ESO 201A: Thermodynamics

2016-2017-I semester

Gas Power Cycle: part 4

Dr. Jayant K. Singh
Department of Chemical Engineering
Faculty Building 469,
Telephone: 512-259-6141
E-Mail: jayantks@iitk.ac.in
home.iitk.ac.in/~jayantks/ESO201/index.html

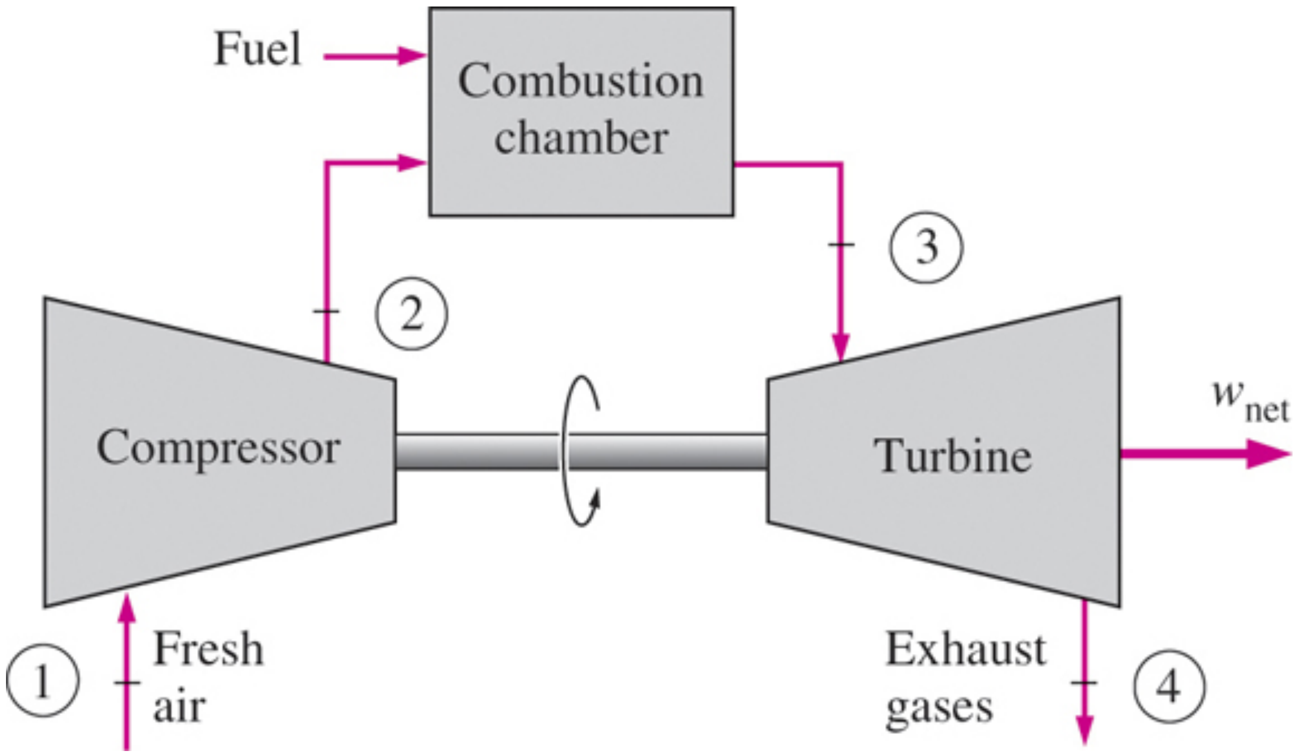
Learning Objectives

- 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, and Brayton cycles.

