Engineering Thermodynamics

ENGG 111

Lecture-2

- Second law places restriction on the direction of heat transfer and the attenable efficiencies of heat engine.
    1) Kelvin Plank Statement
    2) Clausius Statement

1) Kelvin Plank Statement

– It is impossible to construct a cyclically operating device such that it produce no other effect than the absorption of energy as heat from single thermal reservoirs performing an equivalent amount of work.
– It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

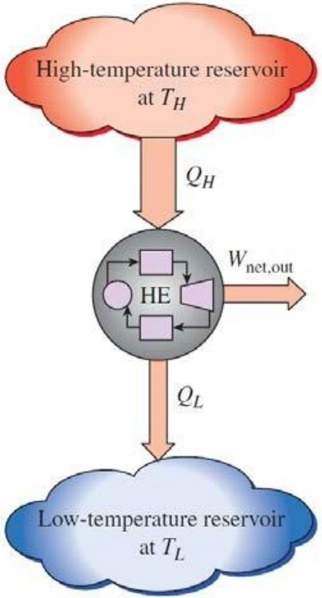


FIGURE 6–13
Schematic of a heat engine.

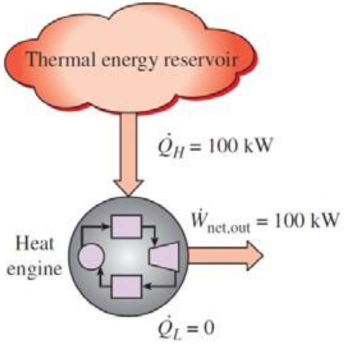


FIGURE 6–18
A heat engine that violates the Kelvin–Planck statement of the second law.

That is, a heat engine must exchange heat with a low-temperature sink as well as a high-temperature source to keep operating. The Kelvin–Planck statement can also be expressed as *no heat engine can have a thermal efficiency of 100 percent* (Fig. 6–18), or as *for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace*.

2) Clausius statement

– It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

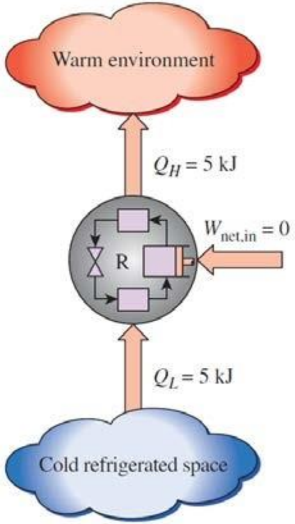
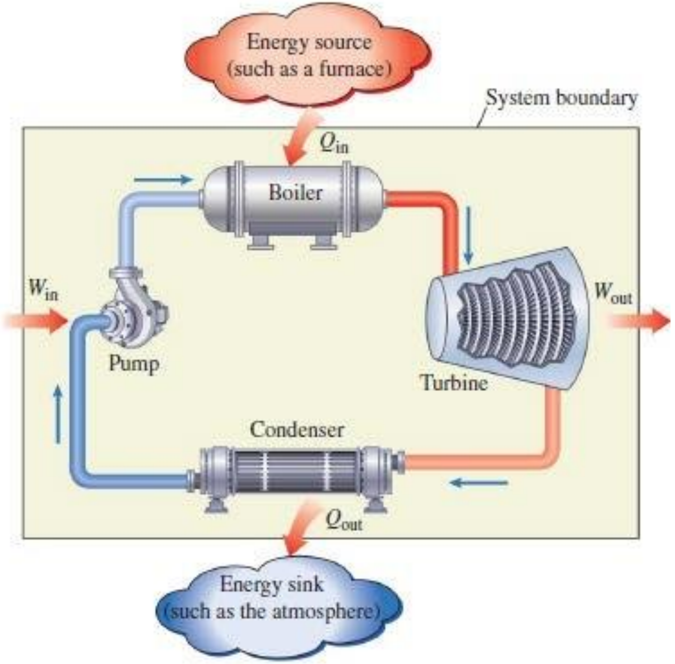
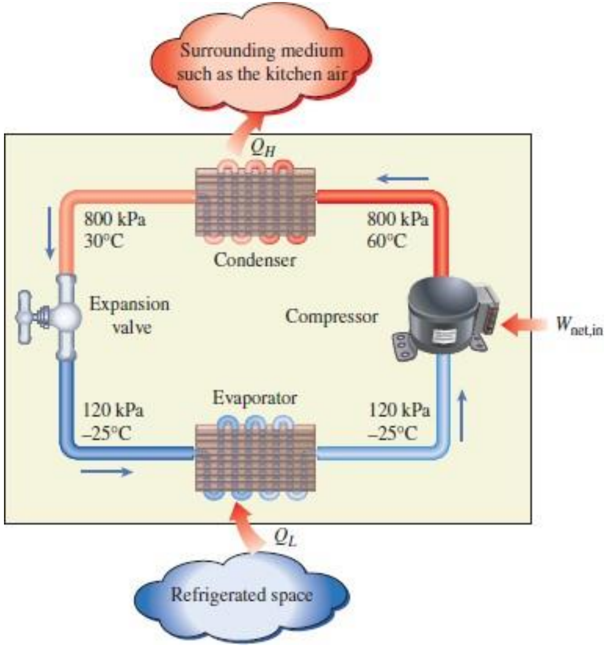


FIGURE 6–25
A refrigerator that violates the Clausius statement of the second law.

