

ANALYSIS OF HEAT DEMAND AND SUPPLY IN MULTICOMPONENT DISTILLATION SYSTEMS

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The energy analysis of distillation systems, especially the identification of heating and cooling zones in a column, is useful in the application of various energy-saving technologies to the systems. A method of analyzing the heat demand and supply for a binary system has been established, but there are few practical applications for multicomponent systems. One of the reasons is that the installation of an intermediate heat exchanger in a multicomponent distillation system changes the composition profile.

This paper proposes an energy analysis method for multicomponent distillation systems. With this method we defined appropriate locations of an intermediate heat exchanger, that is, heating and cooling zones, and its maximum exchangeable energy load. Especially, the relationships between the patterns of heating and cooling zones and the locations of pinch zones are investigated.

As a result, the upper and lower hypothetical pinch zones in a multicomponent distillation column terminate the heating zone at lower temperature, and the cooling zone at higher temperature, respectively. The conclusions are generalized by using graphical representations of the composition profiles.

Introduction

Distillation systems are most widely used as separation processes in chemical industry, but their energy consumption is much larger than that of other separation systems. It is necessary to carry out an analysis of heat demand and supply in distillation systems in order to reduce their energy demand. Naka *et al.*⁶⁾ have proposed several such energy-saving technologies, using the heat availability concept. Ishida *et al.*³⁾ have proposed an analysis method based on the exergy-direction factor diagram, which evaluates the exergy losses in a distillation column. However, both methods are applicable only to binary distillation systems.

Energy analyses of multicomponent distillation systems has been carried out that aim at representing the distinction graphically between unavoidable exergy loss and avoidable exergy loss⁴⁾, or to improve column design through the concept of practical near-minimum thermodynamic condition (PTNMC)¹⁾. However, these methods cannot be applied to a practical multicomponent distillation system design. One of the reasons is that the addition of an intermediate heat exchanger makes changes in the composition profile such that the desired products may not be assured.

The purpose of this work is to analyze the heating and cooling zones in a multicomponent distillation system by simulating one with an intermediate heat

exchanger. Furthermore, the calculated results will be generalized by use of the graphical representation method.

1. Heat-Exchanging Zones and Hypothetical Pinch Zones

For binary distillation systems with an infinite number of plates, there is one pinch point which generally separates the intermediate heating zones into heating and cooling zones. But for multicomponent systems there are one or two pinch points, and their locations can be categorized into four patterns as follows⁸⁾:

(Case P1) Non-distributed components exist in neither distillate nor bottoms. One pinch point appears at the feed plate.

(Case P2) Non-distributed components exist in distillate but not in bottoms. There are two pinch points in the enriching section and two more at the feed plate.

(Case P3) Non-distributed components exist in bottoms but not in distillate. Two pinch points appear in the stripping section and at the feed plate.

(Case P4) Non-distributed components exist in both distillate and bottoms. Two pinch zones appear in the enriching section and two more in stripping section.

As there is no method to calculate the pinch points in a multicomponent distillation column, in this paper the hypothetical pinch zones are defined by the concept

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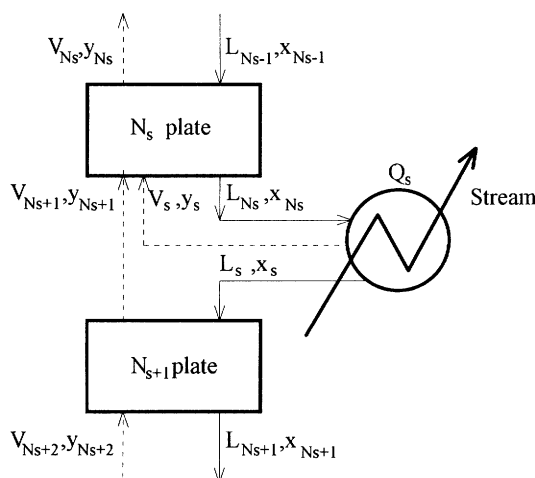


