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ABSTRACT

A heat-driven distillation process combined with evaporators and condensers was proposed for the improvement of separation performance and the reduction of energy consumption. In this process, a rectifying stage is divided into an evaporator and a condenser and the mass transfer between these phase converters can be controlled by the recycle flow rates, $R_{C_j}$ and $R_{E_j}$, which are adjusted by the supply of heat to the evaporator and the release of heat from the condenser. Binary distillation of methanol and water was computed for a 12-stage heat-driven distillation system. The increase in the recycle flow rates was very effective for improving the separation performance. When the recycle flow rates were increased from 1 to 5 mol/s, the separation factor of methanol was increased to about 230 times, however, the energy consumption was also increased to about 5 times, because of the increase in the supply of heat to the evaporators. Such energy consumption was reduced drastically by the introduction of internal heat-exchange process between the evaporator and the condenser, in which the heat generated by the isentropic compression of vapor phase in the condenser was utilized to the vaporization of liquid in the evaporator. The pressure of each condenser was adjusted appropriately under the condition that total exergy loss was minimized. Then, the sum of external heat provided to the evaporators was reduced to zero and the sum of works required for the compression of vapor flows to the condensers was evaluated as less than 4% of energy consumption of conventional distillation system with the same separation performance. These results suggest that the heat-driven distillation system introducing the internal heat-exchange is valuable as a new energy-saving technology.

KEYWORDS

distillation, heat-driven distillation system, heat exchange, energy saving, exergy

INTRODUCTION

Distillation is a key technology of chemical industry and is utilized widely to various industrial fields, such as oil refining, pharmaceutical industry, food industry etc. In the conventional distillation processes, a large quantity of energy is supplied to a reboiler and removed from a top condenser. Namely, much energy is consumed in distillation processes. In Japan, about 25% of primary energy is consumed by the chemical industry and about 40% of the energy consumption of chemical industry is caused by the distillation processes. Therefore, the saving energy of distillation processes is valid directly for reducing the use of fossil energy and decreasing the release of green house gas to the atmosphere. The energy-saving of distillation process has been investigated, for example, the divided-wall column (DWC) proposed by Wright and Elizabeth (Write et al., 1949, Petlyuk et al., 1965, Yamada et al., 1989) and the ideal heat-integrated distillation column (HIDic) by Takamatsu et al(Nakaiwa et al. 1998 and 2000, Huamg et al., 1997) and the multi-effect batch distillation system by Hasebe and Skogestad (Hasebe et al., 1997, Wittgens et al., 1997) etc. By applying these technologies, 10 to 30% of energy required for
reboiler can be reduced successfully. However, in these previous works, there is no discussion on the substantial improvement of mass and heat transfer mechanism. Further promotion of energy saving may be achieved by the improvement of mass and heat transfer mechanism.

In this study, a heat-driven distillation (HDD) system combined with evaporators and condensers was investigated. This system has a new concept on the mass and heat transfer in the distillation process. As shown in Figure 1(a), in the conventional distillation system, the mass and heat transfer occurs by contacting vapor and liquid in the rectifying stages and is restricted strongly by the mechanical structure of rectifying stage. On the other hand, as shown in Figure 1(b), in the HDD system, a rectifying stage is divided into an evaporator and a condenser. The exchange of materials between the evaporator and the condenser is done by the vapor flow obtained by the heating of evaporator ($R_E$) and the liquid (condensate) flow by the cooling of condenser ($R_C$). Therefore, this process, which is operated by the supply of heat to the evaporator and the release of heat from the condenser, is called “heat-driven distillation system”. In this paper, a mathematical model of HDD system was established and binary distillation of methanol and water was calculated for a 12-stage HDD system. Both the energy-saving effects and the separation performance of proposed system were evaluated by the aid of exergy analysis method. From these calculation results, the applicability of HDD system as an energy-saving technology was discussed.

