

New Concepts in Material and Energy Utilization

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(Received 13 July 2004 • accepted 15 October 2004)

Abstract—New criteria in material and energy utilization are proposed. The potential index (Θ^*) is assigned to explain some natural processes in the world and to identify reasonably the preferable process instead of the efficiency. In addition, this term can first integrate the independent knowledge of the fields of mechanical, electrical and chemical engineering. It not only describes satisfactorily the transformation processes that are well-known in mechanical and electrical engineering, but also the increasing potential processes familiar in chemical engineering.

Key words: Material, Energy, Utilization, Potential, Potential Index

INTRODUCTION

In the beginning, chemical engineering originated by developing and applying the law of conservation of material, momentum and energy to explain simple phenomena in industrial processes. This was concerned with fundamentally designing equipment and operating processes well-known as “unit operations.” Also, this knowledge was dramatically extended to a benign environmental approach, e.g. a waste treatment process. This can only minimize negative environmental impact in downstream, but it is not enough to optimize the usage of material and energy to acquire the highest gain or the lowest loss. Subsequently, a state-of-the-art method of cleaner technology was pronounced to be a promising way to manage the material and energy, since this procedure can determine an upstream route of processes. However, there is still some doubtfulness about this because most human beings tend to regard economic profits more than long-term planning. In addition, selecting the most suitable process is a difficult decision, especially in separation processes in chemical engineering, because there is not yet an indicator for analysis and interpretation. For example, which favorable process between distillation and solvent extraction is more worthy of the utilization of material and energy. On the contrary, most processes of energy transformation for mechanical and electrical engineering can be reliably altered by using the efficiency (η). Because of this we cannot point out the best direction of research and development in future. As mentioned above, we intend to propose a new approach to manage, utilize and optimize material and energy coincident with executive decision to select the preferable process in worldwide circumstances.

Usually in engineering work, we are familiar with the term efficiency, which is defined as the useful energy or work we want over the energy or work we have input. In addition, chemical engineers compare new process with conventional processes through the terms

efficiency, conversion or recovery, which are usually defined the same as efficiency. The usage of efficiency, conversion and recovery is spread through many areas of chemical engineering such as packed bed columns [Han et al., 1985], combustion & conversion [Choi et al., 1985; Jung et al., 1988; Yun et al., 2001], distillation [Yoo et al., 1988; Kang et al., 1996], absorption [Park et al., 1990; Oh et al., 1999], fluidized beds [Kage et al., 1999; Jang, 2002] and membranes [Kang et al., 2002]. None of them can compare the processes that are different than their definition of efficiency, conversion and recovery. Most of them compared the new method in the same machine to the old process of the same machine and used it in the process design work only. That is the reason why we have proposed a new way of looking at efficiency, conversion or recovery, and distributed these terms through many processes that we defined as the system and the surroundings. We have found many amazing results through the use of the potential index, as we will explain in detail as follows.

DETAILS

The basic idea of the law of conservation of mass, momentum and energy is mathematically expressed as follows [Smith et al., 2001; Jui, 1993; Van, 1959; Bird, 1960].

$$\begin{aligned} \text{Rate of M.M.E. accumulation} &= \text{Rate of M.M.E. generation} \\ &+ \text{Rate of M.M.E. Net I/P} \end{aligned} \quad (1)$$

where M.M.E. refers to mass or momentum or energy and I/P refers to input minus output.

Eq. (1) can be applied to investigate simply mass minimization and energy preservation, but it still lacks a universal representative to evaluate and manipulate ineffective processes due to just a macroscopic approach. However, if the principle of energy interconversion and balance, which is the simplest expression of the first law of thermodynamics, is only considered, a measure of accomplishment of any processes may be definitely evaluated in terms of the efficiency (η) [Smith et al., 2001; Jui, 1993; Van, 1959] as defined:

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$$\eta = \frac{\text{Energy output (desired)}}{\text{Energy input}} \quad (2)$$

Disadvantages of this term are that it is just confined for processes of energy transformation and cannot be used to compare reasonably, not economically, the two types of different processes, e.g., an electric heater and a fuel heater.

Focusing on the use of Eq. (2), a Carnot engine, which is the simplest heat engine operating in a completely reversible manner, is considered. This engine converts thermal to mechanical energy. Eq. (2) can be rewritten as follows [Smith et al., 2001; Jui, 1993; Van, 1959]:

$$\eta = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H} \quad (3)$$

where T_H and T_L are temperatures of hot and cold reservoirs, respectively.

