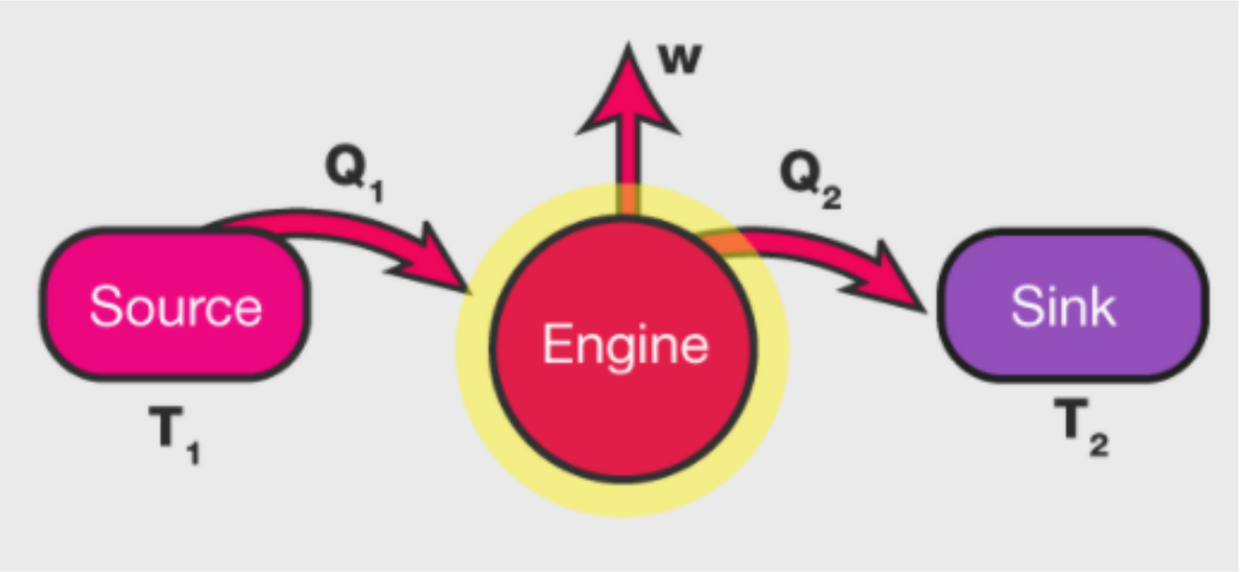
Chemical Engineering Thermodynamics

Lecture 6 Heat Engine

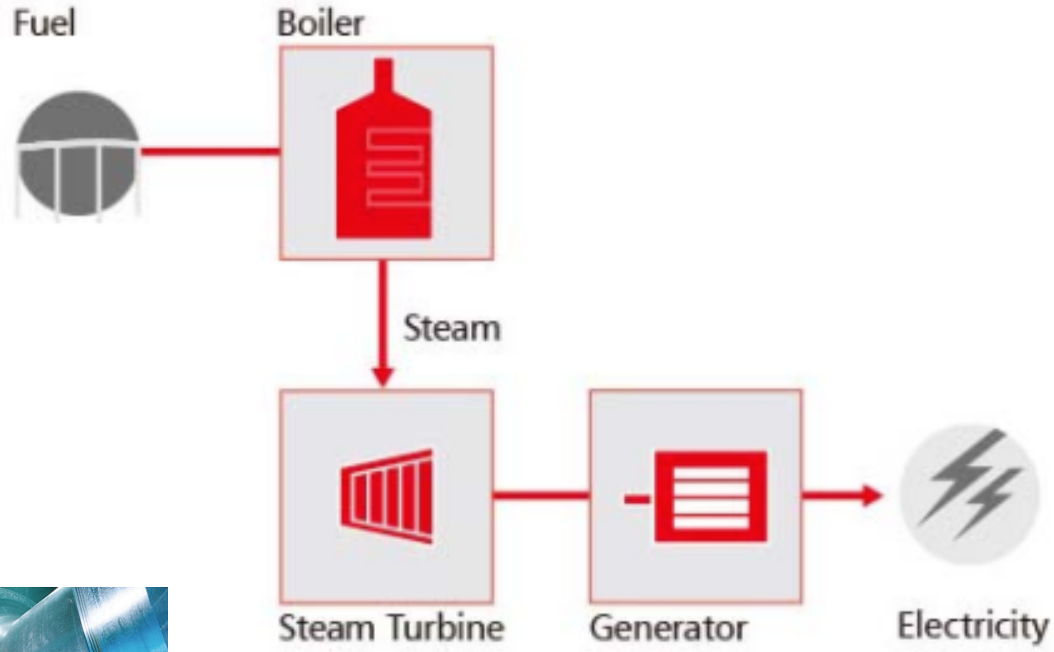
Xiaofei Xu



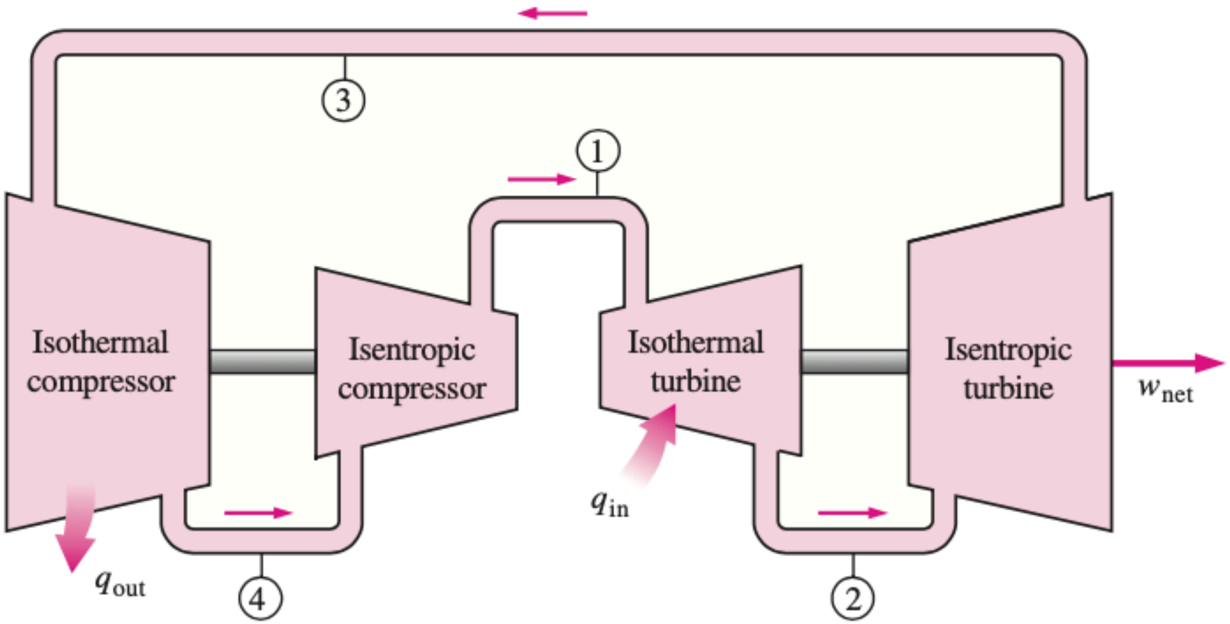
Power Cycles

- Heat Engines: The devices or systems used to produce a net power output
- Power cycles: Thermodynamic cycles of heat engines
- Refrigerators / heat pumps: The devices or systems used to produce a refrigeration effect; refrigeration cycles
- Gas cycles: working fluid is the gas phase
- Vapor cycles: working fluid is vapor/liquid