Fig. 1 Intermediate heater at the N_s -th plate

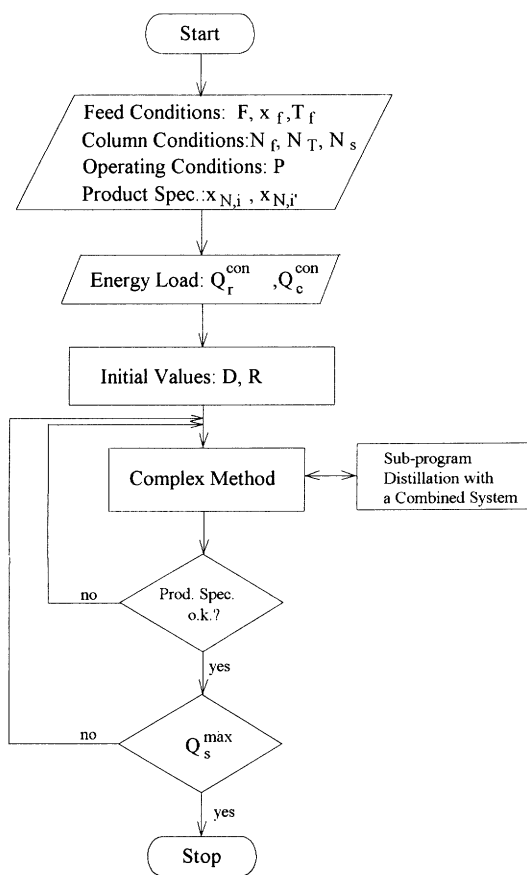


Fig. 2 Flowchart of computational procedures of Case H-2 and C-2

of a hypothetical pinch plate under the condition of a finite number of plates⁸⁾.

For energy saving, the following issues should be investigated: (1) the maximum exchangeable energy at a certain plate, and (2) the relationship between the heat exchanging zones and the hypothetical pinch zones. Both issues will be addressed by simulating a multicomponent distillation system with an intermediate heat exchanger, to be called a combined system hereafter.

Table 1. Operating conditions

System: Water(1)-Methanol(2)-Acetone(3)		
Reflux ratio	4.67	
Distillate flow rate	0.14	(kmol/h)
Feed flow rate	1	(kmol/h)
Feed temperature	58°C	
Feed composition	1) water	60.0%
	2) methanol	28.7%
	3) acetone	11.3%
Product specification	$x_{dh} \leq 0.00001$	
	$x_{wl} \leq 0.00001$	
Total number of plates	30	
Feed plate	14	
Operating pressure	101.3	(kPa)

Antoine's constants, Wilson's constants, specific heat capacity and latent heat vaporization are taken from Kojima, K⁵⁾

2. Simulation

For a conventional distillation system with multi-components, given the feed conditions of F , q and its components, and the operating pressure, it is possible to specify two independent variables—for example, two compositions of the bottoms. If an intermediate heater is added to the N_s -th plate as shown in Fig. 1, then one more degree of freedom is added. The simulation problems are described in accordance with the specification of the degree of freedom as follows:

Case H-1,C-1: Determination of feasible zones for intermediate heating (H) and cooling (C).

The flow rate of the distillate, D and two compositions of the bottoms are specified so that the products of a combined system are similar to those of a conventional distillation system. In this case, the exchangeable energy load (Q_s) can be obtained as a unique solution. The feasible heat-exchanging zone is defined as the zone where Q_s is more than zero.

Case H-2,C-2: Determination of maximum exchangeable energy load for heating (H) and cooling (C) at the N_s -th plate.

The maximum exchangeable energy load at the N_s -th plate ($Q_s^{\max}$) is defined as the maximum value of exchangeable energy under such conditions that the specified values of products are satisfied and the total energy load is equal to that of the conventional system. The reason why the $Q_s^{\max}$ is constrained as above will be explained further in section 3.2.

The computational procedures of Cases H-2 and C-2 are shown in Fig. 2. A combination of the matrix and relaxation methods is employed for the composition profile calculation, and the complex method is used for optimization.

