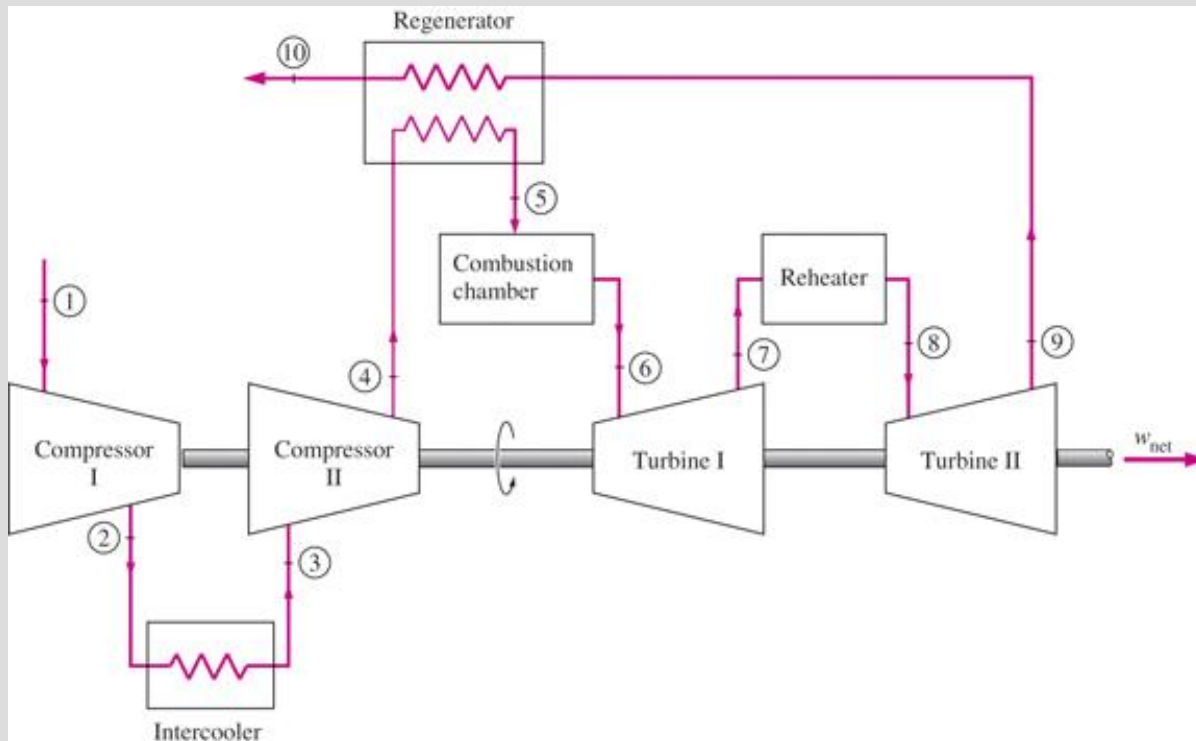
A gas-turbine engine with two-stage compression with intercooling, two-stage expansion with reheating, and regeneration and its *T-s* diagram.