Steam Power Plant



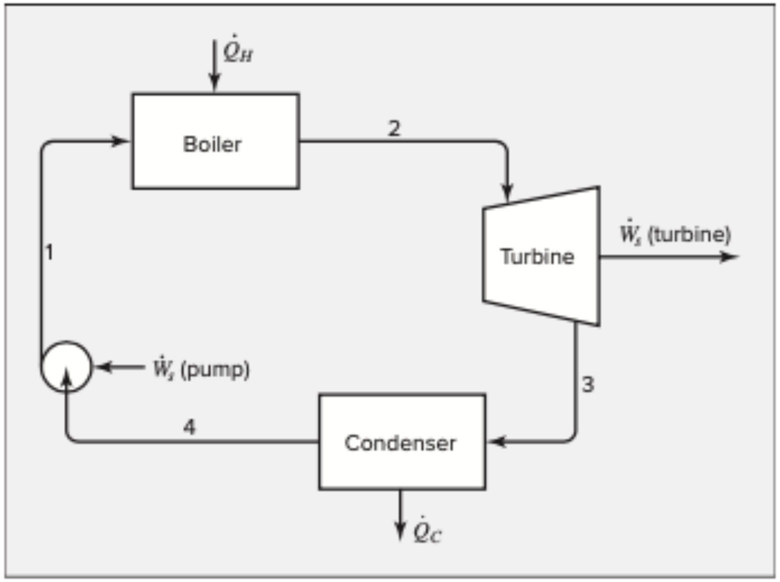
Steam Turbine

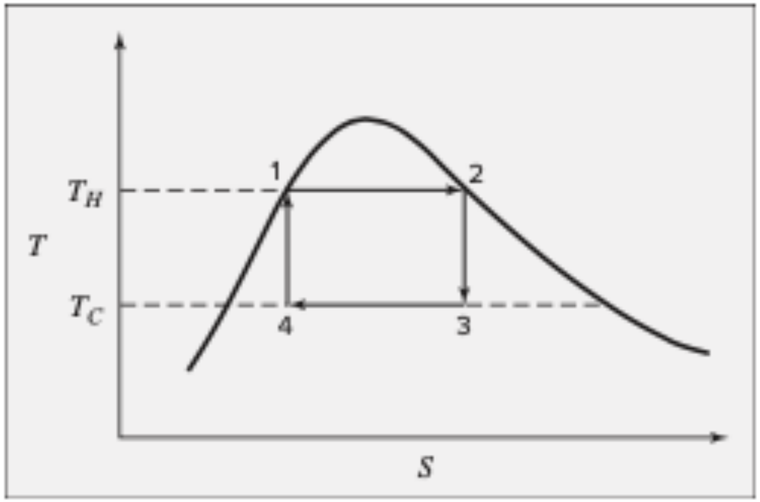


A steady flow Carnot engine

Steam Power Plant

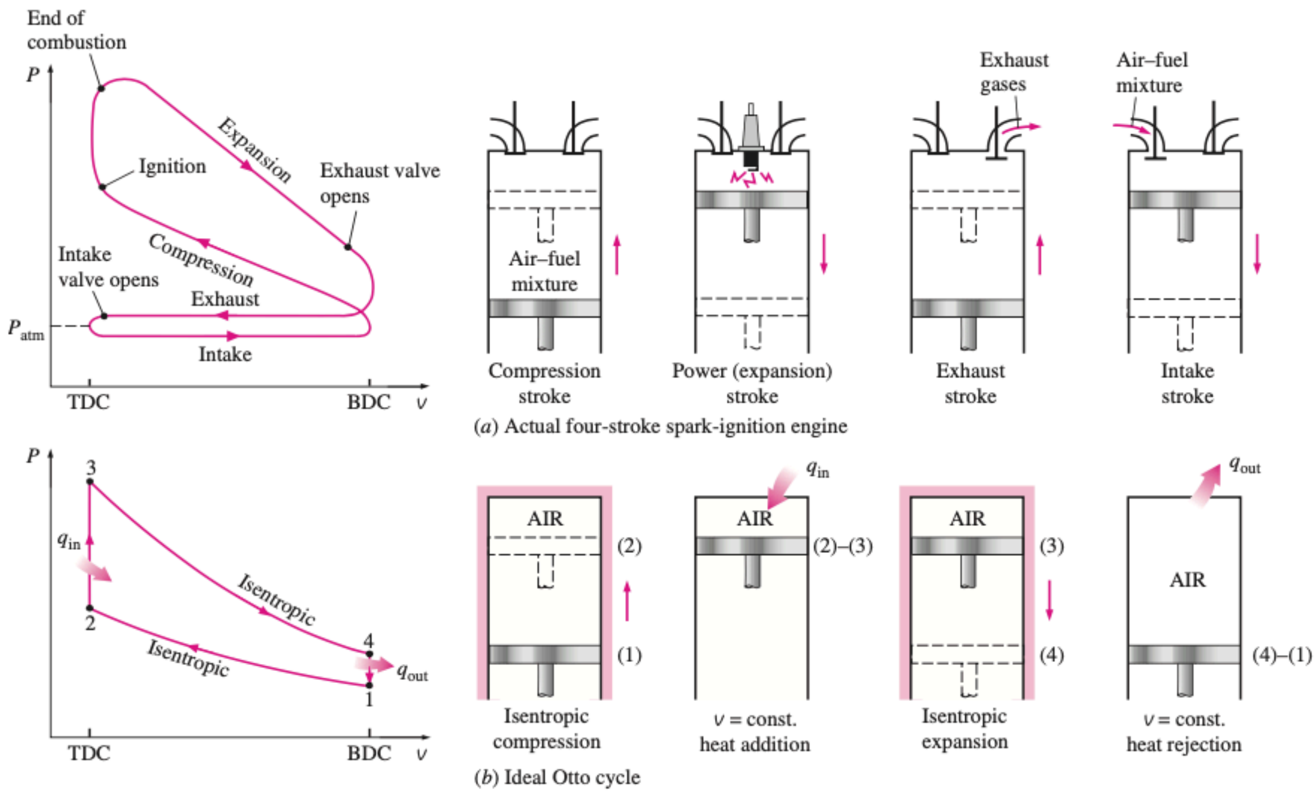
- Steady-state steady-flow cyclic process