Brayton Cycle: The Ideal Cycle for Gas Turbine Engines

Ideal Brayton Cycle

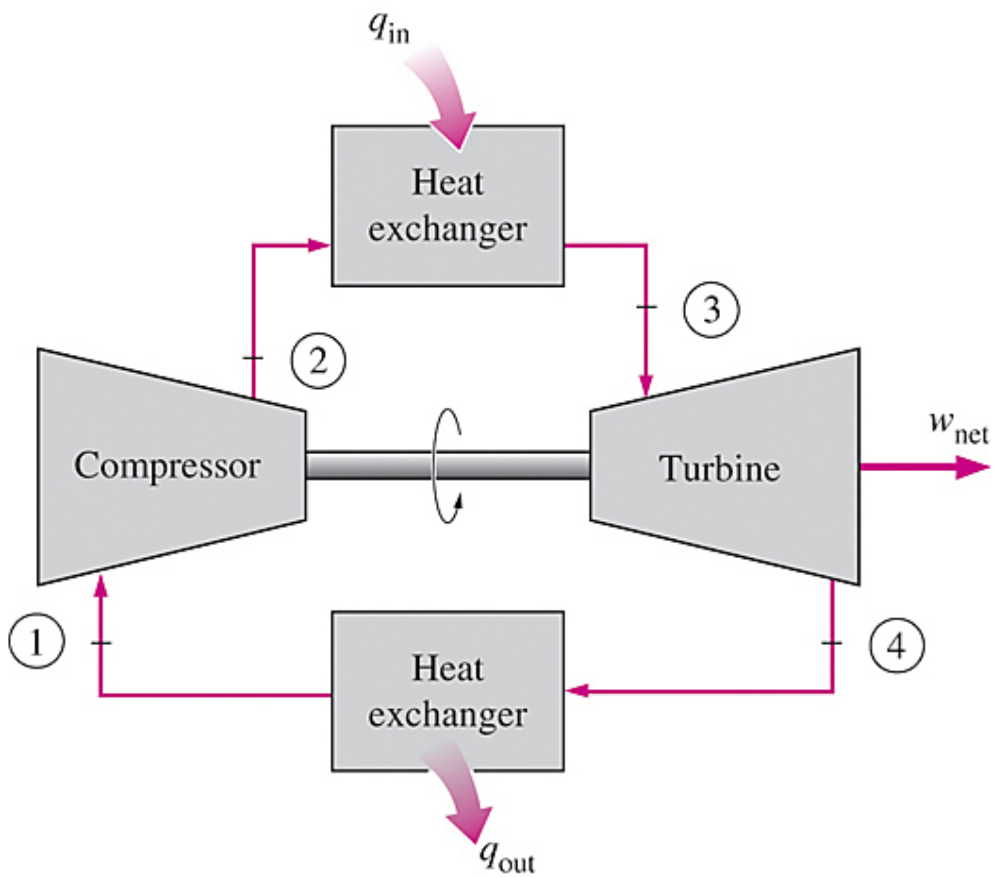
- In reality, gas turbines operate on an open cycle
- Fresh air is continuously drawn into the compressor and exhaust gases are thrown out



Brayton Cycle: The Ideal Cycle for Gas Turbine Engines

Ideal Brayton Cycle (cont.)

- The open gas-turbine cycle can be modeled as a closed cycle
- The combustion process is replaced by a constant-pressure heat-addition process and the exhaust process is replaced by a constant-pressure heat-rejection process



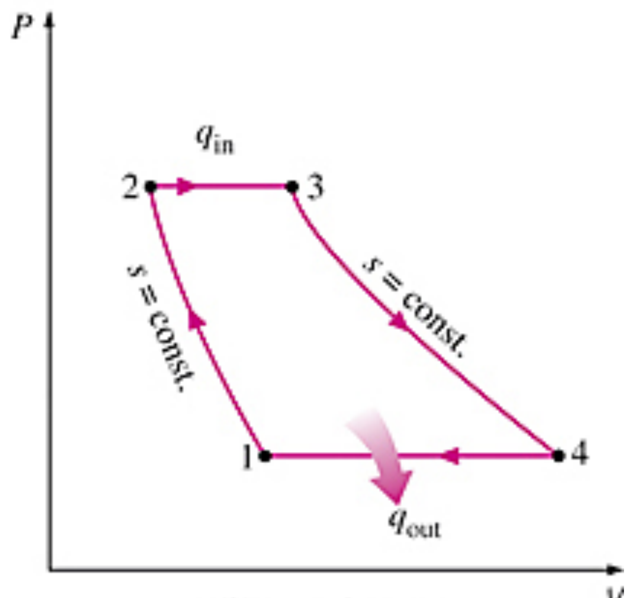
Brayton Cycle: The Ideal Cycle for Gas Turbine Engines

Ideal Brayton Cycle (cont.)

