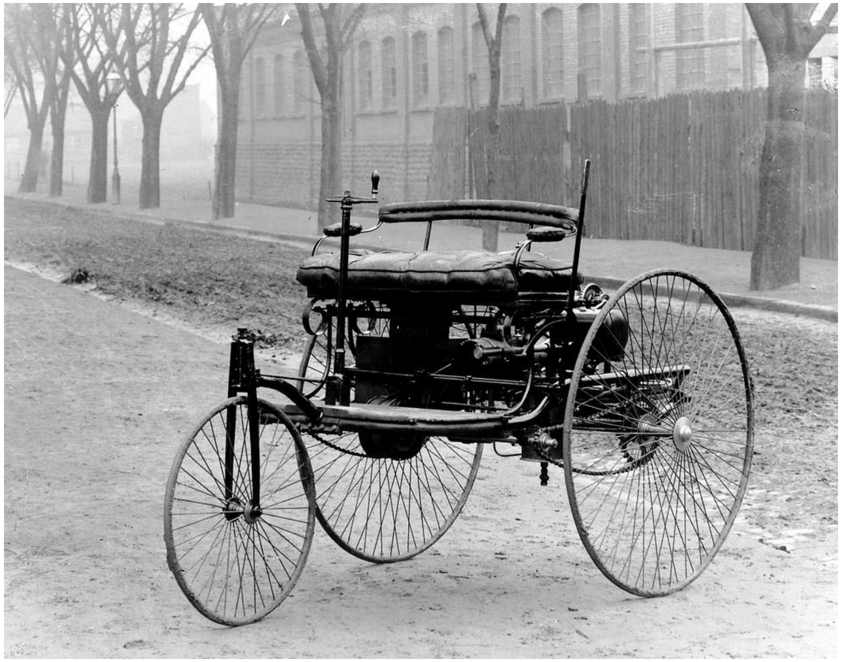
Gas Power Cycles

Ranjan Ganguly

In1894, the Times newspaper predicted… "In 50 years, every street in London will be buried under nine feet of manure."

The crisis would be soon over …

- Carl Benz



The original Benz Patent-Motorwagen, first built in 1885 and awarded the patent for the concept

Source: Wikipedia

https://clipartstation.com/air-pollution-from-cars-clipart-4/

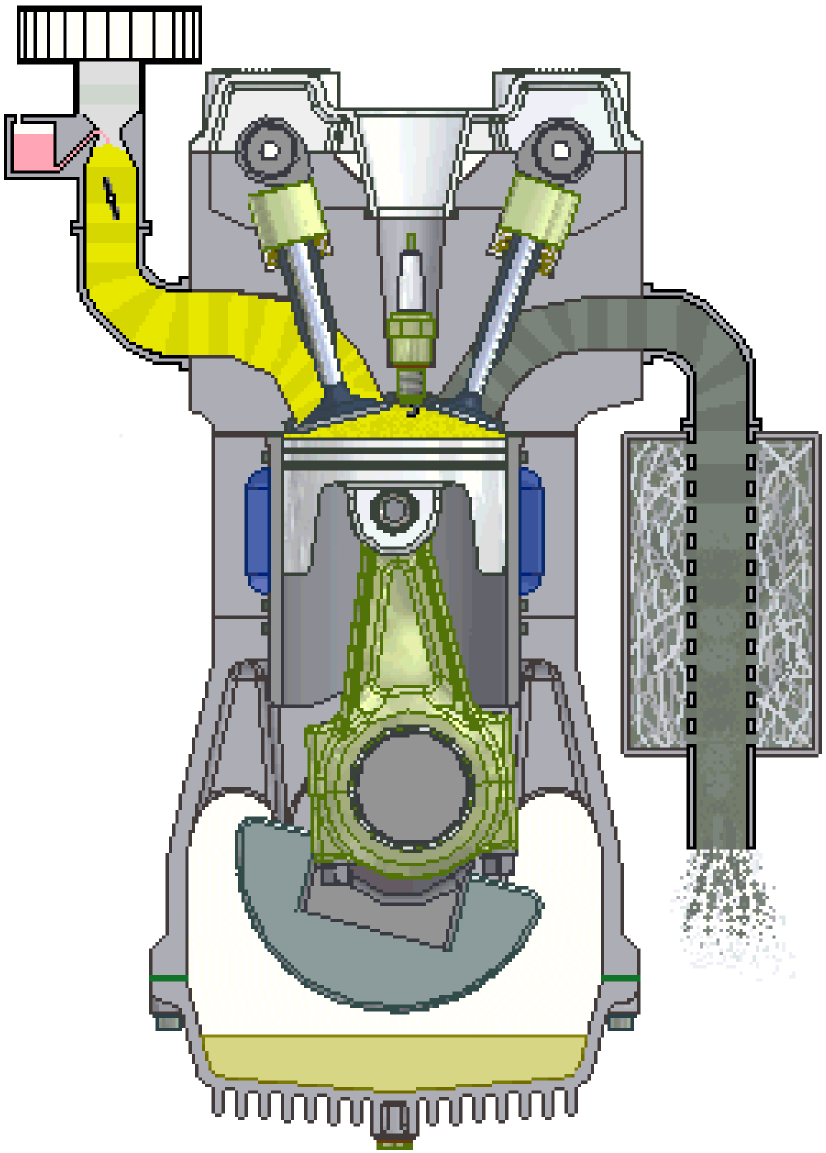
Classification of power cycles

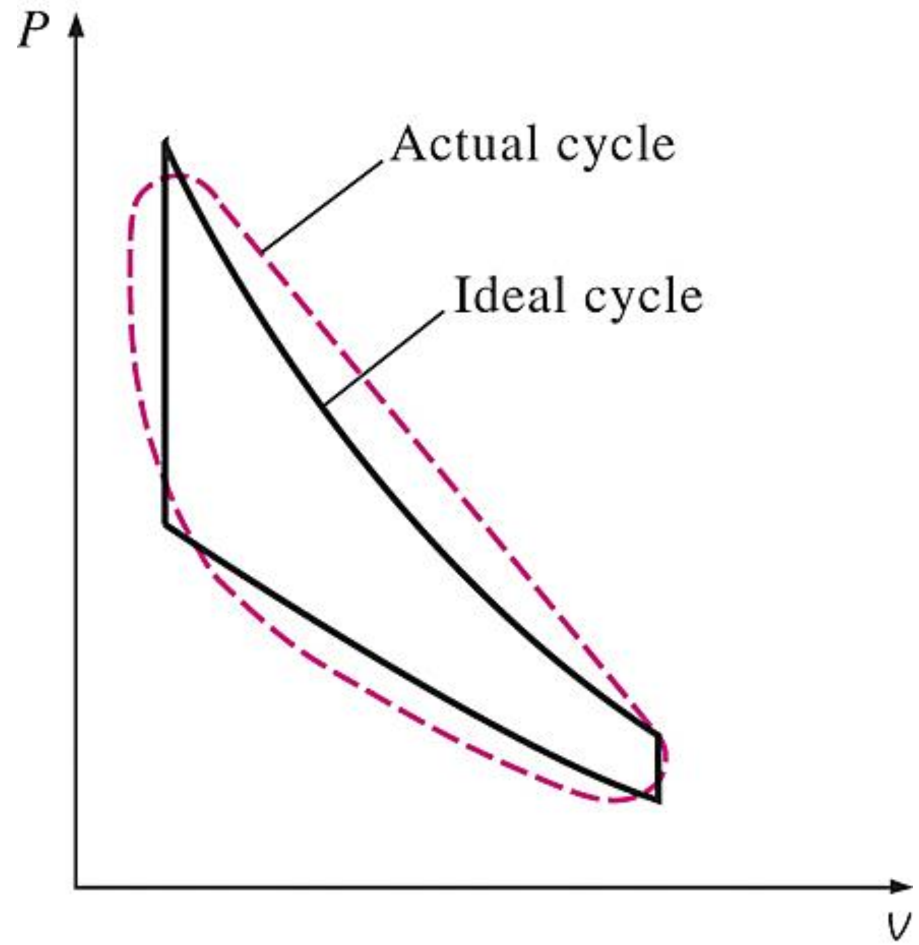
- Power Cycles
  - Gas vs vapor
  - Closed vs Open
  - Internal Combustion vs External Combustion
    - Coal fired power plant is an externally fired engine
    - IC engine is an internally fired engine
- Simple cycle vs Combined Cycles