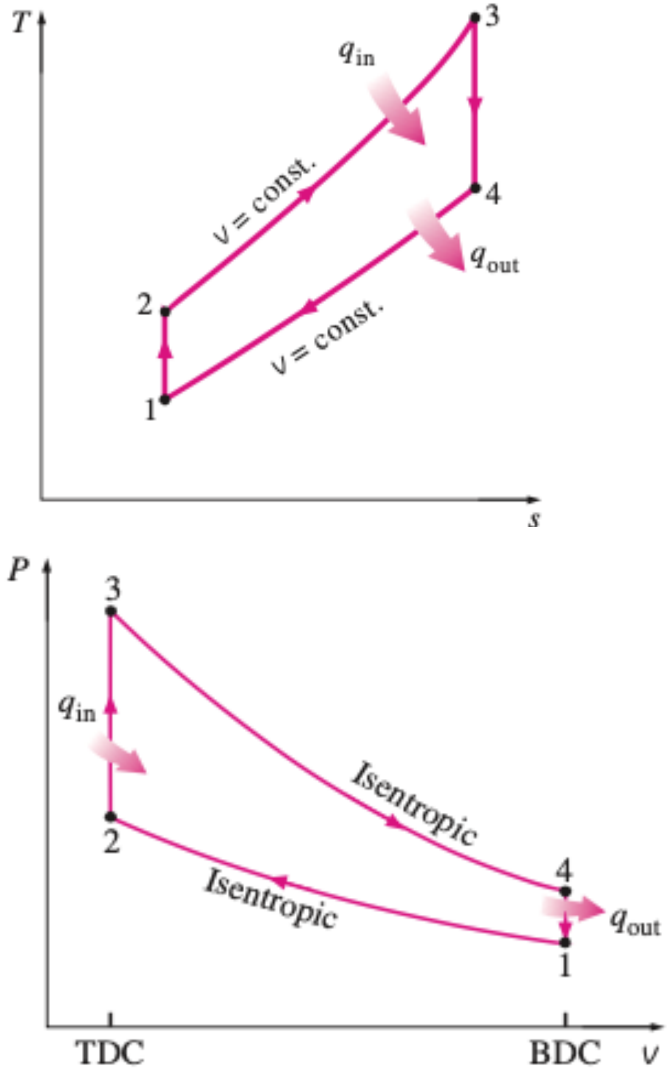


The Otto Cycle

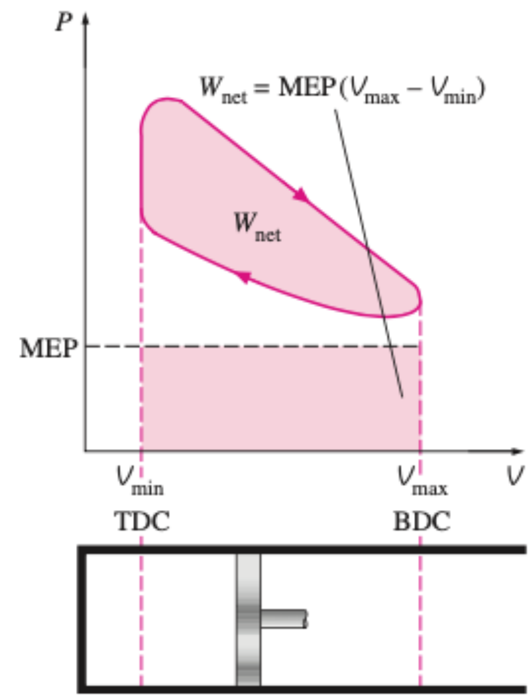
- The ideal cycle for spark-ignition engines
- Four-stroke internal combustion engines



The Ideal Otto Cycle



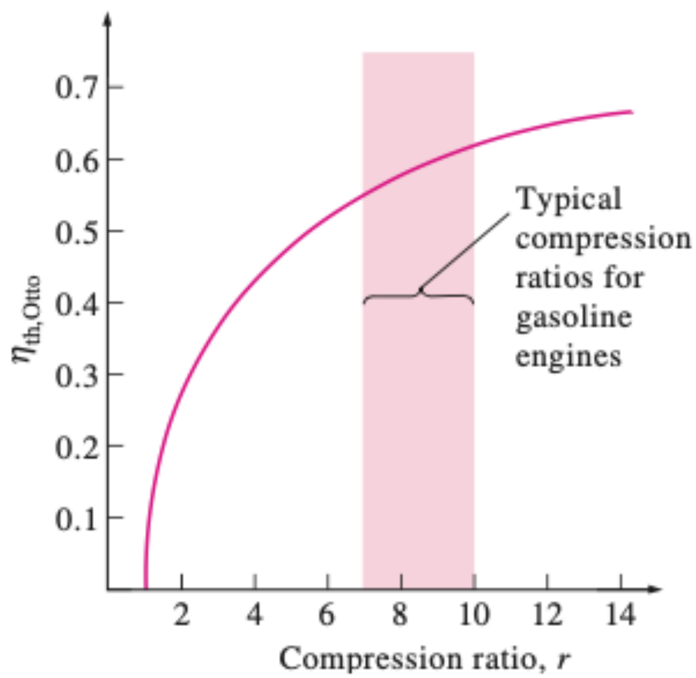
1-2 Isentropic compression
2-3 Constant-volume heat addition
3-4 Isentropic expansion
4-1 Constant-volume heat rejection