**MATHEMATICAL MODEL OF HEAT-DRIVEN DISTILLATION SYSTEM**

Figure 2 shows the flow sheet of proposed heat-driven distillation system. Based on this flow sheet, a mathematical model for multi-component distillation (the number of component: m) is established. The mass and heat balance equations
are summarized in Appendix. The calculation procedures for the concentration profiles of components are as follows:

(i) The rates of vapor flows left from the j-th evaporator, R_{Ej}, and liquid from the j-th condenser, R_{Cj}, and the reflux ratio, R_{Cj}/D, are determined initially as the operating conditions.

(ii) The rate of vapor flow left from the j-th condenser, V_j, and the liquid flow rate from the j-th evaporator, L_j, can be calculated from total mass balance equations, Eqs.(A1a) to (A5a).

(iii) By assuming the equilibrium ratios in the evaporators and the condensers, K_{Cij} and K_{Eij}, the mole fraction of methanol and water in the evaporator and the condenser, x_{Eij}, y_{Eij}, x_{Cij} and y_{Cij}, can be calculated by solving the mass balance equations for each component, Eqs.(A1b) to (A5b).

(iv) From these mole fractions, the new equilibrium ratios, K_{Cij} and K_{Eij}, are calculated by the Raoult’s law considering non-ideality of liquid phase,

\[ K_{Cij} = \frac{y_{ij}^E}{x_{ij}^C} = \frac{p_0^E(T_j^C)y_{ij}}{P}, \quad K_{Eij} = \frac{y_{ij}^E}{x_{ij}^C} = \frac{p_0^E(T_j^E)y_{ij}}{P} \]  

where P and \( \gamma_{ij} \) denote total pressure and the activity coefficient for the i-th component in liquid phase, respectively. Then, the vapor pressures of the i-th component, \( P_0^i(T_{Cj}) \) and \( P_0^i(T_{Ej}) \), were calculated by the Anoine equation. Boiling points in evaporators and condensers, T_{Cj} and T_{Ej}, are calculated from following relations

\[ \sum_{i=1}^{m} K_{Cij} x_{ij} - 1 = 0 , \quad \sum_{i=1}^{m} K_{Eij} x_{ij} - 1 = 0 \]  

(v) The external heat supplied from a heat source to the evaporators, Q_{Ej}, and the heat released from the condensers to a heat sink, Q_{Cj}, are calculated by the heat balance equations, Eq.(A7) to (A12).

(vi) The mass and heat balance equations is satisfied by repeating the calculation procedures of (ii) to (v). Then, the convergence of calculation is decided by the condition that the sum of remainders of mass balance equations is less than \( 10^{-5} \), namely \( \sum_{j=1}^{n} \sum_{i=1}^{m} (M_{Ej} + M_{Cj}) < 10^{-5} \).

Thus, the equilibrium ratios, K_{Cij} and K_{Eij}, the concentration profiles of components, x_{Eij}, y_{Eij}, x_{Cij} and y_{Cij}, and the temperature profile, T_{Cj} and T_{Ej}, can be determined.

In this study, the binary distillation of methanol (i=1) and water (i=2) is calculated for a 12-stage heat-driven distillation system. An equimolar mixture of methanol and water is used as a feed solution. A half of feed solution is vaporized by an external evaporator (q=0.5) and the obtained vapor and liquid flows are fed to the 6th evaporator and the 6th condenser, respectively, at the rate of 0.5 mol/s. The flow rates of distillate, D, and bottom, B, are given as 0.5 mol/s. The operating pressure of evaporator, P_{Ej}, is kept constant at 1.01x10^5 Pa and that of condenser, P_{Cj}, is changed freely by the compressors when necessary. The activity coefficients of methanol and water in the liquid phase, \( \gamma_{ij} \), which is required for the correction of Raoult’s law (Eq.1), are evaluated by the Wilson’s equation. From the calculation results, the overall separation factor for methanol, defined as \[ \frac{y_{C1}/(1-y_{C1})}{x_{E1}/(1-x_{E1})} \], is evaluated.