Eq. (3) shows the thermal efficiency in terms of temperature. It is possible to imply that the efficiency is very close to some state property directly, perhaps indirectly. However, the crucial obstacle is identification of the property coincident with types of energy. The theory of transport phenomena, which deals with microscopic form of mass, momentum and energy transfer, contributes to their linkage. Fourier's law of heat conduction is an example relation of the heat flux and the temperature gradient in case of a variety of thermal energy as shown in one-dimensional equation [Bird, 1960].

$$q_y = -k \frac{dT}{dy} \quad (4)$$

where q_y =heat flux ($\text{Jm}^{-2}\text{s}^{-1}$), k =thermal conductivity ($\text{Jm}^{-1}\text{s}^{-1}\text{K}^{-1}$), T =temperature (K) and y =distance (m).

Eq. (4) indicates that for thermal energy the temperature behaves as the driving force to overcome a thermal resistance. In the same way, we can determine the driving force of the other energy. Velocity and voltage are the examples of the driving forces of the mechanical and electrical energy following Newton's law and Ohm's law, respectively [Alan, 1980]. In addition to the energy issue, the relative driving force of mass transport is also obtained via the theory of transport phenomena as shown in Fick's law equation [Bird, 1960].

$$J_{Ay} = -D_{AB} \frac{\partial c_A}{\partial y} \quad (5)$$

where J_{Ay} =molar flux of A ($\text{mole m}^{-2}\text{s}^{-1}$) with respect to molar average velocity, D_{AB} =diffusivity (m^2s^{-1}), c_A =concentration of A (mole m^{-3}) and y =distance (m).

Eq. (5) exhibits that the driving force of mass items becomes concentration difference. Hence, we can conclude in an elementary sense by the same general type of the following transport equation and define the driving force as "potential difference":

$$\text{Rate of transfer process} = \frac{\text{Driving force}}{\text{Resistance}} = \frac{\text{Potential difference}}{\text{Resistance}} \quad (6)$$

Generally, in chemical engineering, the definition of efficiency is different from that in mechanical and electrical engineering. It is the ratio of real to ideal sizes such as stage efficiency [Bird et al., 1960; Octave, 1972], which becomes a benefit to designing reactors and unit operations. It is better to extend the efficiency into the

field of chemical engineering, especially for mass transformation. From the relationship between thermal efficiency (η) and thermal potential (T) in Eq. (3), we duplicate it in an analogous expression to worldwide use. A new term instead of efficiency is addressed as the potential index (Θ^*) in dimensionless form as follows:

$$\Theta^* = \frac{\text{high potential} - \text{low potential}}{\text{high potential}} \quad (7)$$

To confirm the use of the potential index, a case study of mass conversion, or chemical reaction, is carefully considered. Every chemical reaction is the conversion of the reactants to the products. The term of conversion is well-known as the following equation [Octave, 1972]:

$$X_A = \frac{C_{A,in} v_{in} - C_{A,out} v_{out}}{C_{A,in} v_{in}} \quad (8)$$

where X_A =conversion of A; $C_{A,in}$ and $C_{A,out}$ =concentration of A (mole m^{-3}) into and out of the reactor, respectively; v_{in} and v_{out} =volumetric flow rate (m^3s^{-1}) into and out of the reactor, respectively.

If volumetric flow rate is given to be constant, that is $v_{in}=v_{out}$, thus

$$X_A = \frac{C_{A,in} - C_{A,out}}{C_{A,in}} = 1 - \frac{C_{A,out}}{C_{A,in}} = \Theta^* \quad (9)$$

Eq. (9) shows definitely that for mass transformation the conversion (X_A) is equal to the potential index (Θ^*) and equivalent to efficiency (η) in case of energy subject. Similarly to the efficiency, the conversion and the potential index implies that the term of the potential index should be a crucial representative to use in selection of process or equipment concerned with material and/or energy. In the energy potential index, the comparisons across the processes are widely accepted as far as the term efficiency of the process. With the dimensionless characteristic of potential index, the mass potential indexes can be compared with each other and even can be compared with the energy potential index. The example of liquid extraction and distillation processes potential indexes between mass and energy can be compared according to our example that follows in this manuscript.

The potential indexes are significant to at least three in four of "The big four of engineers—civil, electrical, mechanical, and chemical engineers." It is well familiar in chemical engineering to the changeability of mass form such as chemical reactions and to the increase of mass potential (concentration) such as separation processes, while the knowledge of mechanical and electrical engineering often deals with energy interconversion such as heater, motor and generator. Therefore, the term "potential index" is very helpful for the next generation of chemical engineering for choosing processes and is comparable with the use of "efficiency" in the fields of mechanical and electrical engineering.