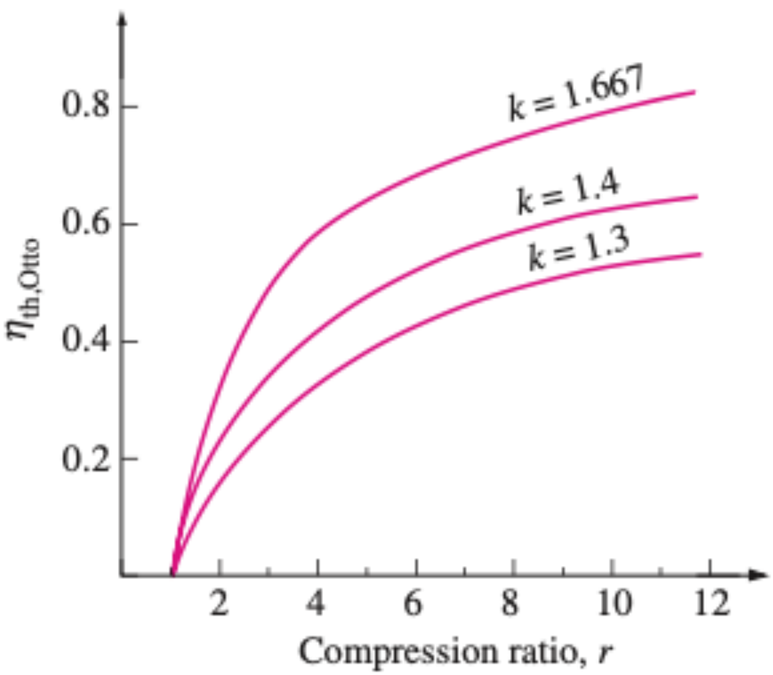


The Ideal Otto Cycle

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

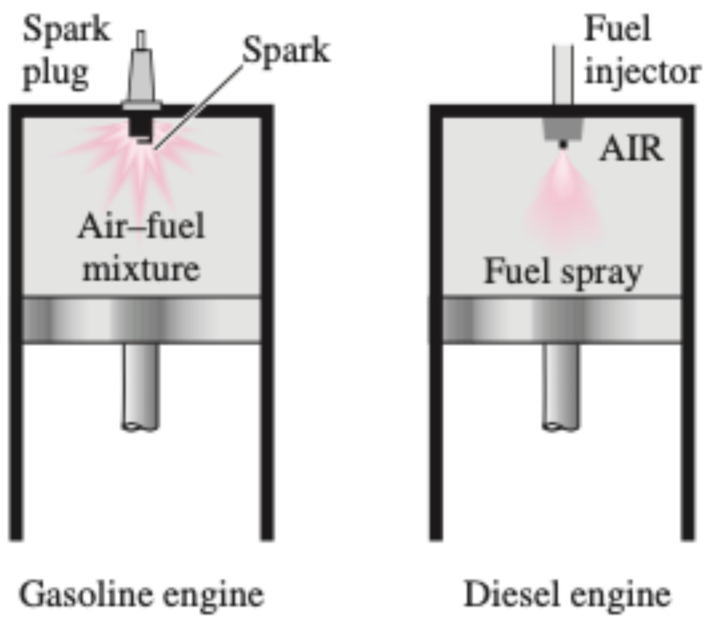
$$r = \frac{V_{\max}}{V_{\min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2}$$





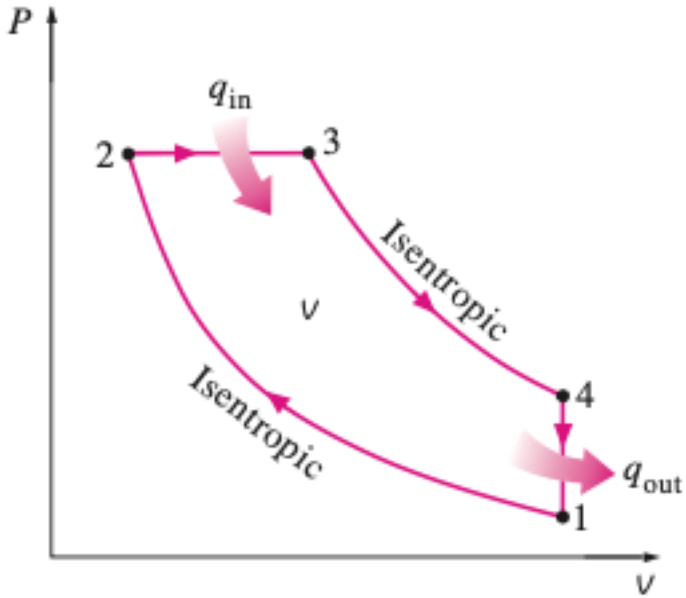
The Diesel Cycle

- In Diesel engines, the spark plug is replaced by a fuel injector, and only air is compressed during the compression process.

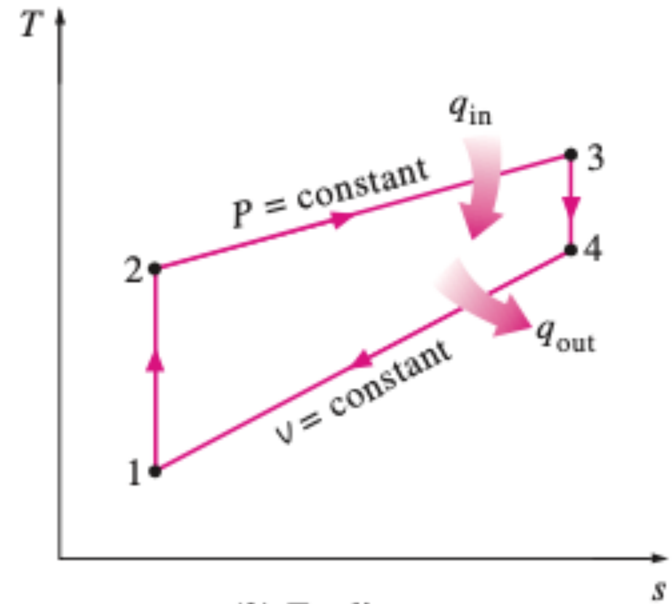


$T <$ autoignition $\quad T >$ autoignition

The Ideal Diesel Cycle



(*a*) *P*- v diagram



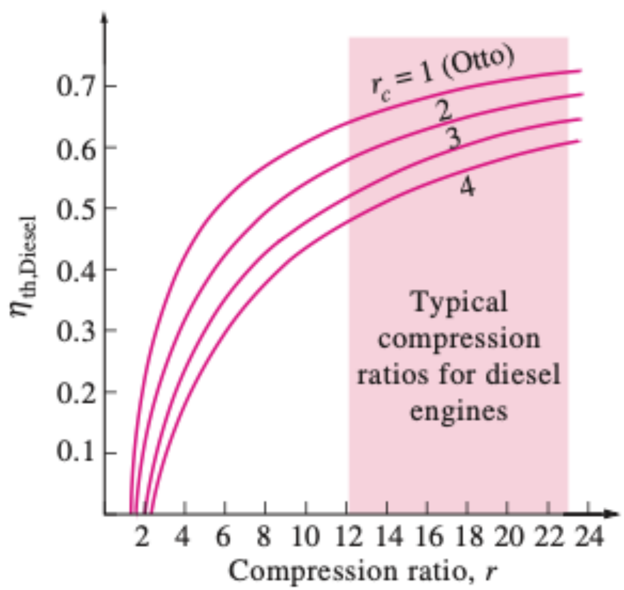
(*b*) *T*-*s* diagram

The Ideal Diesel Cycle of Ideal Gas

- Thermal efficiency

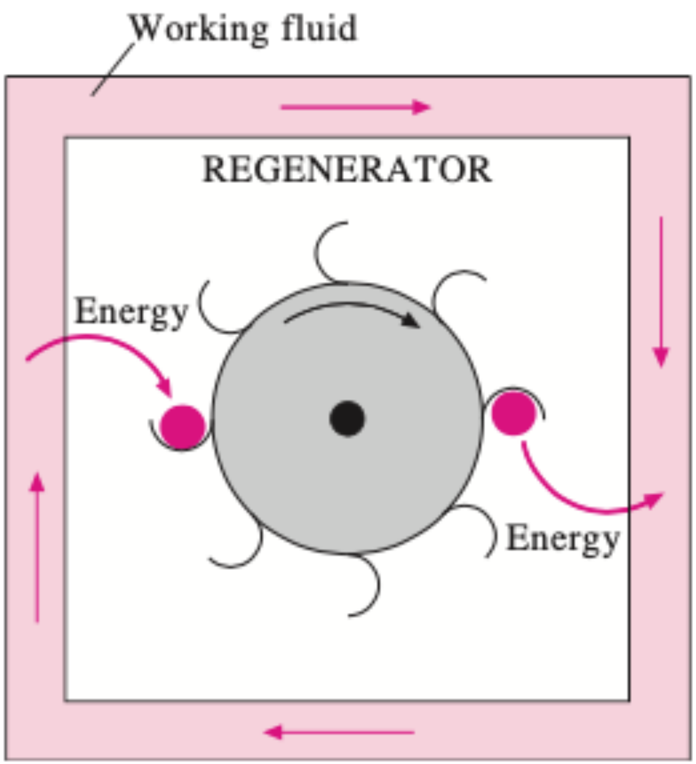
$$\eta = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$$