– It is common knowledge that heat does not, of its own volition, transfer from a cold medium to a warmer one. The Clausius statement does not imply that a cyclic device that transfers heat from a cold medium to a warmer one is impossible to construct. In fact, this is precisely what a common household refrigerator does. It simply states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor (Fig. 6–25). This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one. That is, it leaves a trace in the surroundings. Therefore, a household refrigerator is in complete compliance with the Clausius statement of the second law

Heat Engine vs Refrigerators





Entropy

- If the energy has opportunity to spread out, it will.
  - Ice melts
  - Cream mixes
  - Tyre deflates

  Because these states has more dispersed state than original
- a thermodynamic quantity representing the unavailability of a system's thermal energy for conversion into mechanical work, often interpreted as the degree of disorder or randomness in the system

Entropy

- It is state variable whose change is defined for a reversible process at temperature ‘T’ and the heat absorbed ‘Q’. It is denoted by ‘S’.

  Mathematically,

$$\Delta S = \frac{Q}{T}$$

- It is a measure of the amount of energy which is available to do work.

- The molecules of a substance in solid phase continually oscillate, creating an uncertainty about their position. These oscillations, however, fade as the temperature is decreased, and the molecules supposedly become motionless at absolute zero. This represents a state of ultimate molecular order (and minimum energy).

- Therefore, *the entropy of a pure crystalline substance at absolute zero temperature is zero* since there is no uncertainty about the state of the molecules at that instant (Fig. 7–21). This statement is known as the **third law of thermodynamics**.

FIGURE 7–21
A pure crystalline substance at absolute zero temperature is in perfect order, and its entropy is zero (the third law of thermodynamics).

Perpetual motion machine

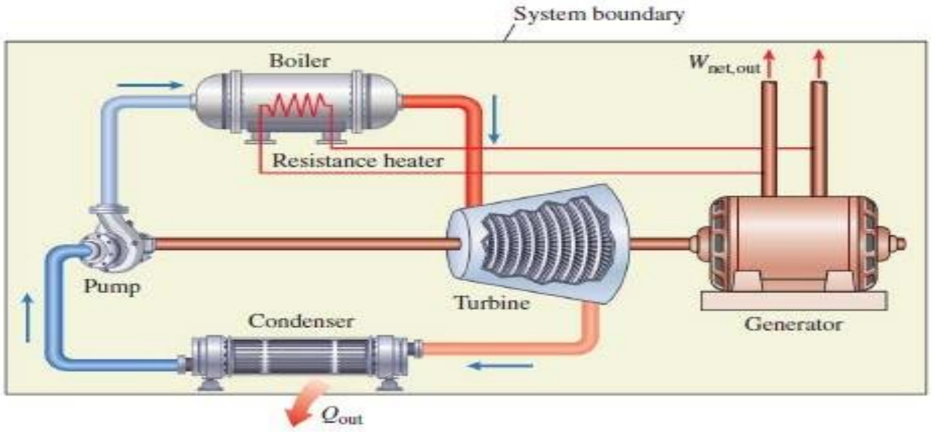


FIGURE 6–27
A perpetual-motion machine that violates the first law of thermodynamics (PMM1).

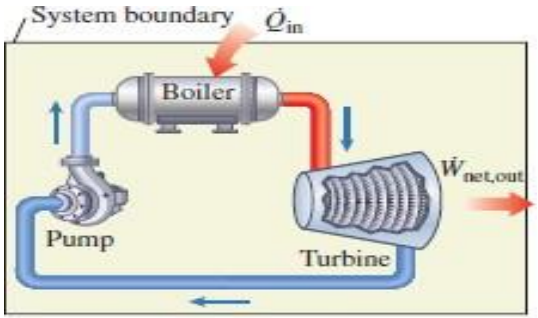
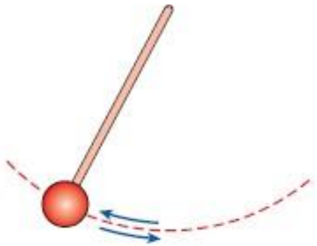


FIGURE 6–28
A perpetual-motion machine that violates the second law of thermodynamics (PMM2).

Reversible and Irreversible Process

- A **reversible process is defined as a *process that can be reversed without*** *leaving any trace on the surroundings (Fig. 6–29). That is, both the system and the surroundings are returned to their initial states at the end of the reverse* process. This is possible only if the net heat *and net work exchange between* the system and the surroundings is zero for the combined (original and reverse) process. Processes that are not reversible are called **irreversible processes.**
- The factors that cause a process to be irreversible are called **irreversibilities.**
- They include friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.


(*a*) Frictionless pendulum

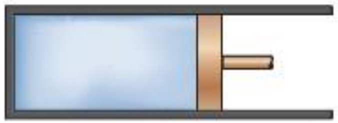

(*b*) Quasi-equilibrium expansion and compression of a gas

FIGURE 6–29
Two familiar reversible processes.