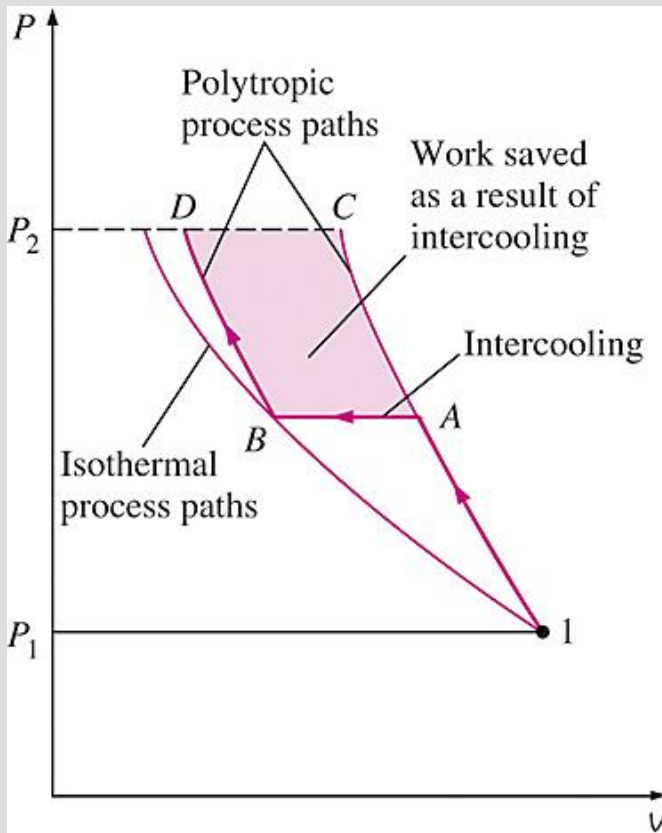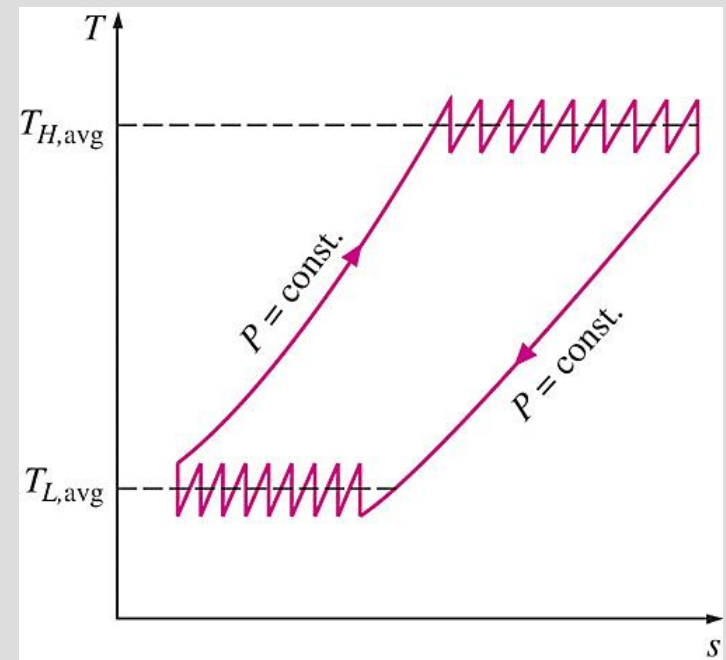**Multistage compression with intercooling:** The work required to compress a gas between two specified pressures can be decreased by carrying out the compression process in stages and cooling the gas in between. This keeps the specific volume as low as possible.

Multistage expansion with reheating keeps the specific volume of the working fluid as high as possible during an expansion process, thus maximizing work output.

Intercooling and reheating always decreases the thermal efficiency unless they are accompanied by regeneration. **Why?**

Comparison of work inputs to a single-stage compressor (1*AC*) and a two-stage compressor with intercooling (1*ABD*).

As the number of compression and expansion stages increases, the gas-turbine cycle with intercooling, reheating, and regeneration approaches the Ericsson cycle.

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IDEAL JET-PROPULSION CYCLES

Gas-turbine engines are widely used to power aircraft because they are light and compact and have a high power-to-weight ratio.

Aircraft gas turbines operate on an open cycle called a **jet-propulsion cycle**.

The ideal jet-propulsion cycle differs from the simple ideal Brayton cycle in that the gases are not expanded to the ambient pressure in the turbine. Instead, they are expanded to a pressure such that the power produced by the turbine is just sufficient to drive the compressor and the auxiliary equipment.

The net work output of a jet-propulsion cycle is zero. The gases that exit the turbine at a relatively high pressure are subsequently accelerated in a nozzle to provide the thrust to propel the aircraft.

Aircraft are propelled by accelerating a fluid in the opposite direction to motion. This is accomplished by either slightly accelerating a large mass of fluid (**propeller-driven engine**) or greatly accelerating a small mass of fluid (**jet** or **turbojet engine**) or both (**turboprop engine**).