In general, to facilitate in a thermodynamic analysis, the processes containing the systems and the surroundings can be divided into two types: reversible and irreversible [Smith et al., 2001; Jui, 1993; Van, 1959]. Each process may consist of at least one of a group of system and surroundings, possibly many of them. Nevertheless, this is not contributing to consideration of material and energy utilization, and therefore we propose a new viewpoint to categorize into two processes in the world as follows:

1. A process in which either material or energy is transformed is named as "Transformation Process".

2. A process in which either material or energy potentials in the system increase but no transformation is named as "Increasing Potential Process".

Mechanical and electrical engineers are interested in energy transformation processes, whereas chemical engineers have emphasized the increasing potential process, especially the separation process. Five examples of transformation of energy are shown as follows:

1. Thermal to mechanical energy.

- Carnot engine gives approximately 50% of the maximum thermal efficiency based on $T_L=300$ K and $T_H=600$ K [Smith et al., 2001; Jui, 1993; Van, 1959].

- Internal combustion engine [Heywood, 1988] shows maximum efficiency of spark ignition (SI) and direct injection (DI) as 0.30 and 0.45-0.53, respectively.

2. Mechanical to electrical energy or vice versa.

- Generator or motor has to be approximate values of efficiency in the range of 0.80-0.95 [Alexander et al., 1962; Sen, 1989].

3. Electrical to thermal energy.

- Heating element always shows 100% of the efficiency [Alexander et al., 1962; Sen, 1989].

4. Chemical to electrical energy.

- Fuel cell [Williams et al., 1966; EG & G. Services, 2002; Vielstich et al., 2003] can exhibit ideal or comparative thermal efficiency (ε_T) as defined in the following equation:

$$\varepsilon_T = \frac{\Delta G'}{\Delta H} = \varepsilon_G \cdot \frac{\Delta G}{\Delta H} \quad (10)$$

where $\varepsilon_G = \varepsilon$, ε_G = the free energy efficiency, ε_v = voltage efficiency and ε_c = current efficiency

Example: if the reaction is $H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O(l)$,

it will show $\Delta G^\circ = -56.69$ kcal and $\Delta H^\circ = -68.32$ kcal at 571 K.

It follows that a fuel cell with a free energy efficiency of 0.60 is as efficient as a device burning hydrogen at a thermal efficiency of

$$\varepsilon_T = 0.60 \times \left(\frac{-56.69}{-68.32} \right) = 0.50$$

5. Light to electrical energy.

- Solar cell shows average efficiency in the range of 7.5-30.5% [Green, 1998].

For all of transformations of one energy type to another, we have observed the same nature in such processes. When the input energy is transformed to the desired energy, the potential in the system relative to the input energy always decreases. The output reservoir shows lower temperature than the input one in a Carnot engine. The drop of voltage and the deceleration of angular velocity occur in motors or heaters and generators, respectively. To understand better the above idea, transformation of mass is also considered.

In every chemical reaction, the concentration of reactants is always reduced. Certainly, the decreasing potential behavior of material conversion is similar to that of energy transformation. As mentioned

above, it is possible to imitate conversion as efficiency. However, the highest value of conversion will be limited by the thermodynamic equilibrium constant (K) [Octave, 1972] as defined in the following equation:

$$K = \frac{\text{concentration of products}}{\text{concentration of reactants}} \quad (11)$$

where K is dependent on reaction temperature.

The above observation leads to the following principle:

Principle 1 For the process in which material or energy is transformed into another form (transformation process), the material or energy potential in the system relative to the mass or energy input always decreases.

The first principle just explains the basic nature of all of processes, but it is not enough to indicate the explicit significance of the application to selecting exact useful processes. For processes concerned with energy conversion in mechanical and electrical engineering, it is well-known that the higher the efficiency, the better the process. For chemical reaction processes in chemical engineering, the promising process frequently shows higher conversion. Due to the familiar relationship of the efficiency, the mass conversion and the potential index, it can be implied that if the potential index of the system in whatever process is very high, such process can be preferable in practical operation. Recalling principle 1 and Eq. (7), it is clear that the drops of the material and energy potential are proportional to the increases of the potential index, and thus the preferable process exhibits much more decrease of the material or energy potential in the system. This statement is rewritten as follows:

Principle 2 For the process in which material or energy is transformed into another form (transformation process), the preferable process will show high potential index in the system relative to the mass or energy input.