Carnot Cycle

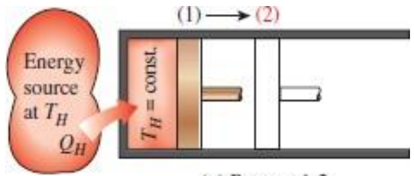
- Carnot cycle is a reversible cycle.
- A reversible cycle is an ideal hypothetical cycle in which all the processes constituting the cycle are reversible.
- Carnot cycle has the greatest efficiency possible of an engine based on the assumption of the absence of incidental wasteful processes such as friction, and the assumption of no conduction of heat between different parts of the engine at different temperatures.

I. A reversible isothermal gas expansion process. In this process, the ideal gas in the system absorbs q_{in} amount heat from a heat source at a high temperature T_h, expands and does work on surroundings.

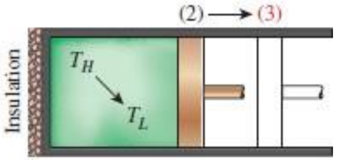
II. A reversible adiabatic gas expansion process. In this process, the system is thermally insulated. The gas continues to expand and do work on surroundings, which causes the system to cool to a lower temperature, T_l.

III. A reversible isothermal gas compression process. In this process, surroundings do work to the gas at T_l, and causes a loss of heat, q_{out}.

IV. A reversible adiabatic gas compression process. In this process, the system is thermally insulated. Surroundings continue to do work to the gas, which causes the temperature to rise back to T_h.

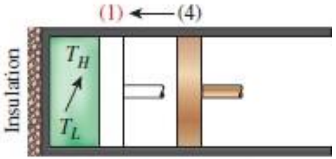


(a) Process 1-2

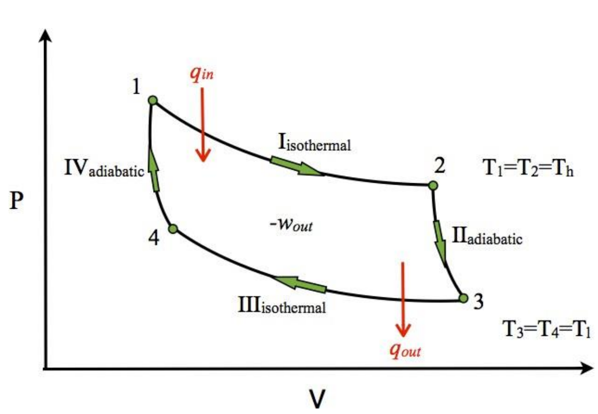


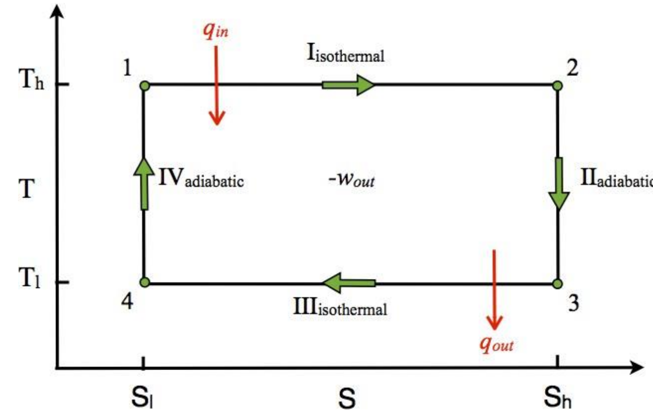
(b) Process 2-3

(c) Process 3-4



(d) Process 4-1





In isothermal processes I and III, ΔU=0 because ΔT=0.
In adiabatic processes II and IV, q=0

In isothermal processes I and III, ΔT=0.
In adiabatic processes II and IV, ΔS=0 because dq=0.

Efficiency of Carnot Heat Engine

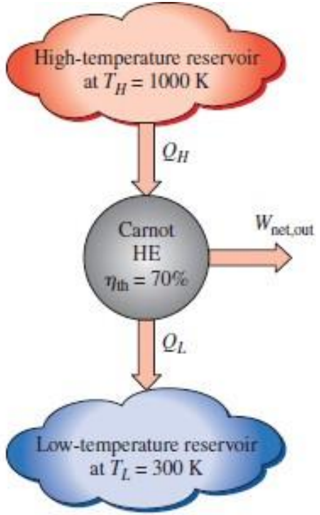


FIGURE 6–45
The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

The ratio of Q_{HighT} to Q_{LowT} must be the same as the ratio of temperatures of high temperature heat and the rejected low temperature heat.

$$\eta'\,(\%) = 1 - \frac{T_{Cold}}{T_{Hot}} \times 100\,\%$$

Note: Use SI unit in calculation
Joule and Kelvin

Problem:
Calculate the Carnot efficiency for an engine operating between the temperature difference of 100 ◦C and 1000◦C respectively.