Practical use of gas power cycle

- **Internal Combustion (IC) Engines**
  - Automobile engines
  - Small aircrafts
  - Ships
  - Locomotive engines
  - DG sets
  - …
- **Gas Turbines**
  - GT Power plants
  - Aircrafts
  - Big ships

Actual cycle vs Air Standard cycle





Almost the entire quantity of the working fluid is air:

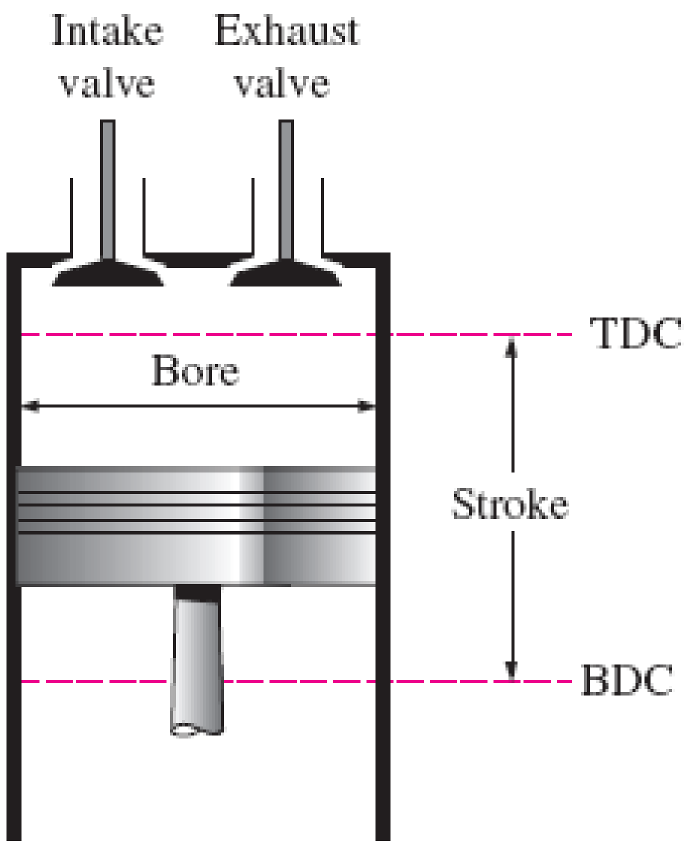
- Air Standard Cycle

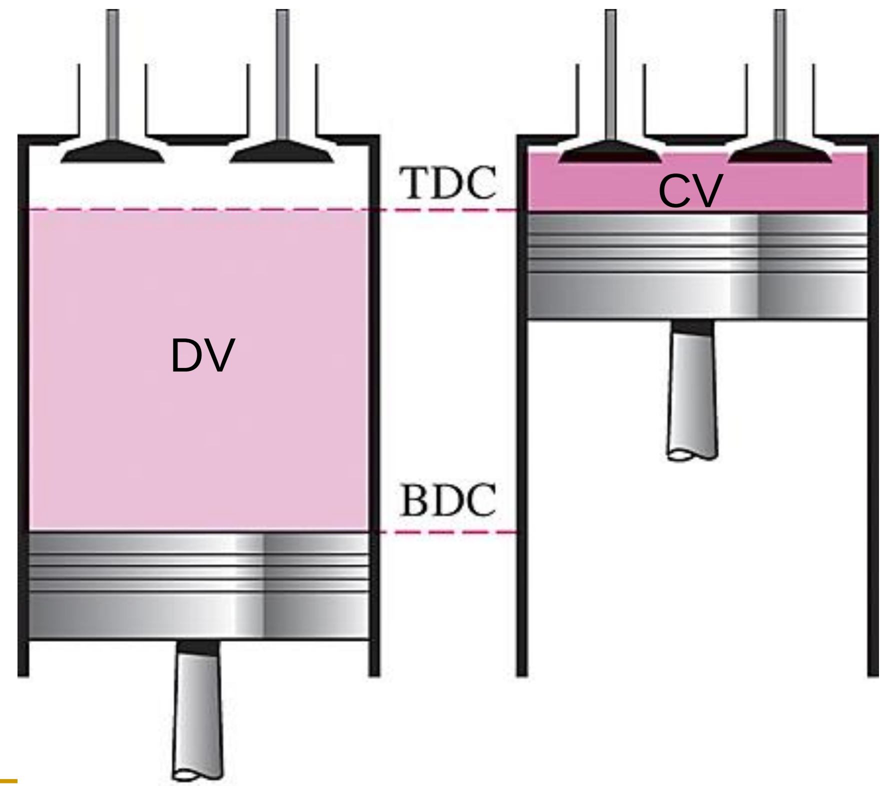
Air-Standard Assumptions

- Air is the working fluid, circulated in a closed loop, is an ideal gas
- All cycles, processes are internally reversible
- Combustion process replaced by heat-addition from external source
- Exhaust is replaced by heat rejection process which restores working fluid to initial state
- Air has constant specific heat

Engine Terms

- Top dead center
- Bottom dead center
- Bore
- Stroke





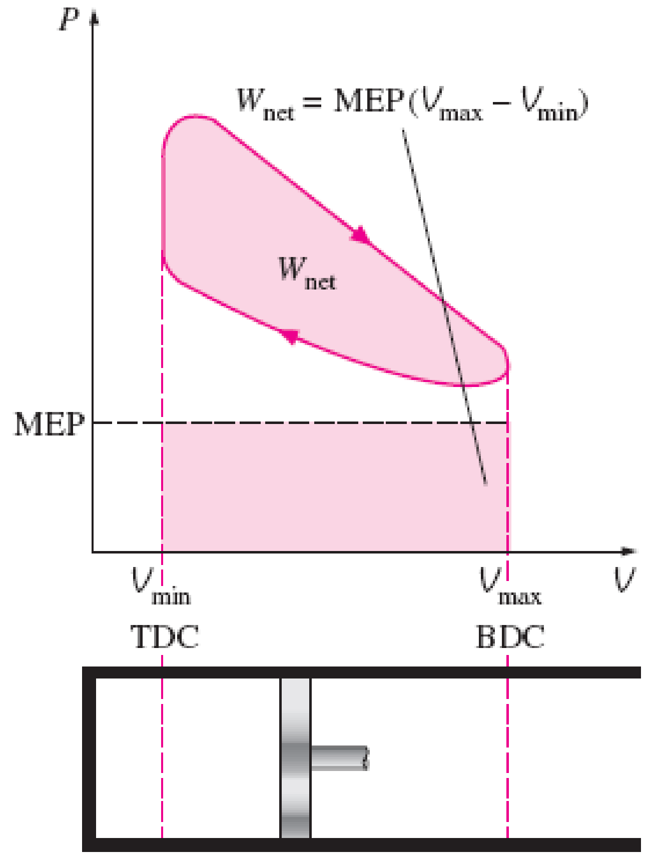
(*a*) Displacement volume

(*b*) Clearance volume

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

Engine Terms

- Mean effective pressure (MEP)