- r: compression ratio
- r_c: cutoff ratio

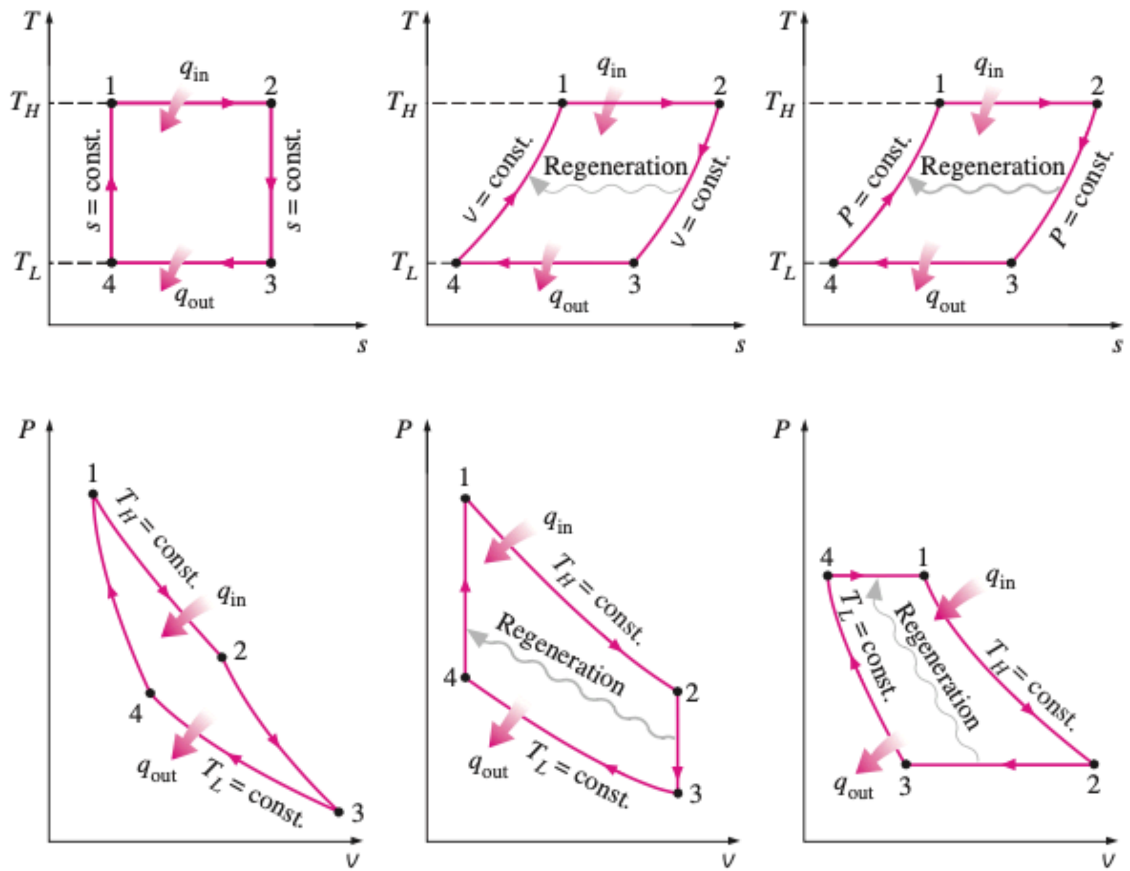


Regenerator

- Borrows energy from the working fluid during one part of the cycle and pays it back during another part.