The same calculation is carried out for a 12-stage conventional distillation system under the conditions that the flow rates of feed (F), distillate (D) and bottom (B), the feed composition and the reflux ratio are the same as those for the heat-driven distillation system. The separation performance and energy consumption are compared with those for the heat-driven distillation system.

**EXERGY LOSS OF HEAT-DRIVEN DISTILLATION SYSTEM**

Exergy loss (EXL) is very useful as a measure to evaluate the wastage of energy and materials in a chemical process, which occurs by heat and mass transfer, chemical reaction, phase transformation etc. For the heat-driven distillation system with evaporators and condensers, we have to consider the exergy
losses for the temperature changes of vapor and liquid flows inputted in evaporators and condensers, the mixing effects of vapor and liquid flows, the heat transfers and the internal heat exchange between the evaporator and the condenser. (Budiman et al., 1997, Ishida et al., 1992, Taprap et al., 1996)

At first, we focus on the j-th evaporator. When considering the input and output of material flows, the exergy losses for the temperature change of liquid flow from the (j-1)th evaporator, feed flow and liquid flow recycled from the (j+1)-th condenser are calculated as follows;

\[
\begin{align*}
EXL_{Tj}^L &= Q_{E,j-1}^L \left( 1 - \frac{T_0^E}{T_j^E} \right) - \left( 1 - \frac{2T_0^E}{T_{j-1}^E + T_j^E} \right) \\
EXL_{Tj}^{FL} &= Q_{T,j+1}^{FL} \left( 1 - \frac{T_0^E}{T_j^E} \right) - \left( 1 - \frac{2T_0^E}{T_{j+1}^F + T_j^E} \right) \\
EXL_{Tj}^{RC} &= Q_{T,j+1}^{RC} \left( 1 - \frac{T_0^E}{T_j^E} \right) - \left( 1 - \frac{2T_0^E}{T_{j+1}^{RC} + T_j^E} \right)
\end{align*}
\]

where \( T_0, T_j^E, T_j^F, T_{j+1}^{RC} \) denote the temperature of ambient environment (298.15 K), the liquid temperature of the j-th evaporator, the temperature of liquid feed inputted to the j-th evaporator and the temperature of liquid flow recycled from the (j+1)-th condenser. \( Q_{E,j-1}, Q_{T,j}^{FL} \) and \( Q_{T,j+1}^{RC} \) represent the heats required for increasing \( T_{E,j-1}, T_{F,j} \) and \( T_{RC,j+1} \), to \( T_j^E \).

The exergy loss for the mixing of these flows, \( EXL_{mix}^j \), is given as

\[
EXL_{mix}^j = RT_0 \sum_{i=1}^{m} \left( L_{j-1} x_{i,j-1}^E \ln \frac{x_{i,j-1}^E}{x_{i,j}^E} + F_j x_{i,j}^F \ln \frac{x_{i,j}^F}{x_{i,j}^E} + R_{C,j+1} x_{i,j+1}^{RC} \ln \frac{x_{i,j}^{RC}}{x_{i,j}^E} \right)
\]

where \( x_{i,j}^E, x_{i,j}^F, x_{i,j+1}^{RC} \) denote the mole fractions of methanol \((i=1)\) and water \((i=2)\) in the liquid flow \((L_{j-1})\), the feed flow \((F_j)\) and the recycle flow \((R_{C,j+1})\), respectively. The evaporators are heated by both the external heat source (temperature: \( T_{n+10}^E \)) and the internal heat exchange from the condenser (temperature : \( T_{C,j}^C \)). The exergy losses for these heating processes, \( EXL_{OE,j} \), \( EXL_{RC,j} \), are given as

\[
\begin{align*}
EXL_{OE,j}^E &= Q_{T,j}^E \left[ \left( 1 - \frac{T_0^E}{T_j^E} \right) - \left( 1 - \frac{T_0^E}{T_{n+10}^E} \right) \right] \\
EXL_{RC,j}^E &= Q_{j}^E \left[ \left( 1 - \frac{T_0^E}{T_j^E} \right) - \left( 1 - \frac{T_0^E}{T_j^C} \right) \right]
\end{align*}
\]