In jet engines, the high-temperature and high-pressure gases leaving the turbine are accelerated in a nozzle to provide thrust.
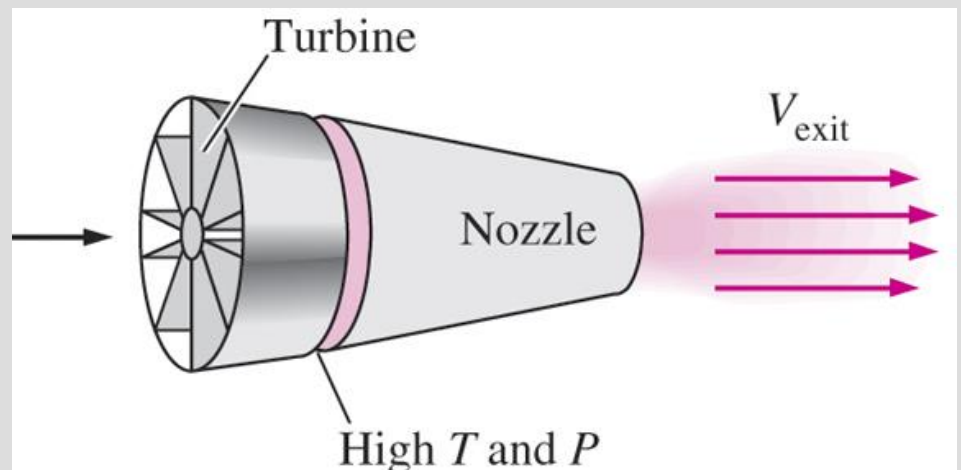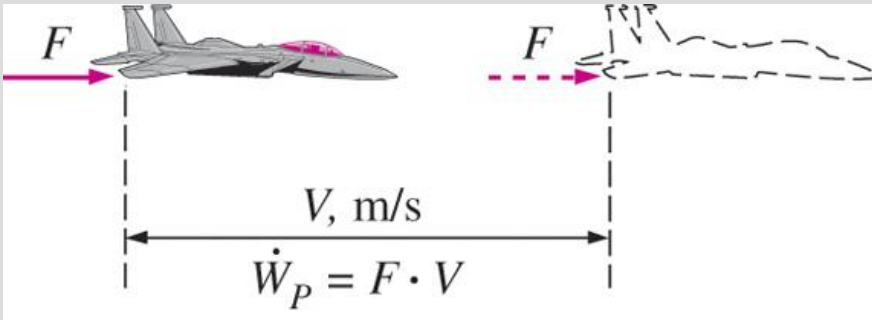
Thrust (propulsive force)

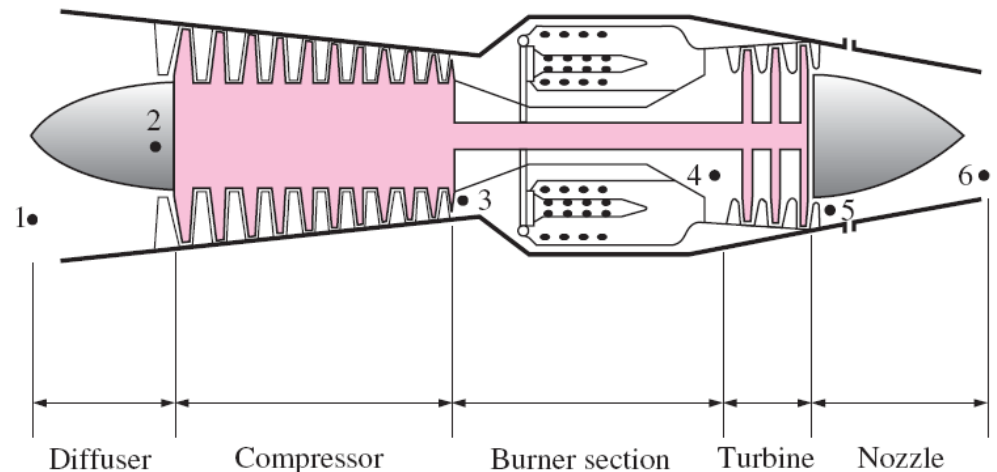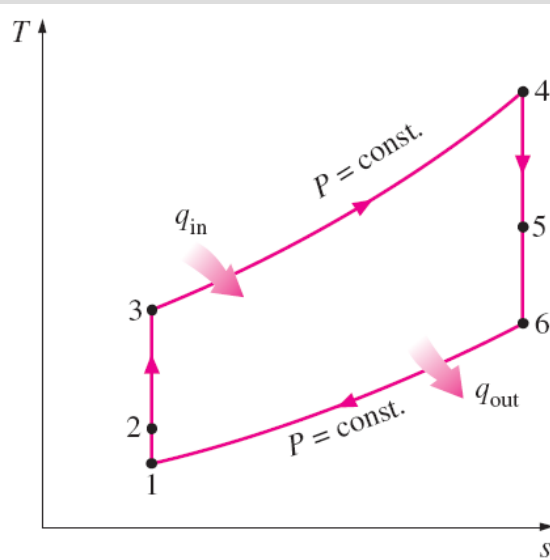$$F = (\dot{m}V)_{\text{exit}} - (\dot{m}V)_{\text{inlet}} = \dot{m}(V_{\text{exit}} - V_{\text{inlet}}) \qquad (N)$$