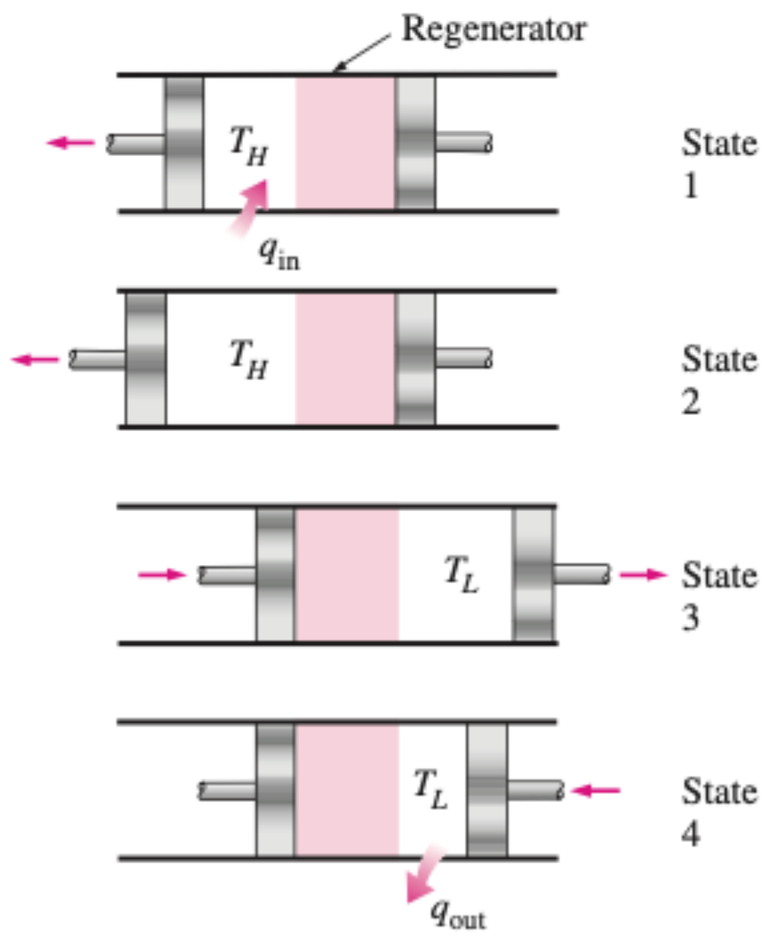
Stirling and Ericsson Cycles



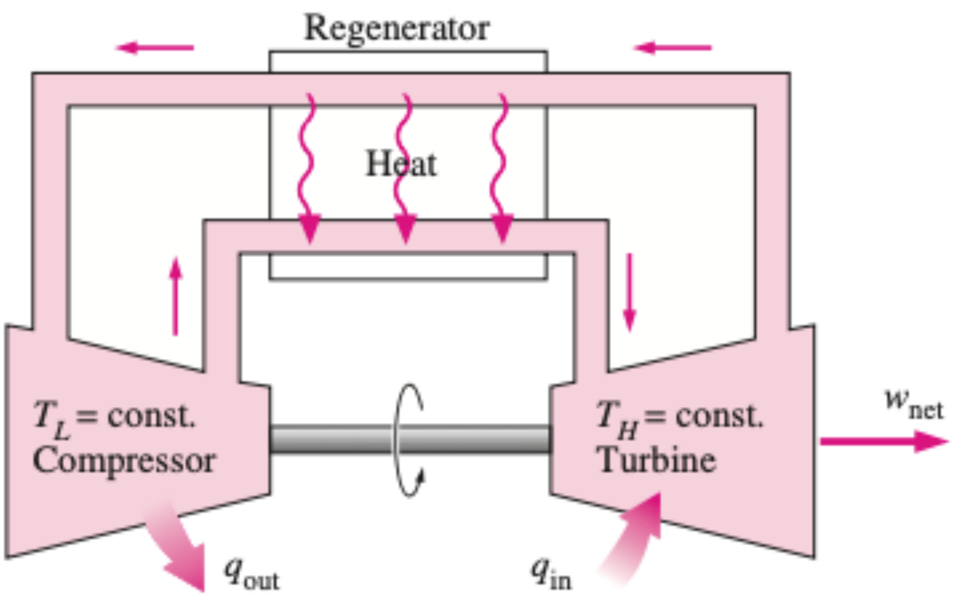
(a) Carnot cycle (b) Stirling cycle (c) Ericsson cycle

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

Stirling Cycle



Ericsson Engine



Ideal Brayton Cycle

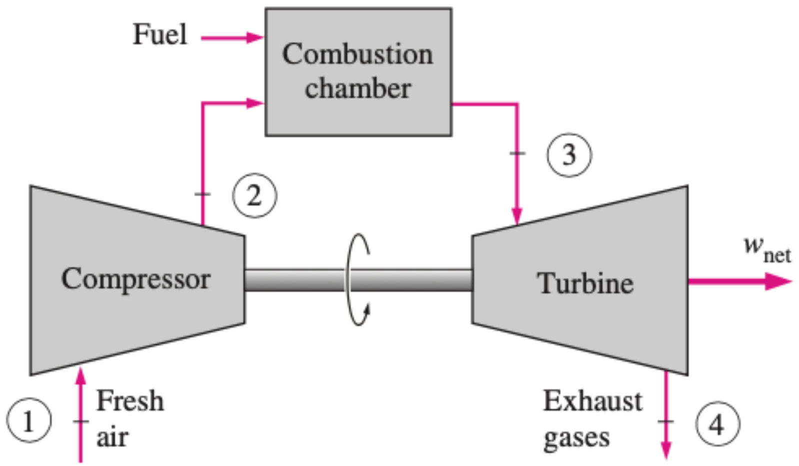
- The ideal cycle for gas-turbine engines

  1-2 Isentropic compression (in a compressor)

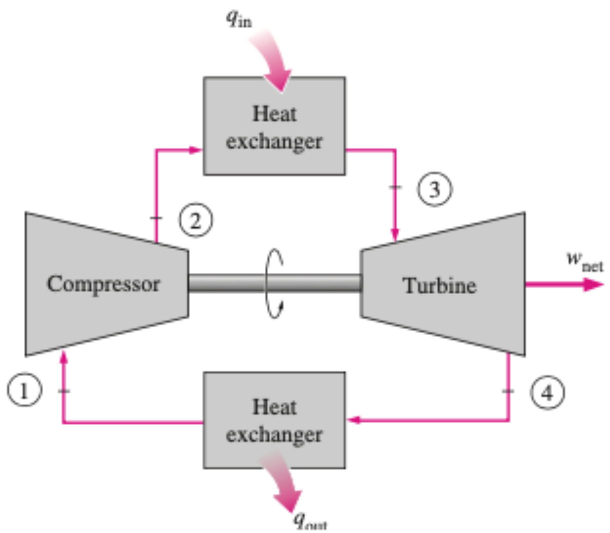
  2-3 Constant-pressure heat addition

  3-4 Isentropic expansion (in a turbine)