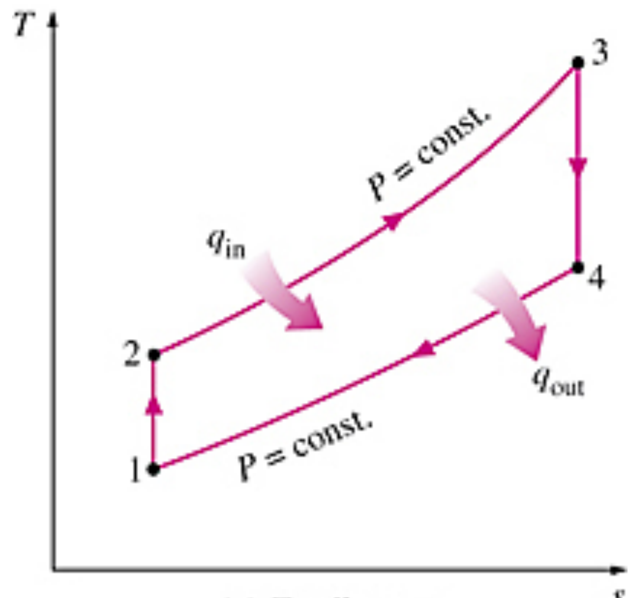
- The idealized closed loop cycle is the Brayton cycle, which consists of the following four internally reversible processes

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

- The corresponding *P-v* and *T-s* diagrams are shown below



(*b*) *P-v* diagram



(*a*) *T-s* diagram

Brayton Cycle: The Ideal Cycle for Gas Turbine Engines

Thermodynamic Analysis

- The four processes of the Brayton cycle are executed in steady-flow devices
- When changes in kinetic and potential energies are neglected, the energy balance for one of the processes can be expressed as

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

- Therefore, heat transfers to and from the working fluid are

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

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

Brayton Cycle: The Ideal Cycle for Gas Turbine Engines

Thermal Efficiency

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

$$\eta_{\text{th, Brayton}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}}$$

$$= 1 - \frac{c_p\left(T_4 - T_1\right)}{c_p\left(T_3 - T_2\right)}$$

$$= 1 - \frac{T_1\left(T_4/T_1 - 1\right)}{T_2\left(T_3/T_2 - 1\right)}$$

- Processes $1 \rightarrow 2$ and $3 \rightarrow 4$ are isentropic, and $P_2 = P_3$ and $P_4 = P_1$

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

Brayton Cycle: The Ideal Cycle for Gas Turbine Engines

Thermal Efficiency (cont.)

