Basic 12
Micro-nano Thermodynamics

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Thermodynamics

Progress limitation of phenomenon (Process)

Equilibrium

Evaluation standard of system design

1) Thermodynamics for material
2) Thermodynamics for process
3) Thermodynamics for system
1) Thermodynamics for material

Energy of material: $E$
Entropy of material: $S$

The number of material phases
Concentrations of material in each phase
Temperature
Pressure

Unit of energy: [J], [J/s]
Unit of entropy: [J/K], [J/(K·s)]

Explanation by Water model
Ex. 1 Water in a flask (Batch)

Same conditions
(Temperature, Pressure, etc.)

Energy

1

$E \ [J]$

2

$2E \ [J]$

Entropy

1

$S \ [J/K]$

2

$2S \ [J/K]$
Ex. 2 Water flow into a tube (Continuous)

Energy $E \,[\text{J/s}]$

Entropy $S \,[\text{J/(K\cdot s)}]$

Same conditions (Temperature, Pressure, etc.)

Energy $2E \,[\text{J/s}]$

Entropy $2S \,[\text{J/(K\cdot s)}]$
Energy: $E$

- Volume changeable vessel:
  - Enthalpy $H$

- Constant volume vessel:
  - Internal energy $U$

What are energy and entropy?

Quantity of energy:
- Enthalpy (Internal energy)

Quality of energy:
- Expression by both enthalpy (Internal energy) and entropy
1) Calculation of enthalpy

Standard generation heat of material:

$\Delta H^0_{298} \text{ [J/mol]}$

Ex. CH$_4$ -74.5 kJ/mol
C and N$_2$ 0 kJ/mol

(Pure material consisting of same element)

Enthalpy of material at temperature of $T$ and the at atmospheric pressure: $H^0_T$

$$H^0_T = n\Delta H^0_{298} + n \int_{298}^{T} C_{p,m} \, dT$$

$n$: mol number of material [mol]

$C_{p,m}$: Heat capacity of material [J/(K・mol)]

$$C_{p,m} = a + bT + cT^2$$
2) Calculation of entropy

Absolute entropy of material: \( S^0_{298} \) [J/(K·mol)]


Ex. CH\(_4\) 186 [J/(K·mol)]

Absolute entropy of material at temperature of \( T \) and at the atmospheric pressure: \( S^0_T \)

\[
S^0_T = S^0_{298} + \int_{298}^{T} \frac{C_{p,m}}{T} dT
\]
2) Thermodynamics for process

Ex. Heating process

- Batch process

Enthalpy change before and after: \( \Delta H \)

\[
\Delta H = H_{\text{out}} - H_{\text{in}}
\]
Ex. Heating process

- Continuous process

Enthalpy change before and after: $\Delta H$

$$\Delta H = H_{out} - H_{in}$$

Energy input:

$H_{in}$ $\rightarrow$ $H_{out}$
Ex. Heating process

- Batch process

- Continuous process

Entropy change before and after: \( \Delta S \)

\[
\Delta S = S_{out} - S_{in}
\]
Material input

\( H_1, S_1 \)

\[ \Delta H = \sum_{j} H_{\text{out},j} - \sum_{j} H_{\text{in},j} \]

\[ \Delta S = \sum_{j} S_{\text{out},j} - \sum_{j} S_{\text{in},j} \]

Material output

\( H_2, S_2 \)

Energy input

Energy output

Enthalpy change

Entropy change

: Intermediary energy
E.g.

\[ \Delta H = H_3 - (H_1 + H_2) \]

\[ \Delta S = S_3 - (S_1 + S_2) \]

\( \Delta H \): Intermediary energy
\( \Delta H : \) Intermediary energy

**Direction:** Positive or Negative of \( \Delta H \)

(Positive: Energy input, Negative: Energy output)

**Quantity:** Absolute value of \( \Delta H \)

**Quality:** Degree of low level \( d \)

\[
d = \frac{\Delta S}{\Delta H} \quad [1/K]
\]

Degree of low level:
Larger \( d \) indicates lower intermediary energy.
What is the “Degree of low level”?  

