Objectives

- Introduce the thermodynamic property entropy (S) using the Clausius inequality
- Recognize the fact that the entropy is always increasing for an isolated system (or a system plus its surroundings) based on the increase of entropy principle
- Analysis of entopy change of a thermodynamic process (how to use thermodynamic table, ideal gas relation)
- Property diagrams involving entropy (T-s and h-s diagrams)
- Entropy balance: entropy change = entropy transfer + entropy change

Entropy

• Entropy: a thermodynamic property, can be used as a measure of disorder. The more disorganized a system the higher the entropy.

• Defined using Clausius inequality

$$\oint \frac{\delta Q}{T} \le 0$$

• This inequality is valid for all cycles, reversible and irreversible.

• Consider a reversible Carnot cycle

$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L}, \text{ from Carnot efficiceny } \eta_{\text{th}} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}, \; \frac{Q_L}{Q_H} = \frac{T_L}{T_H}$$

Therefore, $\oint \frac{\delta \mathrm{Q}}{\mathrm{T}} = 0$ for a reversible Carnot cycle $\oint \left(\frac{\delta \mathrm{Q}}{\mathrm{T}} \right)_{rev} = 0$

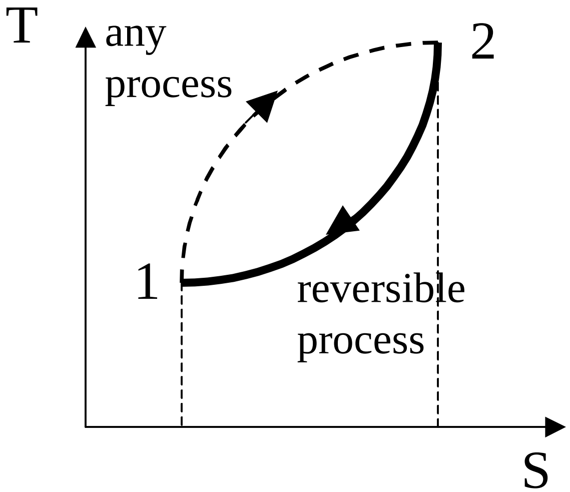
• Define a thermodynamic property entropy (S), such that

$$dS = \left. \frac{\delta Q}{T} \right|_{rev}, \text{ for any reversible process } \int_1^2 \mathrm{dS} = \int_1^2 \left. \frac{\delta Q}{T} \right|_{rev} = S_2 - S_1$$

The change of entropy can be defined based on a reversible process

Entropy-2

- Since entropy is a thermodynamic property, it has fixed values at a fixed thermodynamic states.



$$\oint \frac{\delta Q}{T} = \int_1^2 \left(\frac{\delta Q}{T}\right) + \int_2^1 \left(\frac{\delta Q}{T}\right)_{rev} \le 0$$

From entropy definition

$$dS = \left(\frac{\delta \mathrm{Q}}{T}\right)_{rev}, \quad \oint dS = 0 = \oint \left(\frac{\delta \mathrm{Q}}{T}\right)_{rev} = \int_1^2 \left(\frac{\delta Q}{T}\right)_{rev} + \int_2^1 \left(\frac{\delta Q}{T}\right)_{rev}$$

$$\text{Therefore, } \int_1^2 \left(\frac{\delta Q}{T}\right) \le \int_1^2 \left(\frac{\delta Q}{T}\right)_{rev} = \int_1^2 dS = S_2 - S_1 = \Delta S$$

$$\Delta S = S_2 - S_1 \ge \int_1^2 \left(\frac{\delta Q}{T}\right), \text{ This is valid for all processes}$$

$$dS \ge \frac{\delta Q}{T}, \text{ since } dS = \left(\frac{\delta \mathrm{Q}}{\mathrm{T}}\right)_{rev}, dS > \left(\frac{\delta \mathrm{Q}}{\mathrm{T}}\right)_{irrev}$$

- The entropy change during an irreversible process is greater than the integral of δQ/T during the process. If the process is reversible, then the entropy change is equal to the integral of δQ/T. For the same entropy change, the heat transfer for a reversible process is less than that of an irreversible. Why?

Entropy Increase Principle

$$\Delta S = S_2 - S_1 \geq \int_1^2 \left(\frac{\delta Q}{T}\right),$$ define entropy generation S_{gen}

$$\Delta S_{system} = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right) + S_{gen} \geq \int_1^2 \left(\frac{\delta Q}{T}\right)$$

where $S_{gen} \geq 0$. If the system is isolated and "no" heat transfer

The entropy will still increase or stay the same but never decrease

$\Delta S_{system} = S_{gen} \geq 0,$ entropy increase principle

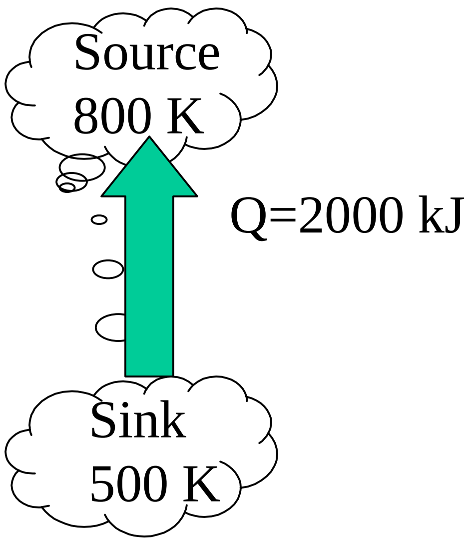
- A process can take place only in the direction that complies with the increase of entropy principle, that is, $S_{gen} \geq 0$.

- Entropy is non-conservative since it is always increasing. The entropy of the universe is continuously increasing, in other words, it is more disorganized and is approaching chaotic.

- The entropy generation is due to the existence of irreversibilities. Therefore, the higher the entropy generation the higher the irreversibilities and, accordingly, the lower the efficiency of a device since a reversible system is the most efficient system.

Entropy Generation Example

Example: Show that the heat can not transfer from the low-temperature sink to the high-temperature source based on the increase of entropy principle.



$\Delta S(\text{source}) = 2000/800 = 2.5$ (kJ/K)
$\Delta S(\text{sink}) = -2000/500 = -4$ (kJ/K)
$S_{gen} = \Delta S(\text{source}) + \Delta S(\text{sink}) = -1.5(\text{kJ/K}) < 0$
It is impossible based on the entropy increase principle $S_{gen} \geq 0$, therefore, the heat can not transfer from low-temp. to high-temp. without external work input

- If the process is reversed, 2000 kJ of heat is transferred from the source to the sink, $S_{gen}=1.5$ (kJ/K) > 0, and the process can occur according to the second law

- If the sink temperature is increased to 700 K, how about the entropy generation?

$\Delta S(\text{source}) = -2000/800 = -2.5(\text{kJ/K})$
$\Delta S(\text{sink}) = 2000/700 = 2.86$ (kJ/K)
$S_{gen} = \Delta S(\text{source}) + \Delta S(\text{sink}) = 0.36 \text{ (kJ/K)} < 1.5 \text{ (kJ/K)}$
Entropy generation is less than when the sink temperature is 500 K, less irreversibility. Heat transfer between objects having large temperature difference generates higher degree of irreversibilities