  4-1 Constant-pressure heat rejection

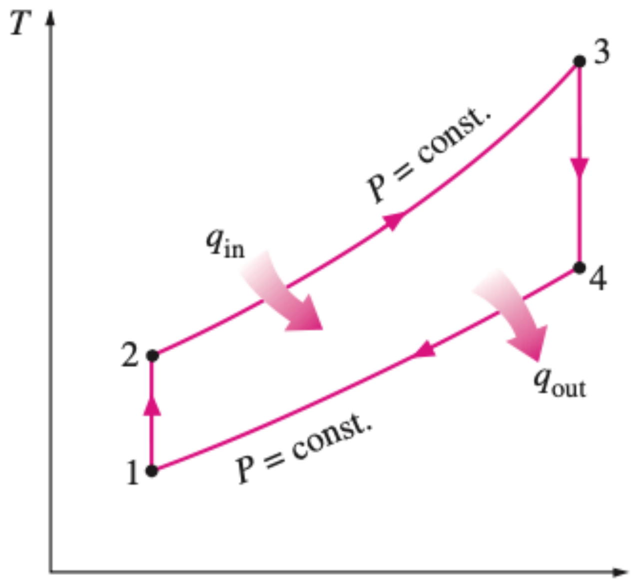


open-cycle

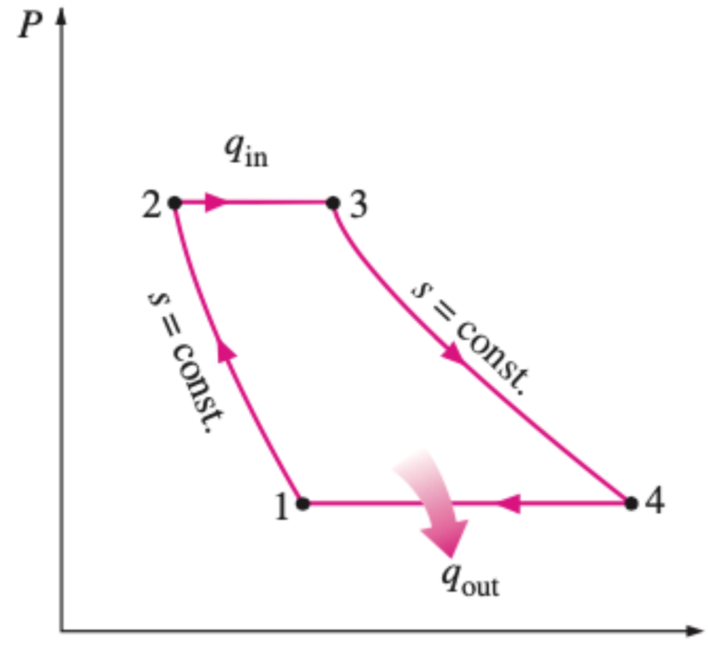


closed-cycle

Ideal Brayton Cycle



(a) T-s diagram



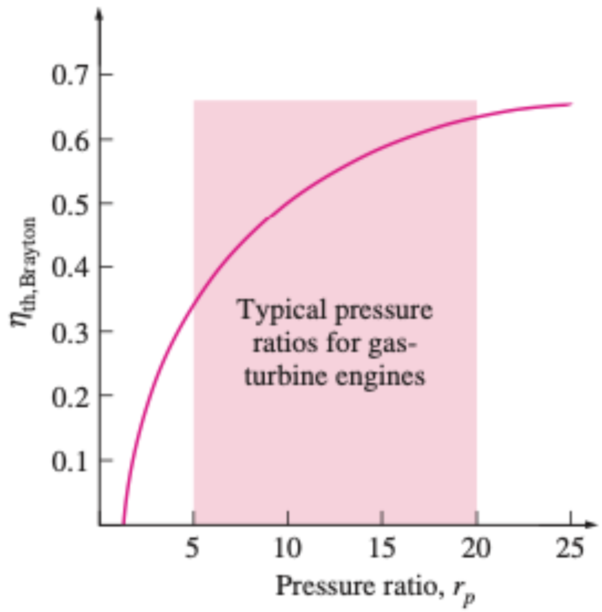
(b) P-v diagram

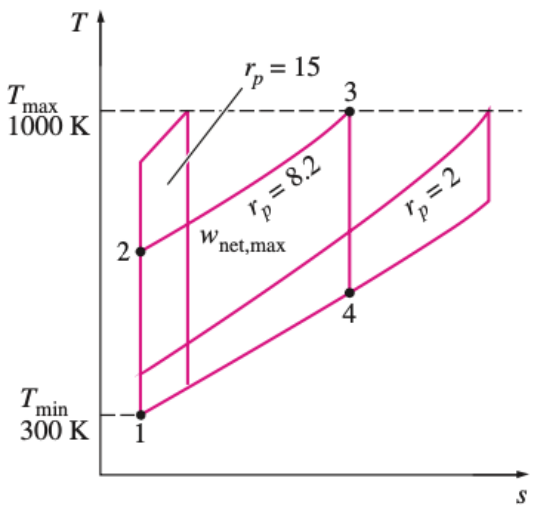
Thermal efficiency: $\eta_{th,Brayton} = 1 - \frac{1}{r_p^{\frac{k-1}{k}}}$

Pressure ratio: $r_p = \frac{P_2}{P_1}$

Ideal Brayton Cycle

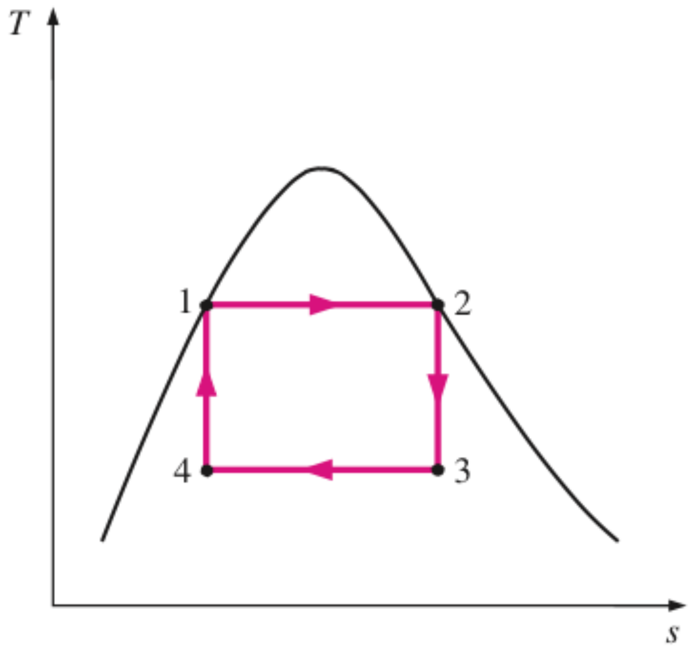
- For given T_1, T_3, the net work has a maximum value as $T_2 = T_4$.

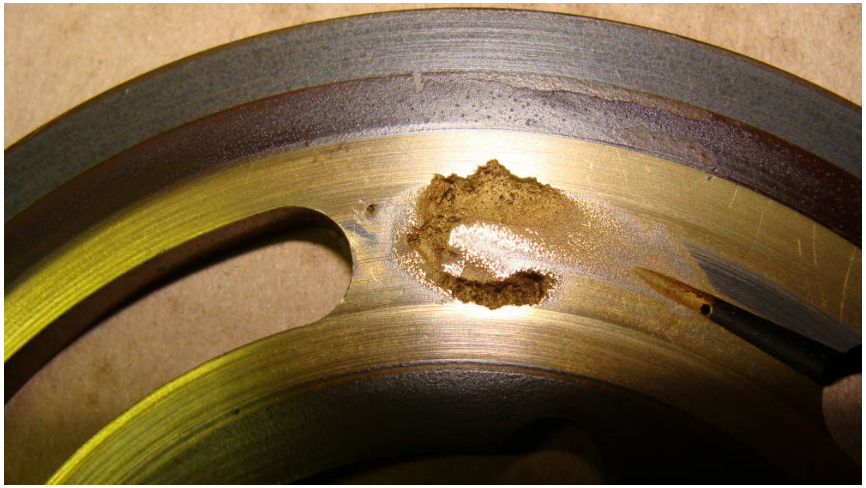




Motivation of Vapor Cycle

- Low thermal efficiency
- Nucleation of liquid bubble
- Handle with two phases.

