

## CHAPTER III



### EXERGY, ENERGY LEVEL AND ENERGY UTILIZATION DIAGRAM IN ENERGY INTEGRATION

It is well known that the objective of the energy analysis is to reveal the feature of energy utilization in a chemical process system and to give some hints on how to improve it. To represent the characteristics of the energy utilization in a system graphically has incredible advantages. The method in this approach is called "graphic exergy analysis". The thermodynamic principle for its foundation will be represented in this chapter.

#### 3.1 Thermodynamics of a Process and a Process System

Figure 3.1 shows the scheme of a process. The circle denotes the control volume of the processes and the arrow denotes the flow of materials.

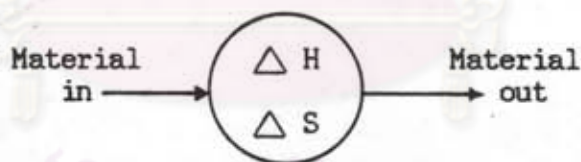


Fig 3.1 Representation of a process

#### 3.1.1 Two Basic Law of Thermodynamics

The two basic law of thermodynamics are

1) Law of conservation of energy :  $\Delta H = Q - W$  (1)

2) Law of increase in entropy :  $\Delta S \geq Q / T$  (2)

For physical processes such as heating, cooling, mixing, and separation, no chemical reactions occur, and all the materials remain unchanged only their thermodynamic states are

changed in the control volume. At the steady state, the moles of each component entering the process must be equal to that leaving the process.

For chemical processes such as reactions, on the contrary, some of the materials are converted. However, the gram atoms of each element must still be constant.

From the total enthalpy and entropy of the input and output material streams, the enthalpy increase  $\Delta H$  and the entropy increase  $\Delta S$  caused by the process can be obtained as follows.

$$\Delta H = H_{out} - H_{in} \quad (3)$$

$$\Delta S = S_{out} - S_{in} \quad (4)$$

Although  $\Delta H$  and  $\Delta S$  for the process are defined based on the input and output streams of the materials, the process may in addition receive heat  $Q_{in}$  or work  $W_{in}$  or may release heat  $Q_{out}$  or work  $W_{out}$ , as schematically shown in Figure 3.2

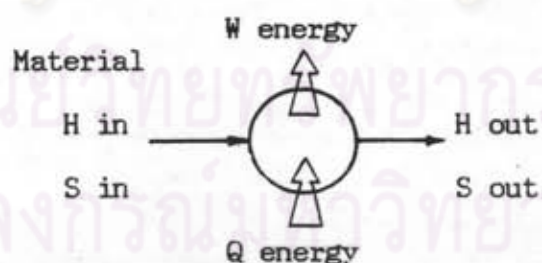


Figure 3.2 Flow of heat  $Q$  and work  $W$ .

### 3.1.2 New Concept of $\Delta H$ and $\Delta S$ for a Process

A new concept of heat and work introduced by Ishida [2] has greatly simplified the thermodynamics of a process system. The following four special processes below have neither input nor output of materials.

Heat source : When a heat reservoir releases a quantity of heat  $Q$  at the temperature  $T$ , it may be regarded as heat source a process. In this case  $\Delta H$  and  $\Delta S$  for the heat source are as shown in Figure 3.3 (a).

Heat sink : Similarly when a heat reservoir absorbs a quantity of heat  $Q$  at the temperature  $T$ , we obtain  $\Delta H$  and  $\Delta S$  for it as shown in Figure 3.3 (b).



Figure 3.3  $\Delta H$  and  $\Delta S$  for a heat source and heat sink

Work source : When a work reservoir releases a quantity of work  $W$ , its  $\Delta H$  and  $\Delta S$  are as shown in Figure 3.4 (a).

Work sink : Similarly when a work reservoir absorbs a quantity of  $W$ , its  $\Delta H$  and  $\Delta S$  are as shown in Figure 3.4 (b).