Propulsive power

$$\dot{W}_P = FV_{\text{aircraft}} = \dot{m}(V_{\text{exit}} - V_{\text{inlet}})V_{\text{aircraft}} \qquad (kW)$$

Propulsive efficiency

$$\eta_P = \frac{\text{Propulsive power}}{\text{Energy input rate}} = \frac{\dot{W}_P}{\dot{Q}_{\text{in}}}$$

Propulsive power is the thrust acting on the aircraft through a distance per unit time.

Basic components of a turbojet engine and the *T-s* diagram for the ideal turbojet cycle.

Modifications to Turbojet Engines

The first airplanes built were all propeller-driven, with propellers powered by engines essentially identical to automobile engines.

Both propeller-driven engines and jet-propulsion-driven engines have their own strengths and limitations, and several attempts have been made to combine the desirable characteristics of both in one engine.

Two such modifications are the *propjet engine* and the *turbofan engine*.
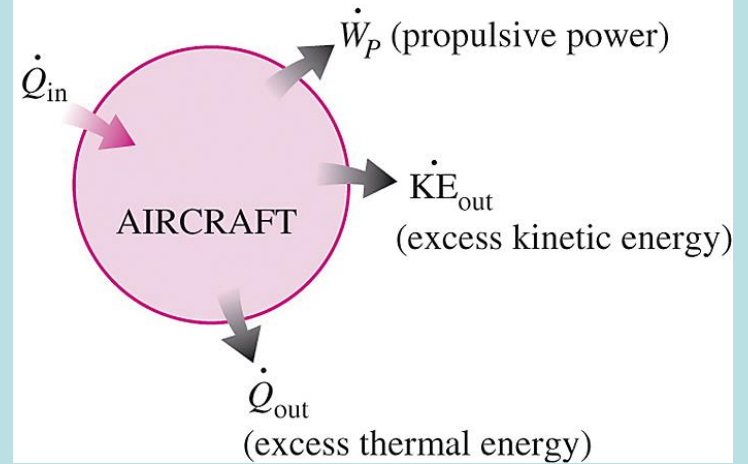
Energy supplied to an aircraft (from the burning of a fuel) manifests itself in various forms.
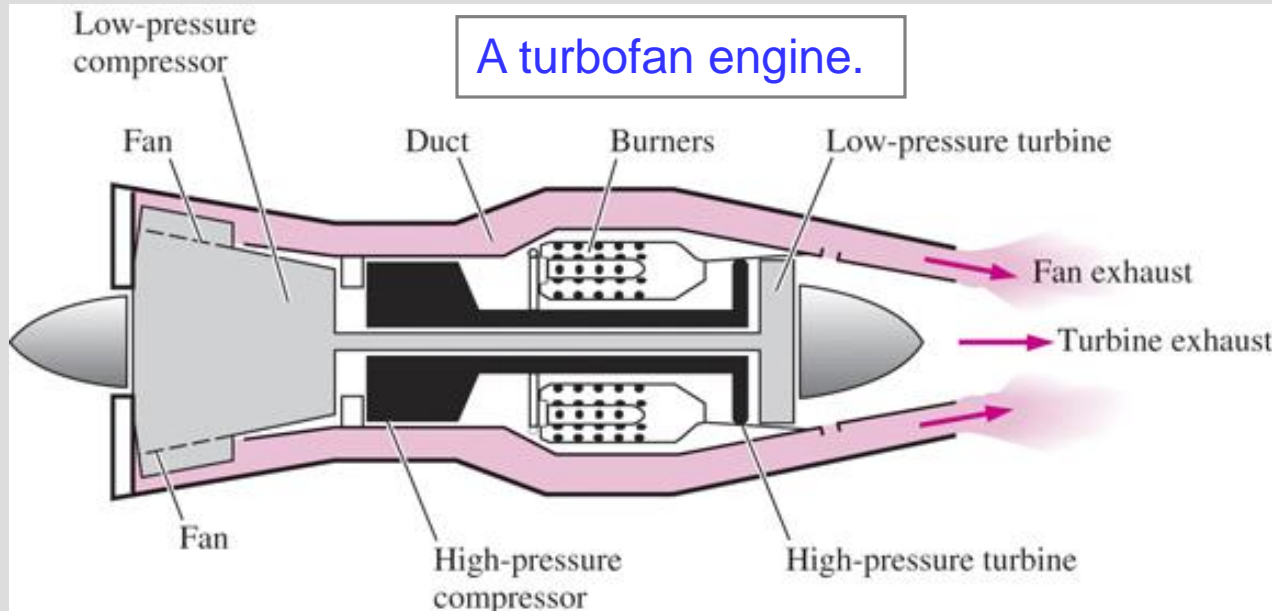
A turbofan engine.