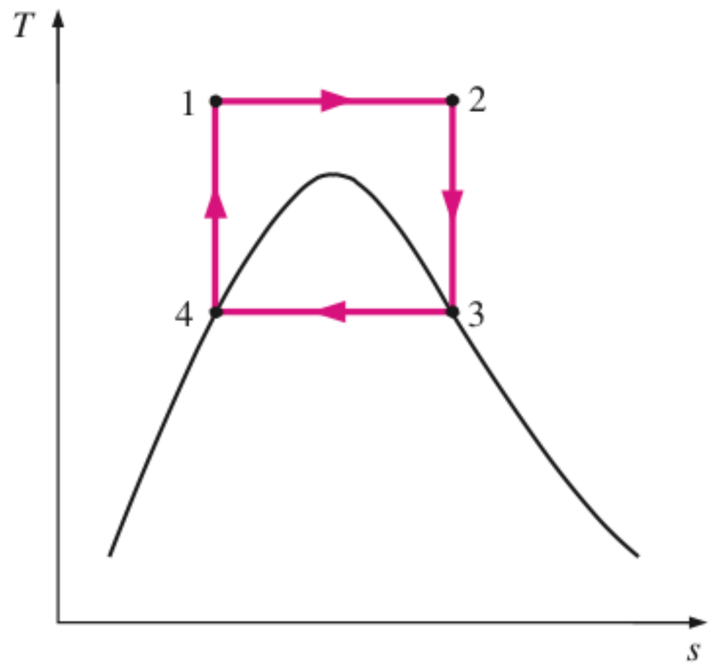




Cavitation Damage

Motivation of Vapor Cycle

- Working pressure is too high
- Isothermal process of 1 to 2 is not isobaric



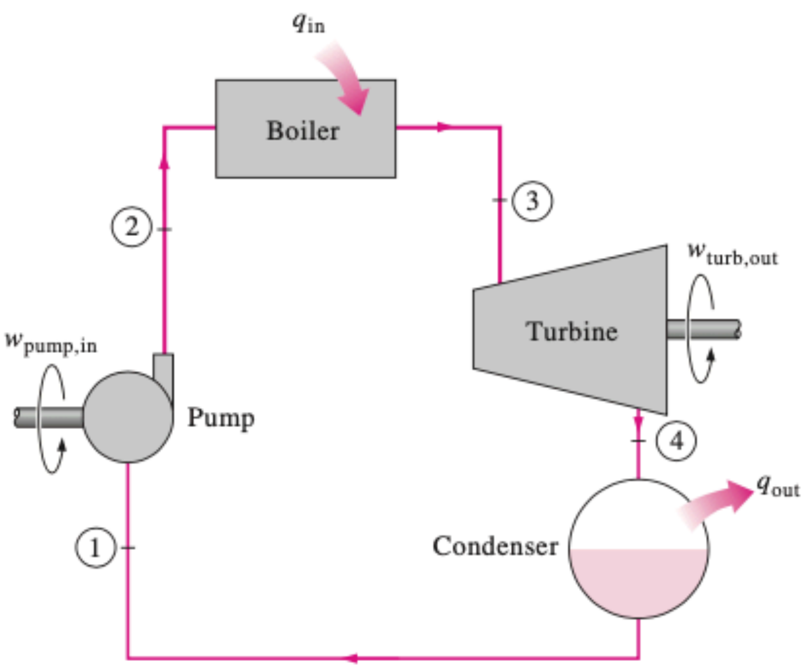
The Rankine Cycle

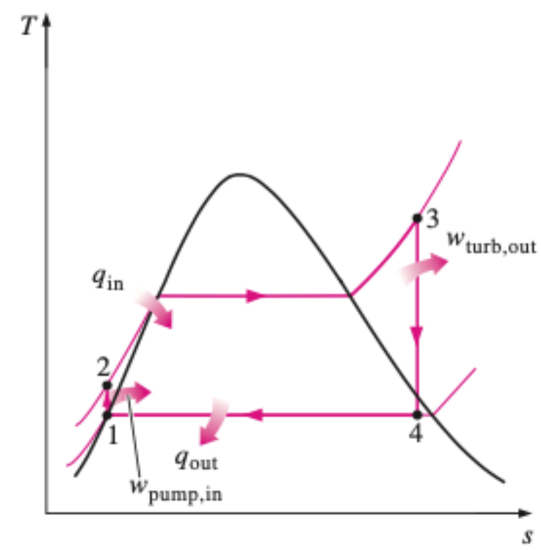
1-2 Isentropic compression in a pump

2-3 Constant pressure heat addition in a boiler

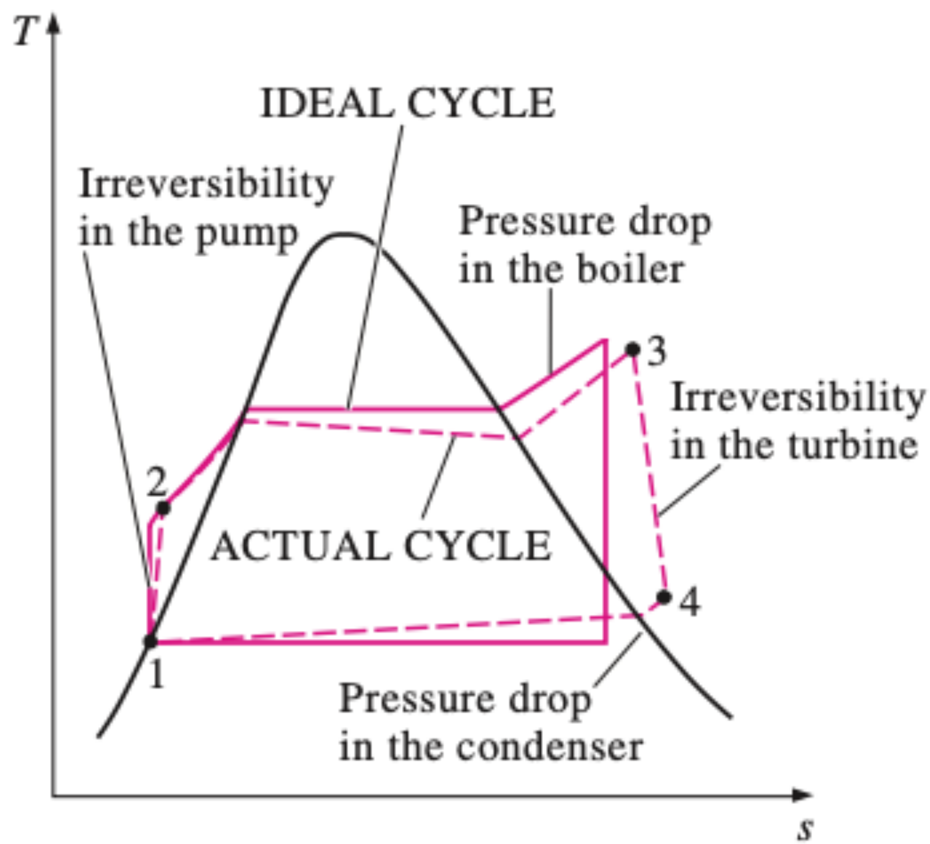
3-4 Isentropic expansion in a turbine

4-1 Constant pressure heat rejection in a condenser





Actual Vapor Power Cycle



(a)

Example

Steam generated in a power plant at a pressure of 8600 kPa and a temperature of 500°C is fed to a turbine. Exhaust from the turbine enters a condenser at 10 kPa, where it is condensed to saturated liquid, which is then pumped to the boiler.

(*a*) What is the thermal efficiency of a Rankine cycle operating at these conditions?

(*b*) What is the thermal efficiency of a practical cycle operating at these conditions if the turbine efficiency and pump efficiency are both 0.75?

(*c*) If the rating of the power cycle of part (*b*) is 80,000 kW, what is the steam rate and what are the heat-transfer rates in the boiler and condenser?

Increasing the Efficiency of the Rankine Cycle

- Lowering the condenser pressure
- Superheating the steam to high temperatures
- Increasing the boiler pressure