Assumption:  
Evolution of 1 J intermediary energy  

\[
\text{Temperature of heat source} \quad 1000K \quad 300K \\
\text{d} \quad \frac{1}{1000} \quad < \quad \frac{1}{300} \\
\text{Higher level of intermediary energy}
\]
Explanation of “Degree of low level” by Water model

Quantity of water = Mass of water

Degree of low level ➔ Position of vessel

Position of vessel
Before change
After change

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Content of enthalpy change: $\Delta H$

\[ \Delta H = (\text{Energy for Work}) + (\text{Energy for thermodynamic heat loss}) \]

Thermal energy which is Impossible to use

Change of Gibbs’ free energy $\Delta G = \Delta H - T\Delta S$
<table>
<thead>
<tr>
<th>Process</th>
<th>Quantity of energy</th>
<th>Temperature</th>
<th>$\Delta H$</th>
<th>$\Delta S$</th>
<th>Degree of low level $d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat source</td>
<td>Output $Q$</td>
<td>$T$</td>
<td>$-Q$</td>
<td>$-Q/T$</td>
<td>$1/T$</td>
</tr>
<tr>
<td>Heat sink</td>
<td>Input $Q$</td>
<td>$T$</td>
<td>$Q$</td>
<td>$Q/T$</td>
<td>$1/T$</td>
</tr>
<tr>
<td>Work source</td>
<td>Output $W$</td>
<td>—</td>
<td>$-W$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Work sink</td>
<td>Input $W$</td>
<td>—</td>
<td>$W$</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- Heat source and sink • • • No work function
  \[ \Delta G = 0 \]

\[ d = \frac{\Delta S}{\Delta H} \]

- Work source and sink • • • No thermal function
  \[ \Delta S = 0 \]

Even if the Work source or sink evolves or takes energy, Respectively, the quality of them does not change.
Heat source

\[ \Delta H = -Q \]
\[ \Delta S = -\frac{Q}{T} \]
\[ d = \frac{1}{T} \]

Work source

\[ \Delta H = -W \]
\[ \Delta S = 0 \]
\[ d = 0 \]
3) Thermodynamics for system

System: Assembly of processes
Ex. System consisting of two processes

Material 1 → Process 1 → Product 1
Material 2 → Process 2 → Product 2

Rule
The intermediary energy must not cross the system boundary.
Ex. Gas heating system for hot water

City gas
Air

Combustor

Cold water

Heat exchanger

Exhaust gas

Combustion energy

Hot water

System
Thermodynamics for system

Rules

Only the materials can cross the system boundary.

The intermediary energy (Heat and Work) must not cross the system boundary.

The 1st law of thermodynamics

(Conservation law of energy)

\[ \sum_j \Delta H_j = 0 \]

The 2nd law of thermodynamics

(Increase law of entropy)

\[ \sum_j \Delta S_j \geq 0 \]
Explanation of the 1st and 2nd law of thermodynamics by Water model

Position of vessel

1kg water

Before change

After the 1st change

After the 2nd change

$\Delta H \rightarrow \text{Change of water mass: } \Delta m$

$d \rightarrow \text{Position of water}$

$\frac{\Delta S}{\Delta H}$
The 1st law of thermodynamics (Conservation law of energy)
\[ \sum_{j} \Delta H_{j} = \sum_{j} \Delta m_{j} = \Delta m_{1} + \Delta m_{2} + \Delta m_{3} = 0 \]

The 2nd law of thermodynamics (Increase law of entropy)
\[ \sum_{j} \Delta S_{j} = \sum_{j} d_{j} \Delta m_{j} = d_{1} \Delta m_{1} + d_{2} \Delta m_{2} + d_{3} \Delta m_{3} = 1 \geq 0 \]
Ex.

Position of vessel

Before change

<table>
<thead>
<tr>
<th>Step</th>
<th>Change</th>
<th>$\Delta m$</th>
<th>$d_i \Delta m_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>$\Delta m_1 = -1$</td>
<td>$d_1 \Delta m_1 = -1$</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>$\Delta m_2 = 1$</td>
<td>$d_2 \Delta m_2 = 2$</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>$\Delta m_3 = -0.9$</td>
<td>$d_3 \Delta m_3 = -0.9$</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>$\Delta m_4 = 0.9$</td>
<td>$d_4 \Delta m_4 = 0$</td>
</tr>
</tbody>
</table>

After change

0.9kg water

0.1kg water

1 kg water
The *1st* law of thermodynamics (Conservation law of energy)

\[
\sum_j \Delta H_j = \sum_j \Delta m_j = \Delta m_1 + \Delta m_2 + \Delta m_3 + \Delta m_4 = 0
\]