Figure 3.4  $\Delta H$  and  $\Delta S$  for a work source and work sink

A process which consists of material flow can be represented by Figure 3.5. Note that, energy flow is not included in the  $\Delta H$  and  $\Delta S$  of a process.



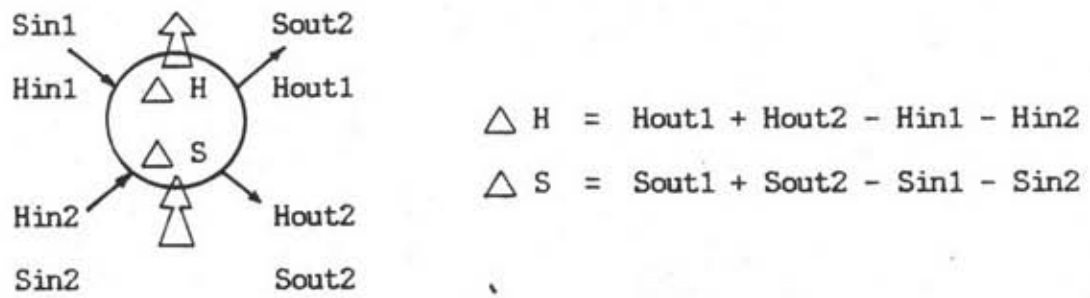
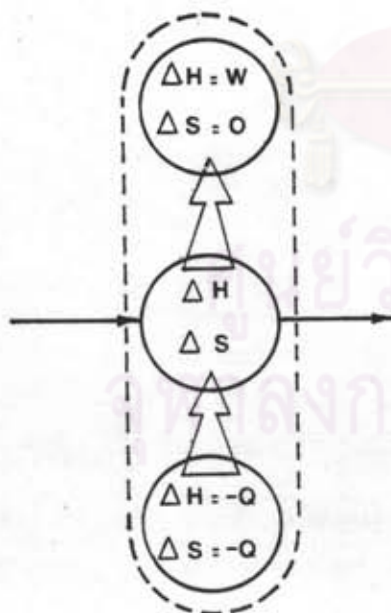


Figure 3.5 A process with material flow

### 3.1.3 Energy Conversion in a Process System

As a general case, let us consider a set of  $n$  processes enclosed in an adiabatic enclosure shown in Figure 3.6. Such a system is called a "process system". The boundary of the process system is represented by the broken line.

The first and second laws of thermodynamics for the present process system is represented by



A. First law of thermodynamics

$$\sum \Delta H_i = 0 \quad (5)$$

B. Second law of thermodynamics

$$\sum \Delta S_i \geq 0 \quad (6)$$

Figure 3.6 Concept of a process system.

The increase in entropy is caused by irreversibility in the system.

### 3.1.4 Exergy Change of a Process, $\Delta E$

The word EXERGY comes from combining "ex" which means "out" and "erg" which is a unit of work. Then, exergy is defined as the work that is available in a material stream as a result of its nonequilibrium conditions relative to some reference condition. Since the sea level and atmospheric conditions serve as the ultimate sink for all terrestrial energy systems, they are generally taken as the reference state. From equation (5) and (6), the exergy destruction in the system is defined as

$$\Delta E = \Delta H - T_0 \Delta S \quad (7)$$

Thus, 
$$\begin{aligned} \sum \Delta E_i &= \sum (\Delta H_i - T_0 \Delta S_i) \\ &= \sum \Delta H_i - T_0 \underbrace{\sum \Delta S_i}_{\geq 0} \end{aligned}$$

So 
$$\sum \Delta E_i \leq 0 \quad (8)$$

In summary :  $\sum \Delta H_i = 0$  : Law of conservation of energy

$\sum \Delta S_i \geq 0$  : Law of increase in entropy

$\sum \Delta E_i \leq 0$  : Law of decrease in exergy

### 3.1.5 Application to the heat exchange

Heat exchange occurs in a binary system composed of two processes. Generally one of the processes is the target and the other donates energy to it or accepts energy from it. Since processes

1 and 2 constitute a process system, the following equations are applicable.