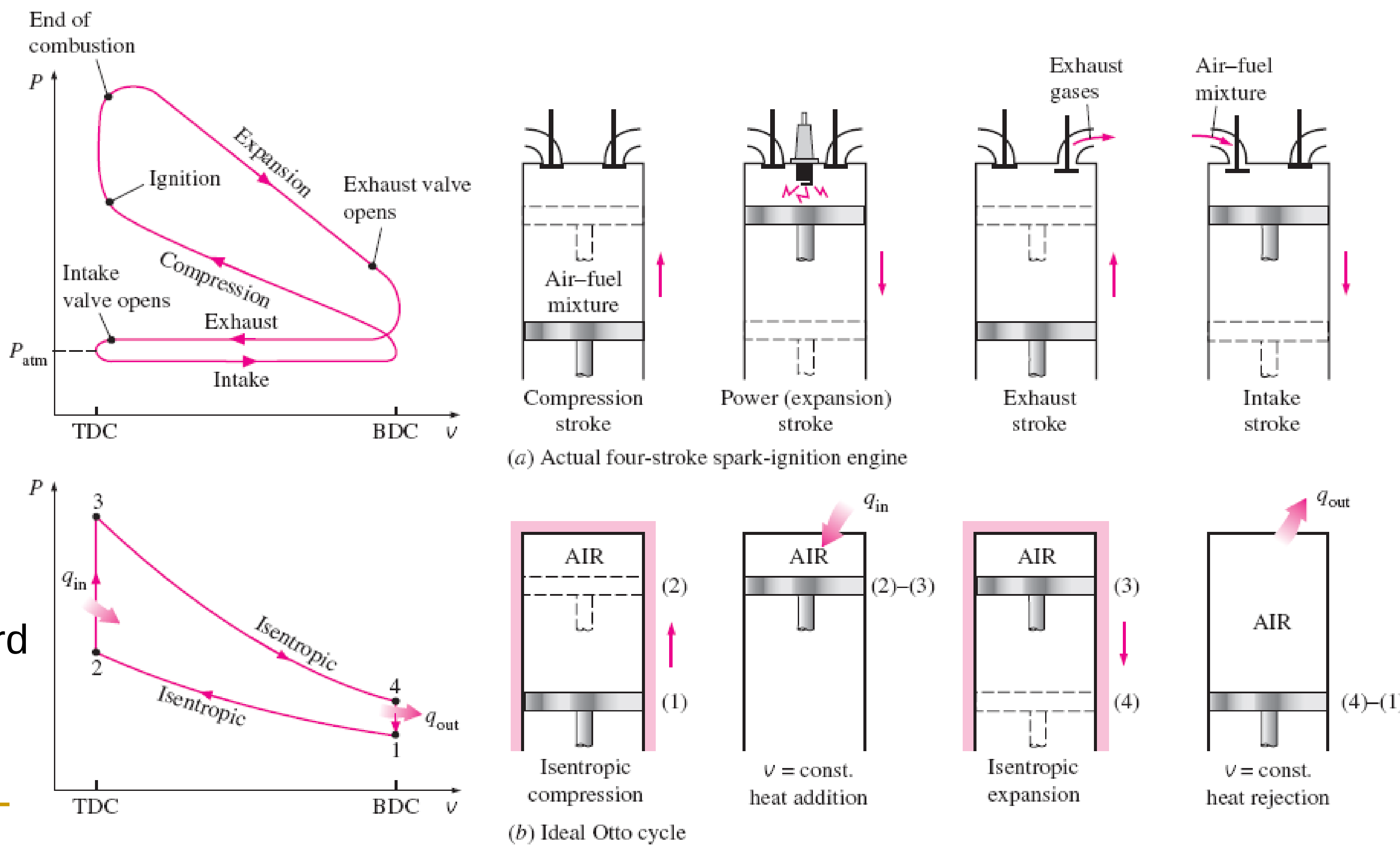
$$W_{net} = \text{MEP} \times \text{Piston area} \times \text{Stroke} = \text{MEP} \times \text{Displacement volume}$$

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

Otto Cycle

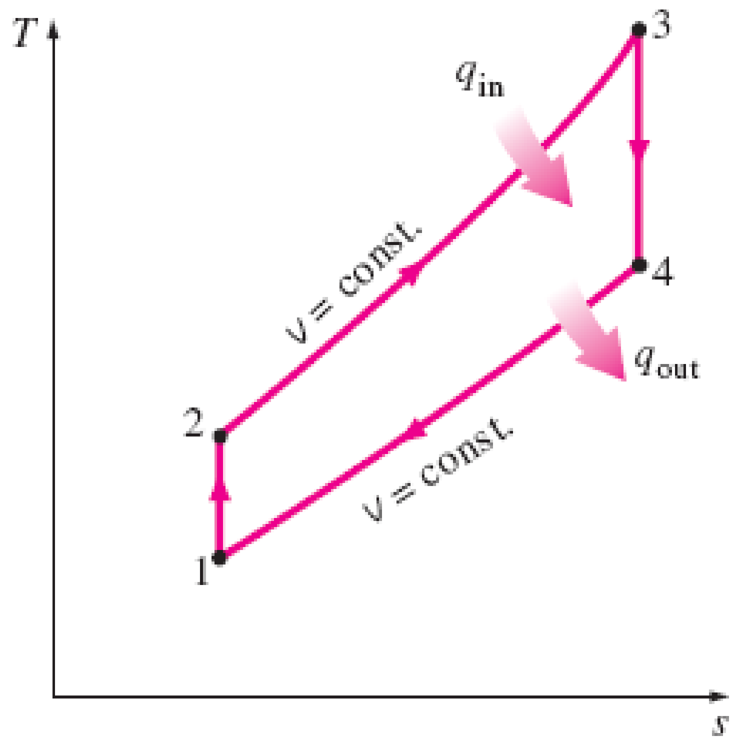
Actual

Air Standard



Otto Cycle

- ***Ideal*** Otto Cycle
- Four internally reversible processes
  - 1-2 Isentropic compression
  - 2-3 Constant-volume heat addition
  - 3-4 Isentropic expansion
  - 4-1 Constant-volume heat rejection



Otto Cycle

- Closed system, pe, ke ≈ 0
- Energy balance (cold air std)

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

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

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

Otto Cycle

- Thermal efficiency of ideal Otto cycle:

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

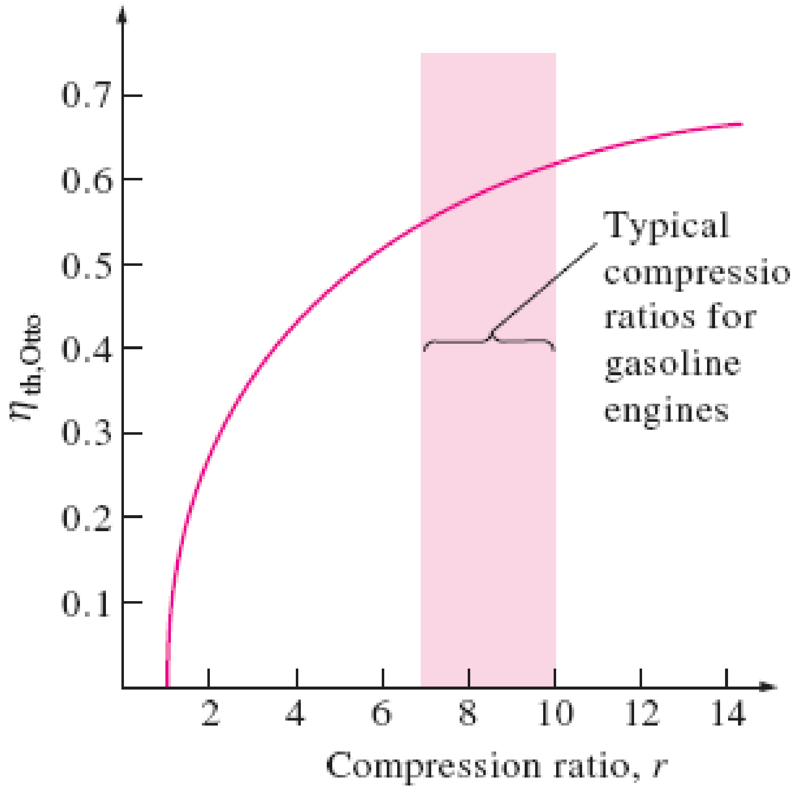
- Since $V_2 = V_3$ and $V_4 = V_1$

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{k-1} = \left(\frac{V_3}{V_4}\right)^{k-1} = \frac{T_4}{T_3}$$

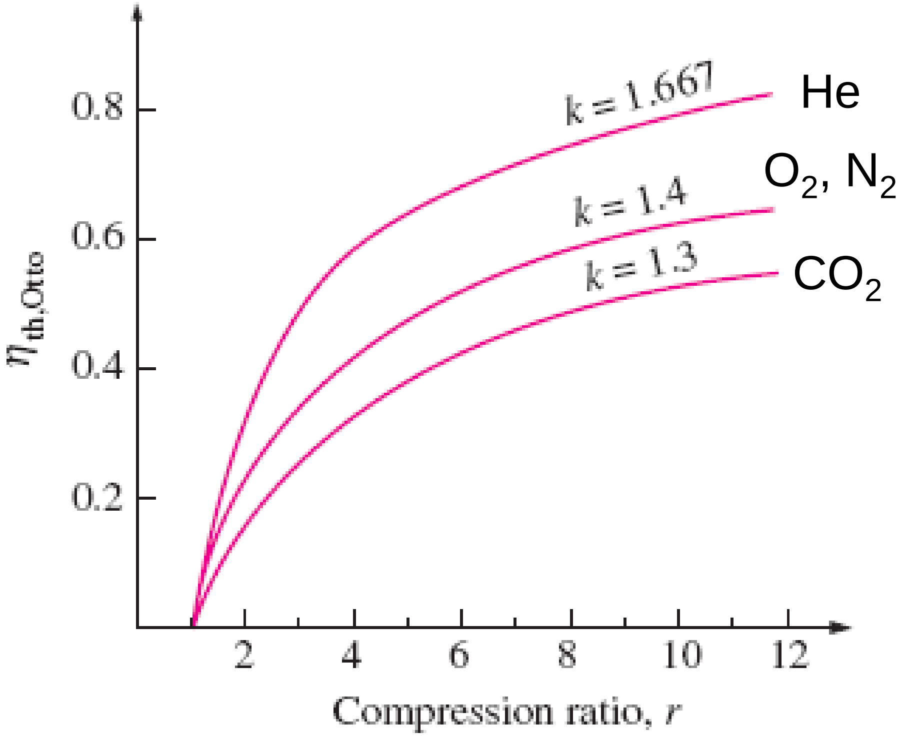
- Where r is compression ratio
  k is ratio of specific heats