The *2nd* law of thermodynamics (Increase law of entropy)

\[
\sum_j \Delta S_j = \sum_j d_j \Delta m_j = d_1 \Delta m_1 + d_2 \Delta m_2 + d_3 \Delta m_3 + d_4 \Delta m_4 = 0.1 \geq 0
\]
Ex. Combustion of H₂ with O₂  \[ H_2 + \frac{1}{2}O_2 \rightarrow H_2O \]
Relationship between enthalpy change ($\Delta H_r$) and reaction heat ($Q_r$)

Energy change by reaction: $\Delta H_r$

Energy change in heat sink: $\Delta H_T$

From the 1st law $\Delta H_r + \Delta H_T = 0$

$\Delta H_T = Q_r$  $\implies$  $\Delta H_r = -Q_r$

$1 \text{mol-H}_2 + 0.5 \text{mol-O}_2$ Combustion energy

$1 \text{mol-H}_2$ $1 \text{mol-H}_2$ $0.5 \text{mol-O}_2$ $1 \text{mol-H}_2$ $0.5 \text{mol-O}_2$ $0.5 \text{mol-O}_2$

$\Delta H_T$ $Q_r$

$\text{Combustor}$ $\text{Heat sink}$

$1 \text{mol-H}_2$ $1 \text{mol-H}_2$ $\Delta H_r$ $\text{System}$

$\text{Combustion energy}$

$\text{Energy change by reaction: } \Delta H_r$

$\text{Energy change in heat sink: } \Delta H_T$

$\text{From the 1st law } \Delta H_r + \Delta H_T = 0$

$\Delta H_T = Q_r$  $\implies$  $\Delta H_r = -Q_r$
Exothermic reaction

\[ Q_r > 0 \rightarrow \Delta H_r : \text{Negative} \]

Endothermic reaction

\[ Q_r < 0 \rightarrow \Delta H_r : \text{Positive} \]
**Exothermic reaction system**

The 1st law
\[ \Delta H_r + \Delta H_T = 0 \]

The 2nd law
\[ \Delta S_r + \Delta S_T \geq 0 \]

\[ \Delta H_T = Q \]
\[ \Delta S_T = \frac{Q}{T} \text{より} \]
\[ \Delta H_r + Q = 0 \]
\[ \Delta S_r + \left( \frac{Q}{T} \right) \geq 0 \]
\[ \Delta H_r + Q = 0 \]
\[ \Delta S_r + \frac{(Q/T)}{\geq 0} \]

Multiply \((-T)\) by both sides

\[ \Delta S_r - \frac{(\Delta H_r/T)}{\geq 0} \]

\[ \Delta H_r - T \Delta S_r \leq 0 \]

**Condition to occur exothermic reaction**

\[ \Delta H_r \leq T \Delta S_r \]

\[ \Delta H - T \Delta S \equiv \Delta G \] : Change of Gibbs’ free energy

**Condition to occur exothermic reaction**

\[ \Delta G_r \leq 0 \]
Content of enthalpy change: $\Delta H$

$$\Delta H = \Delta G + T\Delta S$$

- **Heat sink**: Temperature $T$
- **Reactor**: Evolution of work energy $\Delta G_r$
  - Degradation of energy quality
  - Convert from work to heat
  - Temperature $T$
- **Heat sink**: Evolution of thermal energy $T\Delta S_r$
  - Heat loss
  - Energy for Work $\Delta G$

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Endothermic reaction system

The condition for the endothermic reactions is the same as the for the exothermic reactions.

Heat source
\[ \Delta H_T = -Q \]
\[ \Delta S_T = -\frac{Q}{T} \]

System
\[ \Delta H_r - Q = 0 \]
\[ \Delta S_r - \left(\frac{Q}{T}\right) \geq 0 \]

\[ \Delta S_r - \left(\frac{\Delta H_r}{T}\right) \geq 0 \]
Endothermic reaction  $\Delta H_r > 0$

- $\Delta G_r \leq 0$
  - Evolution of work energy $\Delta G_r$
  - Degradation of energy quality
  - Convert from work to heat

- Taking thermal energy $T\Delta S_r$
  - Evolution of heat

Driving force for reaction
Ex. 1 Thermodynamic analysis of electric decomposition of water

\[
\begin{align*}
\Delta H_r & + \Delta H_w = 0 \\
\Delta S_r & + \Delta S_w \geq 0
\end{align*}
\]

The 1st law

\[
\begin{align*}
\Delta H_r - W & = 0 \\
\Delta S_r & \geq 0
\end{align*}
\]

The 2nd law
Electric decomposition of water occurs by electric energy less than the theoretical heat of reaction.