$$\sum \Delta H_i = \Delta H_h + \Delta H_l = 0$$

$$\sum \Delta S_i = \Delta S_h + \Delta S_l \geq 0$$

$$\Delta H_h = -Q ; \Delta S_h = -Q/T_h$$

$$\Delta H_l = Q ; \Delta S_l = Q/T_l$$

Heat Source ( $T_h$ )



Heat Sink ( $T_l$ )

Figure 3.7 Process scheme of heat exchange

$$\begin{aligned} \therefore -Q/T_h + Q/T_l &\geq 0 \\ Q, T &> 0 \\ \therefore T_h &\geq T_l \end{aligned} \quad (9)$$

That is, heat must flow from a higher to a lower temperature.

### 3.2 Energy Utilization Diagram

#### 3.2.1 Availability Factor

In contrast to the first law, the importance of the second law is that : The first law deals with the quantity of energy in terms of a conservation rule. The second law deals with the quality of energy based on a nonconservation rule. According to the exergy concept, various forms of energy of the same quantity may differ in their potential usefulness to our society. The same thing can be said of the same thermal energy but at different temperature levels. Hence, a new indicator called availability factor, or simply energy level,  $A$  is defined as

$$A_i = \Delta \epsilon_i / \Delta H_i \quad (10)$$

It describes the content of exergy in a certain quantity of energy, in other words, the exergy content is the maximum fraction of energy which can be converted to useful work.

#### 3.2.2 Energy Level of an Energy - Donating and an Energy - Accepting Process

The basic equations for any binary process system are

1.  $\sum \Delta H_i = \Delta H_{ed} + \Delta H_{ea} = 0$
2.  $\sum \Delta S_i = \Delta S_{ed} + \Delta S_{ea} \geq 0$
3.  $\sum \Delta \epsilon_i = \Delta \epsilon_{ed} + \Delta \epsilon_{ea} \leq 0$

The significant of the availability factor can be shown as follows.



$$\begin{aligned}
 \text{Thus} \quad -\sum \Delta \epsilon_i &= -\sum (\Delta H_i - T_0 \Delta S_i) \\
 &= 0 + T_0 \sum \Delta S_i \geq 0 \\
 &= \Delta H_{ea} \left( \frac{\Delta \epsilon_{ed}}{\Delta H_{ed}} - \frac{\Delta \epsilon_{ea}}{\Delta H_{ea}} \right) \\
 &= \Delta H_{ea} (A_{ed} - A_{ea}) \geq 0 \\
 \therefore A_{ed} &\geq A_{ea} \tag{11}
 \end{aligned}$$

That is, for any binary process system, an energy level of energy donating process ( $A_{ed}$ ) is always greater than an energy level of energy accepting process ( $A_{ea}$ ) as shown in Figure 3.8.