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

Otto Cycle



0.7
0.6
0.5
0.4
0.3
0.2
0.1
$\eta_{th,Otto}$
2
4
6
8
10
12
14
Compression ratio, r
Typical compressio ratios for gasoline engines



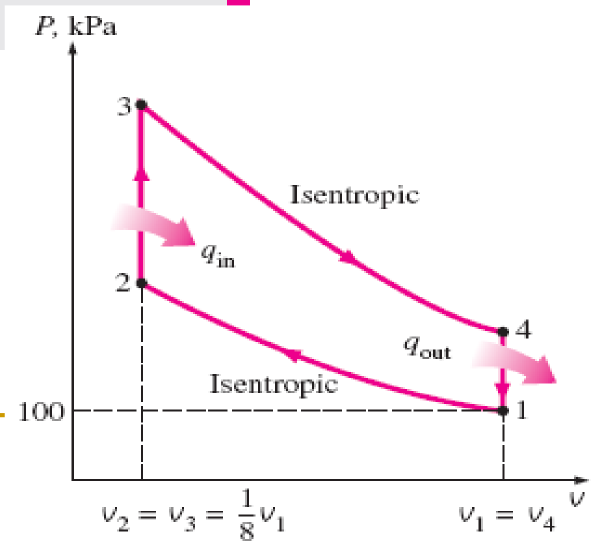
0.8
0.6
0.4
0.2
$\eta_{th,Otto}$
k = 1.667
He
k = 1.4
O_2, N_2
k = 1.3
CO_2
2
4
6
8
10
12
Compression ratio, r

EXAMPLE 9–2 The Ideal Otto Cycle

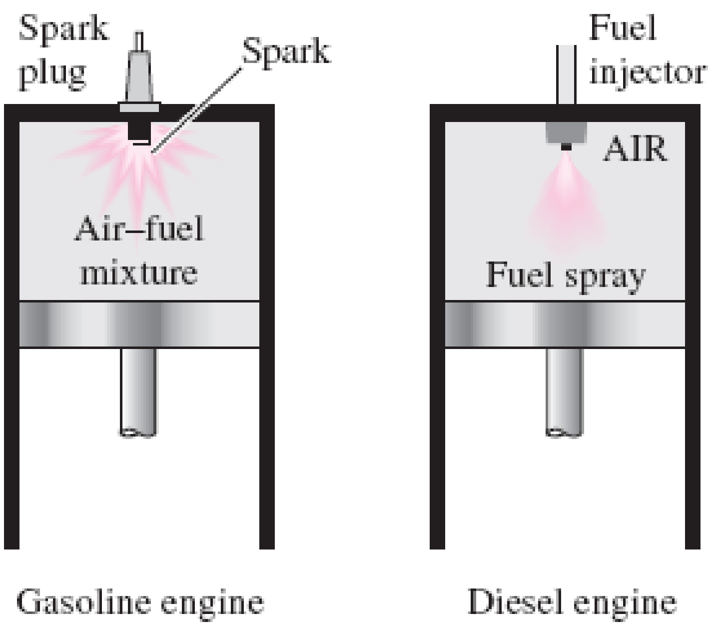
An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, air is at 100 kPa and 17°C, and 800 kJ/kg of heat is transferred to air during the constant-volume heat-addition process. Ignoring for the variation of specific heats of air with temperature, determine (*a*) the maximum temperature and pressure that occur during the cycle, (*b*) the net work output, (*c*) the thermal efficiency, and (*d*) the mean effective pressure for the cycle.

Solution An ideal Otto cycle is considered. The maximum temperature and pressure, the net work output, the thermal efficiency, and the mean effective pressure are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** The variation of specific heats with temperature is ignored.



Spark vs Compression Ignition



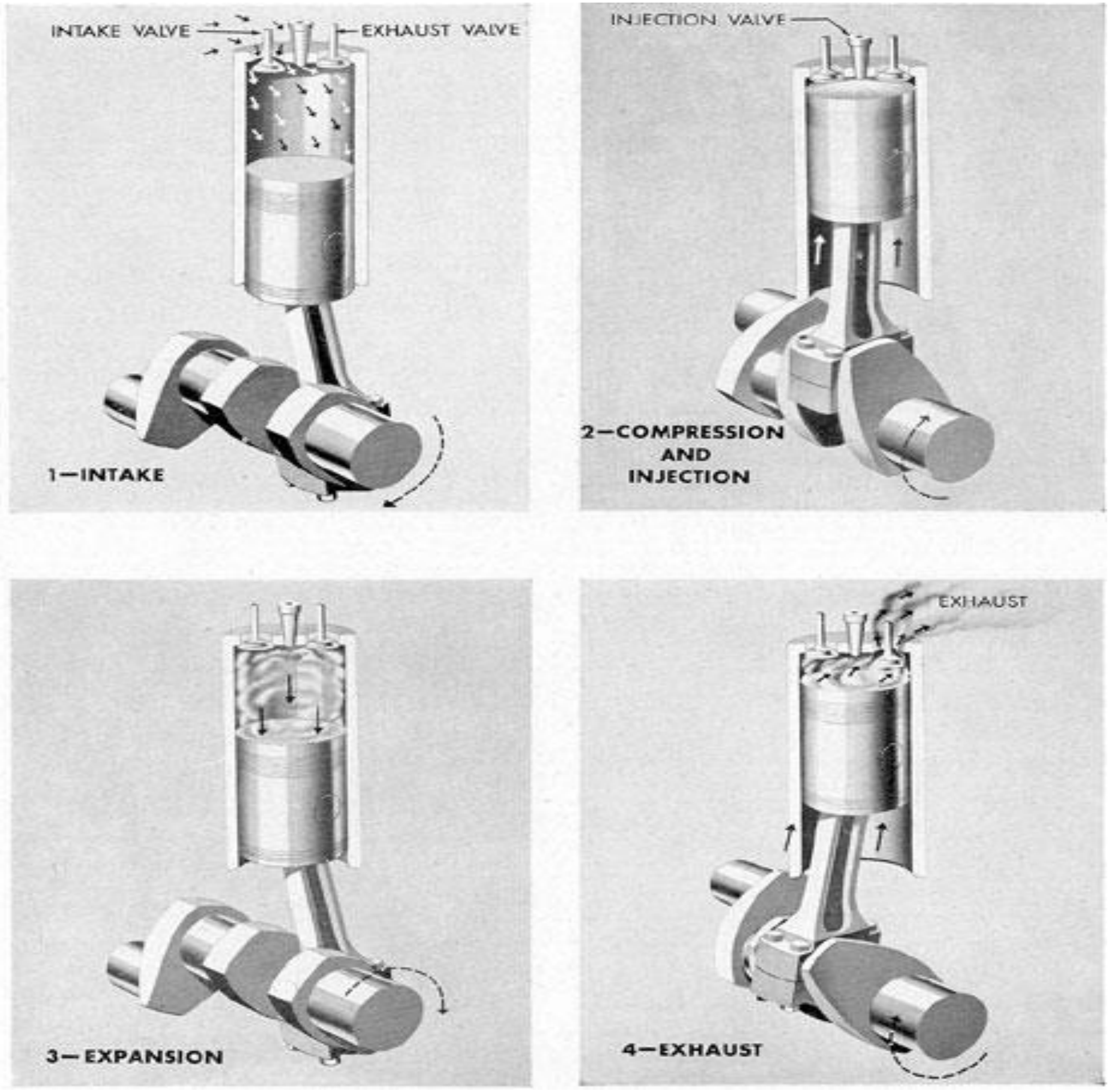
- Spark (Otto), air-fuel mixture compressed (constant-volume heat addition)
- Compression (Diesel), air compressed, then fuel added (constant-pressure heat addition)

Diesel Engine: what's different from Petrol Engine?

