Second Law of Thermodynamics. 9.1

Second Law of Thermodynamics
Carnot cycle efficiency
-Heat engines
- Refrigerators

Second Law of Thermodynamics

Three Statements of the second law

Heat engines (Kelvin-Planck Law)

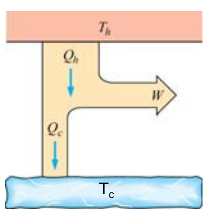
Refrigerators (Claussius Statement)

Entropy Principle

Heat Engines

A heat engine takes in heat at a high temperature and exhausts heat at a low temperature.

In the process of heat flow some of the input heat is converted to work



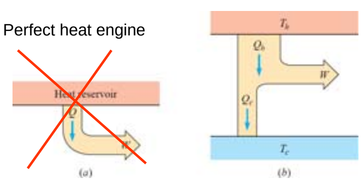
First Law (for a cycle)

$$Q = Q_h + Q_c = W$$

Second Law (puts limits on Q_h and Q_C)

Kelvin-Planck Statement of the second law of thermodynamics

Perfect heat engine

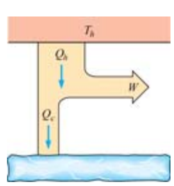


It is impossible to construct a heat engine operating in a cycle that extracts heat from a reservoir and delivers an equal amount of work.

No perfect heat engine

Efficiency of a heat engine

The efficiency is the fraction of the heat input at high temperature converted to work.



$$e = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h}$$

$$e = 1 - \frac{Q_c}{Q_h}$$

In calculating efficiencies Q_h and Q_c are taken as positive quantities.
(i.e. the magnitude of the heat)

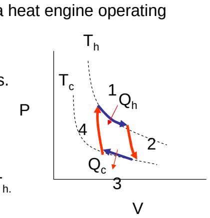
The second law says that a heat engine cannot be 100% efficient.

Carnot Cycle

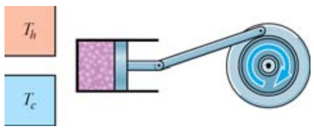
Sadi Carnot, a French engineer (1796-1832) proposed a cycle set the limits to the efficiency of a heat engine operating between two temperatures.

The cycle consists of 4 reversible steps.

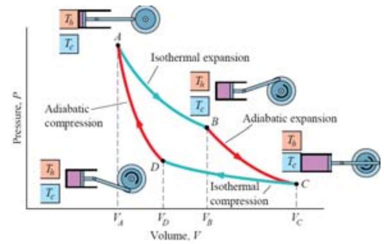
1. Isothermal expansion at T_h
2. Adiabatic expansion from T_h to T_c
3. Isothermal compression at T_c
4. Adiabatic compression from T_c to T_h.



Heat engine.



Heat engine undergoing the Carnot cycle.

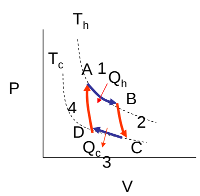


Work is done by the gas in expansion
Work must be done on the gas to compress it to the initial state

Heat transfer in the Carnot cycle

In the Carnot cycle the magnitude of the heat transferred at T is proportional to the absolute temperature T.

$$\frac{Q_h}{Q_c} = \frac{T_h}{T_c}$$ (here Q is always positive)



From the relations
Isothermal expansion and compression

$$Q_h = RT_h \ln\frac{V_B}{V_A} \qquad Q_c = RT_c \ln\frac{V_C}{V_D}$$

Adiabatic expansion and compression

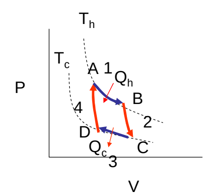
$$T_h V_B^{\gamma-1} = T_c V_C^{\gamma-1}$$
$$T_h V_A^{\gamma-1} = T_c V_D^{\gamma-1} \longrightarrow \frac{V_B}{V_A} = \frac{V_C}{V_D} \longrightarrow \frac{Q_h}{T_h} = \frac{Q_c}{T_c}$$

Efficiency of the Carnot cycle

$$e = 1 - \frac{Q_c}{Q_h}$$

becomes

$$e = 1 - \frac{T_c}{T_h}$$



The efficiency only depends on the ratio of the absolute temperatures.

The efficiency would be 100% if Q_c =0.

This is only possible if T_c = 0 K (i.e absolute Zero)

A temperature of absolute zero cannot be attained.
(Third law of thermodynamics)

Carnot's Theorem

All Carot engines operating between temperatures T_h and T_c have the same efficiency.

$$e = 1 - \frac{T_c}{T_h}$$

No other heat engine operating between these temperatures can have a greater efficiency

Stirling Engine

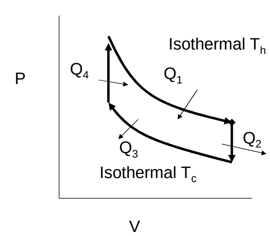
Maximum efficiency is less than the Carnot efficiency.

$w_2 = w_4 = 0$ $\qquad Q_2 = Q_4$

then $\qquad e = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{Q_1 - Q_3}{Q_1 + Q_4}$

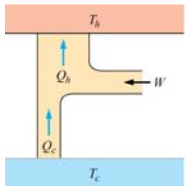
For isothermal processes same volume change $\qquad \frac{Q_1}{T_h} = \frac{Q_3}{T_c}$

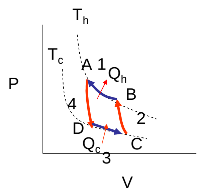
then $\qquad e = e_{carnot}\left(\frac{1}{1 + \frac{Q_4}{Q_1}}\right)$



Efficiency lower due to extra heat added.