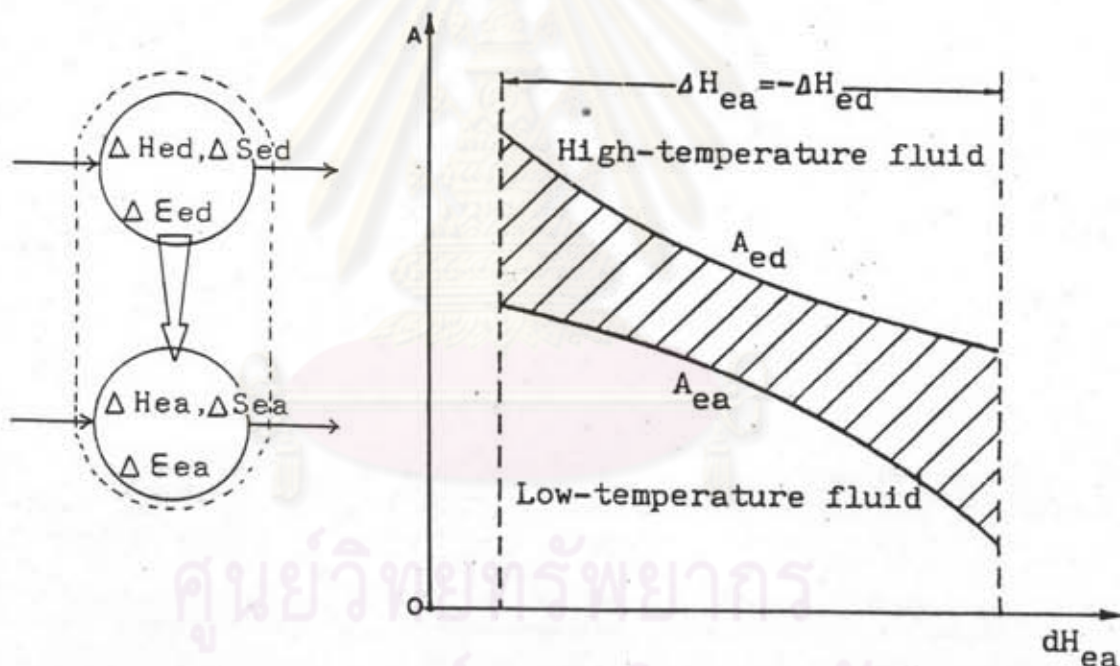


Figure 3.8 Energy levels of an energy donor and acceptor

Hence, we may conclude that a process, in which  $A_{ed} < A_{ea}$  happens at some points, is infeasible even if the average  $A_{ed}$  is much greater than the average  $A_{ea}$ . The point at which the difference between  $A_{ed}$  and  $A_{ea}$  is smallest (but nonnegative) is called the pinch point.

### 3.2.3 Special Form of Energy Level, A

The availability factor, or energy level, of heat and work is given by

$$\text{Heat : } \Delta H = Q \quad \text{and} \quad \Delta S = Q/T$$

The exergy change of equation (7) can be rearranged as

$$\Delta E = \Delta H - T_0 \Delta S = Q (1 - T_0/T)$$

Then, equation (10) yields

$$A = \Delta E / \Delta H = 1 - T_0/T \quad (12)$$

$$\text{i.e.,} \quad -\infty < A \leq 1$$

For heat, energy level is equal to  $1 - T_0/T$  which is equivalent to Carnot efficiency. Since, heat changes its temperature from zero to infinity, therefore, the range of A changes from minus infinity to unity. The unity is the maximum value of energy level of heat occurred at infinite temperature (high temperature). Energy level is equal to zero when its temperature equal to reference state or ambient temperature ( $T_0$ ). In case of temperature lower than reference state, A becomes negative. Note that, at temperature approach to zero (low temperature), A becomes minus infinity (see Figure 3.9).

$$\text{Work : } \Delta H = W \quad \text{and} \quad \Delta S = 0$$

The exergy change of equation (7) can be rearranged as

$$\Delta E = \Delta H - T_0 \Delta S = W$$

Then, equation (10) yields

$$A = \Delta E / \Delta H = 1 \quad (13)$$

For work, the energy level is equal to unity.