3. Results

3.1 Conventional system

We introduce a conventional distillation system which satisfies $x_{N,1}$ and $x_{N,2}$ of the bottom products as a reference state, to evaluate a combined system with the

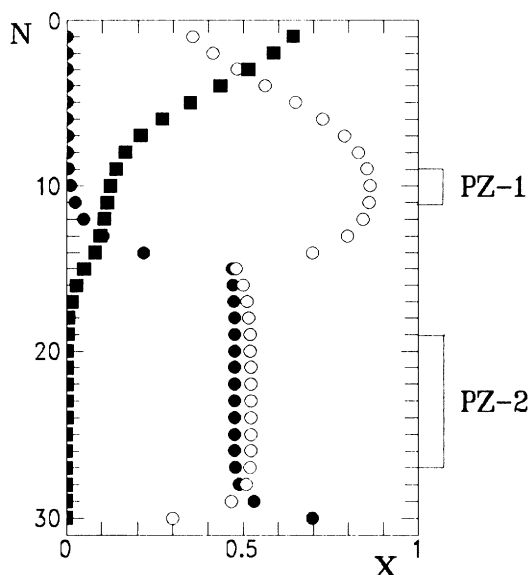


Fig. 3 Composition profile of conventional distillation column

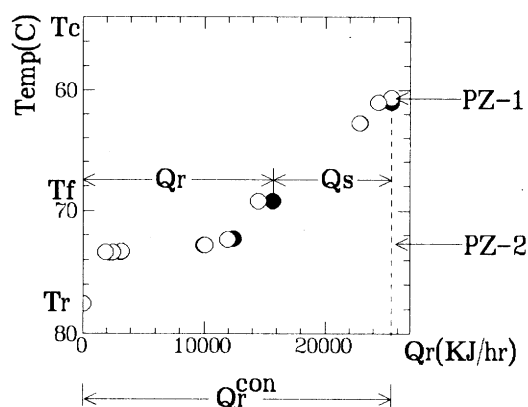


Fig. 4 Q_r , Q_s and the temperature in Case P4

same product specifications. The distillation system of water-ethanol-acetone was simulated and its operating conditions were determined so as to minimize the energy required at the reboiler, $Q_r^{\min}$, as shown in Table 1. The composition profile is shown in Fig. 3. There are two hypothetical pinch zones, one in the enriching section (PZ-1) and the other in the stripping section (PZ-2), which correspond to Case P4. The hypothetical pinch zones are recognized if the differences in compositions between two pairs of adjoining plates is regarded as zero.

3.2 Combined distillation system

(Intermediate heater) For Cases H-1 and H-2, the relationships among energy loads of the reboiler and the intermediate heater, Q_r and Q_s , and the temperature of the intermediate heater are shown in Fig. 4. The black and white circle points denote Cases H-1 and H-2, respectively. Q_r at a given plotted point shows the energy load of the reboiler in the case of intermediate energy load, Q_s , with temperature T_s . All points can be obtained by changing N_s , PZ-1 and PZ-2 in the reference

Table 2. The relationship among Q_s , Q_r and Q_c

N_s	Q_s (10^3 kJ/h)	Q_r (10^3 kJ/h)	Q_c (10^3 kJ/h)
20	7.5	18.1	25.2
20	15.5	10.1	25.1
20	20.0	9.9	29.5
20	22.5	9.8	31.5

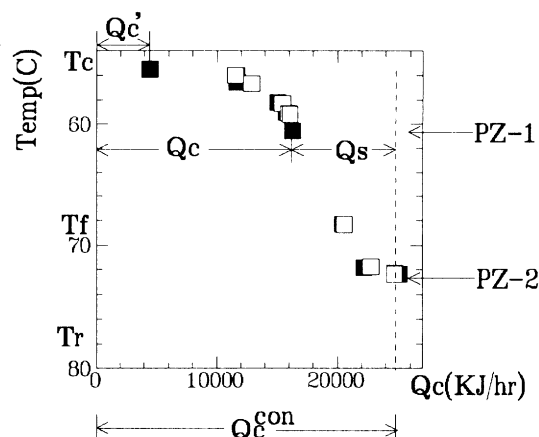


Fig. 5 Q_c , Q_s and the temperature in Case P4

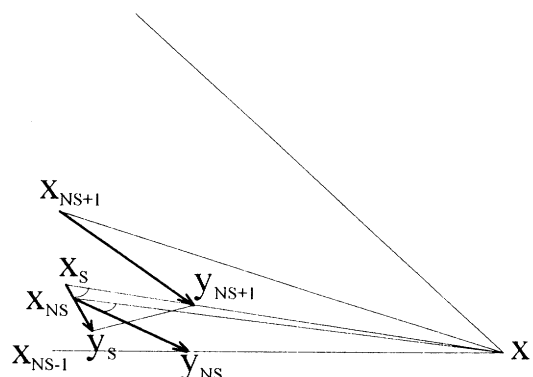


Fig. 6 Graphical representation of an intermediate heater in the enriching section

state are shown by arrows.