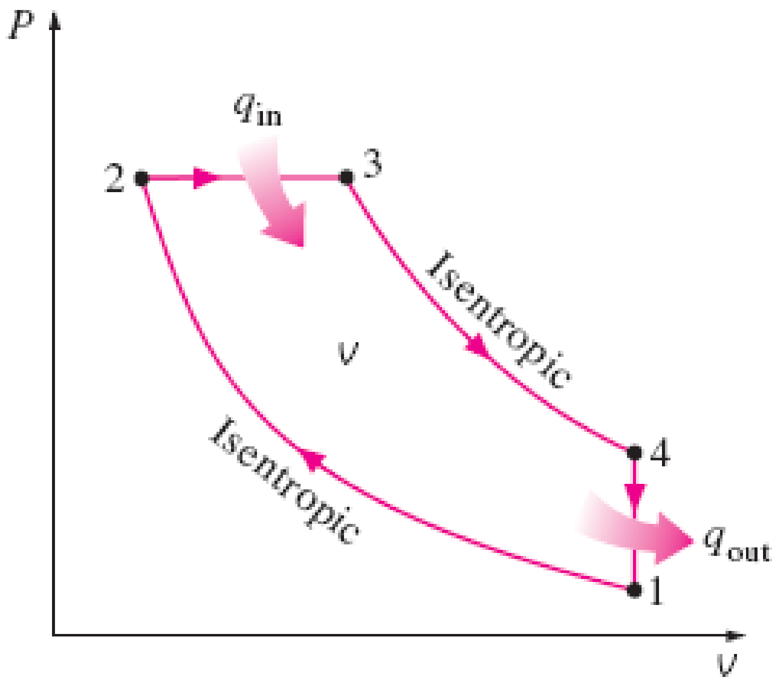
- The Diesel engine takes in JUST air.
- The compression ratio is higher, thus higher efficiency.
- Diesel engines use direct fuel injection.
- No spark plug required.

CI Engine

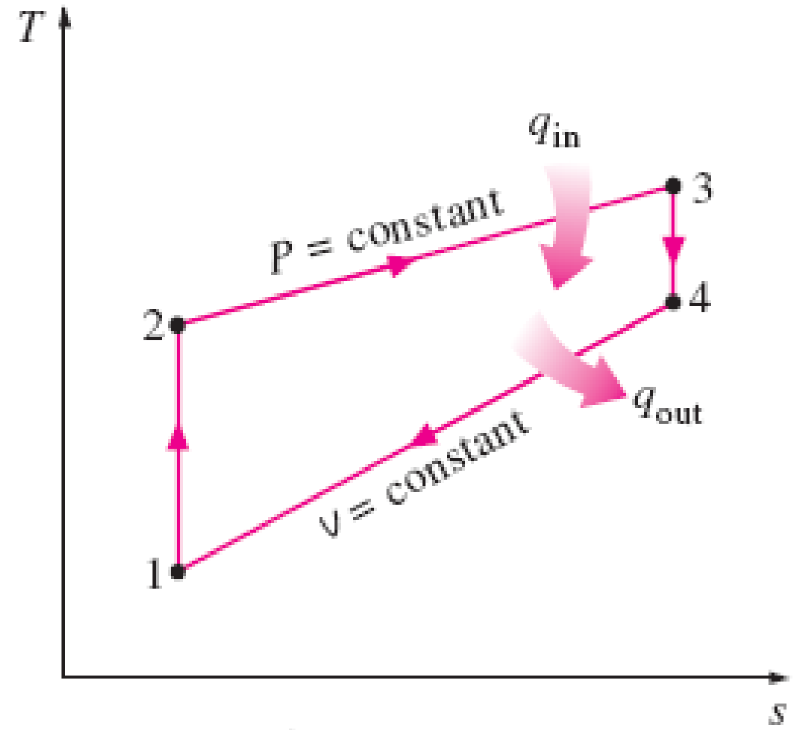
4 strokes in a diesel cycle



Diesel Cycle



(a) P- v diagram



(b) T-s diagram

Diesel Cycle

- Processes of Diesel cycle:
- Isentropic compression
- Constant-*pressure* heat addition
- Isentropic expansion
- Constant-*volume* heat rejection

Diesel Cycle

- For ideal diesel cycle

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

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

$$\eta_{\text{th,Diesel}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{kT_2(T_3/T_2 - 1)}$$

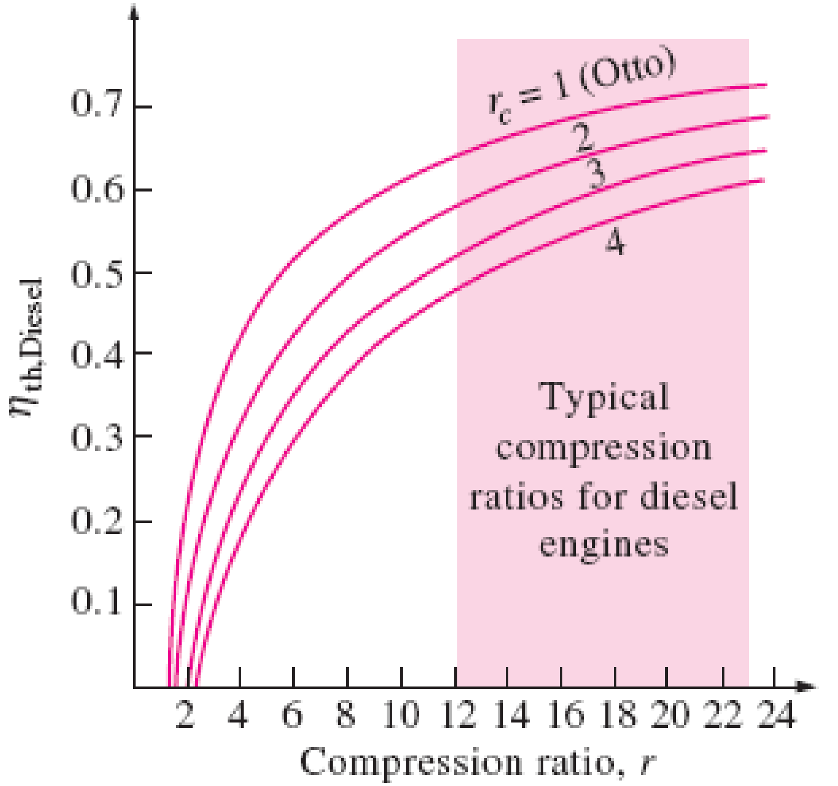
Diesel Cycle

- Cut off ratio r_c

$$r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2}$$

- Efficiency becomes

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



Advantages and disadvantages of CI Engines

- Advantages
  - There is no KNOCKING in the diesel engine.
  - Higher efficiency.
  - Less operating expense

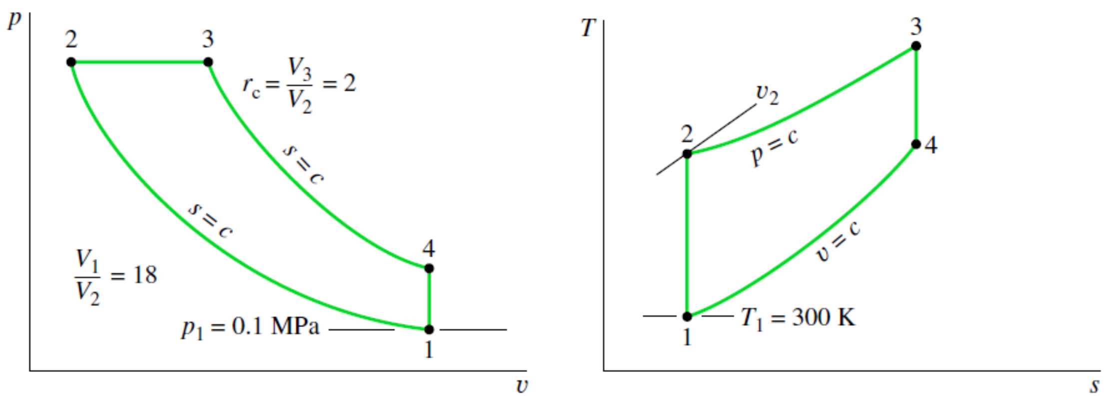
- Disadvantages
  - Pollution
  - Heavy
  - Initial high cost

At the beginning of the compression process of an air-standard Diesel cycle operating with a compression ratio of 18, the temperature is 300 K and the pressure is 0.1 MPa. The cutoff ratio for the cycle is 2. Determine (a) the temperature and pressure at the end of each process of the cycle, (b) the thermal efficiency, (c) the mean effective pressure, in MPa.

