2nd law of Thermo

1st law: \[ Q_{z} = \Delta E + W_{z} \]
\[ \int Q = \int W \]

Heat engine -
A device that operates in a cycle.
It does a certain net positive work through transfer of heat from a high temp body to a low temp body.

Working fluid - Substance to which heat is being transferred.

Steam power plant

- Heat transferred \( Q_{h} \) from high temp body.
- Heat transferred \( Q_{l} \) to low temp body.
- \( Q_{h} \) and \( Q_{l} \) determined by definition of system.
Efficiency

Thermal efficiency for heat engine:

\[ \eta_{\text{thermal}} = \frac{W}{Q_h} \]

\[ \Delta Q = \Delta W \] (\text{if there are no losses})

\[ Q_u - Q_l = W \] \[ \Rightarrow \eta_{\text{thermal}} = \frac{Q_u - Q_l}{Q_u} = 1 - \frac{Q_l}{Q_u} \]

Refrigerator

\[ Q_u \]

\[ \text{Condenser} \]

\[ \text{Expansion valve} \]

\[ \text{Compressor} \]

\[ \text{Evaporator} \]

\[ Q_l \]

Coefficient of performance ("efficiency" of a refrigerator):

\[ \beta = \frac{Q_l}{W} = \frac{Q_l}{Q_u - Q_l} \cdot \frac{\dot{Q}_l}{\dot{Q}_u} = \frac{1}{\frac{Q_u}{Q_l} - 1} \]

for a heat pump (objective is to get heat to the hot thing)

\[ \beta' = \frac{Q_u}{W} = \frac{Q_u - \dot{Q}_u}{\dot{Q}_u - Q_l} \cdot \frac{\dot{Q}_u}{\dot{Q}_l} = \frac{1}{1 - \frac{Q_l}{Q_u}} \]

for a heat engine

\[ \beta' - \beta = 1 \]
Some definitions & symbols:

Hot reservoir - a body of such a large mass that it may absorb or reject an unlimited quantity of heat without suffering an appreciable change in temperature (or in any other thermodynamic property).

Path tube - ice cube.

Cyclic device (or combination of devices).

Heat engine:
\[ \eta_e = \frac{W}{Q_H} = 1 - \frac{Q_L}{Q_H} \]

Refrigerator:
\[ \beta = \frac{Q_L}{W} = \frac{1}{\frac{Q_L}{Q_H} - 1} \]

Heat pump:
\[ \beta' = \frac{Q_H}{W} = \frac{1}{\frac{Q_H}{Q_L} - 1} \]
Second law of thermo

Kelvin-Planck statement

\[ \frac{\frac{T_f}{Q_f}}{\frac{T_i}{Q_i}} \rightarrow W \]

impossible

\( \text{impossible to construct a device where heat is transferred from a single reservoir and converted entirely into work} \)

\( \text{Note: } \eta = \frac{W}{Q_i} \) cannot have an engine \( \eta = 1 = 100\% \)

\( \eta < 1 \)

Clausius statement

\[ \frac{\frac{T_f}{Q_f}}{\frac{T_i}{Q_i}} \rightarrow \]  \[ \frac{W}{Q_i} \]

impossible

\( \text{impossible to construct a device where heat is transferred from low } T \) to high \( T \) without any work input, for \( W \) any other effects \)

\( \text{Note: } \beta = \frac{Q_i}{W}, \beta' = \frac{Q_{i'} Q_{i}}{W} \)

\( W > 0 \therefore \beta, \beta' < \infty \)

Reversible Process

A process in which the system and surroundings can be returned to their original condition after the process has been executed (generally quasi-equilibrium processes)

\[ \text{[All natural processes are irreversible]} \]

1. it is performed quasi-statically
2. it is not accompanied by any dissipative effects
Irreversible processes & factors leading to irreversibility

1. Friction
2. Unrestrained expansion
3. Heat transfer across a finite temperature difference
4. Mixing 2 different substances (spontaneous mixing)
5. Rapid chemical reactions (spontaneous chem reactions)
6. Electric current flow through a resistance \( I^2R \)
7. Magnetization or polarization with hysteresis
8. Inelastic (plastic) deformation

Reminder...