For Case H-1, it is obvious that Q_s can be supplied to the plates from PZ-1 to the reboiler, which is the heating zone. PZ-1 terminates the low-temperature side of the heating zone.

For Case H-2, if there is no restriction of total energy supplied to the column or removal of energy, the $Q_s^{\max}$ cannot be determined. As Q_s of an intermediate heater at the 20th plate increases, Q_r decreases but Q_c is kept constant, as shown in Table 2. However, when the sum of Q_s and Q_r is more than the minimum heat energy supplied to the conventional column, $Q_r^{\min}$, Q_r does not decrease but Q_c increases. It is clear that the excess energy of Q_s is removed by the condenser. Therefore, $Q_s^{\max}$ should be defined under the constraint of $Q_r^{\min}$. There is little difference in Q_r between Cases H-1 and H-2, because of the similarity of the top-product compositions in the individual cases. It is remarkable that the

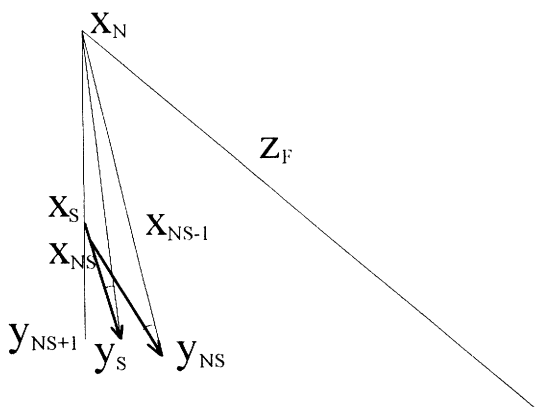


Fig. 7 Graphical representation of an intermediate heater in the stripping section

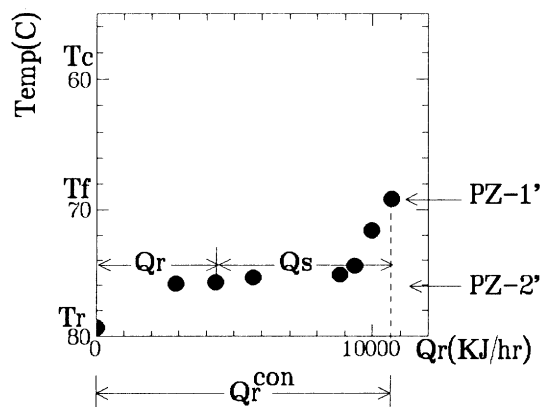


Fig. 8 Q_r , Q_s and the temperature in Case P3

heating zone from the results of both cases is terminated at the same pinch zone.

(Intermediate cooler) **Figure 5** shows the relationships among Q_s , Q_c and T_s at the N_s -th plate, where Q_s is removed in Cases C-1 and C-2. The black and white squares correspond to Cases C-1 and C-2, respectively. Q_c' shows the minimum requirement of heat energy to condense the vapor corresponding to D . It is clear that the results of Case C-1 are similar to those of Case H-1, as shown in Fig. 4. The cooling zone exists from the top to PZ-2. The PZ-2 in the stripping section bounds the cooling zone. $Q_s^{\max}$ cannot be defined for the same reason for an intermediate heater. The cooling zone from the results in both cases is terminated at that same pinch zone.