The most widely used engine in aircraft propulsion is the **turbofan** (or *fanjet*) engine wherein a large fan driven by the turbine forces a considerable amount of air through a duct (cowl) surrounding the engine.

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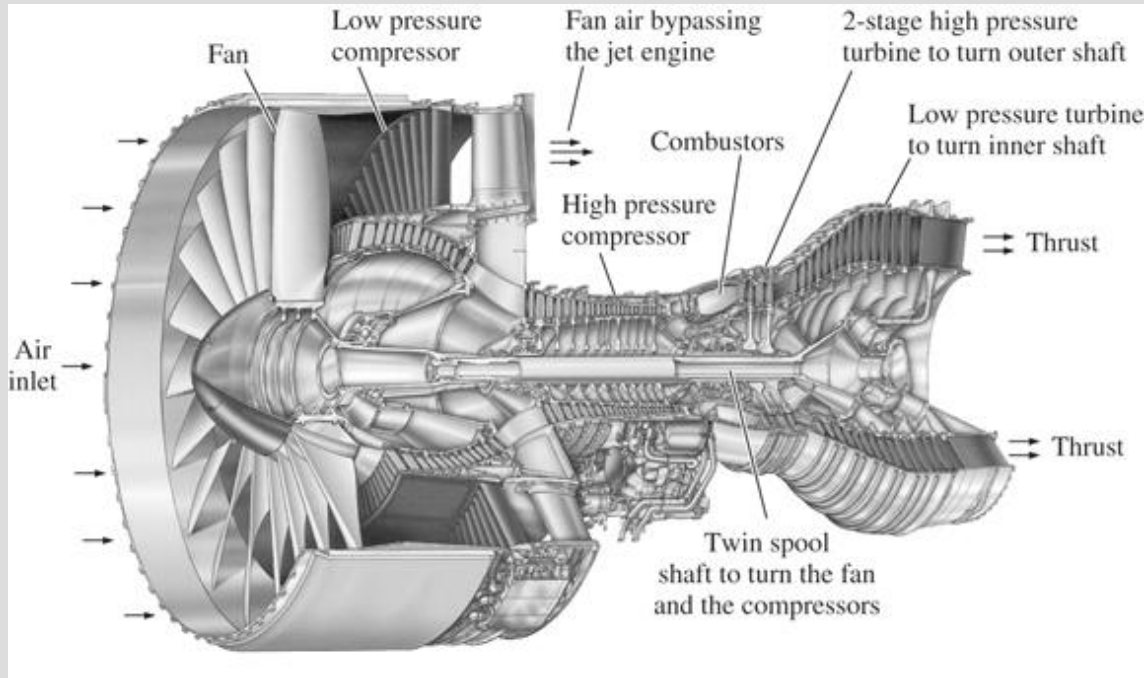
A modern jet engine used to power Boeing 777 aircraft. This is a Pratt & Whitney PW4084 turbofan capable of producing 374 kN of thrust. It is 4.87 m long, has a 2.84 m diameter fan, and it weighs 6800 kg.

Various engine types:
Turbofan, Propjet, Ramjet, Sacramjet, Rocket
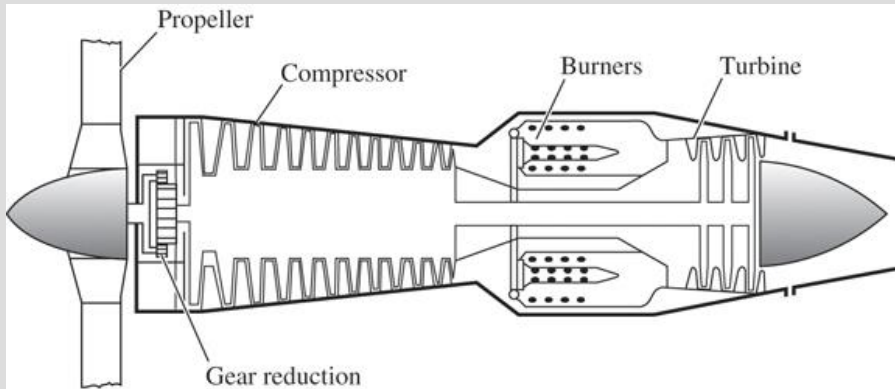
A turboprop engine.