The exergy losses for the j-th condenser are also considered in a similar manner. The exergy losses for the temperature changes of vapor flows, \( EXL_{Tj}^V \), \( EXL_{Tj}^{FL} \), \( EXL_{Tj}^{RC} \), that for the vapor mixing, \( EXL_{mix}^V \), and those for the cooling processes, \( EXL_{OE,j}^V, EXL_{RC,j}^V \), should be considered. Furthermore, the exergy loss for the pressure change of vapor flow,

\[
EXL_{mix}^P = RT_0 (V_{j+1} \ln \frac{P_{j+1}^C}{P_j^C} + F_j \ln \frac{P_j^F}{P_j^C} + R_{C,j} \ln \frac{P_{j+1}^{RC}}{P_j^C})
\]

has to be considered. All exergy losses for the evaporators and the condensers are summed up and total exergy loss for the heat-driven distillation system, \(TEXL\), is evaluated.

**RESULTS AND DISCUSSION**

**Separation Performance of Heat-driven Distillation (HDD) System**

Figure 3 shows the relation between the separation factor of methanol and the reflux ratio defined as the flow ratio, \( R_{C,j}/D \). In this figure, the rates of recycle flows, \( R_j^E \) and \( R_j^C \), were kept constant except \( R_1^E \) and \( R_n^E \) determined by the reflux ratio and were varied in the range of 1 to 5 mol/s. The optimum
reflux ratio, in which the separation factor was maximized, was found for each recycle flow rate. It should be noted that these optimum reflux ratios are small values less than 4. The increase in the recycle flow rates is very effective for improving the separation performance. The maximum separation factor at the conditions that $R_C = R_E = 5$ mol/s ($S_{max} = 1.73 \times 10^7$) corresponds to about 230 times that under the conditions that $R_C = R_E = 1$ mol/s ($S_{max} = 7.53 \times 10^4$). The dotted line shows the change of the separation factor for the conventional distillation system. The flow rates of feed, distillate and bottom were the same as those for the HDD system. The separation factor increased with increasing the reflux ratio. This tendency is quite different from that for the HDD system. The high reflux ratio is required for the improvement of separation performance. As shown in Table 1, the reflux ratio has to be more than 50 to obtain the separation factor of $3 \times 10^6$, which can be attained by the HDD system under the conditions that $R_C = R_E = 3$ mol/s.

Figure 4 shows the comparison of concentration profiles of methanol and water between the HDD system and the conventional one at the reflux ratio of 3.7. For the HDD system, the recycle flow rates, $R_C$ and $R_E$, were given as 5 mol/s. As shown in Fig. 4(a), the mole fraction of methanol vapor in the condenser was maintained at more than 0.9 until the 9th stage. On the other hand, that for the conventional system is until the 5th stage. These results suggest that the material exchange between the evaporator and condenser by heat is more effective than the mass transfer based on the vapor-liquid equilibrium in the conventional system. The material exchange of the HDD system is not restricted by the vapor-liquid equilibrium and is controlled by the heat transport, such as supply of heat to the evaporator and the release of heat from the condenser. It is concluded that the HDD
Energy Saving Effect of Heat-driven Distillation System with Internal Heat-exchange

The energy saving effect of the heat-driven distillation (HDD) system introducing the internal heat exchange between the evaporator and the condenser is discussed in this section. The concept of internal heat exchange between the evaporators and the condensers is shown in Figure 5. The heat obtained by the compression of vapor phase in the condensers is transferred to the evaporator and used for the vaporization of liquid in evaporators. If the temperature of condenser is assumed to be higher than that of evaporator by 13 K, total heat transfer is evaluated as 225 kJ/s under the conditions that the area of heat transfer, A=5 m², and the overall heat transfer coefficient h=3000 W m⁻² K⁻¹. As the latent heat of vaporization of feed solution is given as 38 kJ/mol, the vaporization rate is evaluated as about 5 mol/s. This estimation indicates that the liquid phase in the evaporator is vaporized sufficiently by the internal heat exchange.