Solution:

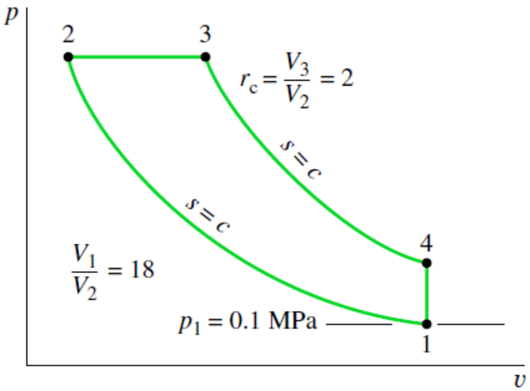
Known: An air-standard Diesel cycle is executed with specified conditions at the beginning of the compression stroke. The compression and cutoff ratios are given.

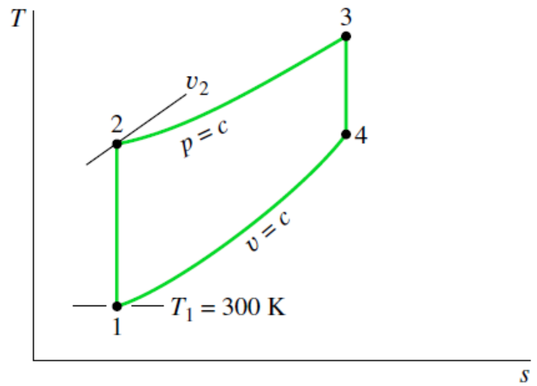
Find: Determine the temperature and pressure at the end of each process, the thermal efficiency, and mean effective pressure.



Assumptions:

1. The air in the piston–cylinder assembly is the closed system.
2. The compression and expansion processes are adiabatic.
3. All processes are internally reversible.
4. The air is modeled as an ideal gas,with constant specific heats.
5. Kinetic and potential energy effects are negligible.


p
2
3
$r_c = \frac{V_3}{V_2} = 2$
s = c
s = c
4
$\frac{V_1}{V_2} = 18$
$p_1 = 0.1$ MPa
1
v


T
3
v_2
2
p = c
4
v = c
1
$T_1 = 300$ K
s

Gas Turbines

Advantages

- Very high power-to-weight ratio, compared to reciprocating engines
- Smaller than most reciprocating engines of the same power rating
- Fewer moving parts than reciprocating engines
- Quicker start up and load changing capability than a vapor power cycle.
- No requirement of cooling water for open cycle GT

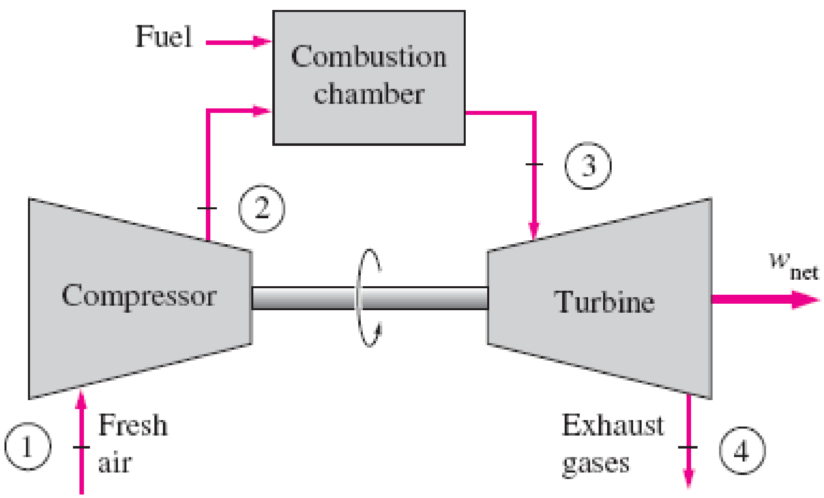
Disadvantages

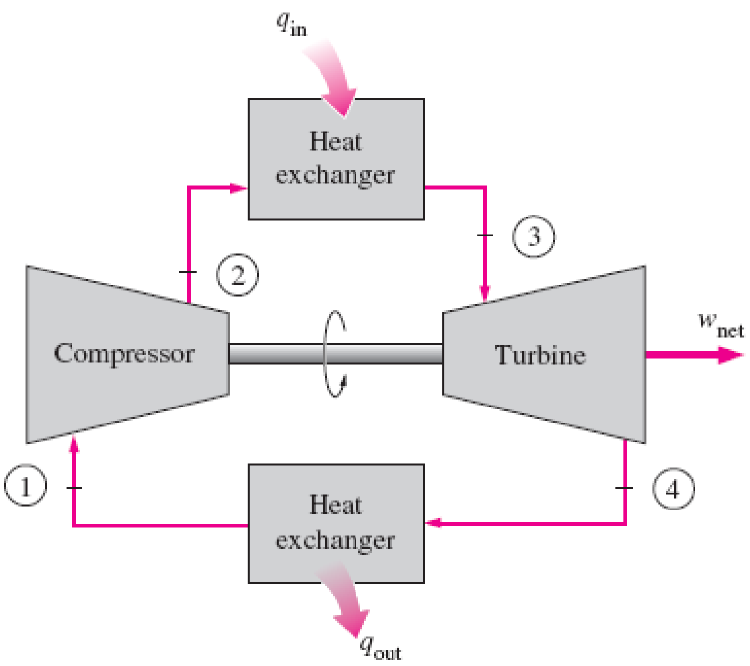
- Usually less efficient than reciprocating engines and vapor power cycles
- Minimum power rating for economic design is too high for small power applications:
  - GT is less suitable for rail and road transportations and helicopters

More suitable for large ships, aircrafts, land-based power plants

Brayton Cycle

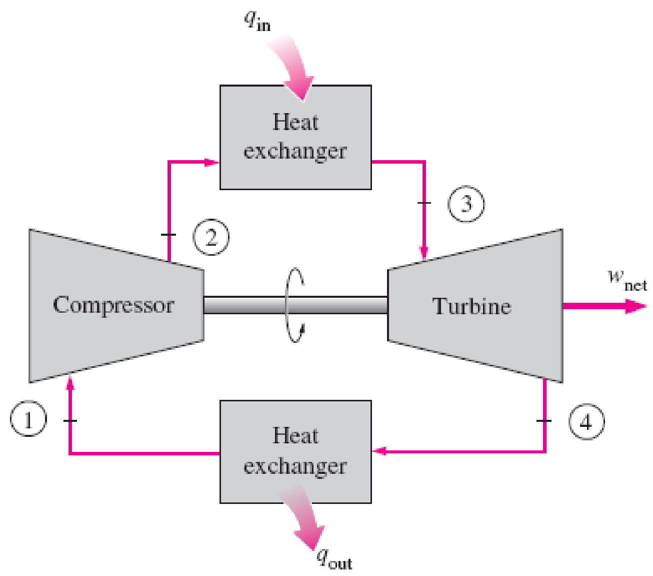
- Gas turbine cycle
- Open vs closed system model

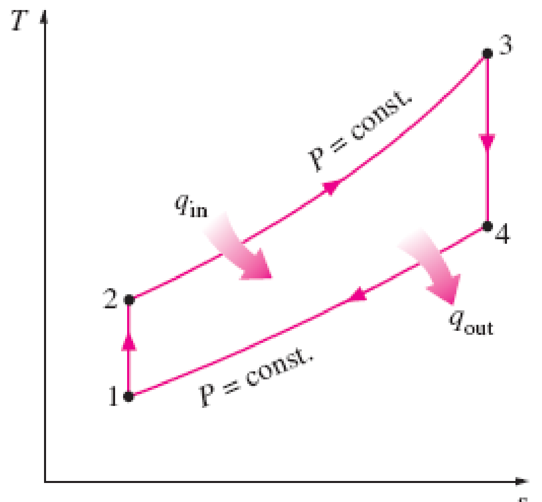




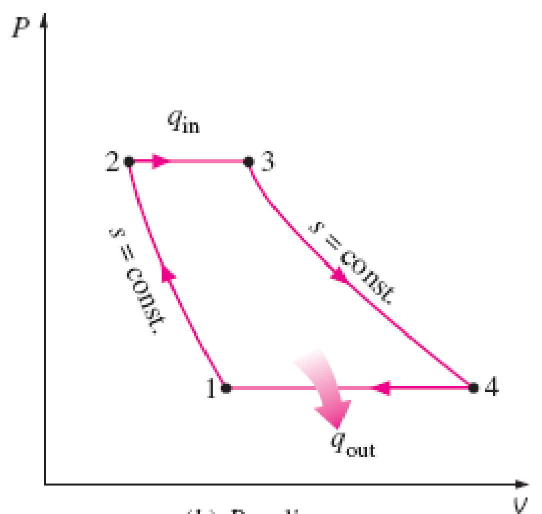
Gas turbine cycles

Schematic of a closed GT (Brayton) cycle





(a) T-s diagram



(b) P-v diagram

1-2 Isentropic compression (in a compressor):

$$w_c = h_2 - h_1 = C_p(T_2 - T_1)$$

2-3 Constant pressure heat addition (in a combustor):