The two principles are greater benefits to the field of mechanical and electrical engineering because most of the equipment in these fields involves energy transformation processes. However, in chemical engineering both principles can be powerfully useful in some situations. An example is the use of the second principle to understand better the second law of thermodynamics. This law affirms that every process proceeds in such a direction that the total entropy change associated with it is positive, the limiting value of zero being attained only by a reversible process. No process is possible for which the total entropy decreases. This can be expressed in the following mathematical statement [Cavassano et al., 1979]:

$$\Delta S_{\text{total}} = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}} \geq 0 \quad (12)$$

Attempts to relate the term of "potential index" with the entropy change (ΔS) are easily made. Considering the changes of thermal to mechanical energy in a reversible process with incompressible substances, the temperature (potential) of the reservoir is decreased from T_H to T_L . The entropy change of the system is expressed as follows [Cavassano et al., 1979]:

$$\Delta S_{\text{system}} = \int \frac{\delta Q}{T} = \tilde{C}_p \int_{T_H}^{T_L} \frac{dT}{T} = \tilde{C}_p \ln \frac{T_L}{T_H} \quad (13)$$

where \tilde{C}_p = average heat capacity (J/K).

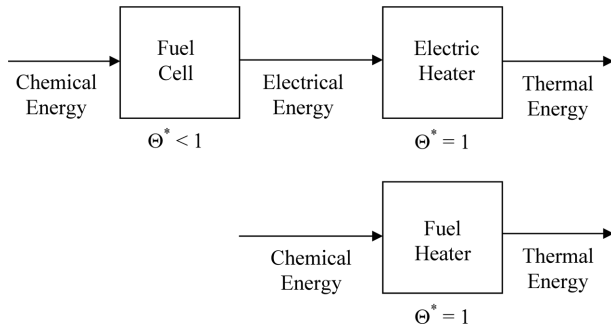


Fig. 1. Comparative process of electric and fuel heater.

From principle 2 and Eq. (13), it can be implied that a process will be great if there is much more entropy change of the system.

The two principles can briefly guide us to being careful in the operation of processes. If the potential index in the system of the transformation process is very low, such a process. Generators, motors and heaters are examples of preferable instruments because their potential indexes are normally unity. However, if there are many types of the instruments, we can select the preferable one as shown in the following example of the heater selection. At present, two main sources of heaters, electric and fuel heaters, are usually used. Both show a unity of the potential index. Nevertheless, if we focus on the same sources of the input energy, the relative difference can be obtained. This is schematically shown in Fig. 1.

Recalling principle 2, the electric heater should be avoided because there is a low potential index in the subsystem of the overall process.

Although the transformation process is very important, most of the processes in chemical engineering become the increasing potential processes, especially various separation processes. Two main examples are as follows:

1. Processes in which material potential in the system is increased.

As mentioned above, if we refer to material, the concentration will be considered as the potential and for all of these processes, the concentration increases. However, in some cases we may assign the mole fraction instead of the concentration. There are many examples in separation processes such as liquid-liquid extraction, solid-liquid extraction, crystallization, distillation, absorption, adsorption, evaporation, drying, filtration, membrane separation, centrifuge, thickener and electrochemical separation. To understand better, some of processes are investigated as follows:

• Liquid-liquid extraction (schematic diagram is shown in Fig. 2) [Herman et al., 1961; Carry, 1982; Warren et al., 1993; Seader et

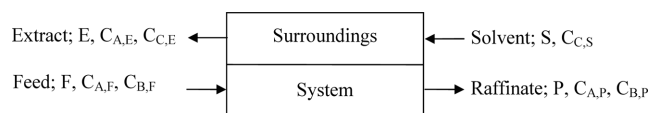


Fig. 2. Liquid-liquid extraction process: A and B=component in solute; C=solvent; F, P, S and E=volumetric flow rate (m^3s^{-1}) of feed, raffinate, solvent and extract, respectively; C_A , C_B and C_C =concentration of A, B and C (mole m^{-3}), respectively.

al., 1998; Alan, 1999; Piyasan, 1999].