The increase in temperature (temperature change: T₁→T₂) by the compression of vapor phase system has two excellent features; (1) the HDD system can be operated mildly at low reflux ratio and (2) high separation factor, which cannot be attained by the conventional distillation system, is obtained under the mild operating condition.

Table 1 shows the comparison of energy consumption between the HDD system and the conventional one. The HDD system shows excellent separation performance, however, it should be noted that the energy consumption is much larger than that for the conventional distillation system. This is because the high exchange rate of materials has to be maintained by the supply of heat to each evaporators and the release of heat from the condenser. For example, when the HDD system is operated under the conditions that the reflux ratio r=3.7 and the recycle flows R₁=3.7 mol/s, the separation factor is given as about 450 times of that for the conventional distillation system with the same reflux ratio, however, total energy consumption of evaporators is also increased to about 36 times. A new technology to suppress the energy consumption should be developed for the practical use of HDD system.

### Table 1 Summary of separation performance, heat consumption, compression work and exergy loss for heat-driven distillation system and conventional one.

<table>
<thead>
<tr>
<th>System</th>
<th>Recycle flows Rj [mol/s]</th>
<th>appropriate reflux ratio Rj/D</th>
<th>Sep. factor [–]</th>
<th>total heat supplied to evaporator ΣQe [kJ/s]</th>
<th>total heat released from condenser ΣQc [kJ/s]</th>
<th>total work used for compression ΣW [kJ/s]</th>
<th>total exergy loss TEXL [kJ/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat-driven distillation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>without internal heat exchange</td>
<td>1 (**) 2.5 1.57E+03</td>
<td>28</td>
<td>36</td>
<td>89</td>
<td>68</td>
<td>92</td>
<td>110</td>
</tr>
<tr>
<td>with internal heat exchange</td>
<td>2 (*) 3.7 8.34E+06</td>
<td>44</td>
<td>25</td>
<td>127</td>
<td>104</td>
<td>92</td>
<td>62</td>
</tr>
<tr>
<td>Conventional distillation</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>1 (**) 3.7 1.57E+03</td>
<td>28</td>
<td>36</td>
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<td>68</td>
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<td></td>
<td>2 (*) 3.7 6.00E+05</td>
<td>44</td>
<td>25</td>
<td>127</td>
<td>104</td>
<td>92</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>3 (*) 2.5 4.49E+05</td>
<td>879</td>
<td>898</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>4 (**) 3.4 3.22E+06</td>
<td>1305</td>
<td>1324</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>5 (*) 2.5 8.10E+05</td>
<td>879</td>
<td>898</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

(*) Heat transfer area between condenser and evaporator is given as A=5 m²
(**) Heat transfer area is increased to A=10 m²

Figure 5 Internal heat exchange in heat-driven distillation system.
(pressure change: \( P_1 \rightarrow P_2 \)) is estimated by
\[
\frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{(R/C_p)}
\]
when the isentropic compression of vapor in the condensers is assumed. For example, as shown in Fig.5, the recycle vapor flow from the \( j \)-th evaporator, \( R^E_j \), has to be compressed from \( P^E_j \) to \( P^E_{j+1} \). Then, the temperature in the recycle flow is given as \( T^{RE}_j = \left( \frac{P^E_{j+1}}{P^E_j} \right) (R/C_p) T^{RE}_j \), where \( T^{RE}_j \) and \( C_p \) denote temperature of \( R^E_j \) flow and heat capacity, respectively. Thus, the work required for the compression of \( R^E_j \) flow is represented as (Ishida, 2002)
\[
W = \sum_{j=1}^{n} \{ R^E_j C_p T^{RE}_j \left[ \frac{P^E_{j+1}}{P^E_j} (R/C_p) - 1 \right] \}
\]

The compression of other vapor flows, \( V_j \) and \( F^V_j \), are also considered in the same manner and total work for the compression of vapor flows can be calculated.