4. Graphical Representation

4.1 Intermediate heater

In the case of an intermediate heater, it is not clear why the heater cannot be applied to PZ-1 while still applicable to PZ-2. The problem with an intermediate cooler is similar. Let us investigate these problems using graphical representation—an approach that represents relationships between mass balance equations and vapor-liquid equilibrium²). **Figure 6** shows the relationship in

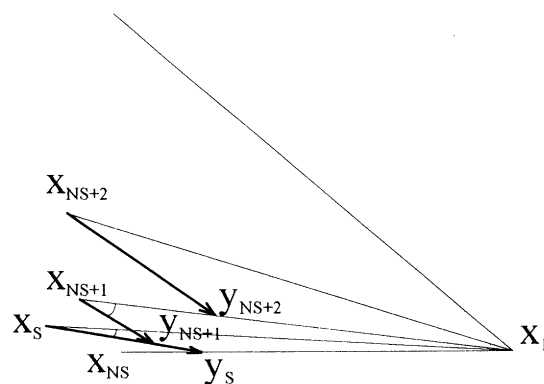


Fig. 9 Graphical representation of an intermediate cooler in the enriching section

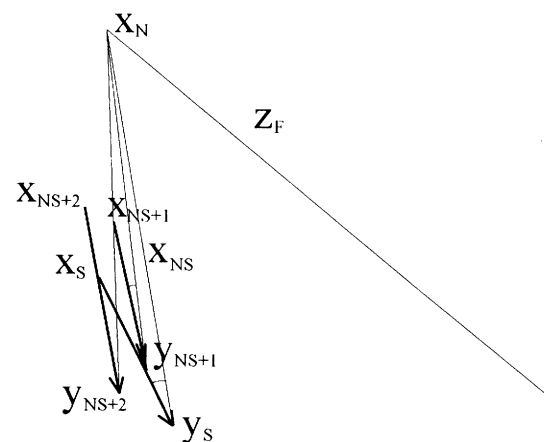


Fig. 10 Graphical representation of an intermediate cooler in the stripping section

the case of an intermediate heater at the N_s -th plate in the enriching section. Each arrow denotes a vapor-liquid tie line. The mass balance lines are denoted by the straight lines. In general, the angle between a vapor-liquid tie line and a mass balance line from a given plate to the top almost corresponds to the degree of separability.

The x_{N_s} point is apart from the x_s due to an intermediate heater having a small amount of heat energy. As the angle of $x_1x_{N_s}y_{N_s}$ is smaller than the angle of $x_1x_sy_s$, the separability with respect to the intermediate heater is less than that of the previous plate. Thus installation of an intermediate heater in the enriching section makes separation more difficult. Particularly, as the mass balance lines in PZ-1 are very closely packed, an intermediate heater in PZ-1 brings the mass balance lines closer together. This indicates that an intermediate heater cannot usefully be installed in PZ-1.

In the case of an intermediate heater installed into the stripping section, as shown in **Fig. 7**, the angle of $x_Ny_{N_s}x_{N_s}$ is larger than the angle of $x_Ny_sy_s$. That is, an intermediate heater makes separation easier. This allows the installation of an intermediate heater in the stripping section.

The above-mentioned results can qualitatively interpret the calculated results of Cases H-1 and H-2

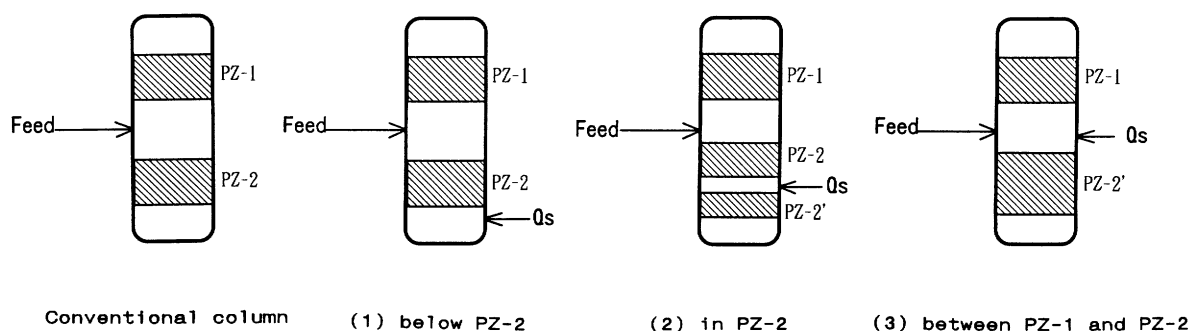


Fig. 11 Influence of an intermediate heater on the composition profiles

with respect to Case P4. The other patterns of the pinch zones as mentioned in Sec. 2 can be similarly interpreted. **Figure 8** shows the relationships among Q_r and Q_s and the temperature of an intermediate heater in Case P3. It is shown that the hypothetical pinch zone around the feed plate, defined as PZ-1', in which non-distributed components do not exist in distillate, terminates the heating zone. As a result, for Case P1, it is obvious that the hypothetical pinch zone bounds the heating and cooling zones, respectively, as in a binary system.