Throttling process in a nutshell (essf)

\[ h_i \left( \frac{V_i^2}{2} \right) = h_e + \frac{V_e^2}{2} \]

If all small or pipe diameters are adjusted

\[ \Delta P = 0 \]

\[ h_i = h_e \] however there is a pressure drop.
The Carnot cycle

Review

Heat engine

\[ \eta_{\text{therm}} = \frac{W}{Q_H} = 1 - \frac{Q_L}{Q_H} \]

Refrigerator

\[ \beta = \frac{Q_L}{W} = \frac{1}{\frac{Q_L}{Q_H}} - 1 \]

Heat pump

\[ \beta' = \frac{Q_H}{W} = \frac{1}{1 - \frac{Q_L}{Q_H}} \]
cannot have H.E. of \( \eta = 100\% \)

what is maximum efficiency when operating between 2 temp reservoirs?

Each step in cycle must be reversible — no losses

Carnot Cycle

1) rev. isothermal proc. heat trans from \( T_u \)
2) rev. adiabatic proc. fluid goes from high to low \( T \)
3) rev. isothermal proc. heat transferred to \( T_u \)
4) rev. adiabatic proc. fluid goes from low to high \( T \)

completely rev,
different substances can be used
different devices.

All Carnot cycles operating between 2 const \( T \) reservoirs

have the same efficiency (regardless of the working fluid)

Carnot's theorem: No engine operating between two given reservoirs can be more efficient than a Carnot engine operating between the same two reservoirs.

A Carnot engine (HE, ret, HP) operates at the maximum possible efficiency.
\[ \eta = \frac{W}{Q_h} \]

- \( \eta_{\text{actual}} < \eta_{\text{carnot}} \) cycle is irreversible
- \( \eta_{\text{actual}} = \eta_{\text{carnot}} \) cycle is reversible
- \( \eta_{\text{actual}} > \eta_{\text{carnot}} \) cycle is impossible

Likewise for \( \beta, \beta' \)

Finding \( \eta, \beta, \beta' \)

Looking at HE

\[ \frac{T_w}{Q_h} \rightarrow W \]

\[ W = Q_h - Q_L \]

\[ \eta_{\text{rev}} = \frac{W_{\text{rev}}}{Q_h} \]

\[ \eta_{\text{irrev}} = \frac{W_{\text{irrev}}}{Q_h} \]

Equality of temp scale

\[ \frac{Q_h}{Q_L} = \frac{T_w}{T_L} \]

\[ \text{using absolute temperatures} \]

\[ W_{\text{rev}} + \text{Load} = W_{\text{rev}} < W_{\text{rev}} \]

\[ W_{\text{irrev}} + \text{Load} = W_{\text{irrev}} \]
The Carnot cycle is a theoretical cycle that describes the maximum efficiency of a heat engine or a refrigerator. The efficiency of a heat engine can be calculated using the Carnot efficiency formula:

$$\eta = \frac{W}{Q_h}$$

where $W$ is the work done and $Q_h$ is the heat input. The maximum efficiency of a heat engine is $\eta_{\text{max}}$ and is given by:

$$\eta_{\text{max}} = 1 - \frac{T_c}{T_h}$$

where $T_c$ is the temperature of the cold reservoir and $T_h$ is the temperature of the hot reservoir.

The Carnot theorem states that no heat engine can have a higher efficiency than that of a Carnot engine operating between the same temperatures.

For a refrigerator, the coefficient of performance (COP) is defined as:

$$\beta = \frac{Q_c}{W} = \frac{1}{1-\frac{T_c}{T_h}}$$

where $Q_c$ is the heat removed from the cold reservoir, $W$ is the work done, and $T_c$ and $T_h$ are the temperatures of the cold and hot reservoirs, respectively.

For a heat pump, which is a device that can both cool and heat, the coefficient of performance (COP) is defined as:

$$\beta' = \frac{Q_h}{W} = \frac{1}{1-\frac{T_h}{T_c}}$$

where $Q_h$ is the heat added to the warm reservoir, $W$ is the work done, and $T_c$ and $T_h$ are the temperatures of the cold and hot reservoirs, respectively.

These equations show how the efficiency and performance of heat engines and refrigerators can be calculated and optimized for different temperature conditions.