**Figure 6** shows the appropriate pressure change of condensers for the HDD system with the internal heat exchange. These pressure profiles were determined under the condition that total exergy loss, \( T^{EXL} \), was minimized. When the pressures of condensers are adjusted according to Fig.6, the vaporization of liquid in the evaporators is done sufficiently by the internal heat exchange and the sum of external heats supplied to evaporators is evaluated as zero, namely \( \Sigma Q^E_j = 0 \).

**Figure 7** shows the effect of internal heat exchange on the energy consumption of HDD system. For the HDD system without the internal heat exchange, both the heat supplied from the heat source (temperature: \( T^n + 10K \)) to the evaporator, \( Q^E \), and that released from the condenser to the heat sink (temperature: \( T^C_j - 10K \)), \( Q^C \), were illustrated in Fig.7(a). A large amount of heat, 879 kJ/s, is supplied to the evaporators and released from the condensers. On the other hand, in the case with the internal heat exchange (heat transfer area: \( A=5m^2 \)), the heat required for
the vaporization of liquid in the evaporator is supplied by the internal heat exchange. Then, the supply of external energy to the process is only the work for the compression of vapor flows. The sum of these compression works is evaluated as 25 kJ/s. This value corresponds to about 1/35 of the heat required for the HDD system without the internal heat exchange and about 1/16 of that for the conventional distillation system. Sufficient energy-saving effect is expected by the introduction of internal heat exchange. From these results, we conclude that the HDD system with the internal heat exchange is valuable as a new energy-saving technology.

As shown in Fig.3, the increase in the recycle-flow rates, \( R_C^j \) and \( R_E^j \), is very effective for improving the separation performance of HDD system. The appropriate pressure change of condensers under the conditions that \( R_C^j=R_E^j=5 \text{ mol/s} \) were shown in Fig.6. When the heat transfer area is given as \( 5 \text{ m}^2 \), the compression of vapor flows in the pressure range of 1.5 to 3 atm is required for maintaining the recycle flow rates of \( 5 \text{ mol/s} \). The pressure of condenser can be reduced by improving the efficiency of internal heat exchange. By the increase in the heat transfer area from 5 to 10\( \text{ m}^2 \), the pressure of condenser is decreased in the range of 1.2 to 2.5 atm and total compression work is decreased from 104 to 68 kJ/s, as shown in Table 1. These results indicate that the energy-saving effect of HDD system can be further improved by the development of heat exchanger with high heat transfer area.

CONCLUSIONS

(1) The increase in the recycle flow rates, \( R_C^j \) and \( R_E^j \), is very effective for improving the separation performance of HDD system. The separation factor of methanol was increased to about 230 times by the increase in the recycle flow rates from 1 to 5 mol/s.

(2) The energy consumption of HDD system is increased in proportional to the recycle flow rates. Such energy consumption is reduced drastically by the introduction of internal heat-exchange process between the evaporator and condenser. The heat required for the vaporization of liquid in the evaporators can be supplied sufficiently from the condenser by the appropriate compression of the vapor flows in the condensers.

(3) The supply of external heat to the evaporators can be reduced to zero by introducing the internal heat exchange. The sum of works required for the compression of vapor flows to the condensers is evaluated as less than 4% of energy consumption of conventional distillation system with the same separation performance.

(4) The heat-driven distillation (HDD) system has excellent features for both the separation performance and the energy saving effect, which is superior to those of conventional distillation system. From these results, we conclude that the HDD system is valuable as a new energy-saving technology.