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

3-4 Isentropic expansion (in a turbine):

$$h_3 - h_4 = C_p(T_3 - T_4)$$

4-1 Constant pressure heat rejection (exhaust to the atmosphere):

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

Efficiency of a simple Brayton cycle

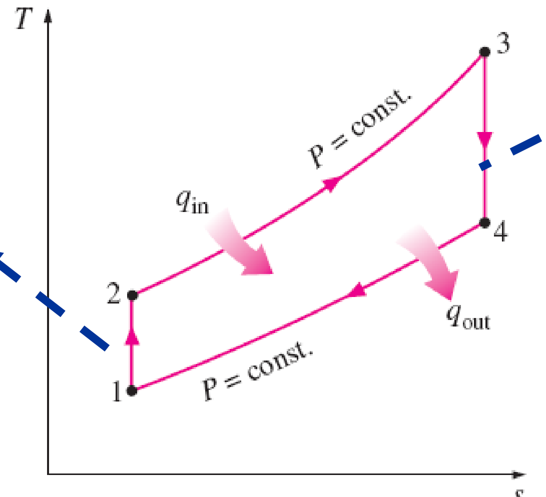
$$w_{net} = c_p\left(T_3 - T_4\right) - c_p\left(T_2 - T_1\right)$$

$$Pressure\ Ratio = r_p = \frac{p_2}{p_1} = \frac{p_3}{p_4}$$

$$\eta_{Brayton} = \frac{net\ work\ output}{energy\ input} = \frac{c_p(T_3 - T_4) - c_p(T_2 - T_1)}{c_p(T_3 - T_2)}$$

$$TempRatio = \frac{T_3}{T_1} = t$$

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$



(a) T-s diagram

$$\frac{p_3}{p_4} = \left(\frac{T_3}{T_4}\right)^{\frac{\gamma}{\gamma-1}}$$

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

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} = \left(r_p\right)^{\frac{\gamma-1}{\gamma}} = c$$

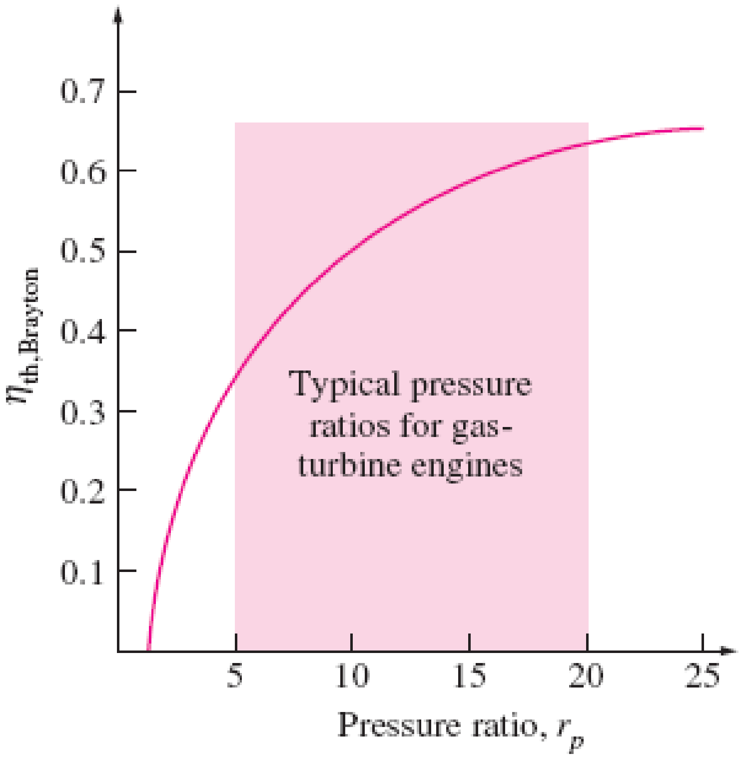
$$\eta_{Brayton} = \frac{c_p T_1(T_3/T_1 - T_4/T_3 \times T_3/T_1) - c_p T_1(T_2/T_1 - 1)}{c_p T_1(T_3/T_1 - T_2/T_1)} = \frac{t - t/c - c + 1}{(t - c)}$$

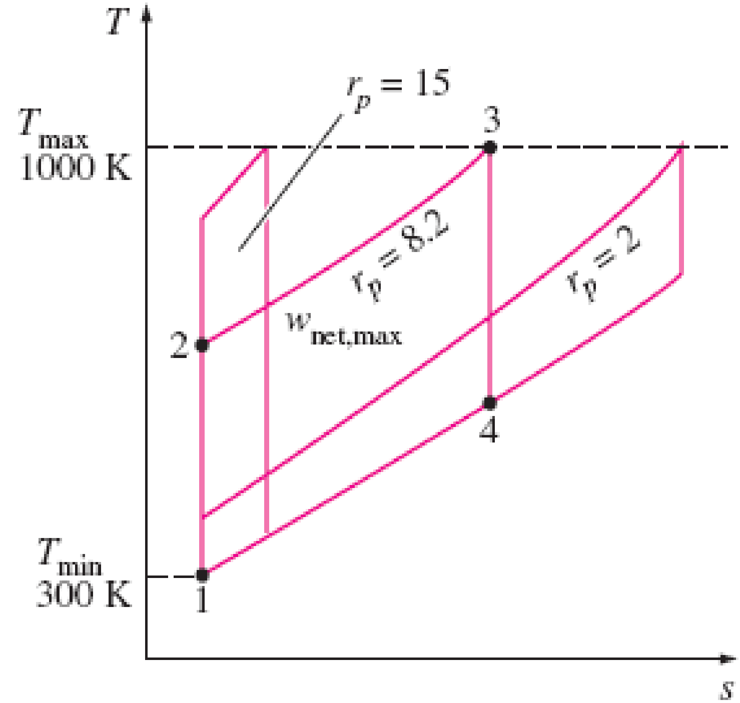
$$= \frac{\frac{t}{c}(c-1) - (c-1)}{(t-c)} = \frac{(t/c - 1)(c-1)}{c(t/c - 1)} = 1 - \frac{1}{c} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

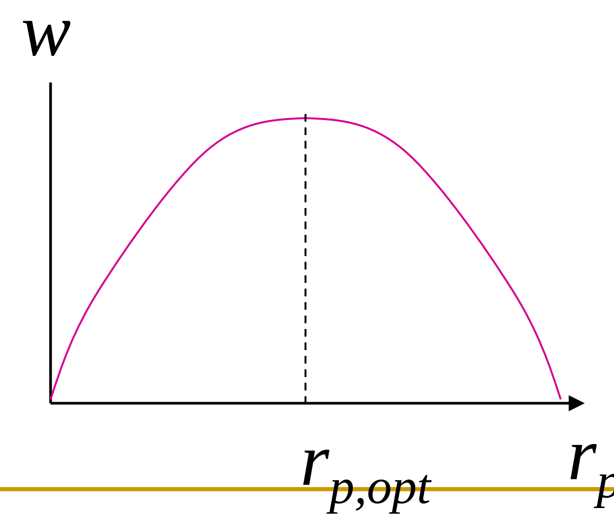
What limits the efficiency?