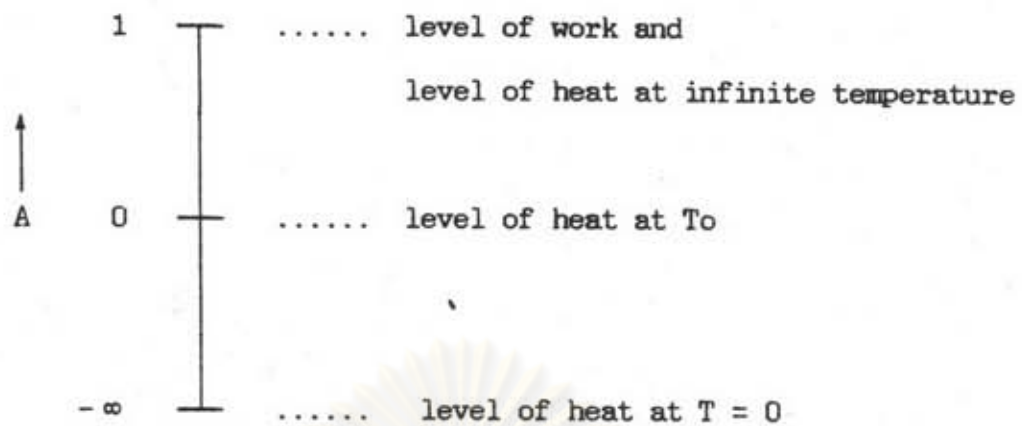


Figure 3.9 Scheme of energy level, A

### 3.3 Exergy Loss

By plotting the availability factor  $A_{ed}$  for the energy donating process and  $A_{ea}$  for the energy accepting process versus the transformed energy  $dH_{ea}$ , the amount of exergy loss in the subsystem is given as the area between the curves of  $A_{ed}$  and  $A_{ea}$ .

Figure 3.10 shows the composite lines of a heat-donating line and heat-accepting line. The figure clearly shows whether the heat supply is enough or what amount of heat or which level of heat is in excess. The total exergy loss in this subsystem is shown as the shade area between these two lines and the minimum temperature difference at the pinch point is also represented. The basic idea of heat integration based on this diagram have been recently discussed by Umeda et al.(1979).

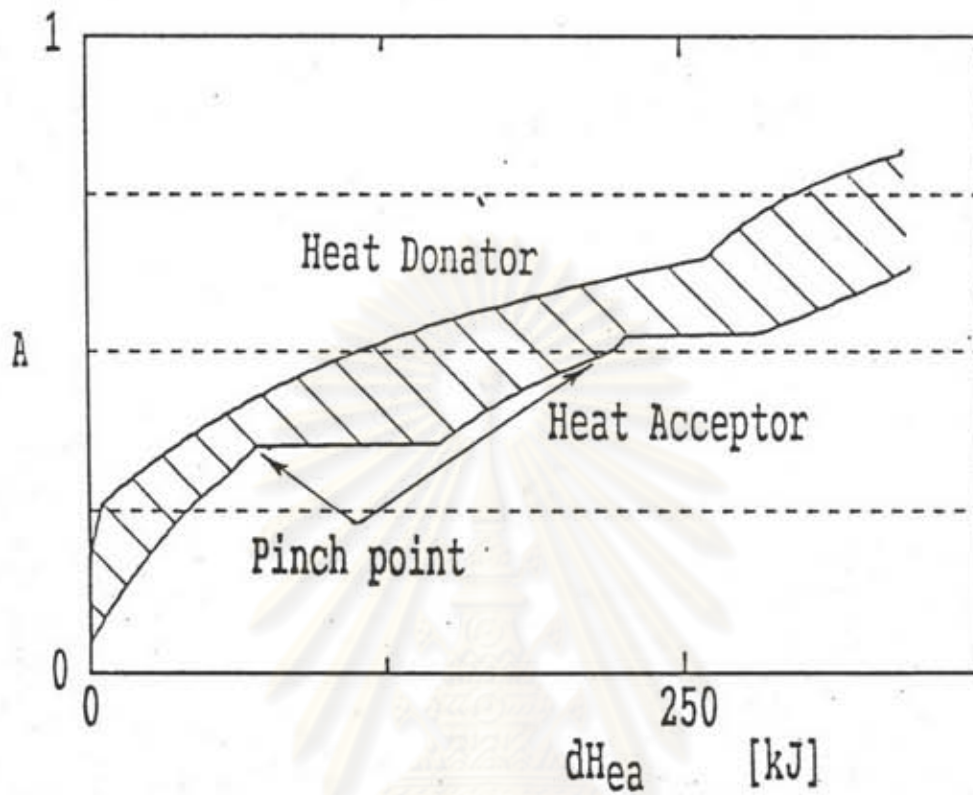


Figure 3.10 Energy utilization diagram

Low exergy loss increases the efficiency of the process, and obtain

- a. high conversion
- b. low requirements of utilities