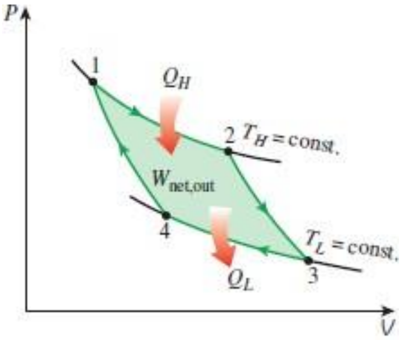
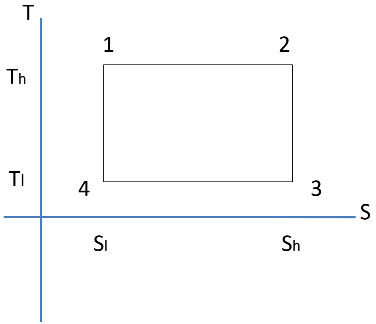
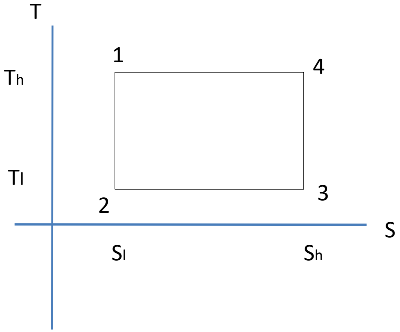


FIGURE 6–37
P-V diagram of the Carnot cycle.





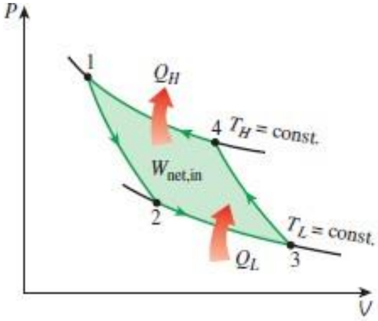


FIGURE 6–38
P-V diagram of the reversed Carnot cycle.

1-2: Reversible Isothermal expansion
2-3: Reversible Adiabatic (Isentropic) expansion
3-4: Reversible Isothermal Compression
4-1: Reversible Adiabatic (Isentropic Compression)

3-4: Reversible Adiabatic (Isentropic) Compression
4-1: Reversible Isothermal Compression
1-2: Reversible Adiabatic (Isentropic) Expansion
2-3: Reversible Isothermal Expansion

A refrigerator or a heat pump that operates on the reversed Carnot cycle is called a **Carnot refrigerator, or a Carnot heat pump.**

Refrigerators and Heat Pumps

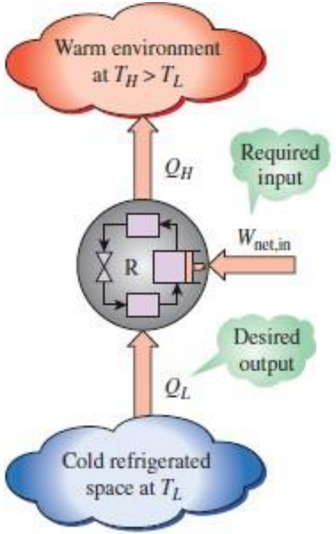


FIGURE 6–20
The objective of a refrigerator is to remove Q_L from the cooled space.

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{net,in}}$$

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

$$COP_{HP} = COP_R + 1$$

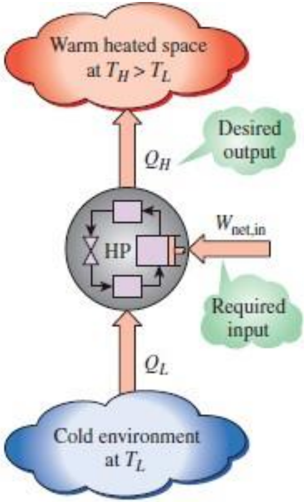


FIGURE 6–21
The objective of a heat pump is to supply heat Q_H into the warmer space.

Reciprocating Engines

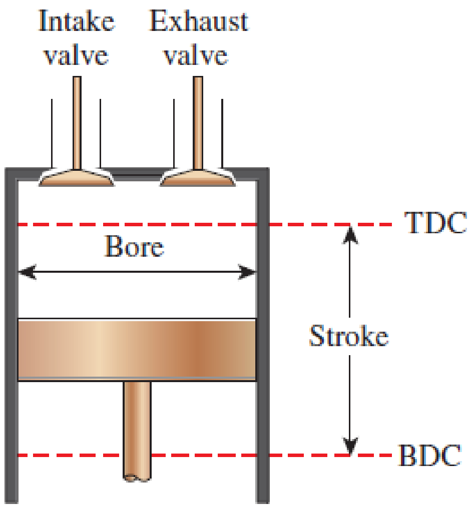
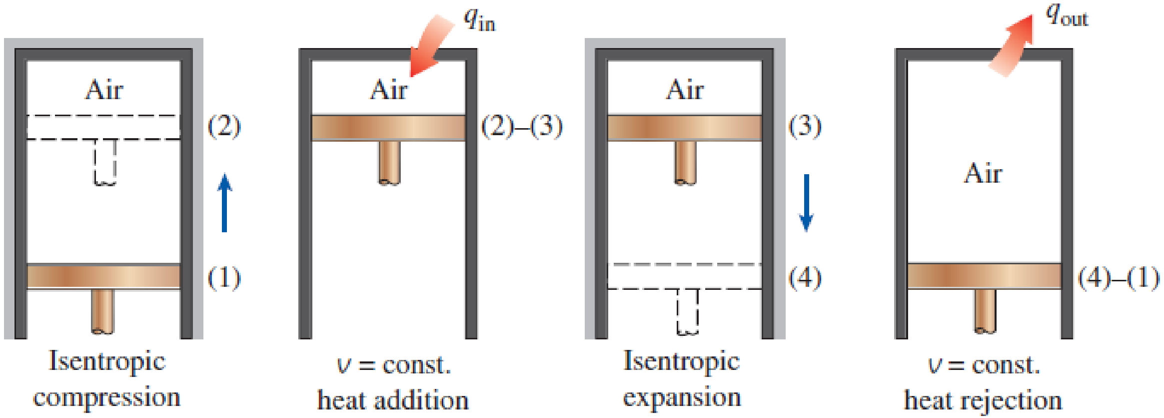
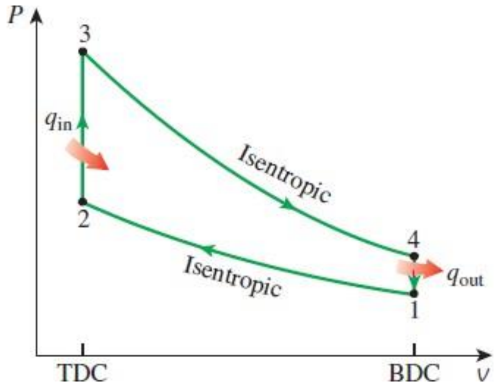