4.2 Intermediate cooler

Figure 9 shows the graphical representation in the case of an intermediate cooler with a small amount of cooling energy in the enriching section. The angle of $x_1x_{N_s+1}y_{N_s+1}$ is larger than the angle of $x_1x_sy_s$. However, for the stripping section the angle of $x_Ny_{N_s+1}x_{N_s+1}$ is smaller than the angle of $x_Ny_sy_s$, as shown in **Fig. 10**. It is clear that an intermediate cooler in the stripping section makes separation more difficult and thus cannot be installed in PZ-2. Similarly to an intermediate heater, the results from the graphical representation can interpret the calculated results for Cases C-1 and C-2.

4.3 Influence of intermediate heating on hypothetical pinch zones

As a result of the above-mentioned simulation, the installation of an intermediate heater influences the hypothetical pinch zones as shown in **Fig. 11** as follows:

- (1) Intermediate heater installed below PZ-2: The compositions and locations of both hypothetical pinch zones are similar to those of the respective references.
- (2) Intermediate heater installed in PZ-2: PZ-2 is divided into two hypothetical pinch zones, one with the same composition as that of PZ-2 and the other with a different one. They are defined as PZ-2 and PZ-2', respectively. The latter is regarded as a new hypothetical pinch zone created by the addition of the intermediate heater.
- (3) Intermediate heater installed between PZ-1 and PZ-2: The composition and location of the hypothetical pinch zone in the enriching section are similar to those of PZ-1. But the composition of the hypothetical pinch zone in the stripping section is different from that of PZ-2, and is defined as PZ-2'. Therefore, the latter seemed to be the new hypothetical pinch zone created by the addition of the intermediate heater and is broader than PZ-2.

When additional installation of an intermediate heater is considered, if an energy load less than $Q_s^{\max}$ is supplied to one intermediate heater at the N_s -th plate, an additional heater can be installed in the region of the reboiler to PZ-1. But if $Q_s^{\max}$ is supplied, an additional heater is possible below the N_s -th plate, so as to satisfy the product specifications. In general, it is possible to reduce some plates within the hypothetical pinch zone. This figure may be utilized in investigating the possibility of a more economical design.

Conclusions

The heating and cooling zones in a multicomponent distillation system were analyzed by simulation and graphical representation in this paper. The following results were obtained.

- (1) The heating zone is bounded by the bottoms and the hypothetical pinch zone, where the heavy key-component disappears. On the other hand, the cooling zone is bounded by the top of the column and the hypothetical pinch zone where the light key-component disappears. Intermediate heating and cooling are possible in the region between two hypothetical pinch zones. For Case P1, the heating and cooling zones can be obtained in a similar way as for a binary system.
- (2) The locations of the hypothetical pinch zones change according to the location where an intermediate heat exchanger is installed.
- (3) $Q_s^{\max}$ at a given plate should be defined under the constraint of $Q_r^{\min}$ and depends upon the feed conditions and product specifications.

The results mentioned above and the calculation method can generally be utilized in designing various energy-saving applications for a distillation system.

Nomenclature

D	= flow rate of distillate	[kmol/h]
F	= Feed flow rate	[kmol/h]
L	= liquid flow rate	[kmol/h]
N	= number of plates	
Q	= energy load	[kJ/h]
R	= reflux ratio	
T	= temperature	[°C]
V	= vapor flow rate	[kmol/h]
W	= flow rate of bottoms	[kmol/h]
x	= liquid mole fraction	

y = vapor mole fraction
z = feed mole fraction

<Subscripts>

b = bottoms
c = condenser
d = distillate
f = feed
h = heavy component
i = component number
j = plate number
l = light component
r = reboiler
s = intermediate heater/cooler
w = bottoms

<Superscripts>

con = conventional
max = maximum
min = minimum

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