Refrigerator and heat pump





A heat engine run in reverse is a refrigerator and heat pump.

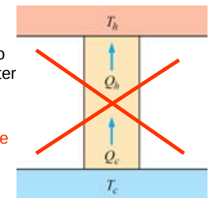
Work is done to move heat from a cold temperature source to a hot sink.

This device and be used for cooling or heating.

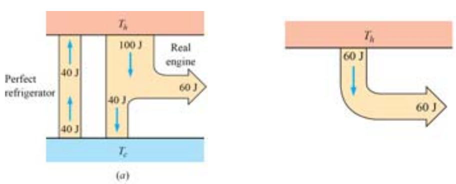
Clausius Statement of the Second Law of Thermodynamics.

It is impossible to construct a refrigerator operating in a cycle whose sole effect is to transfer heat from a cooler object to a hotter one.

Heat always flows from high temperature to low temperature.



Equivalence of the Kelvin-Planck and Clausius statements.

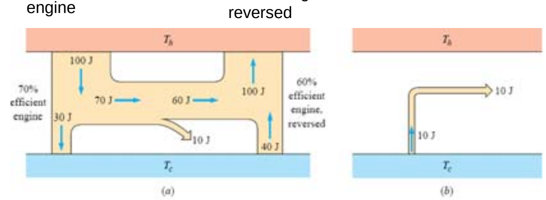


If a perfect refrigerator were possible (Clausius) then a perfect heat engine could be constructed (Kelvin-Planck). Thus, the impossibility one implies the impossibility of the other.

Proof of the Carnot Principle

higher efficiency engine

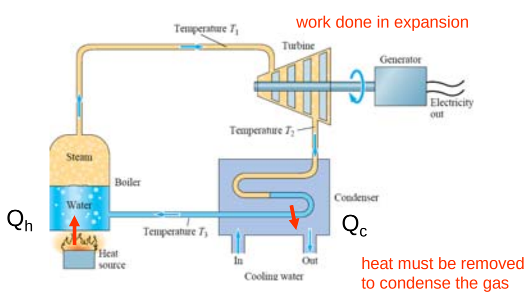
Carnot engine reversed



If a heat engine with a higher efficiency than a Carnot engine could exist. Then it could convert heat to work with 100% efficiency.

The Carnot engine has the highest efficiency for any heat engine acting between two temperatures.

Real Heat Engines



Power Plant

Example

In a wood burning power plant the steam in the turbine operates between the high temperature of 810 K and a low temperature of 366 K. What is the Carnot efficiency for this plant.

$$e = 1 - \frac{T_c}{T_h} = 1 - \frac{366}{810} = 0.55$$

Compare this to the efficiency calculated from the electrical power output of 59 MW and heat power input of 165 MW (see prob. 60)

$$e = \frac{W}{Q_h} = \frac{P}{H} = \frac{59\text{MW}}{165\text{MW}} = 0.35$$

The actual efficiency is less than the Carnot efficiency.

How to improve the efficiency of a heat engine.

Increase T_h This requires high temperature materials

Decrease T_c This requires efficient heat transfer.

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Cogeneration
Use of waste heat

This power plant in Denmark uses the waste heat to heat green houses nearby.

Refrigerators

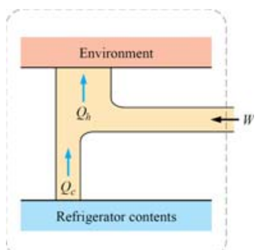
Coefficient of performance
COP- the heat removed from the cold source divided by the work done.

$$COP = \frac{Q_c}{w} = \frac{Q_c}{Q_h - Q_c}$$

The maximum Carnot COP

$$COP = \frac{T_c}{T_h - T_c}$$

since $\frac{Q_h}{T_h} = \frac{Q_c}{T_c}$



Refrigerator

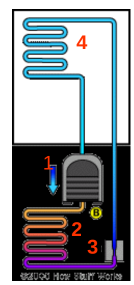
The refrigerator uses a liquid with a low boiling point. The evaporation takes up heat from the refrigerator and the condensation of the gas releases the heat outside the refrigerator.

1 Compressor – gas is compresses and heated

2 Heat exchange coils - the heat is released from the gas and exhausted outside of the refrigerator.

3 Expansion valve – The pressure is decreased after going through the valve. The gas is cooled

4 Cooling coils- Heat is absorbed from within the refrigerator. The gas is heated.



Refrigerator

A freezer is kept at a temperature of 0° F. What is the maximum COP for a Carnot refrigerator with output temperature of 85° F. If the electrical energy use is 500kWh/year how much heat is removed in one year, assume 90% conversion of electrical energy to work.

COP

$$COP = \frac{T_c}{T_h - T_c} = \frac{255}{302 - 255} = 5.4$$

T_c = (0 -32)(5/9) +273=255 K

T_h =(85-32)(5/9)+273=302 K

Work

$$W = 0.9(500x10^3 W \cdot hr)\left(\frac{60\min}{hr}\right)\left(\frac{60s}{\min}\right) = 1.62x10^9 J$$

Heat

$$COP = \frac{Q_c}{w}$$

$$Q_c = COP(w) = 5.4x1.62x10^9 = 8.7x10^9 J$$ Heat removed

Summary

- The second law of thermodynamics limits the efficiency of heat engines to less than 100%
- The Carnot cycle is a reversible cycle taking in heat at high T and exhausting heat at low T.
- The maximum efficiency of a heat engine working between two temperatures is the Carnot efficiency that depends only on the ratio of the absolute temperatures.
- Refrigerators and heat pumps are heat engines run in reverse.
- The maximum coefficient of performance is determined by a Carnot cycle.