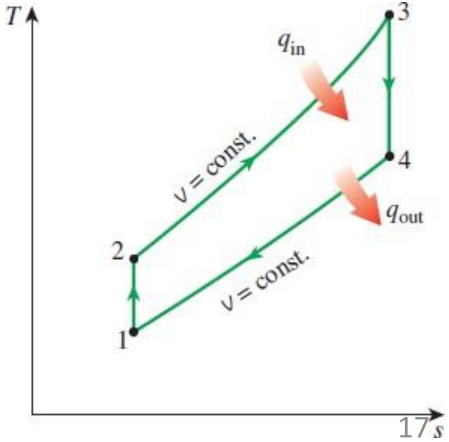
FIGURE 9–9
Nomenclature for reciprocating engines.

top dead center (TDC)-the position of the piston when it forms the smallest volume in the cylinder
bottom dead center (BDC)-the position of the piston when it forms the largest volume in the cylinder.
Stroke - distance between the TDC and the BDC is the largest distance that the piston can travel in one direction, diameter of the piston
Bore- diameter of the piston
clearance volume-The minimum volume formed in the cylinder when the piston is at TDC
Displacement volume-The volume displaced by the compression ratio - piston as it moves between TDC and BDC
compression ratio-The ratio of the maximum volume formed in the cylinder to the minimum (clearance) volume