Basically, the process efficiency is given by recovery (R) as the following equation:

$$R = \frac{A \text{ extracted}}{A \text{ fed}} = \frac{FC_{A,F} - PC_{A,P}}{FC_{A,F}} \quad (14)$$

Let $F=P$

$$R = \frac{C_{A,F} - C_{A,P}}{C_{A,F}} = 1 - \frac{C_{A,P}}{C_{A,F}} \quad (15)$$

While

$$\Theta_{\text{sys}}^* = \frac{C_{B,P} - C_{B,F}}{C_{B,P}} = 1 - \frac{C_{B,F}}{C_{B,P}} \quad (16)$$

It is found that R and Θ_{sys}^* are quite different but still coincident. Additionally, if we just consider the surroundings, the potential index can be also expressed as follows:

$$\Theta_{\text{sur}}^* = \frac{C_{C,S} - C_{C,E}}{C_{C,S}} = 1 - \frac{C_{C,E}}{C_{C,S}} \quad (17)$$

where Θ_{sys}^* =the potential index of the system, Θ_{sur}^* =the potential index of the surroundings.

A remarkable observation is that for the extraction process if the concentration of one substance in the system is increased, the concentration of the other in the surroundings is always decreased. The “B” fraction out of the raffinate is increased, whereas the “C” fraction out of the extract is decreased.

• Binary distillation (schematic diagram is shown in Fig. 3) [Herman et al., 1961; Alan et al., 1980; Carry, 1982; Warren et al., 1993; Christie, 1993; Seader et al., 1998; Alan, 1999; Piyasan, 1999].

Again, the following recovery, potential index of the system and potential index of the surroundings are expressed:

$$R = \frac{\text{output (desired)}}{\text{Input}} = \frac{Dy_{A,D}}{Fz_{A,F}} \quad (18)$$

$$\Theta_{\text{sys}}^* = \frac{x_{C,B} - z_{C,F}}{x_{C,B}} \text{ or } \frac{y_{A,D} - z_{A,F}}{y_{A,D}} \quad (19)$$

$$\Theta_{\text{sur}}^* = \frac{T_H - T_L}{T_H} \quad (20)$$

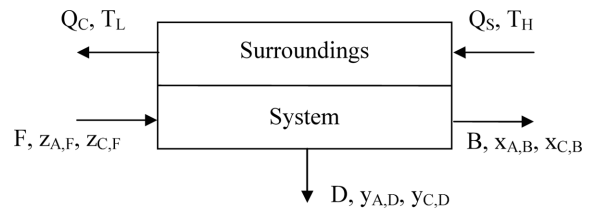


Fig. 3. Binary separation process: A and C=mixture component; F, B and D=molar flow rate (mole s^{-1}) of feed, bottom and top of distillation column, respectively; z , x and y =mole fraction in feed, bottom and top of distillation column, respectively; Q_S and Q_C =the heat flow (J s^{-1}) into reboiler and out of condenser, respectively; T_H and T_L =temperature (K) of reboiler and condenser, respectively.

The gain of potential in the system may be encountered in either the “A” component out of the top or the “C” component out of the bottom. It is clear that while “A” or “C” concentration is increased, the temperature of the bottom is higher than that of the top. This is consistent with the case of liquid-liquid extraction, but the decreasing potential term in the surroundings becomes the temperature instead of the solvent concentration.

In energy terms, potential index can be widely compared across the systems and processes similar to the term efficiency. These usually happen in case of mass terms; the potential index can be compared even with energy. In an instrument that performs similar actions such as distillation and liquid extraction, the surrounding potential index is defined as temperature in case of distillation, while the surrounding potential index is defined as concentration in the case of liquid extraction. However we can compare the potential index and select the better method according to previous or consequent processes that need to be performed in terms of potential index of the substance. The more purity of the substances, the more precious the materials.

Two examples of the processes in which material potential in the system is increased show the contradictory direction of the Θ_{syst}^* and the Θ_{surr}^* . To confirm this, we also focus on the processes in which energy potential in the system is increased.

2. Processes in which energy potential in the system is increased.

- Heat exchanger (schematic diagram is shown in Fig. 4) [Cavaseno et al., 1979; Smith et al., 2001].

A heat exchanger is a device in which energy is transferred from one fluid to another across a solid surface. The potential indexes of the system and the surroundings are shown in Eqs. (21) and (22), respectively.

$$\Theta_{syst}^* = \frac{T_H - T_L}{T_H} \quad (21)$$

$$\Theta_{surr}^* = \frac{T_{in} - T_{out}}{T_{in}} \quad (22)$$

- Pump or Compressor (schematic diagram is shown in Fig. 5)

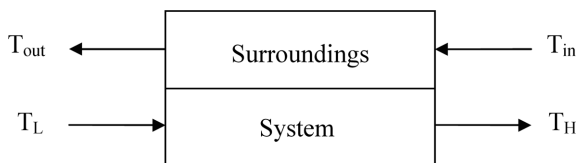


Fig. 4. Heat exchanger: T_L and T_{out} =low temperature (K), T_H and T_{in} =high temperature (K).