Why?
Temperature $T$

Heat source (Atmosphere)

$\Delta H_T, \Delta S_T$

$\Delta H_r, \Delta S_r$

$\Delta H_w, \Delta S_w$

System

Reactor

$Q$

$H_2$

$O_2$

$H_2O$

$W$
The 1st law \[ \Delta H_r + \Delta H_W + \Delta H_T = 0 \]

The 2nd law \[ \Delta S_r + \Delta S_W + \Delta S_T \geq 0 \]

\[ \Delta H_r - W - Q = 0 \]

\[ \Delta S_r - Q/T \geq 0 \]

\[ Q = \Delta H_r - W \]

\[ \Delta S_r - \frac{\Delta H_r - W}{T} \geq 0 \]

\[ W \geq \Delta H_r - T \Delta S_r = \Delta G_r \]

The reactor takes thermal energy of \( T\Delta S_r \) from atmosphere.

Experimental results:

Consumed electricity \( \cong \) Theoretical electricity

The electricity is reduced at high atmospheric temperature.
The diagram illustrates the concepts of energy and work in thermodynamics. The graph shows the relationship between energy and work, with specific equations and labels for different processes. The text below the diagram provides additional explanations:

- **Energy for Work**
  - $\Delta H$
  - $\Delta G$
  - $T\Delta S$

- **Heat Loss**

- **Taking Work**
  - $\Delta G_r$

- **Evolution of Work Energy**

- **Electric Decomposition**
  - $\Delta H$

- **Taking Heat**
  - $T\Delta S_r$

- **Evolution of Thermal Energy**

The equations shown in the image are:

- $W = \Delta G_r$
- $W > \Delta G_r$

These equations indicate:

- No degradation of intermediary energy
- Increase of electric energy and low thermal energy from heat sink
Ex. 2 Thermodynamic analysis of heat pump

**Cooling**

Heat source: Room

Low temp. heat source: Room

Process 1: Vaporization

Process 2: Compression & Liquefaction

Process 3: Heat release

Temperature: $T_h$

Media: Refrigerant

System

Work $W$

$Q_1$

$Q$

$Q_h$

$W$

System

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Temperature: $T_i$

Heat source

$\Delta H_i, \Delta S_i$

Process 1

$H_1, S_1$

$\Delta H_2, \Delta S_2$

Process 2

$H_2, S_2$

Process 3

$H_3, S_3$

Heat sink

$\Delta H_h, \Delta S_h$

$Q_h$

$\Delta H_w, \Delta S_w$

Work

$\Delta H_3, \Delta S_3$

Temperature: $T_h$
The 1st law

\[
\Delta H_1 + \Delta H_2 + \Delta H_3 + \Delta H_l + \Delta H_w + \Delta H_h = 0
\]

The 2nd law

\[
\Delta S_1 + \Delta S_2 + \Delta S_3 + \Delta S_l + \Delta S_w + \Delta S_h \geq 0
\]

\[
\Delta H_1 + \Delta H_2 + \Delta H_3 = (H_1 - H_3) + (H_2 - H_1) + (H_3 - H_2) = 0
\]
\[
\Delta S_1 + \Delta S_2 + \Delta S_3 = (S_1 - S_3) + (S_2 - S_1) + (S_3 - S_2) = 0
\]
\( \Delta H_l + \Delta H_w + \Delta H_h = 0 \)

\( -Q_l - W + Q_h = 0 \)

\( \Delta S_l + \Delta S_w + \Delta S_h \geq 0 \)

\( -\frac{Q_l}{T_l} + (0) + \frac{Q_h}{T_h} \geq 0 \)
Room heating

Heat source

Low temp. heat source: Outside air

Process 1

Q_l

Process 2

Work

W

Process 3

Q_h

High temp. heat sink: Room

Heat sink

System

Temperature: T_l

Temperature: T_h

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Room heating

\[-Q_l - W + Q_h = 0\]

\[Q_l = -W + Q_h\]

\[-\frac{Q_l}{T_l} + \frac{Q_h}{T_h} \geq 0\]

\[\frac{W - Q_h}{T_l} + \frac{Q_h}{T_h} \geq 0\]

\[W - Q_h + \frac{T_l}{T_h} Q_h \geq 0\]

Cooling

\[W \geq \frac{T_h - T_l}{T_h} Q_h\]
Room heating

\[ W \geq \frac{T_h - T_l}{T_h} Q_h \]

Heat at \( T_l \) in the air is taken. \( T_h > T_l \)
The room at \( T_h \) is heated at heating rate of \( Q_h \).