OTTO CYCLE: The ideal cycle for spark-ignition engines

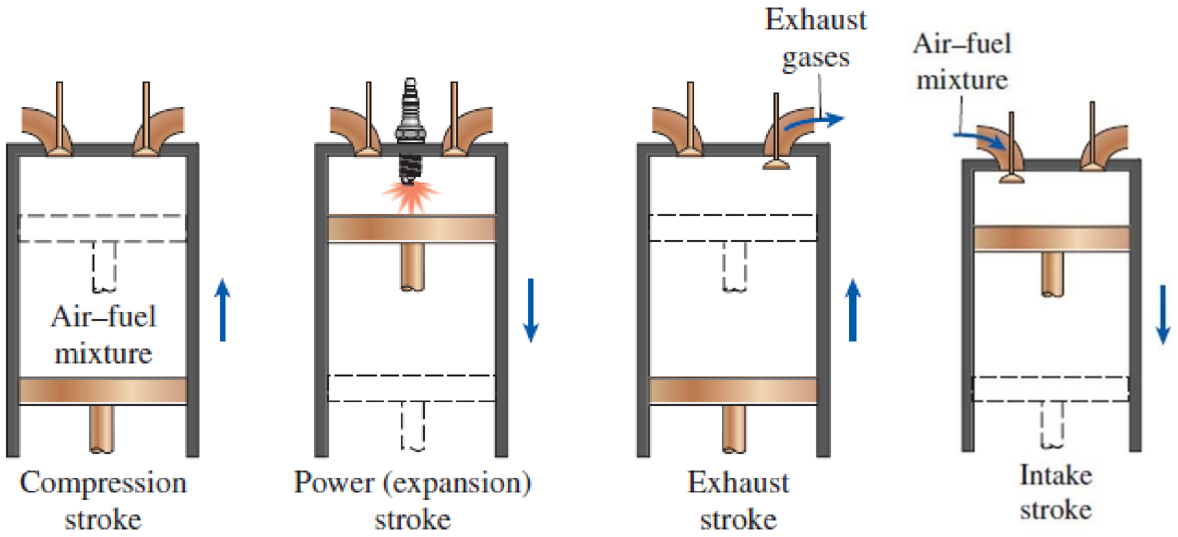


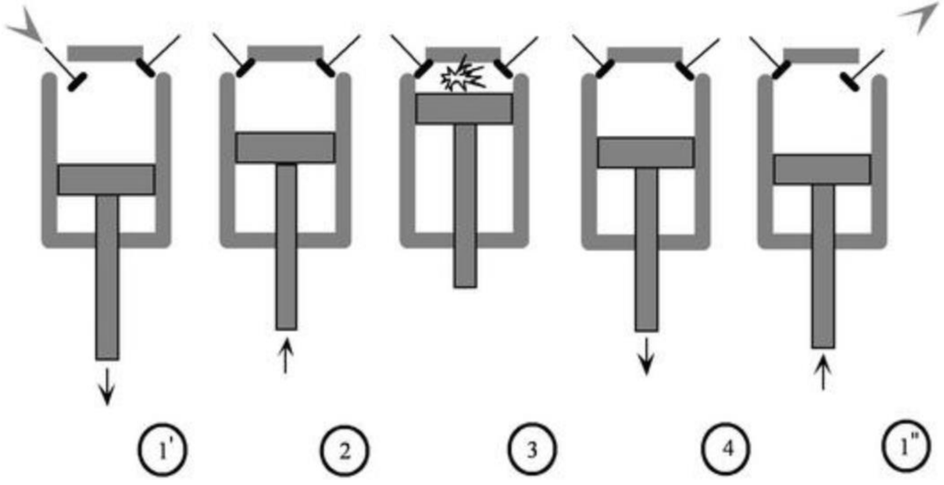


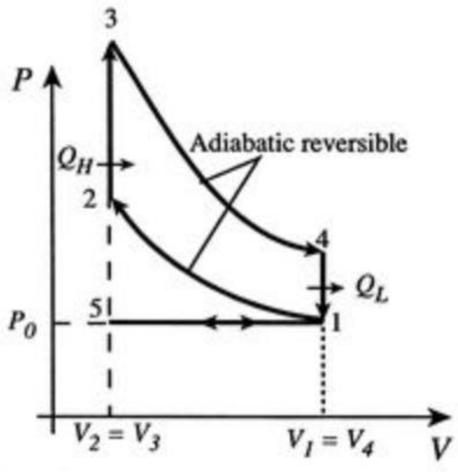


1-2 Isentropic (reversible adiabatic) compression
2-3 Constant volume (Isochoric) heat addition
3-4 Isentropic (reversible adiabatic) Expansion
4-1 Constant volume heat rejection

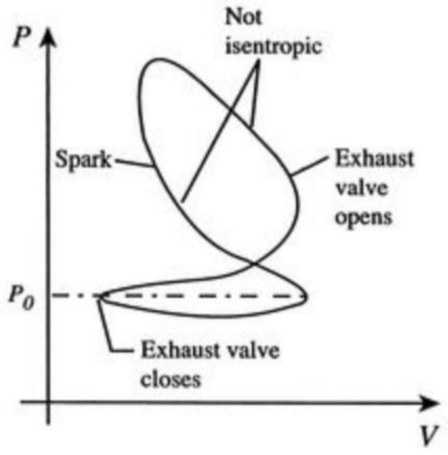
Actual Four Stroke SI engine







Ideal Otto Cycle including intake and exhaust stroke



Sketch of an actual Otto Cycle

1. Intake stroke, gasoline vapor and air drawn into engine ($5 \rightarrow 1$).
2. Compression stroke, p , T increase ($1 \rightarrow 2$).
3. Combustion (spark), short time, essentially constant volume ($2 \rightarrow 3$). Model: heat absorbed from a series of reservoirs at temperatures T_2 to T_3 .
4. Power stroke: expansion ($3 \rightarrow 4$).
5. Valve exhaust: valve opens, gas escapes.
6. ($4 \rightarrow 1$) Model: rejection of heat to series of reservoirs at temperatures T_4 to T_1 .
7. Exhaust stroke, piston pushes remaining combustion products out of chamber ($1 \rightarrow 5$).

Adapted from: http://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node26.html

Efficiency of Otto cycle

$$\eta = \frac{\text{work}}{\text{heat input}} = \frac{Q_H + Q_L}{Q_H} = 1 + \frac{Q_L}{Q_H}.$$

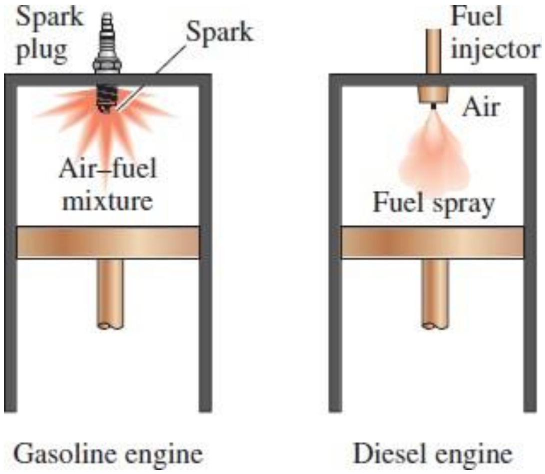
Compression ratio of the Otto cycle is the volume at bottom dead centre (V1) by Volume at Top Dead centre (V2).

i.e. $V_1/V_2 = r$

In terms of compression ratio, the efficiency of an ideal Otto cycle is:

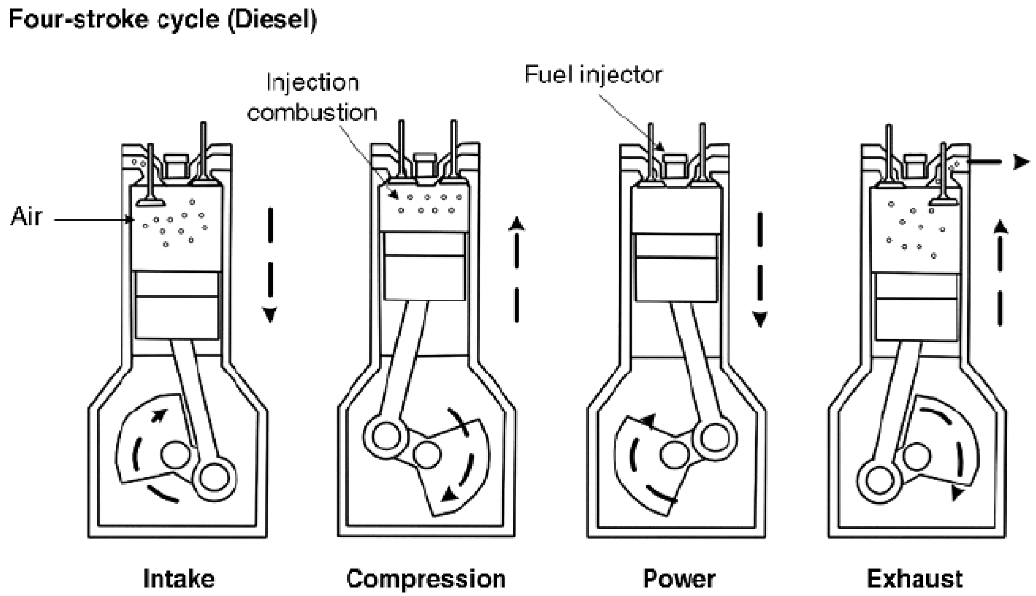
$$\eta_{\text{Otto}} = 1 - \frac{1}{(V_1/V_2)^{\gamma-1}} = 1 - \frac{1}{r^{\gamma-1}}.$$

Diesel Cycle

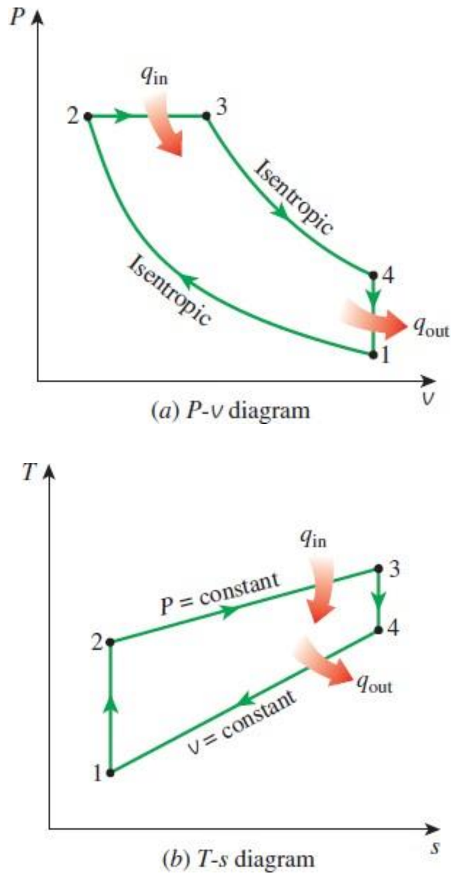


In diesel engines, the spark plug is replaced by a fuel injector, and only air is compressed during the compression process.

- In spark-ignition engines (also known as *gasoline engines*), the air–fuel mixture is compressed to a temperature that is below the autoignition temperature of the fuel, and the combustion process is initiated by firing a spark plug.
- In CI engines (also known as *diesel engines*),the air is compressed to a temperature that is above the autoignition temperature of the fuel, and combustion starts on contact as the fuel is injected into this hot air.



Source: Fallah, Saber. (2014). Electric and Hybrid Vehicles - Technologies, Modeling and Control: A Mechatronic Approach.



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

Fig: P-v and T-s diagram for the ideal Diesel Cycle

Efficiency of diesel cycle

- Cutoff ratio r_c,
  - the ratio of the cylinder volumes after and before the combustion process
  - $r_c = V_3/V_2$

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

Generally, thermal efficiency of Diesel cycle is higher but for same compression ratio

$$\eta_{\text{th,Otto}} > \eta_{\text{th,Diesel}}$$

Brayton Cycle: The ideal cycle for gas-turbine engines

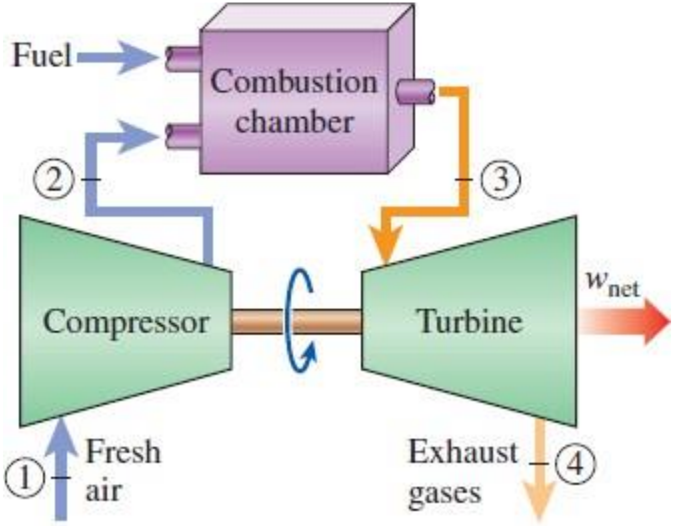


FIGURE 9–29
An open-cycle gas-turbine engine.