- Substituting these expressions into the thermal efficiency relation yields

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

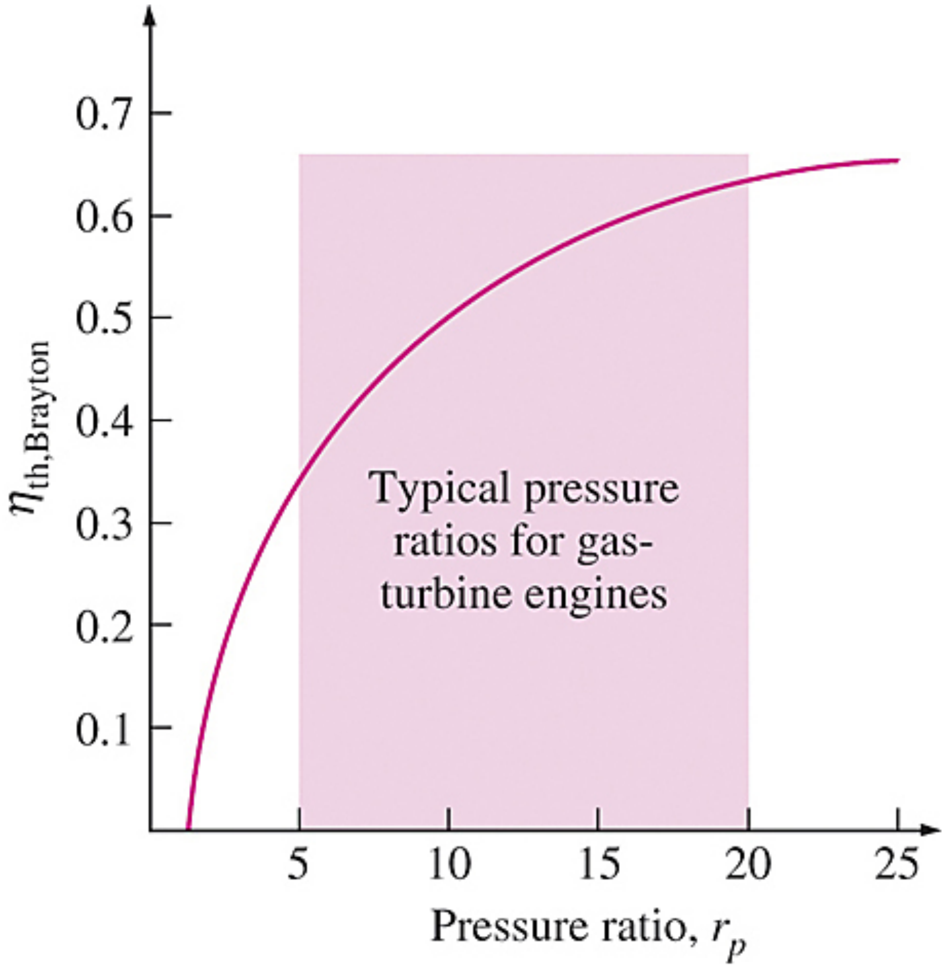
- Where r_P is the pressure ratio

$$r_P = \frac{P_2}{P_1}$$

Brayton Cycle: The Ideal Cycle for Gas Turbine Engines

Thermal Efficiency (cont.)

- The thermal efficiency increases with both the pressure ratio (r_P) and the specific heat ratio (k)
- The plot to the right shows the thermal efficiency as a function of the compression ratio
- The two major application areas of gas-turbine engines are aircraft propulsion and electric power generation



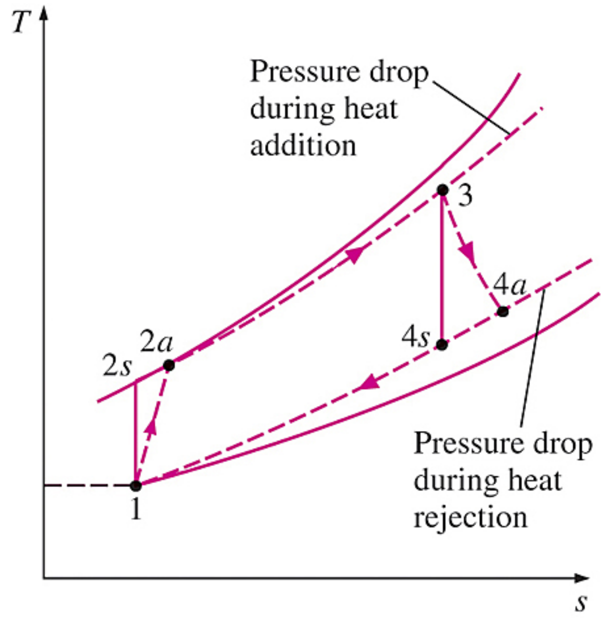
Brayton Cycle: The Ideal Cycle for Gas Turbine Engines

Deviation of Actual Gas-Turbine Cycles from Idealized Ones

- The deviation of actual compressor and turbine behavior, due to irreversibility, can be accurately accounted for by utilizing the isentropic efficiencies of the turbine and compressor

$$\eta_C = \frac{w_s}{w_a} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad \text{and} \qquad \eta_T = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

- The actual and isentropic states of a gas-turbine cycle are illustrated below



Problem

Air is used as the working fluid in a simple ideal Brayton cycle that has a pressure ratio of 12, a compressor inlet temperature of 300 K, and a turbine inlet temperature of 1000 K. Determine the required mass flow rate of air for a net power output of 70 MW, assuming both the compressor and the turbine have an isentropic efficiency of (*a*) 100 percent and (*b*) 85 percent. Assume constant specific heats at room temperature.