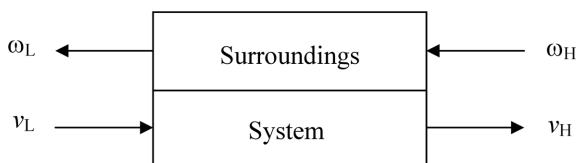


Fig. 5. Pump or compressor: v_L and v_H =liquid or gas velocity (m s⁻¹), ω_L and ω_H =angle velocity of the pump core (rpm).

[Cavaseno et al., 1979; Smith et al., 2001].

A pump is a device for moving a liquid or gas from one place to another. The potential indexes of the system and the surroundings are shown in Eqs. (23) and (24), respectively.

$$\Theta_{syst}^* = \frac{V_H - V_L}{V_H} \quad (23)$$

$$\Theta_{surr}^* = \frac{\omega_H - \omega_L}{\omega_H} \quad (24)$$

From the two examples, there is agreement with the explanation of the processes in which material potential in the systems is increased. For the heat exchanger, the temperature of the cold stream into the system is increased, whereas the temperature of the hot stream into the surroundings is decreased. For the pump or compressor, the fluid velocity into the system is increased while the angle velocity of the pump core of the surroundings is decreased. Hence, the following principle can be expressed:

Principle 3 For the process in which either material or energy potential in the system increases (increasing potential process), the material or energy potential in the surroundings always decreases.

Principle 3 is related to the second law of thermodynamics as well. From Eq. (13), the potential difference is proportional to the entropy change, and therefore the potential index can be referred to instead of the entropy change. Hence, the contradiction of ΔS_{system} and $\Delta S_{surroundings}$ in Eq. (12) implies the increases of Θ_{syst}^* coincident with the decreases of Θ_{surr}^* .

Considering some examples such as heat exchangers, a suitable heat exchanger is the one that possesses minimum mass flow rate of the substance according to economic reasons. Hence, the temperature difference, referred to as potential difference of its surroundings, is maximum. Another good example is liquid-liquid extraction. If the extract or solvent phase flow rate should be minimized, its concentration difference between input and output should consequently be high. Therefore, another principle is introduced to explain a general concept as in the above examples.

Principle 4 For the process in which either material or energy potential in the system increases (increasing potential process), if the increases of potential in the specific systems are the same, the process which shows the highest potential index in the surroundings will be preferable.

From principle 4, the calculations of liquid-liquid extraction, binary distillation and the other processes can be summarized as follows:

- Liquid-liquid extraction [Herman et al., 1961; Alan et al., 1980; Warren et al., 1993]: Θ_{syst}^* in the range of 0.080-0.530 and Θ_{surr}^* in the range of 0.120-0.595

- Binary distillation [Carry, 1982; Warren et al., 1993; Seader et al., 1998; Piyasan, 1999]: Θ_{syst}^* in the range of 0.430-0.583 and Θ_{surr}^* in the range of 0.180-0.308

- Stripping [Carry, 1982; Warren et al., 1993; Seader et al., 1998; Piyasan, 1999]: Θ_{syst}^* in the range of 0.00035-0.166 and Θ_{surr}^* in the range of 0.021-0.593

- Absorption [Alan et al., 1980; Warren et al., 1993; Shuzo, 1993;

Christie, 1993, 2003]: Θ_{sys}^* in the range of 0.012-0.196 and Θ_{surr}^* in the range of 0.0003-0.005

It is clear that if the Θ_{sys}^* of liquid-liquid extraction and binary distillation are the same, the preferable process is liquid-liquid extraction. Another observation is that if the Θ_{sys}^* of liquid-liquid extraction, stripping and absorption are the same, the preferable process becomes stripping.

The important suggestion is that whatever processes containing low potential index steps should be avoidable in operations. These are, for example, the processes involving biodiesel, gasohol, or hydrogen fuel cells. Biodiesel is produced from vegetable oil, whereas gasohol comes from ethanol. It is not worth increasing the purity of ethanol from 99.5% to 99.9% to make gasohol. Similarly, hydrogen used for fuel cells in cars is not an attractive way. These example processes are all comprised of systems of low potential index. If they are compared to other processes of fuel production such as petroleum distillation, which shows higher potential index, the latter may be more. Hence, an increase of potential index in the process is one of ways to achieve better production.

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