- Fresh air at ambient conditions is drawn into the compressor, where its temperature and pressure are raised.
- The high-pressure air proceeds into the combustion chamber, where the fuel is burned at constant pressure.
- The resulting high- temperature gases then enter the turbine, where they expand to the atmospheric pressure while producing power.
- The exhaust gases leaving the turbine are thrown out (not recirculated), causing the cycle to be classified as an open cycle.

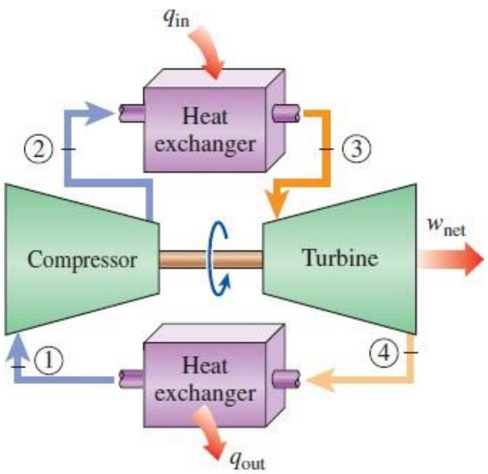


FIGURE 9–30
A closed-cycle gas-turbine engine.

The ideal cycle that the working fluid undergoes in this closed loop is the **Brayton cycle**, which is made up of four internally reversible processes:

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

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

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

r_p is the pressure ratio

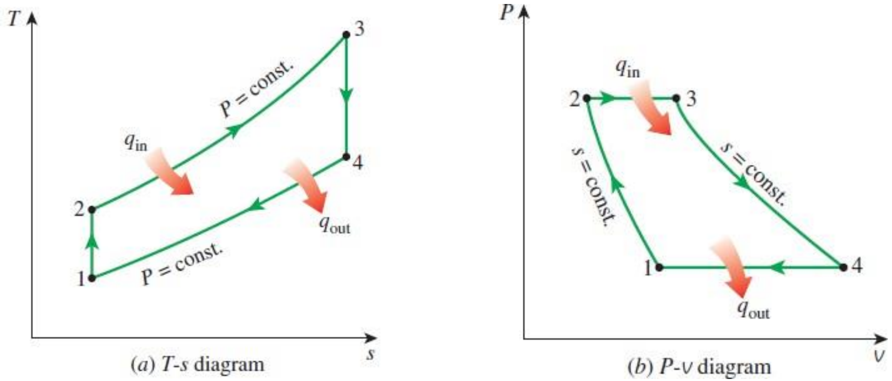
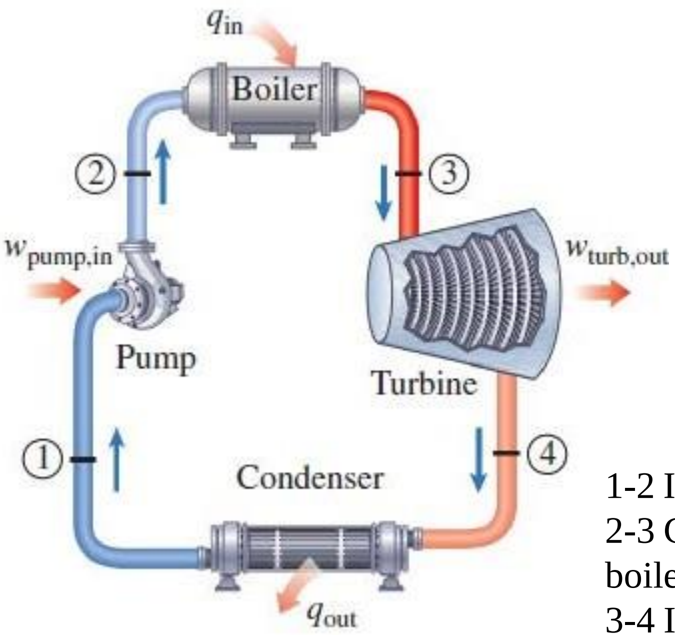
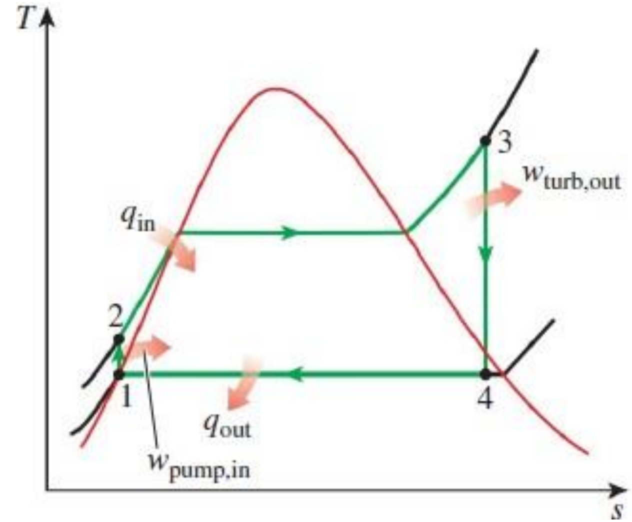


Fig: t-s and P-v diagram for ideal Brayton Cycle

Rankine cycle: The ideal cycle for vapor power cycles



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



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

THANK YOU