NOMENCLATURE

\( A \quad \text{Heat transfer area between evaporator and condenser \([m^2]\)}\)
\( B \quad \text{Flow rate of bottom \([\text{mol/s}]\)}\)
\( C_p \quad \text{Heat capacity of vapor \([J/\text{mol K}]\)}\)
\( D \quad \text{Flow rate of distillate \([\text{mol/s}]\)}\)
\( F_{L}^j \quad \text{Liquid feed to the j-th evaporator \([\text{mol/s}]\)}\)
\( F_{V}^j \quad \text{Vapor feed to the j-th condenser \([\text{mol/s}]\)}\)
\( \text{EXL}_{Tj}^L \quad \text{Exergy loss for temperature change of liquid flow at the j-th evaporator \([kJ/s]\)}\)
\( \text{EXL}_{Tj}^H \quad \text{Exergy loss for temperature change of liquid feed at the j-th evaporator \([kJ/s]\)}\)
\( \text{EXL}_{Tj}^R_C \quad \text{Exergy loss for temperature change of } R_C^j \text{ flow at the j-th evaporator \([kJ/s]\)}\)
\( \text{EXL}_{j}^{\text{max L}} \quad \text{Exergy loss for mixing of liquid flows at the j-th evaporator \([kJ/s]\)}\)
\( \text{EXL}_{j}^{\text{max V}} \quad \text{Exergy loss for pressure change of vapor flows at the j-th condenser \([kJ/s]\)}\)
**APPENDIX ---Mass and heat balance equations---**

For the calculation of mass and heat balance of heat-driven distillation system, the equilibrium between vapor and liquid are assumed for all evaporators and condensers. Therefore, both total mass balance and the mass balance for the i-th component are described as the following algebraic equations; For the top condenser and evaporator ($j=1$),

\[
F_1^V + V_2 = D + R_i^C
\]  \hspace{1cm} (A1a)

\[
F_1^C + R_2^C = L_1 + R_i^E
\]  \hspace{1cm} (A2a)

for the j-th condenser ($2 \leq j \leq n-1$)

\[
F_j^V + V_{j+1} + R_{j-1}^E = V_j + R_j^C
\]  \hspace{1cm} (A3a)

\[
F_j^C + R_j^C = L_j + R_j^E
\]  \hspace{1cm} (A4a)

and for the bottom condenser and evaporator ($j=n$)

\[
F_n^V + V_n = D + R_n^C
\]  \hspace{1cm} (A1b)

\[
F_n^C + R_n^C = L_n + R_n^E
\]  \hspace{1cm} (A2b)

\[
F_n^V + V_{n+1} + R_{n-1}^E = V_n + R_n^C
\]  \hspace{1cm} (A3b)

\[
F_n^C + R_n^C = L_n + R_n^E
\]  \hspace{1cm} (A4b)
On the other hand, the heat balance is calculated by use of the enthalpies of vapor and liquid. For the top condenser and evaporator (j=1),

$$Q = (C_{1n} - C_{1n}L) + (V_{1n} - V_{1n}L)$$  (A5a)

$$Q = (C_{1n}L - C_{1n}) + (V_{1n}L - V_{1n})$$  (A5b)

$$Q = (C_{1n} - C_{1n}L) + (V_{1n} - V_{1n}L)$$  (A6a)

$$Q = (C_{1n}L - C_{1n}) + (V_{1n}L - V_{1n})$$  (A6b)

For the j-th condenser (2 ≤ j ≤ n-1),

$$Q = (C_{j} - C_{j}L) + (V_{j} - V_{j}L)$$  (A7)

$$Q = (C_{j}L - C_{j}) + (V_{j}L - V_{j})$$  (A8)

for the j-th evaporator (2 ≤ j ≤ n-1),

$$Q = (C_{j} - C_{j}L) + (V_{j} - V_{j}L)$$  (A9)

$$Q = (C_{j}L - C_{j}) + (V_{j}L - V_{j})$$  (A10)

and for the bottom condenser and evaporator (j=n),

$$Q = (C_{n} - C_{n}L) + (V_{n} - V_{n}L)$$  (A11)

$$Q = (C_{n}L - C_{n}) + (V_{n}L - V_{n})$$  (A12)

From these equations, the supply of heat to evaporator, $Q^E_j$, and the release of heat from the condenser, $Q^C_j$, are evaluated. If the heat exchange between the j-th evaporator and the j-th condenser is considered, the heat transfer rate, $Q_j = A \cdot H \cdot (C_j^T - T_j^T)$, should be added in the heat balance equations, where A and H denote heat transfer area and heat transfer coefficient, respectively.

REFERENCES


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