- In theory, as the pressure ratio goes up, the efficiency rises. The limiting factor is frequently the **turbine inlet temperature**.
- The turbine inlet temp is restricted to about 1,700 K.
  - Consider a fixed turbine inlet temp., T_3

Brayton Cycle



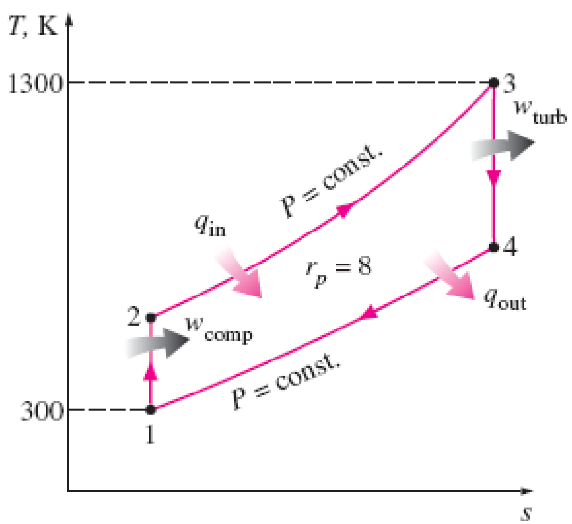




$$r_p = (T_{max}/T_{min})^{k/[2(k-1)]}$$

EXAMPLE 9–5 The Simple Ideal Brayton Cycle

A gas-turbine power plant operating on an ideal Brayton cycle has a pressure ratio of 8. The gas temperature is 300 K at the compressor inlet and 1300 K at the turbine inlet. Utilizing the air-standard assumptions, determine (*a*) the gas temperature at the exits of the compressor and the turbine, (*b*) the back work ratio, and (*c*) the thermal efficiency.



Solution A power plant operating on the ideal Brayton cycle is considered. The compressor and turbine exit temperatures, back work ratio, and the thermal efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The air-standard assumptions are applicable. **3** Kinetic and potential energy changes are negligible. **4** The variation of specific heats with temperature is to be considered.

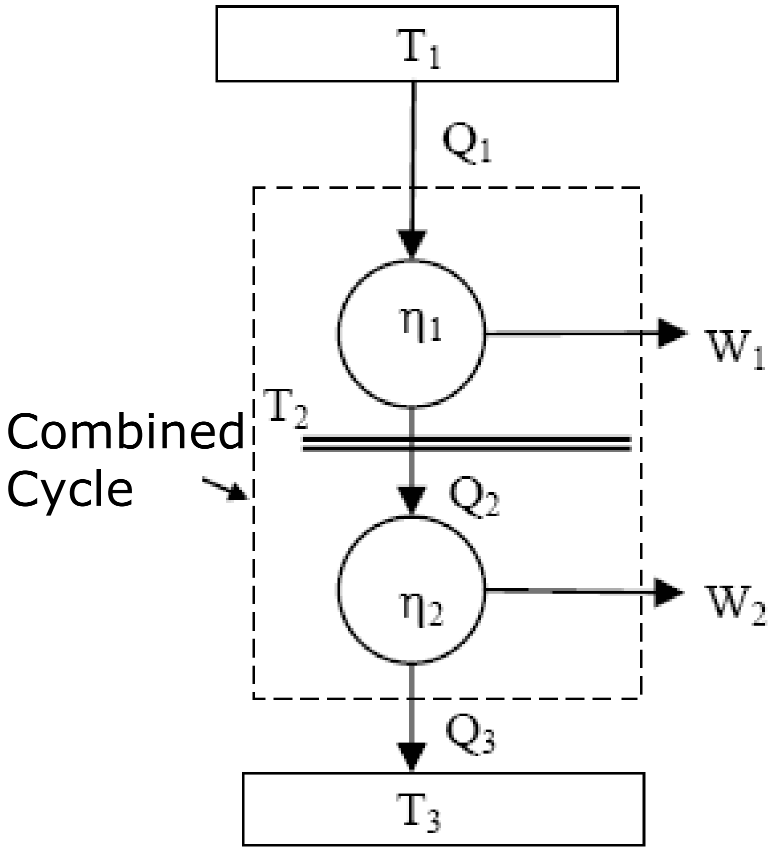
Analysis The *T-s* diagram of the ideal Brayton cycle described is shown in Fig. 9–35. We note that the components involved in the Brayton cycle are steady-flow devices.

(*a*) The air temperatures at the compressor and turbine exits are determined from isentropic relations:

References

- See the following links:
- http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/otto.html#c1
- http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/diesel.html
- http://www.pwc.ca/en_markets/demonstration.html

Basic concept of combined cycle



For cycle 1 (topping cycle) : $W_1 = \eta_1 Q_1$

$\therefore \quad Q_2 = (1-\eta_1)Q_1$

For cycle 2 (bottoming cycle): $W_2 = \eta_2 Q_2$

$\therefore \quad Q_3 = (1-\eta_2)Q_2$

$= (1-\eta_1)(1-\eta_2)Q_1 \ldots\ldots\ldots(i)$

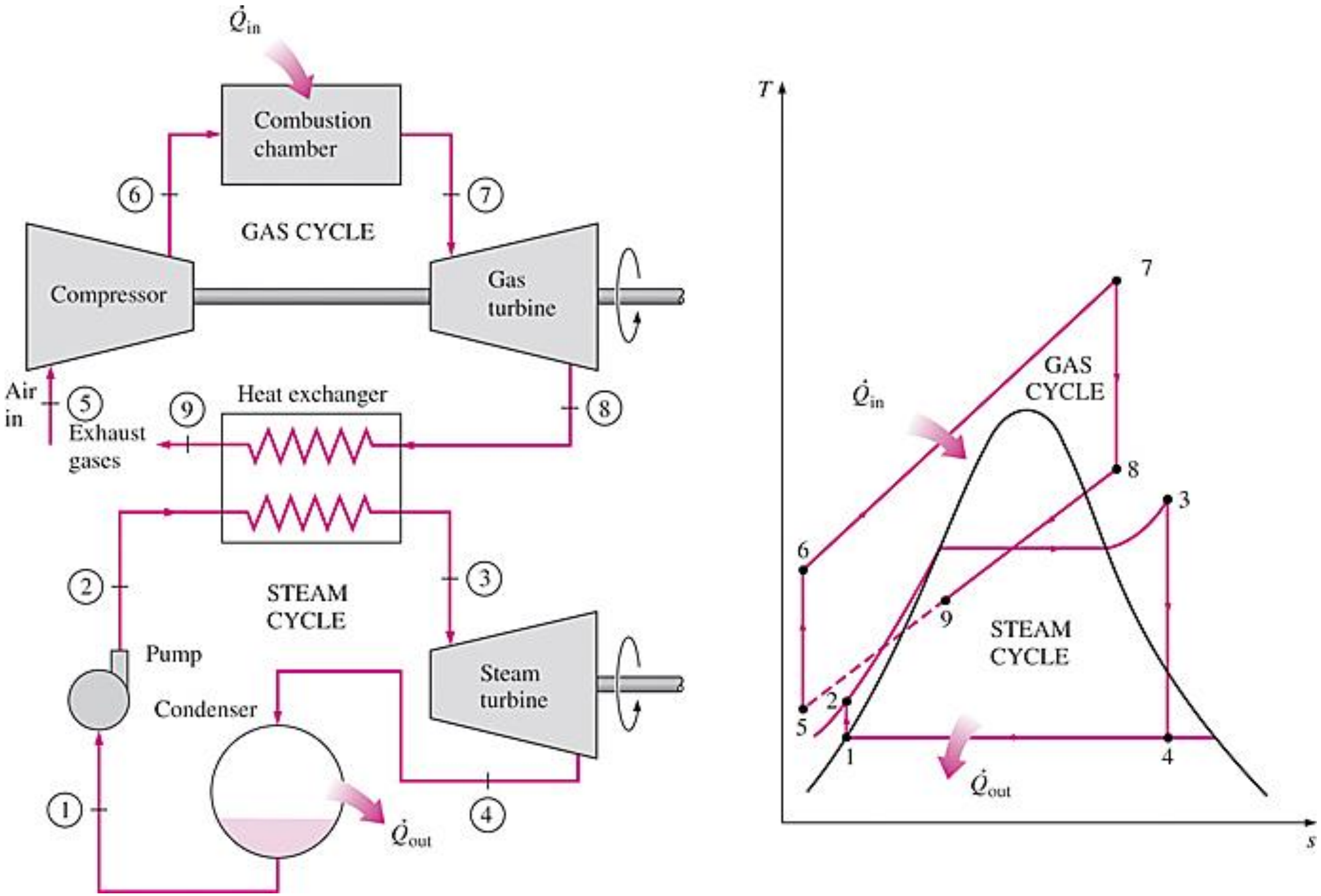
For the combined cycle,

$W = W_1 + W_2 = \eta Q_1$

While, $Q_3 = (1-\eta)Q_1 \ldots\ldots\ldots\ldots\ldots(ii)$

Comparing (i) and (ii), overall inefficiency

$(1-\eta) = (1-\eta_1)(1-\eta_2)$



Combined gas–steam power plant.