Ex. Outside temp.: \(-3^\circ C(=270K)\)
Room temp.: \(27^\circ C(=300K)\)

Heating rate = 1 kW = \((1 \text{ kJ/s}) = Q_h\)

\[ W \geq \frac{T_h - T_l}{T_h} Q_h = \left[\frac{(300) - (270)}{300}\right](1) = 0.1 \text{ [kW]} \]

Comparison  Joule heating

\[ W = 1 \text{ kW} \]
High temp. heat sink: Combustor

Process 1
Vaporization

Process 2
Power generation

Process 3
Heat release

Media: Water

Work sink

System

Temperature: $T_h$

$Q_h$

$Q_l$
High temp. heat source: 600°C (=873K)
Low temp. heat sink: 50°C (=323K)

\[ W \leq \frac{T_h - T_l}{T_h} Q_h = \frac{[(873) - (323)]}{(873)} Q_h = 0.63Q_h \]

Temp. of heat source \rightarrow Conversion efficiency to electricity
\[ W - Q_h + Q_l = 0 \]
\[- \frac{Q_h}{T_h} + \frac{Q_l}{T_l} \geq 0 \]

\[ Q_l = Q_h - W \geq \frac{T_l}{T_h} Q_h \]

Heat from high temp. heat source: \( Q_h \)

\[ W \leq \frac{T_h - T_l}{T_h} Q_h \]

\[ \frac{W}{Q_h} \leq \frac{T_h - T_l}{T_h} \]

Carnot efficiency: \( \frac{W}{Q_h} \leq \frac{T_h - T_l}{T_h} \)

Ratio of the max. work energy taken to thermal energy taken to...
Change of Gibbs free energy

\[ \Delta G = \Delta H - T \Delta S \]

Temperature: \( T \) \( \rightarrow \) Ambient temp. \( T_0 (=298K) \)

\[ \Delta \varepsilon = \Delta H - T_0 \Delta S \]

\( \Delta \varepsilon \) : Change of exergy \( [J], [J/s] \)

The 2nd law

\[ \sum_j \Delta S_j \geq 0 \]

\[ \sum_j \Delta \varepsilon_j = \sum_j (\Delta H_j - T_0 \Delta S_j) = -T_0 \sum_j \Delta S_j \leq 0 \]

Decreasing law of exergy
Quality of energy

Degree of low level \( d \)

\[
A = \frac{\Delta \varepsilon}{\Delta H} = \frac{\Delta H - T_0 \Delta S}{\Delta H} = 1 - T_0 \frac{\Delta S}{\Delta H} = 1 - T_0 d
\]

Energy level

The 1st law \( \sum_j \Delta H_j = 0 \)

The 2nd law \( \sum_j A_j \Delta H_j \leq 0 \)
Explanation of energy level by Water model

$$\sum \Delta m_j = 0, \sum A_j \Delta m_j \leq 0$$

Energy level A

Before change

1 kg water

After the 1st change

$$\Delta m_1 = -1 \quad A_1 \Delta m_1 = -2$$

$$\Delta m_2 = 1 \quad A_2 \Delta m_2 = 1$$

$$\Delta m_3 = 0 \quad A_3 \Delta m_3 = 0$$

After the 2nd change

$$\Delta m_1 = 0 \quad A_1 \Delta m_1 = 0$$

$$\Delta m_2 = -1 \quad A_2 \Delta m_2 = -1$$

$$\Delta m_3 = 1 \quad A_3 \Delta m_3 = 0$$
The 2nd law (Decreasing law of exergy)