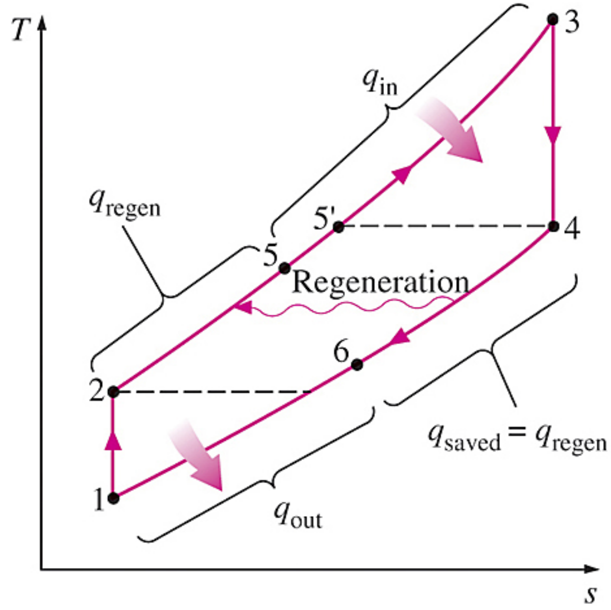
Properties The properties of air at room temperature are $c_p = 1.005$ kJ/kg·K and $k = 1.4$ (Table A-2).

THE BRAYTON CYCLE WITH REGENERATION

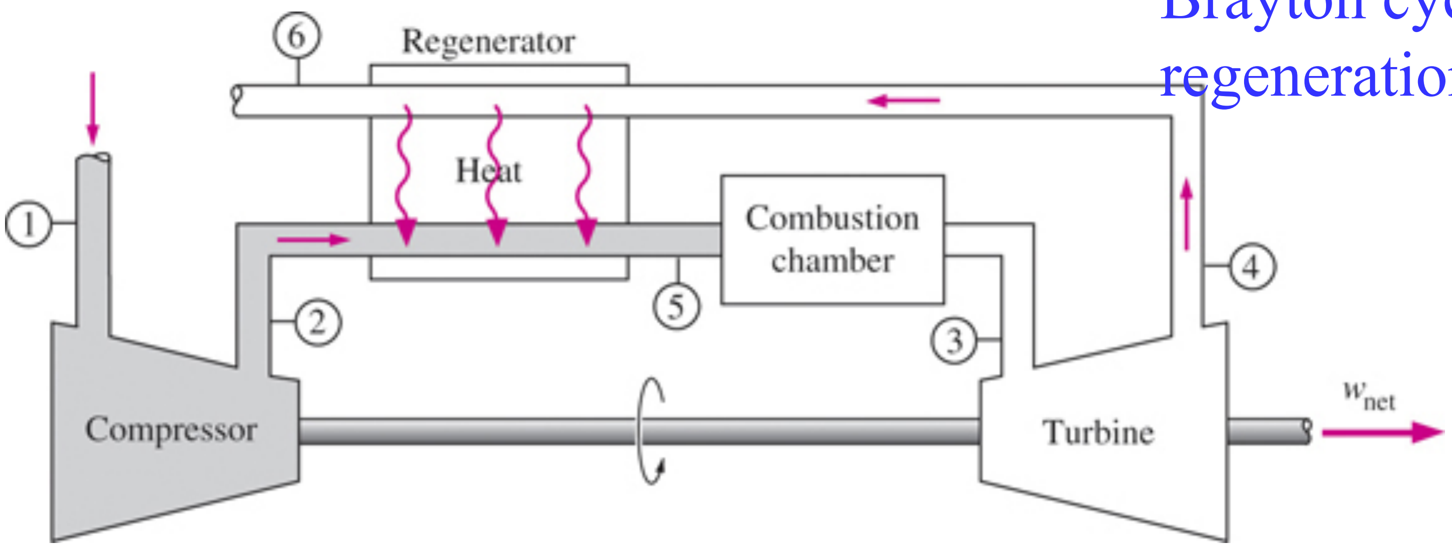
In gas-turbine engines, the temperature of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the compressor.

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.

Summary

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