A ramjet engine.

SECOND-LAW ANALYSIS OF GAS POWER CYCLES
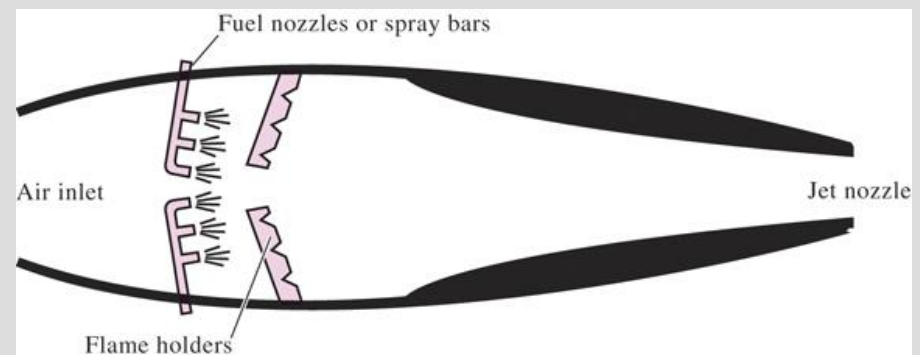
$$X_{\text{dest}} = T_0 S_{\text{gen}} = T_0(\Delta S_{\text{sys}} - S_{\text{in}} + S_{\text{out}})$$
$$= T_0\left[(S_2 - S_1)_{\text{sys}} - \frac{Q_{\text{in}}}{T_{b,\text{in}}} + \frac{Q_{\text{out}}}{T_{b,\text{out}}} \right] \quad (\text{kJ})$$

Exergy destruction for a closed system

$$\dot{X}_{\text{dest}} = T_0\dot{S}_{\text{gen}} = T_0(\dot{S}_{\text{out}} - \dot{S}_{\text{in}}) = T_0\left(\sum_{\text{out}} \dot{m}s - \sum_{\text{in}} \dot{m}s - \frac{\dot{Q}_{\text{in}}}{T_{b,\text{in}}} + \frac{\dot{Q}_{\text{out}}}{T_{b,\text{out}}} \right) \quad (\text{kW})$$

For a steady-flow system

$$X_{\text{dest}} = T_0 s_{\text{gen}} = T_0\left(s_e - s_i - \frac{q_{\text{in}}}{T_{b,\text{in}}} + \frac{q_{\text{out}}}{T_{b,\text{out}}} \right) \quad (\text{kJ/kg})$$

Steady-flow, one-inlet, one-exit

$$x_{\text{dest}} = T_0\left(\sum \frac{q_{\text{out}}}{T_{b,\text{out}}} - \sum \frac{q_{\text{in}}}{T_{b,\text{in}}} \right) \quad (\text{kJ/kg})$$

Exergy destruction of a cycle

$$x_{\text{dest}} = T_0\left(\frac{q_{\text{out}}}{T_L} - \frac{q_{\text{in}}}{T_H} \right) \quad (\text{kJ/kg})$$

For a cycle with heat transfer only with a source and a sink

$$\phi = (u - u_0) - T_0(s - s_0) + P_0(v - v_0) + \frac{V^2}{2} + gz$$

Closed system exergy

$$\psi = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

Stream exergy

A second-law analysis of these cycles reveals where the largest irreversibilities occur and where to start improvements.

Summary

- Basic considerations in the analysis of power cycles
- The Carnot cycle and its value in engineering
- Air-standard assumptions
- An overview of reciprocating engines
- Otto cycle: The ideal cycle for spark-ignition engines
- Diesel cycle: The ideal cycle for compression-ignition engines
- Stirling and Ericsson cycles
- Brayton cycle: The ideal cycle for gas-turbine engines
- The Brayton cycle with regeneration
- The Brayton cycle with intercooling, reheating, and regeneration
- Ideal jet-propulsion cycles
- Second-law analysis of gas power cycles