$$\sum_j \Delta \varepsilon_j = \sum_j A_j \Delta m_j = A_1 \Delta m_1 + A_2 \Delta m_2 + A_3 \Delta m_3 = -1 \leq 0$$
<table>
<thead>
<tr>
<th>Process</th>
<th>Quantity of energy</th>
<th>Temperature</th>
<th>$\Delta H$</th>
<th>$\otimes \varepsilon$</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat source</td>
<td>Output $Q$</td>
<td>$T$</td>
<td>$-Q$</td>
<td>$-\frac{T-T_0}{T}Q$</td>
<td>$\frac{T-T_0}{T}$</td>
</tr>
<tr>
<td>Heat sink</td>
<td>Input $Q$</td>
<td>$T$</td>
<td>$Q$</td>
<td>$\frac{T-T_0}{T}Q$</td>
<td>$\frac{T-T_0}{T}$</td>
</tr>
<tr>
<td>Work source</td>
<td>Output $W$</td>
<td>—</td>
<td>$-W$</td>
<td>$-W$</td>
<td>1</td>
</tr>
<tr>
<td>Work sink</td>
<td>Input $W$</td>
<td>—</td>
<td>$W$</td>
<td>$W$</td>
<td>1</td>
</tr>
</tbody>
</table>

$\Delta \varepsilon = \Delta H - T_0 \Delta S$

Energy level of work source and sink = 1

Energy level of heat source and sink ➡️ Carnot efficiency at $T_l = T_0$

Temp. of heat source and sink = $T_0$, $A=0$

Temp. of heat source and sink = $\infty$, $A=1$

Corresponding to work source and sink
Thermodynamic compass?

\[ \Delta \varepsilon = \Delta H - T_0 \Delta S \]

\[ \Delta S = 0 \]

\( (\Delta H, \Delta \varepsilon) \) : Process vector

Gradient of the vector \( = A \)

\[ A = \frac{\Delta \varepsilon}{\Delta H} \]
Expression of the 1st and 2nd laws on the coordinate
System: Addition of two process vectors

The additional vector must be negative or 0 on the $\Delta \varepsilon$ axis

**Reasons**

**The 1st law**

$$\sum_j \Delta H_j = 0$$

**The 2nd law**

$$\sum_j \Delta \varepsilon_j \leq 0$$
How to use the thermodynamic vector

\[ \Delta S = 0 \]

Determination of Process 1

Finding the vector to satisfy that the additional vector must be negative on the \( \Delta \varepsilon \) axis

\[ \sum_j \Delta H_j = 0 \]

The 1st law

\[ \sum_j \Delta \varepsilon_j \leq 0 \]

The 2nd law

* Several vectors are available.
Red processes: Depending on process

**Process examples**

- **Heated type**
  - Temp. increase from 100°C to 200°C

- **Heating type**
  - Temp. decrease from 200°C to 100°C

- **Cooling type**
  - Temp. increase from -50°C to -30°C

- **Cooled type**
  - Temp. decrease from -30°C to -50°C

- **Separation type**
  - Separation of air to N₂ and O₂

- **Mixing type**
  - Mixing of N₂ with O₂

\[ A = \frac{\Delta \varepsilon}{\Delta H} \]
Process selection against target process

Ex. Target process: Heated process at 373K

Exergy loss

Driving force to realize the process

Heated process at 373K

Heating at 323K

Heating at 423K

Heating by electricity

Max. exergy loss: Utilization of electricity

Exergy loss: EXL
\[ A = \frac{T - T_0}{T} \quad T_0 = 298 \text{ [K]} \quad A = 0.5 \]

Thermal energy \(-\infty < A \leq 1\)

Cooled type

\[ A = -0.5 \quad T = 199K \]

Heating type

\[ A = 0.5 \quad T = 596K \]

Work source

\[ A = 1 \quad T = \infty \]

Work sink

\[ A = 0.5 \quad T = 596K \]

Heated type

\[ A = 1 \quad T = \infty \]

Cooling type

\[ A = -0.5 \quad T = 199K \]

\[ T = \frac{T_0}{A - 1} = \frac{(298)}{(0.5) - 1} = 596 \text{ [K]} \]
Example of vectors of endothermic reaction

\[ A = \frac{T - T_0}{T} \]

\[ T = \frac{T_0}{A - 1} \]
Example of vectors of exothermic reaction

- CO + 2H₂ → CH₃OH
- CO₂ + 3H₂ → CH₂OH + H₂O
- CO + 0.5O₂ → CO₂
- H₂ + 0.5O₂ → H₂O
- C + 0.5O₂ → CO
- ATP 水解
- H⁺ + OH⁻ → H₂O
- 0.5H⁺ + 0.5Cl⁻ → HCl
- ATP = ATP 水解
- 200
- 100
- 0